Geosci. Model Dev., 7, 2359–2391, 2014
www.geosci-model-dev.net/7/2359/2014/
doi:10.5194/gmd-7-2359-2014

Geoscientific Model Development
Open Access

Grassland production under global change scenarios for New Zealand pastoral agriculture

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Received: 4 April 2014 – Published in Geosci. Model Dev. Discuss.: 12 May 2014
Revised: 15 September 2014 – Accepted: 15 September 2014 – Published: 16 October 2014

Abstract. We adapt and integrate the Biome-BGC and Land Use in Rural New Zealand models to simulate pastoral agriculture and to make land-use change, intensification of agricultural activity and climate change scenario projections of New Zealand's pasture production at time slices centred on 2020, 2050 and 2100, with comparison to a present-day baseline. Biome-BGC model parameters are optimised for pasture production in both dairy and sheep/beef farm systems, representing a new application of the Biome-BGC model. Results show up to a 10 % increase in New Zealand's national pasture production in 2020 under intensification and a 1–2 % increase by 2050 from economic factors driving land-use change. Climate change scenarios using statistically downscaled global climate models (GCMs) from the IPCC Fourth Assessment Report also show national increases of 1–2 % in 2050, with significant regional variations. Projected out to 2100, however, these scenarios are more sensitive to the type of pasture system and the severity of warming: dairy systems show an increase in production of 4 % under mild change but a decline of 1 % under a more extreme case, whereas sheep/beef production declines in both cases by 3 and 13 %, respectively. Our results suggest that high-fertility systems such as dairying could be more resilient under future change, with dairy production increasing or only slightly declining in all of our scenarios. These are the first national-scale estimates using a model to evaluate the joint effects of climate change, CO_2 fertilisation and N-cycle feedbacks on New Zealand's unique pastoral production systems that dominate the nation's agriculture and economy. Model results emphasise that CO_2 fertilisation and N-cycle feedback effects are responsible for meaningful differences in agricultural systems. More broadly, we demonstrate that our model output enables analysis of decoupled land-use change scenarios: the Biome-BGC data products at a national or regional level can be re-sampled quickly and cost-effectively for specific land-use change scenarios and future projections.

1 Introduction

Intensive pasture grazing systems dominate New Zealand's agricultural production, in contrast to the cultivated cropland and animal feeding operations that make up the majority of agriculture in other developed countries worldwide. In this respect New Zealand is unusual, with the national scale and economic importance of its pastoral agriculture system representing an extreme. The dairy and sheep/beef industries in particular are central to the New Zealand economy. Production from primary industries makes up 12 % of New Zealand's GDP, of which the dairy industry alone contributes almost 3 %. Dairy products comprise over a quarter of New Zealand's total exports, with an export value of NZD 13.9 billion for the year 2011/12. Meat and wool exports are also significant, with beef and lamb export value at NZD 5.6 billion in 2011/12 (New Zealand Ministry for Primary Industries, 2012; Schilling et al., 2010). While sheep and beef farms still make up the majority of agricultural land, dairy farming is rapidly expanding in size and area, continuing a long-term decadal shift towards more intensive but historically more profitable dairy pasture. New Zealand's future

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pasture production thus features prominently in many national projections in economics, primary production and the environment, including water quality and climate change impacts and adaptation.

Consequently, there is a need to understand possible changes to the productivity of New Zealand's pastoral agriculture systems under a range of future scenarios. Because New Zealand depends almost exclusively on pasture for animal feed, climate change could have considerable effects on the nature and profitability of dairy and sheep/beef farming in the short and long term. In addition to economic considerations, pasture production estimates are crucial in addressing questions of environmental sustainability. Unlike most developed countries, whose greenhouse gas (GHG) emissions are largely derived from fossil fuels and carbon dioxide (CO_2), almost half of New Zealand's GHG emissions arise from agriculture and methane (CH_4). Accurate estimates of pasture production are required to understand such questions as whether feed supply can become a limiting factor on the number of grazing animals used to calculate New Zealand's emissions of methane and nitrous oxide (N_2O).

Complex environmental and policy questions such as these can be addressed through integrated modelling assessments of the impact of climatic, economic, and land management factors on future agricultural productivity. There are many examples of studies at the global, regional, and national level that couple dynamic biophysical process-based or statistical crop models with climate and land-use data sets to estimate quantities such as carbon flux and storage, net primary productivity (NPP) and water availability for both managed and natural ecosystems under future climate and management scenarios (Beer et al., 2010; Bondeau et al., 2007; Gumpenberger et al., 2010; Rost et al., 2009; Roudier et al., 2011). Coupling models in this way is important in accounting for non-linear feedbacks and interactions between climate, the carbon cycle, and land-use and management decisions, which can be quite significant (Ronneberger et al., 2006). Additionally, it is essential to integrate climate change effects and feedbacks into economic and policy assessments for their impact to be considered in the decision-making process and to affect long-term planning and preparedness.

The present study is intended to develop flexible output and data products at a national or regional level that enable the examination and analysis of a range of scenarios and their possible impacts on pasture production in New Zealand at particular time slices over the next 100 years. It builds on previous research efforts and existing data sets to understand some of the biophysical, climatic, economic, and land management variations that might affect the future productivity of New Zealand's pastoral agriculture. Like many small countries, New Zealand (population 4.5 million, land area 260 000 km^2) requires cost-effective model infrastructure that is capable of evaluating policy options on timescales of months or weeks. The development of the Land Use in Rural New Zealand (LURNZ) model meets this challenge and, importantly, enables the integration of global change scenarios with contemporary policy choices. Before outlining the rationale for our model infrastructure, it is useful to briefly review the history of integrated model development in New Zealand, primarily aimed at the climate change component of global change.

Earlier integrated modelling studies of New Zealand pasture include the 2001 CLIMPACTS study (Warrick et al., 2001), which used a global climate model in combination with New Zealand data sets to produce estimates of pasture production based on scenarios from the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report. The more recent EcoClimate Report (Stroombergen et al., 2008) estimated productivity for 2030 and 2080 for several agricultural sub-sectors, including sheep/beef and dairy pasture systems, and provided a preliminary integrated assessment of possible economic costs and benefits of climate change. National and regional projections were based on a climate-index approach (Baisden, 2006) and statistically downscaled scenarios from the HadCM2 model in the 2001 IPCC Third Assessment Report (Mullan et al., 2005). However, the methodology does not account for the potentially important effects of increased carbon dioxide concentrations in the atmosphere (CO_2 fertilisation) and the interaction with progressive nitrogen (N) limitation. The earlier CLIMPACTS methodology accounted for CO_2 fertilisation but not N limitation. These omissions could alter results substantially because studies involving the effect of CO_2 fertilisation on plant physiology and growth suggest that plant biomass increases overall under elevated CO_2, but the response depends strongly on nutrient (N and P) availability (Ainsworth and Long, 2005; de Graaff et al., 2006; Newton et al., 2010).

To address these concerns about the lack of CO_2–N–climate interactions and feedbacks, and also to fulfil the need for a suitable temporal and spatial resolution, we use the Biome-BGC model. The model provides a level of complexity intermediate between simple climate-index-driven pasture production and a full farm system model (e.g. APSIM, Keating et al., 2003), which can be difficult to extrapolate across space and apply at a national scale. Biome-BGC is able to simulate daily climate variables, water availability and irrigation, CO_2 fertilisation effects, all relevant nitrogen inputs and outputs, and the utilisation of pasture by grazing animals without requiring an overwhelming level of detail about individual farms.

We simulate the two dominant types of pasture systems in New Zealand, which we will refer to as "dairy" and "sheep/beef". The main difference between these two systems is the intensity of grazing, dairy being the more intensive of the two. Dairy farming is associated with highly productive pasture and therefore involves higher stocking rates, more nitrogen fertilisation, a larger amount of animal products extracted from the system, and often the addition of irrigation (which we do not model here). We develop model parameterisations for each type of pasture system that enables the simulation of national and regional pasture production for the present baseline and projections for future scenarios. By then sampling the model's output across land-use extents, we introduce analysis of decoupled land-use change scenarios (DLUCSs): the pasture data products at a national or regional level can be re-sampled quickly and cost-effectively for specific land-use change projections. This is a flexible approach that can be easily applied to many specific scenarios of climate and land-use change, not only the ones presented here. Herein, we describe our process of parameterising Biome-BGC for grazed pasture agro-ecosystems on a ~ 5 km grid covering New Zealand, explain our methodology and choice of model scenarios, and report national production results for dairy and sheep/beef systems.

2 Methods

2.1 Biome-BGC model

The Biome-BGC (Bio-Geochemical Cycles) model v4.2 Final Release (Thornton et al., 2005) is an ecosystem process model that simulates the biological and physical processes controlling cycles of carbon, nitrogen and water of vegetation and soil in terrestrial ecosystems. The model is capable of simulating evergreen, deciduous and broadleaf forests, C3 and C4 grasslands, and shrub ecosystems. The primary input consists of weather conditions at a daily time step, as well as site-specific information such as elevation, soil composition and rooting depth. In addition, there is a set of 43 adjustable ecological parameters that can be customised for a particular ecosystem. The model and its parameters are described in detail in Thornton et al. (2002), White et al. (2000), and Thornton (1998). The Biome-BGC model has been extensively tested and validated for North American and European evergreen and deciduous forest, grassland, and mixed ecosystems (Jung et al., 2007; Pietsch et al., 2005; Bond-Lamberty et al., 2005; Wang et al., 2009). There have also been other adaptations of the Biome-BGC model to managed agricultural systems and crops (Hidy et al., 2012; Di Vittorio et al., 2010; Wang et al., 2005) that involve supplementary code and/or that are specific to grasses and crops in other regions. Extension to New Zealand ecosystems and managed pasture systems represents a new application. We adapt the model through parameter adjustments rather than by modifying model code.

We used the Biome-BGC model's built-in C3 grassland mode to simulate our two managed pasture systems: dairy and sheep/beef. While the core model is not currently designed for farm systems or the presence of grazing animals, we can reinterpret or redefine some of the model's ecological parameters and calibrate them to adequately represent grazing and harvest. Specifically, the "annual whole-plant mortality fraction" parameter can be related via a simple algebraic formula to pasture utilisation (the fraction of above-ground biomass production eaten by grazing animals):

$$\text{whole plant mortality} = \frac{\text{pasture utilisation}}{(1 + \text{leaf : fine root C})}, \tag{1}$$

where leaf : fine root C is a model parameter representing the relative allocation of carbon above and below ground. Intuitively, plant mortality increases along with the amount of grass eaten. For the sake of simplicity we have assumed a nationwide fixed level of pasture utility of 0.55 and 0.90 in sheep/beef and dairy pasture systems, respectively. This results in a mortality proportion that is much higher than that of a natural grassland (default is 0.1). In the same manner, the removal of meat and milk products from the system is factored into the model's "annual fire mortality fraction" parameter, which describes the proportion of plants that die due to fire each year and that is effectively removed from the ecosystem. Since fire is not normally a significant occurrence in managed pasture, in our model this fraction represents the approximate proportion of nutrients removed from the ecosystem via milk and meat production. We have set dairy systems to have twice the proportion removed (0.2) as sheep/beef (0.1). (The default for grassland is 0.1.)

We have also included the combined effects of managed fertiliser application and fertility-driven nitrogen fixation through the model's site-specific nitrogen fixation input parameter. The symbiotic and asymbiotic nitrogen fixation rate is typically of the order of 10^{-4} kgN m^{-2} year^{-1} for most naturally occurring ecosystems. To represent fixation under high P fertilisation regimes and urea or other N additions common in New Zealand dairy farming, we have set this rate much higher, of the order of 10^{-2}. In our parameterisation, dairy systems have twice the rate of N input via fixation and fertilisation (0.032 kgN m^{-2} year^{-1}) as sheep/beef (0.018 kgN m^{-2} year^{-1}).

2.2 LURNZ model

To develop an estimate of actual total national pasture productivity, we combined information from the Land Use in Rural New Zealand (LURNZ) model v2 with the pasture production outputs from the Biome-BGC model. The LURNZ model (Hendy et al., 2007, 2008; Timar, 2011; Kerr et al., 2012) was developed to explain and simulate changes in four major rural land-use types in New Zealand: dairy, sheep and beef, plantation forestry and regenerating natural forest (henceforth termed scrubland). LURNZ models land use both dynamically, based on national time-series econometric estimates of land-use change, and spatially, based on cross-sectional observations of biophysical and socio-economic land attributes. Of most relevance to modelling future pasture production is the ability of LURNZ to evaluate any scenario that can be expressed as a commodity price change in one of the four sectors. The model provides a baseline of actual land use in 2008 and scenario projections for changes to land use in 2020 and 2050 in response to an imposed price on carbon (and agricultural CH_4 and N_2O emissions, converted to CO_2 equivalent terms). In the climate change scenarios that follow, our dairy and sheep/beef regional breakdown and total national estimates are based on the LURNZ model's observed land-use distribution in 2008, and land-use scenarios are based on projected dynamic change in dairy and sheep/beef land uses in 2020 and 2050.

2.3 Climate and input data sets

The New Zealand National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station Network (VCSN) provides the daily weather input required by the Biome-BGC model. The VCSN is a set of virtual "weather stations" that uses interpolation techniques to provide detailed weather information at each point on 0.05° grid covering all of New Zealand, approximately 5×5 km resolution (Tait et al., 2006). Daily weather data are available for each grid cell from 1972 to the present. Direct and indirect inputs to the model from the network include maximum and minimum temperature, precipitation, solar radiation, relative humidity, vapour pressure deficit, and wind run (available from 1997). Before running each model scenario, the model is first "spun up" by recycling the input data sets as many times as necessary for the model to reach a steady state over $\sim$ 1000–2000 years (Thornton and Rosenbloom, 2005).

Future climate change scenarios circa 2050 and 2100 were statistically downscaled to the VCSN using three global climate models (GCMs) from the IPCC Fourth Assessment Report (AR4): giss-eh (NASA/Goddard Institute for Space Shuttles, USA, rererred to as "GIEH"), mpi_echam5 (from the Max Planck Institute in Germany, referred to as "MPI") and cccma_cgcm3_1 (from the Canadian Climate Centre, referred to as "CCC"). This input nominally refers to the 9-year period from 2046 to 2054 and the 15-year period from 2097 to 2111, although it is meant to represent an approximate time frame of 50 and 100 years from the present day. Further explanation of these scenarios is in Sect. 3 (see also Renwick et al., 2013; Baisden et al., 2010).

Although the Biome-BGC model does not have an explicit mechanism to incorporate daily wind speed, wind does have a significant evaporative effect on pasture growth in many New Zealand regions. We account for the role of wind in enhancing water loss from pastures by correcting the daily water vapour pressure deficit (VPD) input data with the predicted FAO Penman–Monteith effect of wind on evapotranspiration for grasslands. This effect is particularly important where hot, dry northwesterly winds enhance seasonal drought in the hill country and plains of New Zealand's east coast regions. The modified VPD (which becomes the direct daily VPD input to the model) is calculated from the following equation for evapotranspiration (Allen et al., 1998):

$$\mathrm{ET_o} = 0.408 \cdot \Delta (R_\mathrm{n} - G) + \frac{\gamma \left(\frac{900}{T+273}\right) u_2 (e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma (1 + 0.34 u_2)}, \qquad (2)$$

where $\mathrm{ET_o}$ is reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), $(e_\mathrm{s} - e_\mathrm{a})$ the saturation vapour pressure deficit (kPa), Δ the slope vapour pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). For our purposes, we take $G = 0$ and $\gamma = 0.054$, and Δ is the following:

$$\Delta = 2503.06 \frac{\exp\left(\frac{17.27T}{237.3+T}\right)}{(237.3+T)^2}, \qquad (3)$$

where T is again the mean daily air temperature.

The required soil texture and effective rooting depth for each site was obtained from the New Zealand Fundamental Soil Layers (FSL) data set (Landcare Research, 2014), which contains spatial information for 16 soil attributes, including soil texture classes. The soil texture classes were matched to the percentages of sand, silt and clay required by the model by visually identifying modal soil textures present in the National Soils Database.

National and regional pasture production is given in terms of both kilograms of dry matter per hectare and metabolisable energy (MJ per kg dry matter). Remote sensing, augmented by on-the-ground calibration, was used to estimate the seasonal metabolisable energy for all sites from model output.

2.4 Model calibration and validation

To adapt the Biome-BGC model for intensive pastoral agriculture, we adjusted key ecological parameters to optimise model output to measured pasture growth data in selected locations across New Zealand. Treating sheep/beef and dairy pasture systems as two different "biomes", we developed a unique parameterisation for each type of system. We used an automated parameter estimation software package, PEST v12.0 (Doherty, 2005), which employs the Gauss–Marquardt–Levenberg inversion method to optimise a model's output to user-supplied observation data. We fit the model's net primary production (NPP) output to historical pasture clipping data from six sites spread temporally and geographically across New Zealand (three dairy and three sheep/beef). Pasture data are typically reported in units of dry matter (DM); NPP can be converted to the equivalent amount of dry matter with the following:

$$\mathrm{DM} = 2.0 \cdot \left(\frac{r_\mathrm{ab}}{r_\mathrm{ab} + 1}\right) \cdot \mathrm{NPP}, \qquad (4)$$

where r_{ab} is the ratio of above-ground to below-ground allocation (given by the inverse of the new fine root C : new leaf C allocation parameter in the Biome-BGC model).

Calibration sites are depicted in Fig. 1 and additional detail about the sites is in Table 1. Pasture growth data at the three dairy calibration sites were obtained from Landcorp Farming (C. Isaacs, personal communication, 2011) and publicly available data from DairyNZ (DairyNZ, 2011) and Lincoln University Dairy Farm (South Island Dairying Development Centre, 2014). Data at the three sheep/beef sites were obtained from Beef + Lamb New Zealand (Clarke-Hill and Fraser, 2007) and previously published articles (Rosser and Ross, 2011; Smith et al., 2012). Data consist of monthly, bi-weekly, or weekly measurements of pasture clippings over a period of at least 2 continuous years and up to 7 years in the case of Winchmore Research Station in Canterbury. These sites were chosen on the basis of geographic location and data availability; we attempted to balance the desire to include a range of climates and regions in New Zealand with the need for high-quality and complete data sets. All data used for calibration were taken from non-irrigated pasture, with the exception of Lincoln University Dairy Farm (in this case irrigation was also simulated in the model during calibration by adding additional precipitation to the meteorological data input file when soil moisture deficit was above a threshold). The site at Te Whanga in the Wairarapa region provides three different data sets from hillside landslide scars of varying ages: a slip that occurred in 1961, a slip in 1977, and one uneroded location. This site is useful for model calibration because recent scars have shallower soils, resulting in lower water storage capacity, thus providing pasture production records under identical climate but varying soil properties (Rosser and Ross, 2011). The Biome-BGC rooting depth parameter is adjusted according to scar age, providing a way to calibrate the model against topsoil depth.

The parameterisation produced a good fit between model output and the observed annual mean production and seasonal cycle of pasture growth. Comparing daily average growth rates over each observation period, the correlation coefficient R^2 for all dairy and sheep/beef sites is 0.64 and 0.70, respectively. Figure 2 displays the pasture clipping data and the optimised model fit for each of the calibration sites on a temporal scale. Figure 3 shows a direct comparison of observed and modelled data from all dairy (left) and sheep/beef (right) sites. Figure 3 also reports major axis regression statistics performed by the lmodel2 v1.7-2 package in R v3.0.2 (Legendre, 2014; R Core Team, 2013) to quantify the model–data relationship. A full list of adjusted and default parameters is in Appendix A.

To validate the sheep/beef model, we chose an additional 22 sites with pasture clipping data (Clarke-Hill and Fraser, 2007) over a similar time period (2003–2005), selected for data completeness and geographical spread. Figure 1 shows the locations of the validation sites. Overall correlation R^2 for these sites when comparing individual measurement intervals is 0.36. The scatter plot shown in Fig. 4 reveals that the model is biased low at higher values, often underestimating the observed peaks in production in spring and summer. The three northernmost sites (Broadwood, Tauranga, and Whakatane) perform very poorly, possibly because the climate is warmer than the rest of New Zealand and C4 grasses (rather than C3) are common. Removing these sites, R^2 rises to 0.41. There is also significant variation in pasture age, hill slope, fertilisation and nutrient content among individual sites that are not included in our model and could account for the large difference in model fit at specific locations. Monthly averages over several years generally compare better to observations (Fig. 4), but there is still a bias during spring and summer months. The correlation coefficient R^2 for monthly averages aggregated over 3 years of pasture clipping data for all validation sites is 0.48, and without the three northern sites is 0.59. The relationship between the model and measurements in Fig. 4 is quantified with major axis regression statistics using the same methodology as in Fig. 3.

Figure 1. Calibration and validation sites. Left: dairy and sheep/beef calibration sites. White circles are sheep/beef sites, and red squares are dairy sites. Right: sheep/beef validation sites. The three most northern sites (Broadwood, Tauranga, and Whakatane) are outliers in terms of model–observation fit.

For the dairy model, no additional spatially varying data were available for validation at the time of our study. Consequently, we use national milk production data as a proxy for pasture growth and an evaluation of model performance. In a separate report, we examined the relation between modelled pasture production and total national milk solids production data for New Zealand (Keller, 2012), finding excellent correlation in the 6 years from June 2006 to May 2012 (annual milk season in New Zealand runs from June to May) and moderate correlation over the last 15 years ($R^2 = 0.86$ and 0.46, respectively). Although indirect, this demonstrated relation to actual milk production data allows us to have reasonable confidence in the national model output.

Table 1. Calibration sites, location, description and dates of pasture growth data used for model calibration.

Site	Location	Description	Data availability	Mean annual rainfall (mm)	Mean daily max/min temperature (°C)
Whatawhata	−37.80° S 175.15° E Waikato	Sheep/beef, easy hills	Jan 2003–Sep 2005 monthly intervals	1607	19/9.6
Te Whanga Station	−41.03° S 175.74° E Wairarapa	Sheep/beef, hillside landslide scars	Jun 2007–Aug 2009 2-month intervals (three distinct sites)	886	18/7.4
Winchmore Irrigation Research Station	−43.83° S 171.71° E Canterbury	Sheep/beef, flat	Jan 1997–Dec 2003 monthly intervals	715	17/5.7
DairyNZ Scott Farm	−37.77° S 175.36° E Hamilton	Dairy, large-scale farm system trials	Aug 2009–May 2011 weekly intervals	1086	19/8.8
Lincoln University Dairy Farm (LUDF)	−43.64° S 172.44° E Canterbury	Dairy, irrigated	Jan 2005–Dec 2009 weekly intervals	604	17/6.8
Landcorp Waitepeka Dairy Farm	−46.29° S 169.67° E Southland	Dairy	Jan 2004–Dec 2009 monthly intervals	701	15/5.7

We focus primarily on seasonal and annual averages at a national level in this study. In addition, because we are evaluating future scenarios relative to the baseline and are not concerned with absolute levels of production, our subsequent analysis is minimally affected by model bias.

2.5 Methodology and model scenarios

We introduce DLUCS methodology to construct and analyse model scenarios: we simulate biophysical conditions affecting grass growth with the Biome-BGC model to produce an estimate of pasture production at all locations on the national grid, then sample selectively according to the specific land use or economic situation modelled with LURNZ. Scenarios can be anything that can be modelled through changes in weather or nutrient input and/or economic drivers of land-use change. Land use is decoupled from the biophysical dynamics of plant growth, and the two are integrated at the final stage. By creating a national production data set with Biome-BGC and then re-sampling it using the output from LURNZ, we are able to quickly examine many different plausible land use and economic scenarios relevant for policy decisions, including the response to climate change.

Scenarios for this project were developed in consultation with the New Zealand Ministry for Primary Industries (MPI) and reflect factors that are assumed to have significant impact on pasture productivity in New Zealand. All scenarios are constructed to represent averages over 9-year periods centred on 2005, 2020, or 2050 and, in the case of climate change in 2100, the 15-year period from 2097 to 2111. We run the model for each type of pasture for all grid cells, regardless of actual land use; results are mapped for dairy and sheep/beef systems as if all available land (exclusive of conservation land, water, year-round ice cover and urban areas) were devoted to that system. We then calculate regional and national pasture production totals by summing production from each grid cell categorised as either dairy or sheep/beef in LURNZ. Spatial mapping and production summation were performed using ArcGIS 9.3 (ESRI, 2009). With the exception of the land-use change scenarios, all land-use categorisations are derived from the LURNZ model's 2008 map, based on actual data, and stay constant at 2008 levels in climate and intensification scenarios at 2020, 2050 and 2100 in order to keep the effects of land-use change separate from the other effects that we simulate. The scenarios chosen are intended, as much as possible, to isolate a single effect, so that the sensitivity of pasture production to that particular effect alone can be estimated relative to the baseline. However, we note that some scenarios are closely linked, and in practice it might not be realistic to consider each one in isolation. We describe each scenario in detail in the following sections.

2.5.1 Baseline

The baseline scenario is the output from the Biome-BGC model run using actual climate data from the VCSN for 2001–2009, averaged over the 9 years. This scenario is intended to represent "present-day" climate and to serve as a

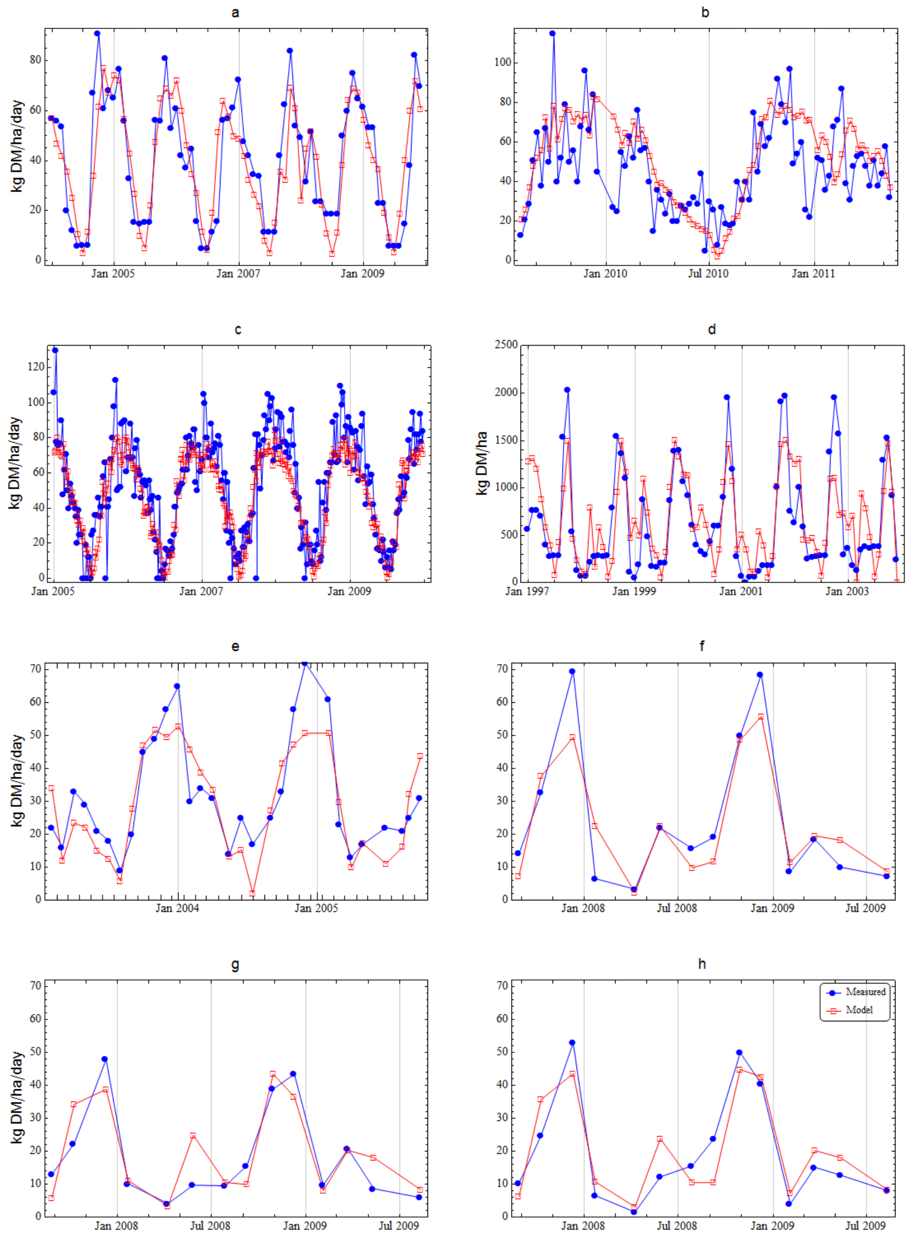

Figure 2. Modelled and measured pasture growth at calibration sites. Growth (in average kilograms of dry matter per hectare per day) versus time at all dairy **(a–c)** and sheep/beef **(d–h)** calibration sites: **(a)** Waitepeka Dairy Farm (Southland) from January 2004 to December 2009; **(b)** Scott Dairy Farm (Hamilton) from August 2009 to May 2011; **(c)** Lincoln University Dairy Farm (Canterbury) from January 2005 to December 2009; **(d)** Winchmore Research Station (Canterbury) from January 1997 to December 2003 (in total kilograms of dry matter per hectare rather than daily averages); **(e)** Whatawhata (Waikato) from February 2003 to October 2005; **(f)** Te Whanga (Wairarapa) uneroded site, **(g)** Te Whanga 1977 slip site, and **(h)** Te Whanga 1961 slip site, from August 2007 to August 2009.

Table 2. Comparison of baseline and intensification Biome-BGC model parameters.

Parameter	Baseline sheep/beef	Intense sheep/beef	Baseline dairy	Intense dairy
Pasture utilisation	0.55	0.60	0.90	0.95
Annual whole plant mortality fraction	0.226	0.247	0.722	0.762
Symbiotic & asymbiotic nitrogen fixation (kgN m^{-2} $year^{-1}$)	0.018	0.021	0.032	0.038

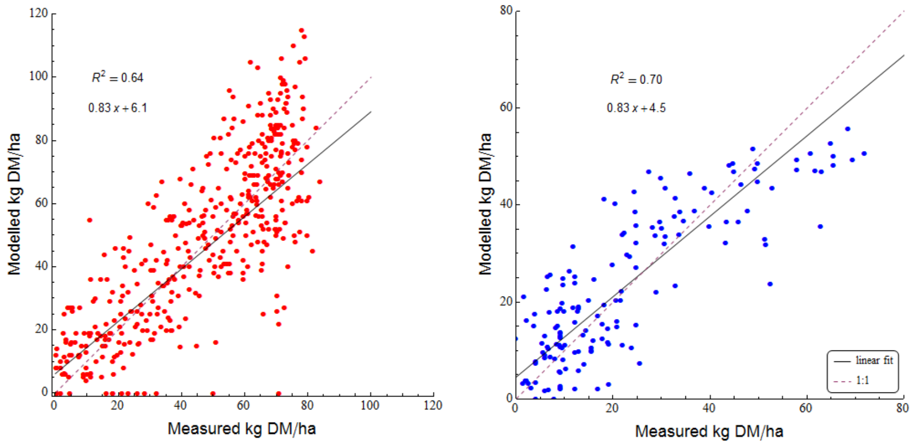

Figure 3. Scatter plot of modelled vs. measured pasture growth for calibration sites. Measured and modelled daily growth rates (kilograms of dry matter per hectare) from all calibrations sites for dairy (left) and sheep/beef (right). Data are daily averages of growth over cutting intervals (between 1 week and 1 month). Correlation coefficient $R^2 = 0.64$ (RMSE = 16.6) for dairy and 0.70 (RMSE = 9.88) for sheep/beef. Type 2 linear regression model shown is $y = 0.83 \pm 0.060x + 6.1 \pm 2.9$ (dairy) and $y = 0.83 \pm 0.090x + 6.1 \pm 2.0$ (sheep/beef). Reported errors are 2σ. The 1 : 1 line is drawn for reference.

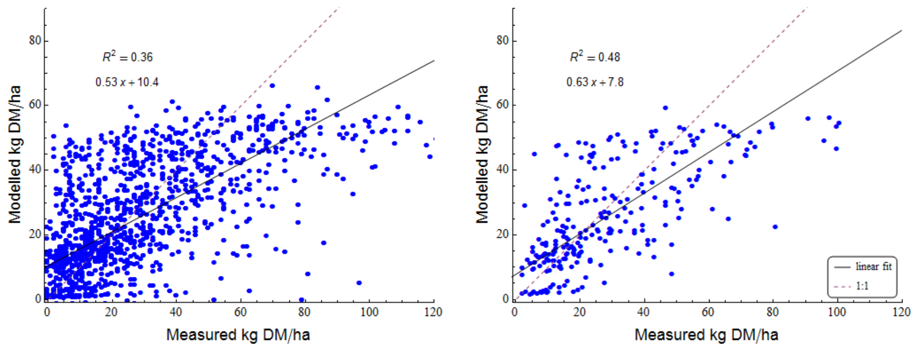

Figure 4. Scatter plot of modelled vs. measured pasture growth for validation sites. Measured and modelled daily growth rates (kilograms of dry matter per hectare) for all sheep/beef validation sites compared at individual cutting intervals (left) and monthly averages over 3 years (right). Correlation coefficient $R^2 = 0.36$ (RMSE = 20.9) and 0.48 (RMSE = 15.9), respectively. Type 2 linear regression model shown is $y = 0.53 \pm 0.040x + 10.4 \pm 1.2$ (left) and $y = 0.63 \pm 0.085x + 7.8 \pm 2.5$ (right). Reported errors are 2σ. The 1 : 1 line is drawn for reference.

benchmark for comparisons to scenarios in 2020 and 2050. The baseline that is used as comparison for the 2100 climate change scenarios is slightly different, covering the 15 years from 1997 to 2011, to correspond to the timing and length of the 2100 simulations. The small inconsistency in the baselines does not alter the general trend in the final results and was chosen to ensure matching with the statistically downscaled climate data sets and a sensible averaging period for the scenarios studied.

2.5.2 Land use

We simulated dynamic land-use changes using the LURNZ model by assuming the primary drivers behind land-use change are economic factors that influence the monetary returns to land under different uses. We selected three scenarios focused on the importance and associated uncertainties of the phase-in of emissions trading, corresponding to low, best guess and high carbon prices (NZD 0, 50 and 100 per tonne CO_{2e}, respectively) under the New Zealand Emissions Trading Scheme (ETS). Land-use projections are provided for 2020 and 2050 and subsequently combined with baseline dairy and sheep/beef pasture production.

Along with land-use change, intensification of current usage is also likely to be a considerable driver of pasture production over the coming decades in the absence of new environmental regulation (Parfitt et al., 2006, 2008). To simulate a representative "intensification" scenario in 2020 with Biome-BGC, we increased the nitrogen fixation levels per hectare and the effective utilisation of pasture nationwide. Parameter values used in the baseline and intensification scenarios are compared in Table 2. Intensification here is based on high nutrient inputs that represent roughly what a farmer would do in a 10-year time frame in response to long-term

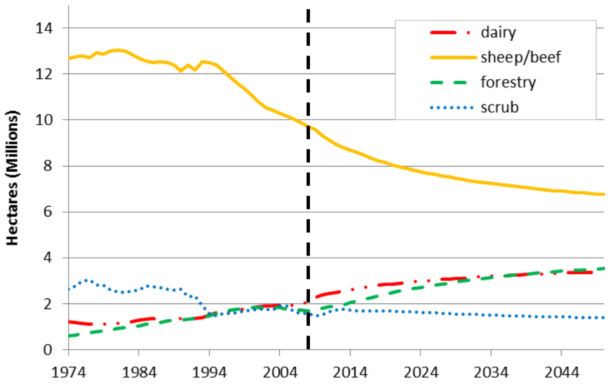

Figure 5. Historical and projected land-use areas in New Zealand (carbon price = NZD 0). Data to the left of the dashed line (2008) are historical, and to the right are estimated by LURNZ based on exogenous forecasts of economic variables.

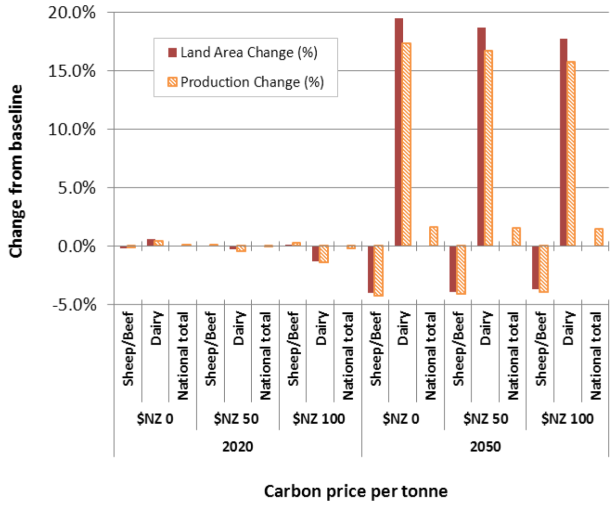

Figure 6. Land area and pasture production changes. Percentage change from baseline estimated by combining outputs of LURNZ and Biome-BGC models in 2020 and 2050.

increases in commodity prices (near doubling). Climate was held constant at present-day inputs, and CO_2 concentrations are increased according to the A2 scenario from the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart, 2000). The combined effects of CO_2 fertilisation and intensification were modelled together in this case to test for strong non-additive interactions between elevated CO_2 and agricultural N cycling.

2.5.3 Climate change

The climate change scenarios we selected provide mid-range and upper-end estimates for the combined impact of climate change and elevated CO_2 on pasture growth circa 2050 and 2100. Scenarios were chosen from the ensemble of IPCC AR4 GCM simulations. The particular models that were chosen are in good agreement with present-day climate in the New Zealand region but forecast significantly different changes in local patterns of precipitation and temperature by 2100. A more complete description of the projected changes for New Zealand and the range of responses in selected AR4 GCMs is in Renwick et al. (2013). Climate projections for New Zealand are based on a downscaling scheme that uses partial least squares regression to statistically downscale rainfall, temperature, and solar radiation from GCMs directly to the VCSN (Clark et al., 2011).

The SRES A2 emissions scenario is used to estimate the increase in CO_2 concentration levels in the atmosphere for all climate change scenarios. This scenario results in approximately 4 °C of global mean average temperature increase by 2100 (measured since pre-industrial times, nominally 1750). A2 is suitable as a mid-range projection in the shorter term out to 2050. In longer-range climate change projections, it represents an upper-end scenario, which becomes the case by 2080. Atmospheric concentrations start at 375 ppm in 2005 and rise to 827.3 ppm in 2099 (Nakicenovic and Swart, 2000; ENSEMBLES, 2009). This scenario is increasingly regarded as more likely since recent emissions have closely tracked its projections.

We first examined the effect of CO_2 fertilisation alone on pasture production, keeping climate patterns the same as the baseline but increasing atmospheric CO_2 concentrations according to the A2 scenario. This is referred to as "elevated CO_2". This scenario was evaluated on the short time frame of 2020 to provide a partial derivative of elevated CO_2 effects on a timescale during which the effects of climate change might remain within the bounds of regional and decadal variability (e.g. Deser et al., 2012).

The climate data for our 2050 mid-range scenario have been downscaled from one GCM, MPI, and broadly represent a "mid-range" projection for the time slice 2045–2055. The upper-end scenario represents the high end of temperature response and, for most of the country, provides a sample of a severe rainfall reduction across all 19 GCMs. Climatic input data for this scenario were provided by downscaled simulations from GIEH.

The two scenarios provided for 2100 (Renwick et al., 2013) use downscaled simulations from the MPI and CCC models and also represent "mid-range" and "upper-end" projections. These models predict an annual mean temperature change in 2090 for New Zealand of 3.0 and 3.9 °C, respectively (relative to 1990). Simulations were run for the nominal years 2097–2111 but are meant to represent general climate in approximately 100 years. These were compared to a present-day baseline scenario covering the period 1997–2011.

Apart from climate and atmospheric CO_2 concentrations, other parameters remained unchanged, thus providing an understanding of possible effects of climate change with little change in agronomic systems.

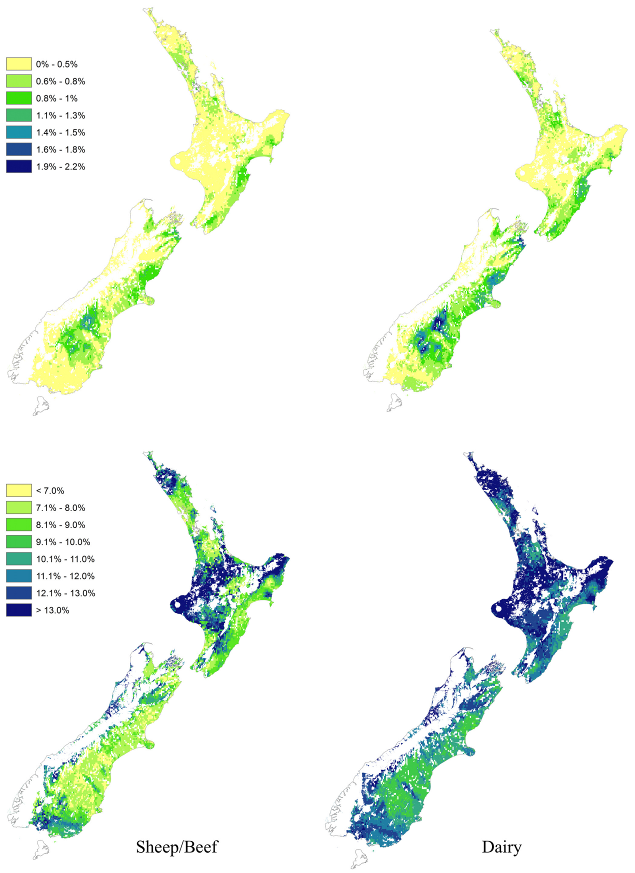

Figure 7. Elevated CO_2 (top) and intensification (bottom) 2020 model scenarios, average annual total pasture production, percentage change from baseline for sheep/beef (left) and dairy (right). Each map shows national pasture production as if all of the available land (excluding urban and conservation land) were devoted to sheep/beef or dairy agriculture systems and is not an actual representation of current or projected land use.

3 Results and discussion

3.1 Results

Results from Biome-BGC and LURNZ for selected scenarios are shown in Tables 3 and 4 and Figs. 6–9. We map production results from Biome-BGC across all of New Zealand, then combine with land uses from LURNZ according to the scenario and tabulate totals nationally. Appendix B contains more detailed results tabulated by region and season.

Our scenario results are reported relative to the baseline scenario to limit the impact of potential biases in the model. The model estimates have absolute uncertainty that has not been determined, and we therefore emphasise that results are expected to be most robust in terms of comparisons between model scenarios. We show here the percentage difference in average annual pasture production for each scenario, as compared to the baseline.

With the baseline model, we calculate that New Zealand's average annual pasture production is approximately 800 to 900 petajoules (PJ) of metabolisable energy available to grazing animals. This number is consistent with the estimates used to compile New Zealand's most recent UNFCCC emissions inventories, which was 970 PJ in 2011 (New Zealand Ministry for the Environment, 2009, 2013).

Land-use change projections from all three modelled carbon price scenarios suggest that, in general, economic factors other than carbon price dominate. Therefore, the current trends in land-use change continue irrespective of carbon price: dairy is expanding, and sheep/beef is contracting over time. Figure 5 shows historical land area under each of the four land-use categories in LURNZ up to and including 2008 and projected future land-use area thereafter, out to 2050, with no carbon price imposed. Overall, LURNZ model projections indicate that carbon prices have very limited effects on land use, and current land-use change trends will continue. However, these trends by themselves can be expected to have a significant effect on New Zealand's pasture production, particularly through an 18–19 % expansion of dairy area. Figure 6 summarises LURNZ projections for 2020 and 2050 in terms of percentage change in land area and in pasture production. All land-use scenarios resulted in little change in 2020 relative to the baseline. In 2050, the LURNZ model projected a 4 % decrease in the area of sheep/beef pasture and an 18–19 % increase in the area of dairy pasture, regardless of carbon price. Pasture production changes were proportional to area changes. At 2050, the sheep/beef decline and dairy expansion nearly offset one another, resulting in a small net increase of 1.5 % in total national pasture production.

Under elevated atmospheric CO_2 concentrations in 2020 (Fig. 7), very small increases in production of the order of $\sim$0.5 % were projected, which can be compared to a 10 % increase over present-day CO_2 concentration levels. (The A2 emissions scenario contains a 37 % increase in CO_2 concentration levels in 2050 and a 94 % increase by 2100.) The increase in production from enhanced CO_2 was slightly greater for dairy systems. No region recorded a loss of production, while the largest regional increases were of the order of 1 %.

Results from the intensification scenario (Fig. 7) indicate potential increases in pasture production of 10 % nationally by 2020. Results ranged between 8 and 14 % in different regions. Overall, dairy systems showed about 2–3 % more of an increase than sheep/beef systems. When compared to the results due to elevated CO_2 alone, the results imply the majority of production increases can be attributed to the change in model parameters due to intensification, with elevated CO_2 explaining only a small portion, 0.5 %.

The modelled climate change scenarios in 2050 suggest relatively small changes at a national scale but potentially more significant regional effects. Results (Fig. 8) suggest a 2 % increase in total national production in 2050 for the mid-range MPI scenario and a 1 % increase for the

Table 3. Summary of model scenario results with constant land-use area, tabulated by scenario and season. Percent change calculated in reference to the baseline scenario. Seasonal numbers are averages over the modelled time slice, and national totals are the annual average sum of sheep/beef and dairy results. ME is metabolisable energy, defined as the amount of energy available to grazing animals.

Scenario	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production (MJ ha^{-1} d^{-1})						
Baseline 2001–2009								
Sheep & beef	7778	73	356	279	159	217	615 126	–
Dairy	1557	163	594	515	353	406	231 014	–
National total	9335						846 140	–
Elevated CO_2 2020								
Sheep & beef	7778	74	356	280	160	218	617 531	0.4 %
Dairy	1557	166	598	517	354	409	232 203	0.5 %
National total	9335						849734	0.4 %
Intensification 2020								
Sheep & beef	7778	80	396	301	172	237	673 861	9.5 %
Dairy	1557	181	668	581	399	457	259 915	12.5 %
National total	9335						933 776	10.4 %
MPI climate change 2050								
Sheep & beef	7778	80	360	276	168	221	627 293	2.0 %
Dairy	1557	186	617	518	364	421	239 427	3.6 %
National total	9335						866720	2.4 %
GIEH climate change 2050								
Sheep & beef	7778	85	354	260	169	217	616 759	0.3 %
Dairy	1557	204	615	498	372	422	239 967	3.9 %
National total	9335						856 726	1.3 %
Baseline 1997–2011								
Sheep & beef	7778	69	350	230	135	196	556 567	–
Dairy	1557	153	588	472	311	381	216 717	–
National total	9335						773 284	–
MPI climate change 2100								
Sheep & beef	7778	97	338	185	143	191	541 710	−2.7 %
Dairy	1557	235	608	408	336	397	225 631	4.1 %
National total	9335						767 341	−0.8 %
CCC climate change 2100								
Sheep & beef	7778	105	326	112	139	170	483 402	−13.1 %
Dairy	1557	258	608	306	331	376	213 593	−1.4 %
National total	9335						696 995	−9.9 %

upper-end GIEH scenario. The dairy model shows slightly larger production increases of about 4 %, regardless of scenario. Sheep/beef production appears more sensitive to the difference in the two scenarios, in particular to the more extreme precipitation decreases from GIEH. Sheep/beef production increases by 2 % with the milder MPI scenario but results in virtually no change in GIEH, with the losses in some regions balancing the gains in others. For comparison, we show the corresponding differences in precipitation from both models in Fig. 10. The decrease in sheep/beef production in the east and north in the GIEH scenario closely follows the pattern of decrease in precipitation in these regions. Despite some strong regional effects, however, the model suggests that overall there will not be a large impact on pasture production in 2050 from climate change within expected bounds. Seasonal results (see Appendix B) indicate that in general winter production will increase and summer

Table 4. Summary of model scenario results with land-use change. Percent change calculated in reference to the baseline scenario in Table 3. Seasonal numbers are averages over the modelled time slice, and national totals are the annual average sum of sheep/beef and dairy results. ME is metabolisable energy, defined as the amount of energy available to grazing animals.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production (MJ ha^{-1} d^{-1})						
Land-use 2020 NZD 0									
Sheep & beef	7766	−0.2 %	73	356	279	159	217	614 327	−0.13 %
Dairy	1566	0.6 %	163	595	514	352	406	232 053	0.45 %
National total	9332							846 380	0.03 %
Land-use 2020 NZD 50									
Sheep & beef	7777	0.0 %	73	356	279	159	217	615 462	0.05 %
Dairy	1552	−0.3 %	163	595	513	352	406	230 025	−0.43 %
National total	9330							845487	−0.08 %
Land-use 2020 NZD 100									
Sheep & beef	7789	0.1 %	73	356	279	159	217	616 684	0.25 %
Dairy	1537	−1.3 %	163	595	513	352	406	227 802	−1.39 %
National total	9326							844 486	−0.20 %
Land-use 2050 NZD 0									
Sheep & beef	7465	−4.0 %	73	354	279	159	216	588 911	−4.26 %
Dairy	1861	19.5 %	157	589	506	345	399	271 076	17.3 %
National total	9326							859 987	1.64 %
Land-use 2050 NZD 50									
Sheep & beef	7475	−3.9 %	73	354	279	159	216	589 695	−4.13 %
Dairy	1848	18.7 %	157	589	506	345	399	269 462	16.6 %
National total	9323							859 157	1.54 %
Land-use 2050 NZD 100									
Sheep & beef	7487	−3.7 %	73	354	279	159	216	590 893	−3.94 %
Dairy	1833	17.7 %	157	590	506	345	399	267 232	15.7 %
National total	9320							858 125	1.42 %

production will decline; spring and autumn production trends vary by region.

Under the two 2100 scenarios, MPI is again associated with milder climate change than is CCC (Fig. 9). Sheep/beef pasture production declines slightly, at around −3 %, and dairy production increases by 4 %, resulting in almost no change nationally with current land use. With the CCC model, however, production for both sheep/beef and dairy systems declined, with national sheep/beef production decreasing by −13 % and dairy decreasing by about −3 %. The decline is especially pronounced in the South Island regions of Canterbury and Otago, where sheep/beef production decreases by −19 and −15 % and dairy decreases by −8 and −7 %, respectively (see Appendix B). These results are consistent with the patterns of climate change predicted for New Zealand by each climate model, with CCC predicting a larger increase in temperatures and more drastic changes in rainfall (Fig. 10), especially in the spring and summer months when the majority of pasture growth occurs. The eastern regions of the South Island in particular are drier and warmer during these crucial growing seasons.

3.2 Comparison of climatic and land management factors

To better understand the effects of inputs and model modifications on the results, we compare the relative significance of selected inputs and parameters in more detail for our case study. Looking at all model results, climatic factors (the primary input to Biome-BGC) are clearly influential in production trends. Land management factors are important as well, but our analysis is limited somewhat by the fact that we have not modelled spatial variation within each land-use subtype.

A general, comprehensive sensitivity analysis of Biome-BGC model parameters has been done by White et al. (2000). The authors found that variations in C : N ratio of leaves,

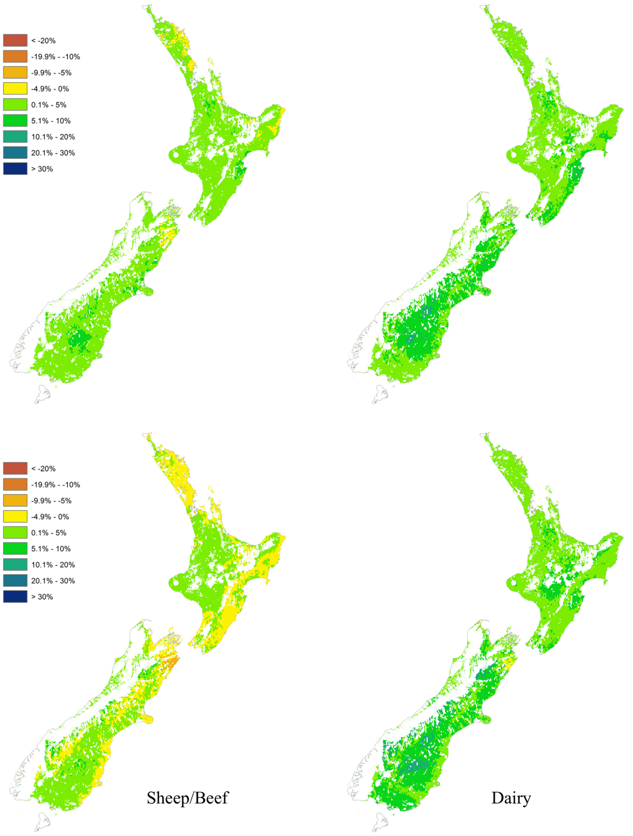

Figure 8. Climate change 2050 MPI (top) and GIEH (bottom) model scenarios, average annual total pasture production, percentage change from baseline for sheep/beef (left) and dairy (right). Each map shows national pasture production as if all of the available land (excluding urban and conservation land) were devoted to sheep/beef or dairy agriculture systems and is not an actual representation of current or projected land use.

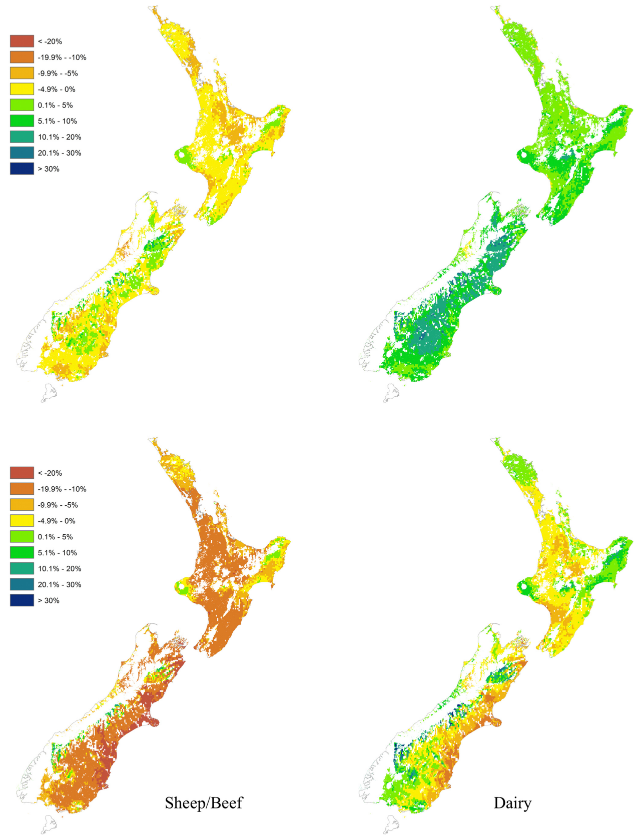

Figure 9. Climate change 2100 MPI (top) and CCC (bottom) model scenarios, average annual total pasture production, percentage change from baseline for sheep/beef (left) and dairy (right). Each map shows national pasture production as if all of the available land (excluding urban and conservation land) were devoted to sheep/beef or dairy agriculture systems and is not an actual representation of current or projected land use.

fire mortality, and parameters relating to litter quality have the most impact on NPP in grass biomes, leading to the conclusion that productivity is primarily nitrogen-limited in nonwoody biomes. In comparison, our calibration reveals that the most significant effects on NPP in both sheep/beef and dairy systems come from varying two different parameters: the maximum stomatal conductance and the fraction of leaf N in Rubisco. This suggests that in our model, New Zealand's highly managed grasslands are primarily water- and photosynthesis-limited rather than nitrogen-limited.

The influence of precipitation is especially visible in model results. Changes in pasture production in our climate change scenarios in 2050 and 2100 closely follow the patterns of change in precipitation (Fig. 10). Looking at the upper-end GIEH scenario in 2050, decreases of 5–10 % in precipitation along the east coast of New Zealand correspond to a 2–3 % regional decrease sheep/beef pasture production. Dairy pasture appears less sensitive to changes in precipitation; one explanation for this could be that the higher nitrogen status of dairy systems leads to an increase in photosynthetic water use efficiency.

Seasonal patterns of growth also play an important role. In our climate change scenarios, winter production tends to increase while summer production decreases, as one would expect from an overall average temperature increase. Spring and autumn production trends vary regionally, with no consistent national pattern. Spring and summer in particular are crucial growing seasons in our model as well as for pasture production historically. A breakdown of seasonal rainfall (not shown) indicates that dry summers might drastically reduce production even if the remaining seasons have normal levels of precipitation.

An examination of model results with and without the wind correction factor applied to VPD input indicates that the modified VPD reduces overall national production by 3–4 % (not shown), although the exact amount varies by region. Hence the general effect of including wind in our simulations is to decrease plant productivity, as is expected from the

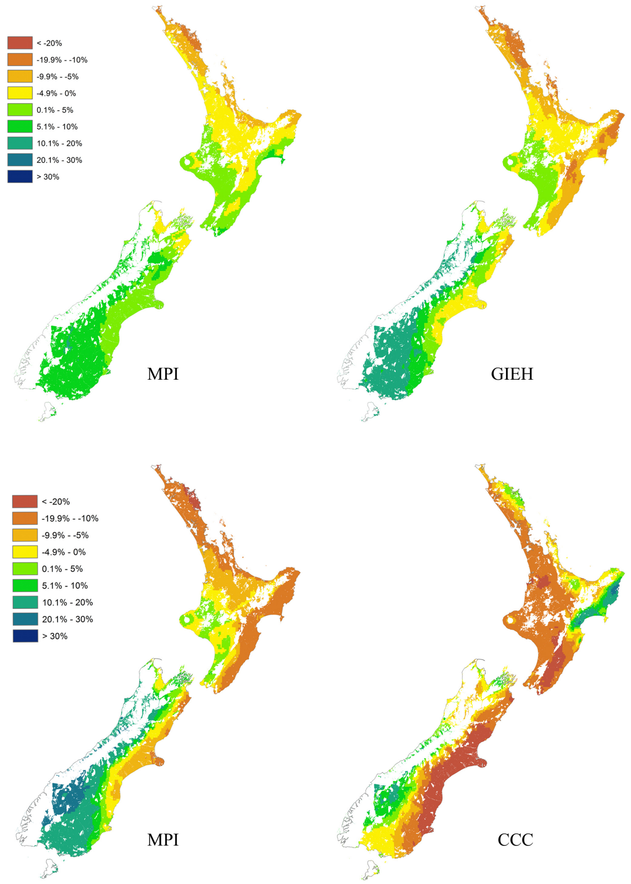

Figure 10. Total annual change in precipitation in 2050 (top) and 2100 (bottom), percentage change from baseline, for MPI (left) and GIEH/CCC (right) climate change scenarios.

elevated water loss that wind induces. Although our climate change scenarios did not modify wind speed from present-day values, global climate models predict that the mean westerly winds over New Zealand will increase, especially over the South Island in winter and spring. If local wind strength does indeed increase in the future, it could cause pasture production to decrease more than we have estimated with our scenarios.

While the model appears most sensitive to weather inputs in the scenarios we considered, parameters involved in grazing and land management are also notable. CO_2 fertilisation is, on the whole, a small effect, resulting in only a 0.5 % in production from a 10 % increase in CO_2 atmospheric concentrations. Nevertheless, with concentrations projected to increase by 90 % or more by 2100, it will become much more significant when compared to present day. The model does respond strongly to increases in the plant mortality and nitrogen fixation parameters, having a relatively large positive effect on production in our intensification scenario. Increasing pasture utilisation by 9 and 6 % and nitrogen fixation (or fertiliser application) by 16 and 19 % for sheep/beef and dairy systems, respectively, produce modelled increases in production of 9.5 and 12.5 %. This should be interpreted with caution, however; our model is a fairly simplistic representation of intensification, as we have treated all land within each subtype as having equal utilisation and equal potential for production gains. In practice, gains would likely be limited due to resource availability, environmental concerns and the considerable spatial variation in land quality. In addition, we have not explicitly considered changes in carbon-cycle feedbacks and other biophysical effects due to land-use change and intensification. Other studies have demonstrated that land-use change affects characteristics such as albedo and radiative forcing (Kirschbaum et al., 2011), carbon storage (Bala et al., 2007), and water yield (Beets and Oliver, 2007). The simulation of these effects is beyond the scope of this study but could be considered in future work.

An advantage of the DLUCS methodology is the ability to rapidly sample results from different models and model updates, assuming that strongly interrelated global change issues such as N status and enhanced pCO_2 can be handled within model projections. With the recent release of the IPCC Fifth Assessment Report (AR5), updated climate projections can be incorporated in our simulations through dynamically downscaled weather input to the Biome-BGC model to more fully explore the trends that we discuss here. The possibility of including downscaled changes in wind strength now exists as well, which is currently lacking in our climate change simulations. Output from other biogeochemistry models (including those coupled to GCMs) and improved versions or alternatives replacing Biome-BGC output can be incorporated in a similar way, as well as new developments in LURNZ that add spatial detail and allow for variations in land productivity and carrying capacity (Timar and Kerr, 2014).

4 Conclusions

Examining all scenarios modelled here, our results suggest a slight increase in pasture production by 2020 is likely, and increases of 10–15 % are plausible. The outlook for 2050 is also favourable given the scenarios considered. The projected continued conversion of land to high-intensity dairy farming will likely increase total national production. Although climate change could have an adverse effect on particular regions by 2050, our modelling estimates a small overall national increase. CO_2 fertilisation effects could also contribute to a slight increase. Projected pasture production in 2100 shows a much larger range of possible outcomes. We find significant differences in the impact on pasture production using weather input from two different GCMs. The CCC model results in a pronounced decline in both sheep/beef and dairy pasture production, while the MPI model shows only a slight decrease in sheep/beef and an increase in dairy production. This highlights that the severity of warming will determine the degree of impact on pasture production for both sheep/beef and dairy agriculture in New Zealand.

Our results demonstrate the capability of the Biome-BGC model to provide useful production data when integrated with global change scenarios, including results from the LURNZ model's estimates of land-use change. With downscaled weather input from GCMs, the model infrastructure enables the investigation of regional effects of projected climate change. The Biome-BGC model also offers the potential to model forest ecosystems (with the model's built-in forest modules) and compare productivity across forest and pasture land uses in future studies of global change. The advantage of our approach is the flexibility of the model components and the variety of future change scenarios that we are able to explore with relative ease: by modelling national production for all locations coupled with climate projections or other initial input, we can quickly re-sample the national grid for any modelled land-use change or economic scenario.

Further work to calibrate the Biome-BGC model to New Zealand conditions is needed to refine and confirm results. Iterative improvements in modelling and experimental approaches will be required to provide robust results given the strong interactions and feedbacks in productive ecosystems. One area to investigate is the interaction between climate change and elevated CO_2 and water and nitrogen availability, and the differences between time-dependent and quasi-steady-state model results. These effects can be constrained by data (for example, eddy covariance towers and FACE experiments) using our modelling approach and have substantial implications for the seasonal cycle of pasture supply, responses to drought and our ability to correctly characterise relative impacts of climate on sheep/beef versus dairy systems. This includes correct estimation of the benefits and limitations of irrigation in both sheep/beef and dairy pasture. Additionally, the simulation of extreme events (e.g. droughts and floods) and new scenarios from the IPCC AR5 with the Biome-BGC model will add to our understanding of the impacts of future climate change. There is also potential for integration with other earth system models. For example, integration with hydrology models would allow us to examine the effects of climate and land-use change on water supply in New Zealand (see, for example, Gerten et al., 2008, and Rockström et al., 2009). While achieving a fully integrated assessment model remains challenging, the DLUCS linkage of models presented here provides a useful methodology to investigate global change, with the ability to generate realistic scenario results on timescales required for policy formulation.

Appendix A: Biome-BGC parameters

Eco-physiological parameters used in the Biome-BGC model for dairy and sheep/beef ecosystems. The parameters that were adjusted are marked with a footnote. All other parameters were set to C3 grass default values provided with the Biome-BGC v4.2 Final Release. Full descriptions of the parameters are contained in the model documentation.

Table A1. Biome-BGC model parameters.

Parameter description	Sheep/beef baseline	Dairy baseline	C3 grass default	Type
annual whole-plant mortality fraction[a,b]	0.226	0.722	0.1	($1\,yr^{-1}$)
annual fire mortality fraction[b]	0.1	0.2	0.1	($1\,yr^{-1}$)
(ALLOCATION) new fine root C : new leaf C[b]	1.43	0.246	1	(ratio)
(ALLOCATION) current growth proportion[b]	0.84	0.424	0.5	(prop.)
C : N of leaves[b]	24.0	24.1	24.0	($kgC\,kgN^{-1}$)
C : N of leaf litter, after retranslocation[b]	49.0	49.0	49.0	($kgC\,kgN^{-1}$)
C : N of fine roots[b]	42.0	42.9	42.0	($kgC\,kgN^{-1}$)
canopy average specific leaf area (projected area basis)[b]	45.0	45.0	45.0	($m^2\,kgC^{-1}$)
fraction of leaf N in Rubisco[b]	0.19	0.05	0.15	(DIM)
maximum stomatal conductance (projected area basis)[b]	0.00534	0.00375	0.005	($m\,s^{-1}$)
boundary layer conductance (projected area basis)[b]	0.07	0.0202	0.04	($m\,s^{-1}$)
1 = WOODY 0 = NON-WOODY	0	0	0	(flag)
1 = EVERGREEN 0 = DECIDUOUS	0	0	0	(flag)
1 = C3 PSN 0 = C4 PSN	1	1	1	(flag)
1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY	0	0	0	(flag)
year day to start new growth (phenology flag = 0)	0	0	0	(yday)
year day to end litterfall (phenology flag = 0)	364	364	364	(yday)
transfer growth period as fraction of growing	1	1	1	(prop.)
litterfall as fraction of growing season	1	1	1	(prop.)
annual leaf and fine root turnover fraction	1	1	1	($1\,yr^{-1}$)
annual live wood turnover fraction	0	0	0	($1\,yr^{-1}$)
(ALLOCATION) new stem C : new leaf C	0	0	0	(ratio)
(ALLOCATION) new live wood C : new total wood C	0	0	0	(ratio)
(ALLOCATION) new coarse root C : new stem C	0	0	0	(ratio)
C : N of live wood	0	0	0	($kgC\,kgN^{-1}$)
C : N of dead wood	0	0	0	($kgC\,kgN^{-1}$)
leaf litter labile proportion	0.39	0.39	0.39	(DIM)
leaf litter cellulose proportion	0.44	0.44	0.44	(DIM)
leaf litter lignin proportion	0.17	0.17	0.17	(DIM)
fine root labile proportion	0.30	0.30	0.30	(DIM)
fine root cellulose proportion	0.45	0.45	0.45	(DIM)
fine root lignin proportion	0.25	0.25	0.25	(DIM)
dead wood cellulose proportion	0.75	0.75	0.75	(DIM)
dead wood lignin proportion	0.25	0.25	0.25	(DIM)
canopy water interception coefficient	0.021	0.021	0.021	($1\,LAI^{-1}\,d^{-1}$)
canopy light extinction coefficient	0.6	0.6	0.6	(DIM)
all-sided to projected leaf area ratio	2.0	2.0	2.0	(DIM)
ratio of shaded SLA : sunlit SLA	2.0	2.0	2.0	(DIM)
cuticular conductance (projected area basis)	0.00001	0.00001	0.00001	($m\,s^{-1}$)
leaf water potential: start of conductance reduction	−0.6	−0.6	−0.6	(MPa)
leaf water potential: complete conductance reduction	−2.3	−2.3	−2.3	(MPa)
vapour pressure deficit: start of conductance reduction	930	930	930	(Pa)
vapour pressure deficit: complete conductance reduction	4100	4100	4100	(Pa)

[a] Whole-plant mortality was calculated as (utilisation) · (above-ground growth) / (above-ground + below-ground growth). The ratio below-ground / above-ground is given by the parameter new fine root C : new leaf C. [b] Parameters adjusted during calibration.

Appendix B: Pasture production results by region and season

The following tables show pasture production results organised by New Zealand's 16 regions and by season, in terms of metabolisable energy (the estimated amount of energy that is available to grazing animals from pasture).

Table B1. Baseline average production by region and season over the period 2001–2009 in units of metabolisable energy.

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)
		Average production (MJ ha^{-1} d^{-1})					
Sheep & beef							
Northland	239	138	423	296	199	264	22 963
Auckland	85	129	445	304	168	262	8158
Waikato	473	112	421	368	201	276	47 532
Bay of Plenty	66	108	402	366	219	274	6580
Gisborne	327	106	431	321	200	264	31 582
Manawatu-Wanganui	936	92	415	373	185	266	90 856
Hawkes Bay	586	94	398	212	179	220	47 121
Taranaki	125	105	398	412	214	282	12 850
Tasman	57	86	406	268	171	233	4841
Marlborough	310	59	310	230	133	183	20 703
Westland	32	81	355	378	204	255	2949
Wellington	281	95	440	249	156	235	24 064
Nelson City	2	87	417	274	142	230	208
Canterbury	1824	54	307	211	131	176	117 080
Otago	1738	46	296	248	134	181	114 986
Southland	698	62	376	370	176	246	62 653
National	7778	73	356	279	159	217	615 126
Dairy							
Northland	172	221	617	464	376	420	26 334
Auckland	53	209	629	504	342	421	8104
Waikato	487	184	628	510	364	422	74 904
Bay of Plenty	80	181	613	540	400	434	12 611
Gisborne	3	176	580	536	392	421	384
Manawatu-Wanganui	127	149	602	538	314	401	18 595
Hawkes Bay	16	136	581	454	334	376	2159
Taranaki	215	168	594	615	394	443	34 784
Tasman	27	139	582	548	357	406	4043
Marlborough	9	126	549	456	303	358	1210
Westland	52	124	532	582	373	402	7690
Wellington	30	142	612	433	298	371	4016
Nelson City	0	121	517	339	295	318	49
Canterbury	119	103	513	362	281	315	13 723
Otago	62	88	523	488	287	346	7799
Southland	106	93	529	564	332	379	14 609
National	1557	163	594	515	353	406	231 014
Combined national	9335						846 140

Table B2. Baseline average production by region and season over the period 1997–2011 in units of metabolisable energy.

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)
		Average production (MJ ha^{-1} d^{-1})					
Sheep & beef							
Northland	239	131	435	247	151	241	20 999
Auckland	85	123	452	266	134	244	7601
Waikato	473	105	446	298	143	248	42 743
Bay of Plenty	66	102	416	298	174	248	5951
Gisborne	327	103	422	341	196	266	31 745
Manawatu-Wanganui	936	87	438	288	137	237	81 024
Hawkes Bay	586	88	387	188	153	204	43 661
Taranaki	125	101	421	402	177	275	12 535
Tasman	57	83	403	231	152	217	4524
Marlborough	310	58	305	253	134	187	21 235
Westland	32	79	369	308	170	231	2677
Wellington	281	89	437	216	129	218	22 317
Nelson City	2	83	408	258	117	217	196
Canterbury	1824	51	291	176	122	160	106 386
Otago	1738	43	272	194	119	157	99 507
Southland	698	57	369	268	146	210	53 466
National	7778	69	350	230	135	196	556 567
Dairy							
Northland	172	213	617	426	325	395	24 815
Auckland	53	199	637	477	293	402	7733
Waikato	487	170	627	470	308	394	69 953
Bay of Plenty	80	169	607	468	354	399	11 617
Gisborne	3	173	577	539	380	418	381
Manawatu-Wanganui	127	137	604	470	261	368	17 063
Hawkes Bay	16	126	561	409	303	350	2007
Taranaki	215	168	598	620	393	445	34 946
Tasman	27	133	578	510	325	386	3843
Marlborough	9	118	529	422	276	337	1136
Westland	52	123	537	547	348	389	7434
Wellington	30	131	599	369	264	341	3690
Nelson City	0.4	114	497	333	266	302	47
Canterbury	119	89	462	289	246	272	11 835
Otago	62	78	485	399	251	304	6833
Southland	106	85	525	497	282	347	13 384
National	1557	153	588	472	311	381	216 717
Combined national	9335						773 284

Table B3. Elevated CO_2 2020.

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production (MJ ha^{-1} d^{-1})						
Sheep & beef								
Northland	239	140	423	297	199	265	23 035	0.3 %
Auckland	85	131	445	305	169	263	8188	0.4 %
Waikato	473	113	421	369	201	276	47 622	0.2 %
Bay of Plenty	66	108	402	367	219	274	6590	0.2 %
Gisborne	327	107	431	323	200	265	31 680	0.3 %
Manawatu-Wanganui	936	92	415	374	185	267	91 042	0.2 %
Hawkes Bay	586	95	398	213	180	222	47 378	0.5 %
Taranaki	125	105	397	412	214	282	12 859	0.1 %
Tasman	57	87	407	269	172	234	4861	0.4 %
Marlborough	310	59	310	231	134	184	20 807	0.5 %
Westland	32	82	355	379	205	255	2955	0.2 %
Wellington	281	96	441	250	157	236	24 186	0.5 %
Nelson City	2	88	418	275	144	231	209	0.5 %
Canterbury	1824	55	308	213	133	177	117 777	0.6 %
Otago	1738	47	297	249	135	182	115 538	0.5 %
Southland	698	63	376	371	176	247	62 803	0.2 %
National	7778	74	356	280	160	218	617 531	0.4 %
Dairy								
Northland	172	225	620	466	377	422	26 467	0.5 %
Auckland	53	213	632	505	342	423	8143	0.5 %
Waikato	487	187	631	512	364	424	75 290	0.5 %
Bay of Plenty	80	183	616	542	400	435	12 664	0.4 %
Gisborne	3	178	583	537	392	423	386	0.4 %
Manawatu-Wanganui	127	151	607	539	314	403	18 695	0.5 %
Hawkes Bay	16	138	585	456	335	378	2172	0.6 %
Taranaki	215	171	597	615	394	444	34 915	0.4 %
Tasman	27	141	585	550	357	408	4061	0.4 %
Marlborough	9	128	553	458	304	361	1218	0.6 %
Westland	52	126	535	583	373	404	7724	0.4 %
Wellington	30	145	617	435	299	374	4046	0.8 %
Nelson City	0	123	522	342	296	321	50	0.8 %
Canterbury	119	105	519	365	283	318	13 851	0.9 %
Otago	62	90	527	489	288	349	7846	0.6 %
Southland	106	94	533	564	332	381	14 675	0.5 %
National	1557	166	598	517	354	409	232 203	0.5 %
Combined national	9335						849 734	0.4 %

Table B4. Intensification 2020.

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production ($MJ\,ha^{-1}\,d^{-1}$)						
Sheep & beef								
Northland	239	153	476	318	217	291	25 337	10.3 %
Auckland	85	142	499	320	178	285	8878	8.8 %
Waikato	473	126	482	406	217	308	53 058	11.6 %
Bay of Plenty	66	122	461	405	240	307	7381	12.2 %
Gisborne	327	117	485	348	218	292	34 886	10.5 %
Manawatu-Wanganui	936	102	474	411	199	297	101 291	11.5 %
Hawkes Bay	586	103	438	223	194	240	51 212	8.7 %
Taranaki	125	119	462	471	235	322	14 652	14.0 %
Tasman	57	94	451	287	185	254	5286	9.2 %
Marlborough	310	64	341	247	143	199	22 533	8.8 %
Westland	32	90	401	418	223	283	3279	11.2 %
Wellington	281	104	488	261	169	255	26 180	8.8 %
Nelson City	2	96	462	290	149	250	225	8.4 %
Canterbury	1824	59	334	224	141	190	126 240	7.8 %
Otago	1738	51	325	265	144	196	124 421	8.2 %
Southland	698	68	423	404	189	271	69 003	10.1 %
National	7778	80	396	301	172	237	673 861	9.5 %
Dairy								
Northland	172	246	698	520	428	473	29 678	12.7 %
Auckland	53	233	712	565	387	474	9136	12.7 %
Waikato	487	204	708	574	411	474	84 222	12.4 %
Bay of Plenty	80	202	694	610	457	491	14 268	13.1 %
Gisborne	3	197	659	612	449	479	437	13.9 %
Manawatu-Wanganui	127	164	675	605	353	449	20 850	12.1 %
Hawkes Bay	16	149	649	505	377	420	2412	11.7 %
Taranaki	215	189	673	708	451	505	39 681	14.1 %
Tasman	27	154	654	621	406	459	4565	12.9 %
Marlborough	9	139	614	515	340	402	1357	12.2 %
Westland	52	136	595	662	423	454	8675	12.8 %
Wellington	30	155	680	478	335	412	4461	11.1 %
Nelson City	0	131	571	375	327	351	54	10.4 %
Canterbury	119	112	563	400	312	347	15 117	10.2 %
Otago	62	96	578	543	319	384	8647	10.9 %
Southland	106	101	590	639	369	425	16 355	12.0 %
National	1557	181	668	581	399	457	259 915	12.5 %
Combined national	9335						933 776	10.4 %

Table B5. Climate change 2050 (GIEH model).

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production ($MJ\,ha^{-1}\,d^{-1}$)						
Sheep & beef								
Northland	239	148	421	288	204	265	23 103	0.6 %
Auckland	85	140	442	299	178	265	8262	1.3 %
Waikato	473	120	421	369	205	279	48 129	1.3 %
Bay of Plenty	66	115	405	361	222	276	6637	0.9 %
Gisborne	327	116	426	305	221	267	31 885	1.0 %
Manawatu-Wanganui	936	98	417	372	191	269	91 999	1.3 %
Hawkes Bay	586	104	392	201	207	226	48 335	2.6 %
Taranaki	125	111	399	412	214	284	12 943	0.7 %
Tasman	57	94	413	266	175	237	4929	1.8 %
Marlborough	310	65	315	218	138	184	20 860	0.8 %
Westland	32	87	358	377	203	256	2967	0.6 %
Wellington	281	103	442	239	174	239	24 545	2.0 %
Nelson City	2	94	423	261	149	232	209	0.7 %
Canterbury	1824	61	311	209	142	181	120 235	2.7 %
Otago	1738	52	307	250	139	187	118 549	3.1 %
Southland	698	67	384	373	177	250	63 704	1.7 %
National	7778	80	360	276	168	221	627 293	2.0 %
Dairy								
Northland	172	250	630	456	385	430	26 999	2.5 %
Auckland	53	237	643	500	351	433	8332	2.8 %
Waikato	487	210	648	517	378	438	77 837	3.9 %
Bay of Plenty	80	205	632	538	412	447	12 995	3.0 %
Gisborne	3	201	596	529	410	434	396	3.1 %
Manawatu-Wanganui	127	169	632	542	321	416	19 309	3.8 %
Hawkes Bay	16	161	604	438	372	393	2258	4.6 %
Taranaki	215	188	618	618	396	455	35 757	2.8 %
Tasman	27	158	609	552	359	419	4172	3.2 %
Marlborough	9	148	575	449	309	370	1250	3.3 %
Westland	52	139	556	584	374	413	7899	2.7 %
Wellington	30	165	642	429	319	389	4207	4.8 %
Nelson City	0	142	545	334	311	333	52	4.7 %
Canterbury	119	126	539	369	309	336	14 629	6.6 %
Otago	62	103	555	491	299	362	8153	4.5 %
Southland	106	107	563	569	338	394	15 181	3.9 %
National	1557	186	617	518	364	421	239 427	3.6 %
Combined national	9335						866 720	2.4 %

Table B6. Climate change 2050 (MPI model).

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production ($MJ\,ha^{-1}\,d^{-1}$)						
Sheep & beef								
Northland	239	154	414	266	210	261	22 729	−1.0 %
Auckland	85	146	441	265	182	259	8063	−1.2 %
Waikato	473	128	423	355	204	277	47 869	0.7 %
Bay of Plenty	66	124	406	345	225	275	6611	0.5 %
Gisborne	327	124	422	284	222	263	31 424	−0.5 %
Manawatu-Wanganui	936	105	420	353	189	267	91 174	0.4 %
Hawkes Bay	586	111	365	189	213	219	46 914	−0.4 %
Taranaki	125	118	402	408	211	285	12 970	0.9 %
Tasman	57	101	407	244	177	232	4835	−0.1 %
Marlborough	310	69	305	199	140	178	20 180	−2.5 %
Westland	32	91	359	372	201	256	2962	0.4 %
Wellington	281	110	435	208	178	233	23 850	−0.9 %
Nelson City	2	101	415	228	152	224	202	−2.6 %
Canterbury	1824	65	298	196	145	176	117 198	0.1 %
Otago	1738	55	305	235	139	184	116 504	1.3 %
Southland	698	71	389	360	174	249	63 274	1.0 %
National	7778	85	354	260	169	217	616 759	0.3 %
Dairy								
Northland	172	267	619	424	401	428	26 855	2.0 %
Auckland	53	255	645	463	358	430	8284	2.2 %
Waikato	487	232	644	495	385	439	78 004	4.1 %
Bay of Plenty	80	227	630	514	423	449	13 044	3.4 %
Gisborne	3	220	592	512	415	435	397	3.3 %
Manawatu-Wanganui	127	187	639	514	321	415	19 268	3.6 %
Hawkes Bay	16	182	586	409	388	391	2246	4.0 %
Taranaki	215	205	625	615	397	460	36 167	4.0 %
Tasman	27	175	614	533	366	422	4198	3.8 %
Marlborough	9	167	566	428	317	369	1247	3.0 %
Westland	52	151	563	583	378	419	8003	4.1 %
Wellington	30	183	642	389	328	386	4174	3.9 %
Nelson City	0	163	527	319	324	333	52	4.8 %
Canterbury	119	144	508	350	329	333	14 491	5.6 %
Otago	62	115	562	468	302	362	8146	4.4 %
Southland	106	119	576	562	341	400	15 393	5.4 %
National	1557	204	615	498	372	422	239 967	3.9 %
Combined national	9335						856 726	1.3 %

Table B7. Climate change 2100 (CCC model).

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production (MJ ha^{-1} d^{-1})						
Sheep & beef								
Northland	239	172	390	127	211	225	19 603	−6.6 %
Auckland	85	156	408	88	179	207	6470	−14.9 %
Waikato	473	152	443	113	158	216	37 346	−12.6 %
Bay of Plenty	66	151	403	112	213	220	5289	−11.1 %
Gisborne	327	157	411	216	235	255	30 427	−4.2 %
Manawatu-Wanganui	936	134	433	102	147	204	69 621	−14.1 %
Hawkes Bay	586	138	299	93	221	188	40 090	−8.2 %
Taranaki	125	144	471	257	133	251	11 439	−8.7 %
Tasman	57	132	390	90	157	192	3999	−11.6 %
Marlborough	310	94	310	116	130	162	18 406	−13.3 %
Westland	32	107	384	205	135	208	2404	−10.2 %
Wellington	281	138	388	59	163	187	19 165	−14.1 %
Nelson City	2	119	384	82	148	183	165	−15.5 %
Canterbury	1824	80	243	80	116	130	86 316	−18.9 %
Otago	1738	68	259	109	98	134	84 713	−14.9 %
Southland	698	84	375	168	126	188	47 947	−10.3 %
National	7778	105	326	112	139	170	483 402	−13.1 %
Dairy								
Northland	172	327	577	275	419	400	25 077	1.1 %
Auckland	53	311	644	249	367	393	7560	−2.2 %
Waikato	487	289	635	249	347	380	67 506	−3.5 %
Bay of Plenty	80	294	606	259	427	396	11 524	−0.8 %
Gisborne	3	294	588	435	437	439	400	5.0 %
Manawatu-Wanganui	127	242	645	238	266	348	16 136	−5.4 %
Hawkes Bay	16	248	510	249	409	354	2032	1.3 %
Taranaki	215	268	697	580	318	466	36 594	4.7 %
Tasman	27	241	638	346	318	386	3837	−0.2 %
Marlborough	9	219	550	228	294	323	1090	−4.1 %
Westland	52	208	617	435	305	391	7470	0.5 %
Wellington	30	244	602	173	302	330	3574	−3.1 %
Nelson City	0	211	484	160	321	294	46	−2.7 %
Canterbury	119	176	387	158	276	249	10 859	−8.2 %
Otago	62	146	488	261	239	283	6381	−6.6 %
Southland	106	153	613	380	257	351	13 507	0.9 %
National	1557	258	608	306	331	376	213 593	−1.4 %
Combined national	9335						696 995	−9.9 %

Table B8. Climate change 2100 (MPI model).

Region	Area (kha)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
		Average production (MJ ha^{-1} d^{-1})						
Sheep & beef								
Northland	239	168	399	183	180	233	20 258	−3.5 %
Auckland	85	153	422	172	157	226	7047	−7.3 %
Waikato	473	142	446	218	149	239	41 195	−3.6 %
Bay of Plenty	66	140	410	199	189	234	5636	−5.3 %
Gisborne	327	148	406	262	219	259	30 890	−2.7 %
Manawatu-Wanganui	936	123	440	209	146	229	78 330	−3.3 %
Hawkes Bay	586	131	320	147	196	199	42 439	−2.8 %
Taranaki	125	127	439	359	160	271	12 350	−1.5 %
Tasman	57	120	399	185	159	216	4490	−0.7 %
Marlborough	310	87	306	209	142	186	21 081	−0.7 %
Westland	32	75	363	279	158	219	2532	−5.4 %
Wellington	281	132	407	153	158	212	21 775	−2.4 %
Nelson City	2	112	393	186	134	206	186	−4.7 %
Canterbury	1824	78	269	153	131	158	105 037	−1.3 %
Otago	1738	60	273	165	113	153	97 026	−2.5 %
Southland	698	68	375	228	137	202	51 436	−3.8 %
National	7778	97	338	185	143	191	541 710	−2.7 %
Dairy								
Northland	172	309	582	346	383	405	25 409	2.4 %
Auckland	53	292	646	363	337	410	7886	2.0 %
Waikato	487	262	642	381	334	405	71 941	2.8 %
Bay of Plenty	80	264	613	359	396	408	11 864	2.1 %
Gisborne	3	270	581	470	421	435	397	4.3 %
Manawatu-Wanganui	127	218	653	378	278	382	17 720	3.8 %
Hawkes Bay	16	224	534	335	378	368	2111	5.2 %
Taranaki	215	242	651	611	382	471	37 034	6.0 %
Tasman	27	212	629	458	342	410	4080	6.1 %
Marlborough	9	204	552	360	307	356	1202	5.8 %
Westland	52	161	581	516	346	401	7665	3.1 %
Wellington	30	225	621	298	309	363	3932	6.6 %
Nelson City	0.4	195	502	286	310	323	50	6.9 %
Canterbury	119	174	434	287	302	299	13 031	10.1 %
Otago	62	132	526	366	267	323	7266	6.3 %
Southland	106	126	597	456	279	365	14 044	4.9 %
National	1557	235	608	408	336	397	225 631	4.1 %
Combined national	9335						767 341	−0.8 %

Table B9. Land-use change, 2020 CO_2 = NZD 0.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production (MJ ha^{-1} d^{-1})						
Sheep & beef									
Northland	248	3.9 %	138	423	295	198	263	23 838	3.8 %
Auckland	83	−2.4 %	129	446	305	168	262	7976	−2.2 %
Waikato	479	1.4 %	112	421	371	201	276	48 332	1.7 %
Bay of Plenty	74	12.5 %	108	403	371	219	275	7444	13.1 %
Gisborne	326	−0.4 %	106	431	322	200	265	31 487	−0.3 %
Manawatu-Wanganui	909	−2.9 %	91	414	373	185	266	88 262	−2.9 %
Hawkes Bay	583	−0.4 %	94	397	212	179	221	46 935	−0.4 %
Taranaki	123	−1.7 %	105	397	412	214	282	12 618	−1.8 %
Tasman	61	7.7 %	86	405	274	173	235	5259	8.6 %
Marlborough	312	0.4 %	59	310	231	133	183	20 827	0.6 %
Westland	39	23.8 %	83	358	381	207	257	3686	25.0 %
Wellington	281	0.0 %	95	440	249	156	235	24 065	0.0 %
Nelson City	3	4.0 %	87	413	269	142	228	214	3.1 %
Canterbury	1820	−0.2 %	54	307	211	131	176	116 850	−0.2 %
Otago	1741	0.1 %	46	296	248	134	181	115 185	0.2 %
Southland	684	−1.9 %	62	375	370	175	246	61 348	−2.1 %
National	7766	−0.2 %	73	356	279	159	217	614 327	−0.13 %
Dairy									
Northland	162	−5.6 %	221	617	464	377	420	24 875	−5.5 %
Auckland	54	2.6 %	209	628	502	342	420	8302	2.4 %
Waikato	482	−1.0 %	186	629	506	363	421	74 063	−1.1 %
Bay of Plenty	71	−10.3 %	183	616	532	402	433	11 299	−10.4 %
Gisborne	5	95.0 %	182	569	472	377	400	712	85.4 %
Manawatu-Wanganui	157	23.1 %	150	603	541	313	402	22 953	23.4 %
Hawkes Bay	18	17.3 %	136	582	422	330	368	2476	14.7 %
Taranaki	217	0.9 %	168	595	615	394	443	35 106	0.9 %
Tasman	22	−18.0 %	142	586	549	358	409	3336	−17.5 %
Marlborough	7	−20.5 %	125	542	428	293	347	930	−23.1 %
Westland	42	−20.6 %	123	533	584	374	403	6122	−20.4 %
Wellington	30	0.3 %	143	614	428	296	370	4021	0.1 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	121	1.4 %	104	515	361	282	315	13 938	1.6 %
Otago	58	−5.3 %	89	526	488	287	347	7409	−5.0 %
Southland	119	12.3 %	93	529	566	334	381	16 480	12.8 %
National	1566	0.6 %	163	595	514	352	406	232 053	0.45 %
Combined national	9332							846 380	0.03 %

Table B10. Land-use change, 2020 CO_2 = NZD 50 per tonne.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production (MJ ha^{-1} d^{-1})						
Sheep & beef									
Northland	248	4.0 %	138	423	295	198	263	23 856	3.9 %
Auckland	84	−2.0 %	129	446	305	168	262	8007	−1.8 %
Waikato	481	1.7 %	112	421	371	201	276	48 463	2.0 %
Bay of Plenty	74	12.7 %	108	403	371	219	275	7455	13.3 %
Gisborne	327	−0.2 %	106	431	322	200	265	31 541	−0.1 %
Manawatu-Wanganui	913	−2.4 %	91	414	373	185	266	88 641	−2.4 %
Hawkes Bay	583	−0.4 %	94	397	212	179	221	46 954	−0.4 %
Taranaki	123	−1.6 %	105	397	412	214	282	12 638	−1.6 %
Tasman	61	7.7 %	86	405	274	173	235	5259	8.6 %
Marlborough	311	0.3 %	59	310	231	133	183	20 820	0.6 %
Westland	39	23.8 %	83	358	381	207	257	3686	25.0 %
Wellington	281	0.0 %	95	440	249	156	235	24 078	0.1 %
Nelson City	3	4.0 %	87	413	269	142	228	214	3.1 %
Canterbury	1820	−0.2 %	54	307	211	131	176	116 849	−0.2 %
Otago	1741	0.1 %	46	296	248	134	181	115 195	0.2 %
Southland	689	−1.2 %	62	375	370	176	246	61 805	−1.4 %
National	7777	0.0 %	73	356	279	159	217	615 462	0.05 %
Dairy									
Northland	162	−5.8 %	221	617	464	377	420	24 830	−5.7 %
Auckland	54	1.8 %	209	628	502	342	420	8237	1.6 %
Waikato	480	−1.3 %	186	629	506	363	421	73 827	−1.4 %
Bay of Plenty	71	−10.6 %	183	616	532	402	433	11 258	−10.7 %
Gisborne	4	63.0 %	180	563	455	373	393	584	52.0 %
Manawatu-Wanganui	152	19.8 %	150	603	541	313	402	22 322	20.0 %
Hawkes Bay	18	16.1 %	136	581	421	330	367	2447	13.3 %
Taranaki	217	0.8 %	168	595	615	394	443	35 083	0.9 %
Tasman	22	−18.0 %	142	586	549	358	409	3336	−17.5 %
Marlborough	7	−20.5 %	125	542	428	293	347	930	−23.1 %
Westland	42	−20.6 %	123	533	584	374	403	6122	−20.4 %
Wellington	30	−0.3 %	143	614	428	296	370	3997	−0.5 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	120	0.8 %	104	515	361	282	315	13 850	0.9 %
Otago	58	−5.9 %	89	526	488	287	347	7361	−5.6 %
Southland	114	7.7 %	93	530	566	334	381	15 811	8.2 %
National	1552	−0.3 %	163	595	513	352	406	230 025	−0.43 %
Combined national	9330							845 487	−0.08 %

Table B11. Land-use change, 2020 CO_2 = NZD 100 per tonne.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production (MJ ha^{-1} d^{-1})						
Sheep & beef									
Northland	249	4.5 %	138	423	295	198	263	23 974	4.4 %
Auckland	84	−1.6 %	129	446	305	168	262	8044	−1.4 %
Waikato	485	2.7 %	112	421	372	201	276	48 968	3.0 %
Bay of Plenty	76	15.1 %	108	403	371	219	275	7621	15.8 %
Gisborne	327	−0.2 %	106	431	322	200	265	31 546	−0.1 %
Manawatu-Wanganui	915	−2.2 %	91	414	373	185	266	88 850	−2.2 %
Hawkes Bay	584	−0.3 %	94	397	212	179	221	47 003	−0.3 %
Taranaki	123	−1.2 %	105	397	412	214	282	12 691	−1.2 %
Tasman	62	8.2 %	86	405	274	173	235	5288	9.2 %
Marlborough	311	0.3 %	59	310	231	133	183	20 813	0.5 %
Westland	40	26.5 %	83	358	381	207	257	3766	27.7 %
Wellington	281	0.1 %	95	440	249	156	235	24 094	0.1 %
Nelson City	3	4.0 %	87	413	269	142	228	214	3.1 %
Canterbury	1819	−0.3 %	54	307	211	131	176	116 801	−0.2 %
Otago	1740	0.1 %	47	296	248	134	181	115 184	0.2 %
Southland	689	−1.2 %	62	375	370	176	246	61 827	−1.3 %
National	7789	0.1 %	73	356	279	159	217	616 684	0.25 %
Dairy									
Northland	161	−6.5 %	221	617	464	377	420	24 633	−6.5 %
Auckland	53	1.0 %	209	628	502	342	420	8180	0.9 %
Waikato	475	−2.3 %	186	629	505	363	421	73 025	−2.5 %
Bay of Plenty	70	−12.7 %	184	616	531	402	433	10 994	−12.8 %
Gisborne	4	61.0 %	180	563	452	372	392	576	49.8 %
Manawatu-Wanganui	150	18.0 %	150	603	541	312	402	21 999	18.3 %
Hawkes Bay	18	12.6 %	137	582	419	330	367	2370	9.8 %
Taranaki	216	0.5 %	169	595	615	394	443	34 961	0.5 %
Tasman	22	−19.1 %	142	586	549	358	409	3290	−18.6 %
Marlborough	7	−21.9 %	125	542	428	293	347	915	−24.4 %
Westland	41	−22.5 %	123	533	585	374	404	5978	−22.3 %
Wellington	29	−0.8 %	143	615	427	296	370	3973	−1.1 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	120	0.3 %	104	515	361	282	315	13 788	0.5 %
Otago	58	−6.2 %	89	526	488	287	347	7331	−6.0 %
Southland	113	7.4 %	93	530	566	334	381	15 761	7.9 %
National	1537	−1.3 %	163	595	513	352	406	227 802	−1.39 %
Combined national	9326							844 486	−0.20 %

Table B12. Land-use change, 2050 CO_2 = NZD 0.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production (MJ ha^{-1} d^{-1})						
Sheep & beef									
Northland	243	1.7 %	138	423	295	198	264	23 337	1.6 %
Auckland	78	−8.2 %	129	446	306	168	262	7514	−7.9 %
Waikato	468	−1.1 %	111	421	373	202	277	47 192	−0.7 %
Bay of Plenty	72	9.5 %	107	403	372	219	275	7246	10.1 %
Gisborne	319	−2.4 %	105	432	324	200	265	30 918	−2.1 %
Manawatu-Wanganui	866	−7.4 %	91	413	373	186	266	84 111	−7.4 %
Hawkes Bay	572	−2.3 %	94	397	213	179	221	46 074	−2.2 %
Taranaki	116	−6.9 %	104	396	412	214	282	11 946	−7.0 %
Tasman	59	3.8 %	86	405	275	173	235	5070	4.7 %
Marlborough	308	−0.9 %	59	310	231	133	183	20 564	−0.7 %
Westland	38	20.6 %	83	358	381	207	257	3593	21.8 %
Wellington	268	−4.8 %	95	439	251	156	235	22 960	−4.6 %
Nelson City	3	1.0 %	87	414	271	142	228	208	0.3 %
Canterbury	1711	−6.2 %	53	303	212	130	175	109 073	−6.8 %
Otago	1718	−1.2 %	46	295	248	134	181	113 356	−1.4 %
Southland	627	−10.2 %	61	373	367	174	244	55 748	−11.0 %
National	7465	−4.0 %	73	354	279	159	216	588 911	−4.26 %
Dairy									
Northland	168	−2.5 %	222	617	465	377	420	25 715	−2.4 %
Auckland	59	11.2 %	209	628	502	341	420	8991	10.9 %
Waikato	495	1.7 %	186	629	506	363	421	76 051	1.5 %
Bay of Plenty	75	−6.5 %	183	615	532	401	433	11 772	−6.7 %
Gisborne	12	390.0 %	179	574	440	370	390	1746	354.5 %
Manawatu-Wanganui	203	59.6 %	149	603	545	313	403	29 830	60.4 %
Hawkes Bay	30	89.7 %	137	578	392	325	358	3899	80.6 %
Taranaki	226	4.8 %	168	595	614	393	443	36 456	4.8 %
Tasman	25	−8.3 %	142	587	539	353	405	3696	−8.6 %
Marlborough	9	−6.5 %	123	538	404	283	337	1064	−12.1 %
Westland	42	−20.1 %	123	533	584	374	404	6164	−19.8 %
Wellington	43	46.5 %	141	614	417	294	367	5815	44.8 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	221	85.0 %	103	520	361	278	315	25 417	85.2 %
Otago	78	26.6 %	89	526	482	284	345	9838	26.1 %
Southland	176	67.1 %	94	532	568	334	382	24 593	68.3 %
National	1861	19.5 %	157	589	506	345	399	271 076	17.34 %
Combined national	9326							859 987	1.64 %

Table B13. Land-use change, 2050 CO_2 = NZD 50 per tonne.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production ($MJ\,ha^{-1}\,d^{-1}$)						
Sheep & beef									
Northland	243	1.9 %	138	423	295	198	264	23 385	1.8 %
Auckland	79	−7.5 %	129	446	306	168	262	7569	−7.2 %
Waikato	469	−0.9 %	111	421	372	202	276	47 283	−0.5 %
Bay of Plenty	72	9.9 %	107	403	372	219	275	7272	10.5 %
Gisborne	319	−2.4 %	105	432	324	200	265	30 920	−2.1 %
Manawatu-Wanganui	867	−7.3 %	91	413	373	186	266	84 201	−7.3 %
Hawkes Bay	572	−2.4 %	94	397	213	179	221	46 069	−2.2 %
Taranaki	117	−6.4 %	104	397	412	215	282	12 013	−6.5 %
Tasman	59	3.9 %	86	405	275	173	235	5075	4.8 %
Marlborough	308	−0.8 %	59	310	231	133	183	20 573	−0.6 %
Westland	38	21.0 %	83	359	381	207	257	3603	22.2 %
Wellington	268	−4.6 %	95	439	251	156	235	22 986	−4.5 %
Nelson City	3	1.0 %	87	414	271	142	228	208	0.3 %
Canterbury	1716	−5.9 %	53	304	211	130	175	109 353	−6.6 %
Otago	1719	−1.1 %	46	295	248	134	181	113 412	−1.4 %
Southland	627	−10.1 %	61	373	367	174	244	55 772	−11.0 %
National	7475	−3.9 %	73	354	279	159	216	589 695	−4.13 %
Dairy									
Northland	167	−3.1 %	222	617	465	377	420	25 557	−3.0 %
Auckland	58	9.8 %	209	628	502	341	420	8878	9.6 %
Waikato	494	1.4 %	186	629	506	363	421	75 862	1.3 %
Bay of Plenty	74	−6.8 %	183	615	532	401	433	11 730	−7.0 %
Gisborne	12	389.0 %	178	573	439	370	390	1741	353.4 %
Manawatu-Wanganui	202	58.7 %	149	603	546	313	403	29 672	59.6 %
Hawkes Bay	30	89.2 %	137	578	392	325	358	3888	80.1 %
Taranaki	225	4.4 %	168	595	614	393	443	36 309	4.4 %
Tasman	25	−8.9 %	142	587	539	353	405	3673	−9.2 %
Marlborough	8	−9.2 %	123	541	410	286	340	1043	−13.8 %
Westland	42	−20.4 %	123	533	584	374	403	6133	−20.2 %
Wellington	43	45.4 %	141	614	417	294	367	5771	43.7 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	216	80.9 %	103	520	363	278	316	24 912	81.5 %
Otago	77	24.7 %	89	527	484	285	346	9721	24.6 %
Southland	176	66.8 %	94	532	568	334	382	24 542	68.0 %
National	1848	18.7 %	157	589	506	345	399	269 462	16.64 %
Combined national	9323							859 157	1.54 %

Table B14. Land-use change, 2050 CO_2 = NZD 100 per tonne.

Region	Area (kha)	Change (%)	Winter	Spring	Summer	Autumn	Average	Total ME (TJ)	Change (%)
			Average production ($MJ\,ha^{-1}\,d^{-1}$)						
Sheep & beef									
Northland	244	2.3 %	138	423	295	198	264	23 471	2.2 %
Auckland	79	−7.3 %	129	446	306	168	262	7585	−7.0 %
Waikato	473	0.2 %	111	421	373	202	277	47 776	0.5 %
Bay of Plenty	74	12.3 %	107	403	372	219	275	7436	13.0 %
Gisborne	319	−2.4 %	105	432	324	200	265	30 926	−2.1 %
Manawatu-Wanganui	870	−7.1 %	91	413	373	186	266	84 413	−7.1 %
Hawkes Bay	572	−2.3 %	94	397	213	179	221	46 102	−2.2 %
Taranaki	117	−6.0 %	104	397	412	215	282	12 065	−6.1 %
Tasman	59	4.3 %	86	405	275	174	235	5095	5.2 %
Marlborough	308	−0.9 %	59	310	231	133	183	20 554	−0.7 %
Westland	39	24.0 %	83	359	381	207	257	3696	25.3 %
Wellington	268	−4.7 %	95	439	251	156	235	22 983	−4.5 %
Nelson City	3	1.0 %	87	414	271	142	228	208	0.3 %
Canterbury	1716	−5.9 %	53	304	211	130	175	109 353	−6.6 %
Otago	1719	−1.1 %	46	295	248	134	181	113 419	−1.4 %
Southland	627	−10.1 %	61	373	367	174	244	55 811	−10.9 %
National	7487	−3.7 %	73	354	279	159	216	590 893	−3.94 %
Dairy									
Northland	165	−3.9 %	222	617	465	377	420	25 359	−3.7 %
Auckland	58	9.1 %	209	628	502	341	420	8818	8.8 %
Waikato	488	0.3 %	186	629	505	363	421	75 035	0.2 %
Bay of Plenty	73	−8.8 %	183	615	530	401	433	11 478	−9.0 %
Gisborne	12	386.0 %	179	573	438	370	390	1729	350.2 %
Manawatu-Wanganui	200	57.0 %	149	603	545	313	403	29 341	57.8 %
Hawkes Bay	29	85.7 %	137	578	391	325	358	3811	76.6 %
Taranaki	224	4.1 %	168	595	614	393	443	36 218	4.1 %
Tasman	25	−10.0 %	142	587	538	353	405	3626	−10.3 %
Marlborough	8	−10.5 %	123	541	410	286	340	1028	−15.1 %
Westland	41	−22.3 %	123	533	585	374	404	5989	−22.1 %
Wellington	43	44.9 %	141	614	417	294	367	5750	43.2 %
Nelson City	0	−41.2 %	124	533	350	300	327	30	−39.5 %
Canterbury	215	80.4 %	103	520	363	278	316	24 844	81.0 %
Otago	77	24.3 %	89	527	484	285	346	9690	24.2 %
Southland	176	66.4 %	94	532	568	334	382	24 485	67.6 %
National	1833	17.7 %	157	590	506	345	399	267 232	15.68 %
Combined national	9320							858 125	1.42 %

Acknowledgements. This work was supported by the New Zealand Ministry for Primary Industries (MPI) and public research funding from the Government of New Zealand (GNS-540GCT81). Pasture production data provided by Collier Isaacs (Landcorp), Brenda Rosser (Landcare Research/GNS Science), Beef + Lamb New Zealand, DairyNZ, and AgResearch. Meteorological VCSN data provided by NIWA. We thank Duncan Smeaton (AgResearch), Anne-Gaelle Ausseil (Landcare Research), William Power (GNS Science) and Wei Zhang (Motu/MPI) for their contributions. Discussion with MPI has improved the final presentation of our results. We thank two anonymous referees whose comments have improved this manuscript.

Edited by: J. Williams

References

Ainsworth, E. A. and Long, S. P.: What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2, New Phytol., 165, 351–371, 2005.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy, 1998.

Baisden, W. T.: Agricultural and forest productivity for modelling policy scenarios: evaluating approaches for New Zealand greenhouse gas mitigation, J. Roy. Soc. New Zealand, 36, 1–15, 2006.

Baisden, W. T., Keller, E. D., Timar, L., Smeaton, D., Clark, A., Ausseil, A., Power, W. L., and Zhang, W.: New Zealand's pasture production in 2020 and 2050, GNS Science consultancy report 2010/154, New Zealand Ministry for Primary Industries, Wellington, New Zealand, 2010.

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., and Mirin, A.: Combined climate and carbon-cycle effects of large-scale deforestation, P. Natl. Acad. Sci. USA, 104, 6550–6555, 2007.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., and Papale, D.: Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate, Science, 329, 834–838, 2010.

Beets, P. N. and Oliver, G. R.: Water use by managed stands of Pinus radiata, indigenous podocarp/hardwood forest, and improved pasture in the Central North Island of New Zealand, New Zeal. J. For. Sci., 37, 306–323, 2007.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Muller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol., 13, 679–706, doi:10.1111/j.1365-2486.2006.01305.x, 2007.

Bond-Lamberty, B., Gower, S. T., Ahl, D. E., and Thornton, P. E.: Reimplementation of the Biome-BGC model to simulate successional change, Tree Physiol., 25, 413–424, 2005.

Clark, A., Mullan, B., and Porteous, A.: Scenarios of regional drought under climate change, NIWA report number WLG2010-32, New Zealand Ministry for Primary Industries, Wellington, New Zealand, 2011.

Clarke-Hill, W. J. and Fraser, T. J.: PasturePlan™: On-farm pasture growth and quality data for sheep and beef farms throughout New Zealand, New Zealand Grassland Association Conference Proceedings, Vol. 69, 2007.

DairyNZ: DairyNZ Farmwatch – Waikato, available at: http://farmwatch.dairynz.co.nz/Home/ShowData/2#table (last access: 21 August 2014), 2011.

de Graaf, M. A., Van Groenigen, K. J., Six, J., Hungate, B., and Van Kessel, C.: Interactions between plant growth and soil nutrient cycling under elevated CO_2: a meta-analysis, Glob. Change Biol., 12, 2077–2091, doi:10.1111/j.1365-2486.2006.01240.x, 2006.

Deser, C., Phillips, A., Bourdette, V., and Teng, H.: Uncertainty in climate change projections: the role of internal variability, Clim. Dynam., 38, 527–546, doi:10.1007/s00382-010-0977-x, 2012.

Di Vittorio, A. V., Anderson, R. S., White, J. D., Miller, N. L., and Running, S. W.: Development and optimization of an Agro-BGC ecosystem model for C4 perennial grasses, Ecol. Model., 221, 2038–2053, 2010.

Doherty, J.: PEST: Model Independent Parameter Estimation User Manual, 5th ed., Watermark Numerical Computing, Brisbane, Australia, 2005.

ENSEMBLES: ENSEMBLES RT2A Results, available at: http://www.cnrm.meteo.fr/ensembles/public/results/results.html (last access: 3 April 2014), 2009.

ESRI: ArcGIS Desktop Release 9.3, ESRI Environmental Systems Research Institute, Redlands, California, USA, 2009.

Gerten, D., Rost, S., von Bloh, W., and Lucht, W.: Causes of change in 20th century global river discharge, Geophys. Res. Lett., 35, L20405, doi:10.1029/2008GL035258, 2008.

Gumpenberger, M., Vohland, K., Heyder, U., Poulter, B., Macey, K., Rammig, A., and Cramer, W.: Predicting pan-tropical climate change induced forest stock gains and losses – implications for REDD, Environ. Res. Lett., 5, 014013, doi:10.1088/1748-9326/5/1/014013, 2010.

Hendy, J., Kerr S., and Baisden, W. T.: The Land Use in Rural New Zealand Model Version 1 (LURNZv1): Model Description, Motu Working Paper 07-07, Motu Economic and Public Policy Research, Wellington, New Zealand, available at: http://www.motu.org.nz/publications/detail/the_land_use_in_rural_new_zealand_model_version_1 (last access: 7 May 2014), 2007.

Hendy, J., Kerr, S., and Baisden, W. T.: Greenhouse gas emissions charges and credits on agricultural land: what can a model tell us?, in: Clean development mechanism and law, first edition, edited by: Lakshmi, L., Icfai University Press, Hyderabad, India, 198–209, 2008.

Hidy, D., Barcza, Z., Haszpra, L., Churkina, G., Pintér, K., and Nagy, Z.: Development of the Biome-BGC model for simulation of managed herbaceous ecosystems, Ecol. Model., 226, 99–119, doi:10.1016/j.ecolmodel.2011.11.008, 2012.

Jung, M., Le Maire, G., Zaehle, S., Luyssaert, S., Vetter, M., Churkina, G., Ciais, P., Viovy, N., and Reichstein, M.: Assessing the ability of three land ecosystem models to simulate gross carbon uptake of forests from boreal to Mediterranean climate in Europe, Biogeosciences, 4, 647–656, doi:10.5194/bg-4-647-2007, 2007.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N.

G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., and Smith, C. J.: An overview of APSIM, a model designed for farming systems simulation, Eur. J. Agron., 18, 267–288, 2003.

Keller, E. D.: Using the Biome-BGC Model to assess New Zealand's production of animal products from 2006/7 to 2011/12 seasons relative to historical averages, GNS Science consultancy letter report 2012/177LR, New Zealand Ministry for Primary Industries, Wellington, New Zealand, 2012.

Kerr, S., Anastasiadis, S., Olssen, A., Power, W., Timar, L., and Zhang, W.: Spatial and Temporal Responses to an Emissions Trading Scheme Covering Agriculture and Forestry: Simulation Results from New Zealand, Forests, 3, 1133–1156, doi:10.3390/f3041133, 2012.

Kirschbaum, M. U. F., Whitehead, D., Dean, S. M., Beets, P. N., Shepherd, J. D., and Ausseil, A.-G. E.: Implications of albedo changes following afforestation on the benefits of forests as carbon sinks, Biogeosciences, 8, 3687–3696, doi:10.5194/bg-8-3687-2011, 2011.

Landcare Research: Fundamental Data Layers (FDLs) – Soils, available at: http://soils.landcareresearch.co.nz/contents/SoilData_FSL_About.aspx?currentPage=SoilData_FSL&menuItem=SoilData, last access: 7 May 2014.

Legendre, P.: lmodel2: Model II Regression, R package version 1.7-2, available at: http://CRAN.R-project.org/package=lmodel2, last access: 21 August 2014.

Mullan, B., Porteous, A., Wratt, D., and Hollis, M.: Changes in drought risk with climate change, NIWA client report WLG2005-23, Ministry for the Environment, Wellington, New Zealand, available at: http://www.mfe.govt.nz/publications/climate/drought-risk-may05/index.html (last access: 7 May 2014), 2005.

Nakicenovic, N. and Swart, R. (Eds.): Special Report on Emissions Scenarios, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, available at: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0 (last access: 22 August 2014), 2000.

Newton, P. C., Lieffering, M., Bowatte, W. S. D., Brock, S. C., Hunt, C. L., Theobald, P. W., and Ross, D. J.: The rate of progression and stability of progressive nitrogen limitation at elevated atmospheric CO_2 in a grazed grassland over 11 years of Free Air CO_2 enrichment, Plant Soil, 336, 433–441, 2010.

New Zealand Ministry for the Environment: New Zealand's Fifth National Communication under the United Nations Framework Convention on Climate Change, New Zealand Ministry for the Environment, Wellington, New Zealand, available at: http://www.mfe.govt.nz/publications/climate/nz-fifth-national-communication/ (last access: 7 May 2014), 2009.

New Zealand Ministry for the Environment: New Zealand's Greenhouse Gas Inventory 1990–2011, MfE Publication number ME 1113, Submission to the United Nations Framework Convention on Climate Change, 12 April 2013.

New Zealand Ministry for Primary Industries: Situation and Outlook for Primary Industries (SOPI) 2012, New Zealand Ministry for Primary Industries, Wellington, New Zealand, available at: http://www.mpi.govt.nz/news-resources/publications (last access: 7 May 2014), 2012.

Parfitt, R. L., Schipper, L. A., Baisden, W. T., and Elliott, A. H.: Nitrogen inputs and outputs for New Zealand in 2001 at national and regional scales, Biogeochemistry, 80, 71–88, 2006.

Parfitt, R. L., Baisden, W. T., Schipper, L. A., and Mackay, A. D.: Nitrogen inputs and outputs for New Zealand at national and regional scales: past, present and future, J. Roy. Soc. New Zeal., 38, 71–87, 2008.

Pietsch, S. A., Hasenauer, H., and Thornton, P. E.: BGC-model parameters for tree species growing in central European forests, Forest Ecol. Manag., 211, 264–295, 2005.

R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, available at: http://www.R-project.org/ (last access: 21 August 2014), 2013.

Renwick, J., Mullan, B., Wilcocks, L., Zammit, C., Baisden, W. T., Keller, E. D., Kirschbaum, M., Meason, D., Harrison, D., Verkerk, G., Cooke, A., Marshall, P., and Clark, A.: Four Degrees of Global Warming: effects on the New Zealand primary sector, NIWA client report WLG2012-24, New Zealand Ministry for Primary Industries, Wellington, New Zealand, available at: http://www.mpi.govt.nz/news-resources/publications (last access: 7 May 2014), 2013.

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: the potential of green water for increasing resilience to global change, Water Resour. Res., 45, W00A12, doi:10.1029/2007WR006767, 2009.

Ronneberger, K., Criscuolo, L., Knorr, W., and Tol, R. S.: KLUM@LPJ: Integrating dynamic land-use decisions into a dynamic global vegetation and crop growth model to assess the impacts of a changing climate. A feasibility study for Europe, Working Papers FNU-113, Research unit Sustainability and Global Change, Hamburg University, Germany, 2006.

Rosser, B. J. and Ross, C. W.: Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand, New Zeal. J. Agr. Res., 54, 23–44, 2011.

Rost, S., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M., and Rockström, J.: Global potential to increase crop production through water management in rainfed agriculture, Environ. Res. Lett., 4, 044002, doi:10.1088/1748-9326/4/4/044002, 2009.

Roudier, P., Sultan, B., Quirion, P., and Berg, A.: The impact of future climate change on West African crop yields: What does the recent literature say?, Global Environ. Chang., 21, 1073–1083, 2011.

Schilling, C., Zuccollo, J., and Nixon, C.: Dairy's role in sustaining New Zealand: the sector's contribution to the economy, The New Zealand Institute for Economic Research, Wellington, New Zealand, available at: http://nzier.org.nz/publications/dairys-role-in-sustaining-new-zealand (last access: 7 May 2014), 2010.

Smith, L. C., Moss, R. A., Morton, J. D., Metherell, A. K., and Fraser, T. J.: Pasture production from a long-term fertiliser trial under irrigation, New Zeal. J. Agr. Res., 55, 105–117, 2012.

South Island Dairying Development Centre: LU Dairy Farm Weekly Data, available at: http://www.siddc.org.nz/lu-dairy-farm/weekly-data/, last access: 21 August 2014.

Stroombergen, A., Stojanovik, A., Wratt, D., Mullan, B., Tait, A., Woods, R., Baisden, W. T., Giltrap, D., Lock, K., Hendy, J., and Kerr, S.: Costs and benefits of climate change and adaptation to climate change in New Zealand agriculture: what do we know so far?, New Zealand Ministry of Agriculture and Forestry, Wellington, New Zealand, available at: http://www.motu.org.nz/publications/detail/costs_and_benefits_of_climate_change_and_adaptation_to_climate_change_in_ne (last access: 7 May 2014), 2008.

Tait, A., Henderson, R., Turner, R., and Zheng, X. G.: Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface, Int. J. Climatol., 26, 2097–2115, 2006.

Thornton, P. E.: Description of a numerical simulation model for predicting the dynamics of energy, water, carbon, and nitrogen in a terrestrial ecosystem, Ph.D. thesis, University of Montana, Missoula, USA, 280 pp., 1998.

Thornton, P. E. and Rosenbloom, N. A.: Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model, Ecol. Model., 189, 25–48, 2005.

Thornton, P. E., Law, B. E., Gholz, H. L., Clark, K. L., Falge, E., Ellsworth, D. S., Goldstein, A. H., Monson, R. K., Hollinger, D., Falk, M., Chen, J., and Sparks, J. P.: Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests, Agr. Forest Meteorol., 113, 185–222, 2002.

Thornton, P. E., Running, S. W., and Hunt, E. R.: Biome-BGC: Terrestrial Ecosystem Process Model, Version 4.2 Final Release, Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, Missoula, USA, available at: http://www.ntsg.umt.edu/project/biome-bgc (last access: 7 May 2014), 2005.

Timar, L.: Rural Land Use and Land Tenure in New Zealand, Motu Working Paper 11-13, Motu Economic and Public Policy Research, Wellington, 2011.

Timar, L. and Kerr, S.: Land-use Intensity and Greenhouse Gas Emissions in the LURNZ Model, Motu Working Paper 14-03, Motu Economic and Public Policy Research, Wellington, 2014.

Wang, Q., Watanabe, M., and Ouyang, Z.: Simulation of water and carbon fluxes using Biome-BGC model over crops in China, Agr. Forest Meteorol., 131, 209–224, doi:10.1016/j.agrformet.2005.06.002, 2005.

Wang, W., Ichii, K., Hashimoto, H., Michaelis, A. R., Thornton, P. E., Law, B. E., and Nemani, R. R.: A hierarchical analysis of terrestrial ecosystem model Biome-BGC: Equilibrium analysis and model calibration, Ecol. Model., 220, 2009–2023, 2009.

Warrick, R. A., Kenny, G. J., and Harman, J. J. (Eds.): The Effects of Climate Change and Variation in New Zealand: An Assessment Using the CLIMPACTS System, International Global Change Institute, University of Waikato, Hamilton, New Zealand, available at: http://docs.niwa.co.nz/library/public/0473079887.pdf (last access: 7 May 2014), 2001.

White, M. A., Thornton, P. E., Running, S. W., and Nemani, R. R.: Parameterization and Sensitivity Analysis of the Biome-BGC Terrestrial Ecosystem Model: Net Primary Production Controls, Earth Interact., 4, 1–85, 2000.