Climatic factors influencing New Zealand pasture resilience under scenarios of future climate change

Elizabeth D. KELLER[1,2*], Mark LIEFFERING[3], Jing GUO[4], W. Troy BAISDEN[5,6] and Anne-Gaelle AUSSEIL[7,8]
[1]*GNS Science, PO Box 31312, Lower Hutt 5040, New Zealand*
[2]*Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand*
[3]*AgResearch, Private Bag 11008, Palmerston North 4442, New Zealand*
[4]*Manaaki Whenua—Landcare Research, PO Box 69040, Lincoln 7640, New Zealand*
[5]*University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand*
[6]*Te Pūnaha Matatini CoRE, School of Environment, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*
[7]*Manaaki Whenua—Landcare Research, PO Box 10345 The Terrace, Wellington 6143, New Zealand*
[8]*now at: Ministry for the Environment, PO Box 10362, The Terrace, Wellington 6143, New Zealand*
*Corresponding author: L.Keller@gns.cri.nz

Highlights

New Zealand's intensively managed pastoral agricultural systems are vulnerable to climate change because of their dependence on grazing livestock and pasture as the primary feed supply. Drawing from recent modelling results, annual pasture yields in New Zealand are projected to be robust to a changing climate due to more favourable growing conditions in winter and early spring and increased plant efficiencies from the CO_2 fertilization effect. However, growth is also expected to become more variable and unpredictable, particularly in water-limited regions. A combination of short-term, incremental changes (already part of current practice) and longer-term strategic interventions will be necessary to maintain consistent feed supply under future climate change.

Keywords: climate change adaptation, pastoral agriculture

Background

New Zealand's intensively managed pastoral agricultural systems, characterised by high stocking rates, high pasture utilisation, frequent grazing, mowing, fertiliser application, irrigation, and/or other management interventions, are vulnerable to climate change because of their reliance on pasture as the primary feed supply (Lee et al. 2013). Projected changes have the potential to affect both the quality and quantity of pasture (Soussana et al. 2010; Giridhar & Samireddypalle 2015) and could threaten the economic viability of farm enterprises (Lieffering et al. 2016). The amount of pasture growth (and therefore the amount available to grazing animals) is impacted by a combination of climatic factors, including but not limited to temperature, precipitation, solar radiation, and relative humidity (Zhang et al. 2007). Not only changes in annual means but also inter-annual and seasonal variability (outside the range of present-day climate), the frequency of extreme events, and interactions with other environmental factors (notably soil properties and nitrogen (N) availability) are important considerations in evaluating the impact of climate change on future pasture yields (Tubiello et al. 2007; Soussana et al. 2010; Thornton et al. 2014; Harrison et al. 2016). At a national level, climate models predict an increase in annual mean temperatures and more frequent extreme precipitation events (both heavy rainfall and drought) under most future climate change scenarios (Tait et al. 2016). However, there is a high degree of regional variation, and considerable uncertainty remains. The impact at a farm level will depend to some degree on local climate effects.

Past studies using both mechanistic, process-based and empirical/statistical models have produced a range of predictions of the response of pasture to climate change in New Zealand. Early work based on statistical models of rainfall, temperature and pasture growth (e.g., Baars et al. 1990; Clark et al. 2001; Kenny et al. 2001; Zhang et al. 2007) found both positive and negative impacts of climate change on pasture growth in New Zealand, depending on the region. However, these models are relatively simple, examine a limited range of factors and/or are unable to account for the complex interactions and feedbacks between physical processes. Keller et al. (2014) used a process-based biophysical model to estimate New Zealand national pasture production under two climate change scenarios in 2050 and 2100, finding that pasture production in both dairy and sheep/beef systems will increase nationally by 2050, with significant regional variation. By 2100, however, sheep and beef systems are much more impacted by extreme warming and decreases in precipitation, with modelling suggesting a decline of 3-13% in regional pasture production. The same study found that dairy yields will experience a modest increase, indicating that

ISSN 0118-8581 (Print) ISSN 2463-4751 (Online)
https://doi.org/10.33584/rps.17.2021.3458

intensively managed pastoral systems, with appropriate adaptations and interventions, might be more resilient to climate change. However, this study is limited by the fact that the model representation of management and grazing is simplistic. In addition, diverse and complex topographical features of steeply-sloping "hill country" (e.g., slope and aspect), which includes a significant portion of sheep and beef farms in New Zealand, are not accounted for.

Other process-based studies at the farm scale such as by Kalaugher et al. (2017) have found that climate change will present challenges to dairy farm systems in regions where they are presently located (Northland, Waikato, Bay of Plenty, Taranaki, Canterbury, Otago). They project that under current management practices (without adaptation), change in annual production ranges from 0% to as much as -18%, although the exact impact will be highly location-specific. The authors note, however, that several modelled adaptations showed the ability to reduce the impact of climate change on pasture productivity. The model also did not include the effects of CO_2 fertilisation, which tends to enhance plant productivity under higher atmospheric CO_2 concentrations, so the adverse impact is likely overstated. Lieffering et al. (2016) modelled climate change impacts on two sheep and beef grazing enterprises in 2040 in Southland and Hawke's Bay, finding small increases in annual pasture growth but marked changes in seasonality. Again, changes in management and new technology have the potential to mitigate much of the negative impact, but not universally. One region (Southland) showed clear benefits from climate change and management adaptations, while in the other (Hawke's Bay) there were no positive impacts from either climate change or the modelled adaptations. Cradock-Henry et al. (2020) also highlighted vulnerabilities of New Zealand pastoral systems to climate change and identified potential adaptive options (some of which are already in use) in a case study of the Hawke's Bay region. This study found that both climatic and non-climatic factors were important drivers of change; while change for the most part will be gradual, and farmers are already accustomed to adjusting for inter-annual climate variability and seasonal feed deficits, flexible forward planning will be even more necessary in the future as climate becomes more unpredictable.

Elsewhere, research has highlighted the vulnerability of pasture to water shortages and drought. A recent study on the impact of climate change on pasture-based dairy systems in Australia (Pembleton et al. 2020) concluded that irrigated systems are resilient to projected changes in climate but dryland pasture annual yields are likely to decline, and both systems will experience a seasonal shift in production away from warmer months and towards cooler ones. Another study in Australia (Moore & Ghahramani 2013) predicted declines in annual pasture yield in five different livestock enterprises out to 2070, with declines more severe in locations with low rainfall. The summer-dry period lengthened in almost all locations, compounding the risk of erosion from lower production. A study of temperate grasslands in the United States showed that not just the magnitude but the timing of droughts and heat waves is important to productivity, with the most impact occurring in the early-to-mid growing season (Craine et al. 2012). Species diversity and richness might also play a role in how resilient managed grasslands are to climate variability, with more diversity associated with greater resilience (Vogel et al. 2012; De Keersmaecker et al. 2016). While these studies examined climates that are considerably different from present-day New Zealand, as conditions increasingly deviate from past experience, farmers everywhere will be faced with similar challenges. Regardless of location, interactions between climate, water and nutrient availability and the local environment will impact pastoral agriculture and require adaptive changes in management systems.

Models often contain multiple, correlated factors which are varied simultaneously, making it difficult to attribute change to specific climatic variables or other aspects of the system. Most of the studies mentioned above do not attempt to quantify the impact of individual climatic attributes. Here we take a closer look at some of the regional impacts of climate change on pasture growth in New Zealand and use a combination of biophysical models and statistical analysis to determine which climatic attributes are most influential to projected changes in pasture growth. We then outline what this might mean for farm management. This paper is structured as follows: a) review of climate projections for New Zealand over the next century; b) discussion of what climate attributes are important for pasture production and how these will impact future pasture growth at a regional level; c) discussion of implications for pastoral farm systems; and d) summary and recommendations for potential adaptation options.

Climate Change Projections and Scenarios

Climate projections

Climate projections for New Zealand have been dynamically downscaled from global general circulation models (GCMs) from the Coupled Model Intercomparison Project (CMIP-5), part of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5, IPCC 2014). The six best-performing models in the New Zealand region were chosen for use in impact studies (Tait et al. 2016). They are: HadGEM2-ES (UK), CESM1-CAM5 (USA), NorESM1-M (Norway), GFDL-CM3 (USA), GISS-

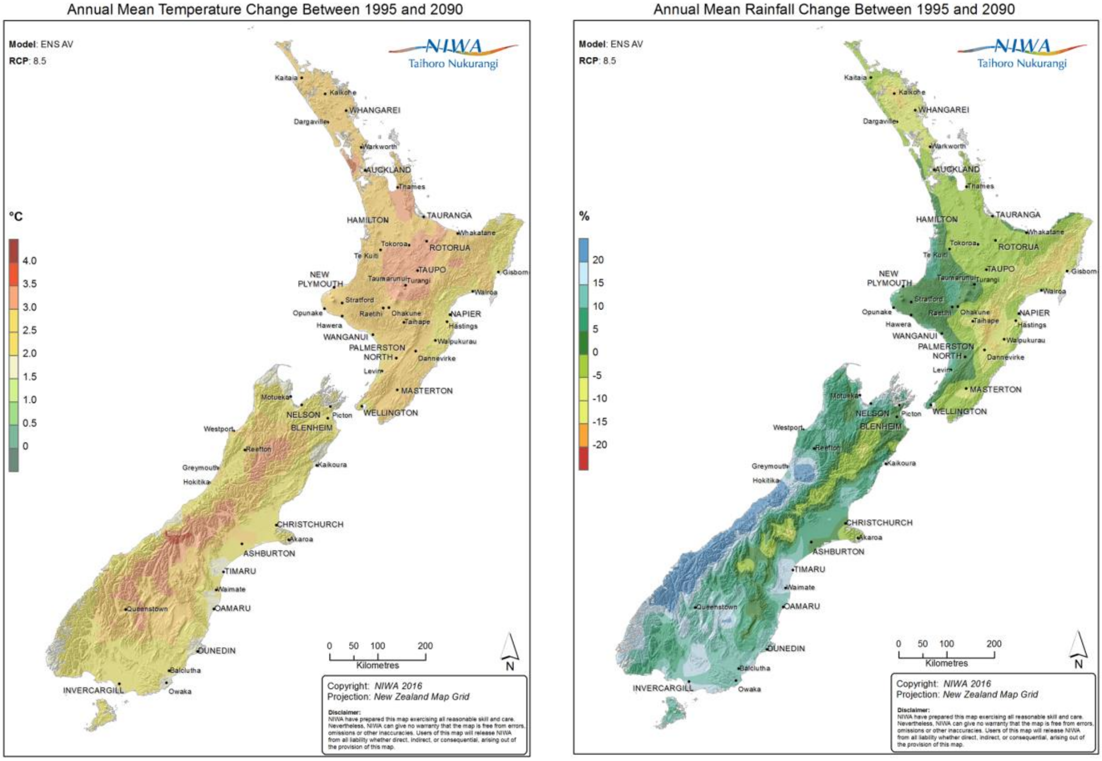

Figure 1 Projected changes in mean annual temperature (left) and annual mean rainfall (right) under RCP 8.5 over the 20-year period of 2081-2100 (centred on 2090), relative to the 20-year historical period of 1985-2006 (centred on 1995). Results represent the ensemble average of all six GCMs. Figure generated from https://ofcnz.niwa.co.nz/#/nationalMaps

E2-R (USA) and BCC-CSM1.1 (China). Each model was bias-corrected and downscaled to the National Institute of Water and Atmospheric Research (NIWA) 5-km Virtual Climate Station Network (VCSN) grid (Tait et al. 2006, 2012; Tait 2008; Tait & Liley 2009; Sood 2015; Mullan et al. 2016). The downscaled data, including uncertainties, have been comprehensively analysed by Mullan et al. (2016).

Following from the IPCC AR5, four scenarios of future greenhouse gas (GHG) emissions, or Representative Concentration Pathways (RCPs), were selected. They are (in order of increasing atmospheric GHG concentrations) RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. RCP 2.6 is a low-end scenario consisting of aggressive emissions reductions and/or CO_2 removal from the atmosphere. On the other end of the spectrum, RCP 8.5 is a high-end, worst-case scenario, with no mitigation of global GHG emissions, which would result in a global mean temperature increase of as much as +4°C by 2100 (IPCC 2014). RCP 4.5 and 6.0 are in between these two extremes. We focus mostly on RCP 8.5 in this paper, as it serves as a baseline worst-case scenario that, given the high amount of uncertainty in future projections and socio-economic conditions, policy makers and farmers should take into account when planning for future change.

Projections of minimum and maximum temperature, precipitation, solar radiation, relative humidity, mean sea level pressure, and average wind speed are available at a daily time step. In the high-emissions scenario (RCP 8.5), annual mean temperatures in New Zealand are projected to increase between 2.0°C and 3.0°C by the end of the century (Figure 1). Areas inland and north (alps in the South Island, parts of Auckland, Bay of Plenty, and central plateau in the North Island) are predicted to experience the most increase (up to 3.5-4.0°C). Hawke's Bay and Southland show more modest increases of 2.0 - 2.5°C. The most significant seasonal temperature increases occur in autumn, with Waikato particularly affected (+4.0°C).

Annual precipitation is projected to increase along the west coast of the North Island and decrease in the eastern regions (Figure 1). The most extreme decreases are in Hawke's Bay and Gisborne, with annual mean differences of -10 to -15% over much of the regions. The spring reduction in Hawke's Bay is particularly noteworthy (-5 to -15%). For most of the South Island precipitation is predicted to increase, except for the area around Christchurch and parts of the Central Alps experiencing no or small declines of as much as -5%. The largest increase is along the West Coast, with

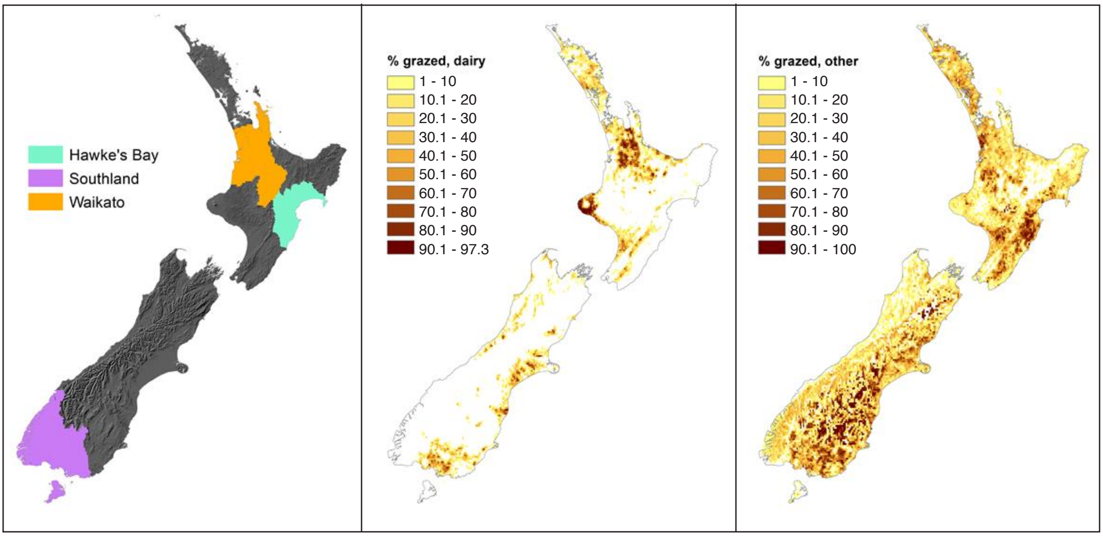

Figure 2 The three study regions: Hawke's Bay, Waikato, and Southland (left map), along with percentage of land used for grazing dairy cows (middle) and other animals (right). Grazed land percentages derived from the LUCAS Land Use Map (Manderson et al. 2019).

annual totals as much as 25% larger. Southland is also projected to see large annual increases of 5-20%. Much of this change occurs in winter and spring. Change across the Waikato region is relatively small, with annual precipitation varying between -5 and 5%.

For more detailed projections (particularly seasonal changes) and other climate variables, see Tait et al. (2016) and https://ofcnz.niwa.co.nz/.

CO_2 fertilization

While it is not an explicit climate variable, the increase in atmospheric CO_2 concentrations affects plants through what is known as the "CO_2 fertilization effect". All else being equal, higher concentrations of CO_2 simultaneously increase the rate of photosynthesis (more CO_2), reduce plant N demand (through enhanced N use efficiency) and decrease water demand (plants do not need to open their stomata as widely to get the same intake of CO_2 and hence lose less water) (Leakey et al. 2009). The atmospheric concentration of CO_2 in the RCP 8.5 scenario reaches ~930 ppm by 2100, more than double present day (~410 ppm). Thus there is theoretical potential for a large boost to photosynthesis rates and yields in C_3 plants in the future in the absence of water, nutrient or other limitations (Tubiello et al. 2007). However, in reality, much of New Zealand pasture is N-limited. Nitrogen dynamics are critical in determining the response of plant growth to elevated CO_2 (Li et al. 2014). Some studies have shown that actual growth enhancement is less than what is theoretically predicted (Leakey et al. 2009; Li et al. 2014) and that much of the gain is below ground in the root system, so would not be available to grazing animals (Dodd 2013). The full effects of CO_2 fertilization and the extent of interactions and feedbacks under future climate are uncertain and a subject of ongoing model development and research (Nowak et al. 2004; Soussana et al. 2010; Li et al. 2014).

Note that gains in yields in C_4 grasses are much smaller or non-existent, since C_4 plants have a different photosynthetic pathway and are more efficient at lower atmospheric CO_2 concentrations (Kimball et al. 2002; Crush & Rowarth 2007; Tubiello et al. 2007; Leakey et al. 2009). This has implications for pastures in northern regions in New Zealand which contain a high proportion of C_4 grasses.

Scenarios and regions

In this study we consider in more detail three future climate scenarios (RCP 2.6, 4.5, and 8.5) in three regions: Waikato, Southland, and Hawke's Bay (Figure 2). These regions were chosen as regions that are significant for pastoral farming with contrasts in climate and soils. Six different GCMs provided the climate input to process-based models of varying complexity (APSIM, Biome-BGC, and WATYIELD; see next section). All scenarios are compared with a baseline present-day scenario "RCP past" (1971-2005). The future scenarios span 2006 to 2100 (with some GCMs extending to 2120). Two future 20-year time slices were examined: mid-century (2046-2065) and end-of-century (2081-2100).

Climatic factors affecting pasture growth

Climate is one of the most important controls on pasture growth. Although other environmental factors such as soil characteristics, erosion and pests also influence production potential, climate is the focus of this paper because projected changes over the next century will have significant impact on pasture growth and will have implications for farm management. Changes in mean climate as well as climate variability and the frequency of extreme events will affect future pasture yields (Tubiello et al. 2007).

In a project funded jointly by the Our Land and Water and Deep South National Science Challenges, we explored the climatic factors influencing land suitability for primary production in New Zealand, with a focus on pasture and maize (Ausseil et al. 2019). We looked at both basic climate indices that can be easily measured (such as annual air temperature) and more complex variables derived from empirical or process-based models (e.g., potential evapotranspiration deficit, PED). Table 1 shows a list of all of the climate attributes that were considered, developed in consultation with experts and stakeholders (Beare et al. 2017).

Models

We used three biophysical, process-based models to evaluate the influence of climate on pasture growth: APSIM (Agricultural Production Systems Simulator, Holzworth et al. 2014), Biome-BGC (Thornton et al. 2002; Thornton & Rosenbloom 2005), and WATYIELD (Fahey et al. 2010). These models represent a range of complexity, from relatively simple models that can be run efficiently on the regional and national scale, to highly complex, data-intensive models designed for the local farm scale.

Of the three models, APSIM is the most complex, with the ability to simulate the growth of both pasture and crops and the effects of different management regimes. It is used in this study to simulate pasture growth at three point locations using six different representative soil types (typical of the respective region). Pastures were modelled as a mixed pasture of *Lolium perenne* (perennial ryegrass) and *Trifolium repens* (white clover). The only *de novo* N input is N fixation by clover, which is the norm in New Zealand hill country. Soil characteristics were taken from typical soil type profiles for the region in S-Map (Landcare Research). While APSIM does not explicitly model farm systems and the multitude of management options that can be implemented, the grazing parameters (Additional online file: Appendix 1) would be typical of a medium-intensity managed sheep and beef pastoral system (with no inputs of fertiliser and/or irrigation). Such systems are more sensitive to changes in environmental conditions relative to more intensively managed systems (i.e., dairy), thus highlighting the impact of climate change. It should be noted that the modelled pasture was on a flat topography, i.e., the effects of slope and aspect were not considered. It is well known that topography can have a marked effect on pasture production, and it can also impact the CO_2 fertilisation effect (Lieffering et al. 2019), but introducing this variable is a challenging task, especially at larger scales (current research efforts are underway to incorporate topography at a farm scale). Hence the modelled pasture results presented here should be considered as illustrative of the magnitude and direction of potential changes to ryegrass/white clover pasture production

Table 1 Final list of climate attributes for statistical analysis with modelled yield (above-ground biomass production).

Climate attribute	Time scale		
	Monthly	Seasonal	Annual
T annual Air temperature		Y	
GDD (Growing Degree Days base 7,10)		Y	Y
Growth Limiting Factor (GLF) – water		Y	Y
Cumulative deep drainage (mm)			Y
Number of frost days			Y
Number of hot days above 25°C (Nbhotdays25)	Y		
Total chill hours in winter		Y	
PCP (precipitation)	Y	Y	Y
PET (Potential evapotranspiration)	Y		
AET (Actual evapotranspiration)	Y		
AET – PET	Y		
SPEI (Standardised Potential Evapotranspiration Index)	Y		
ET-PET		Y	
Relative Soil Moisture		Y	
Potential Evapotranspiration Deficit (PED, mm)		Y	Y

(on flat sites), recognising that different species and topographies may show different responses.

Biome-BGC is a somewhat simpler ecosystem process model which simulates the biological and physical processes controlling carbon, N and water fluxes in vegetation and soil. Here it is used to simulate regional-level pasture growth. We simulated a generic functional-type C_3 grass using parameters calibrated with pasture clipping data from New Zealand sheep and beef farms, including sites with easy/rolling hills and more steeply-sloping ground (Keller et al. 2014). While slope and aspect are not explicitly represented, the model's effective soil depth parameter is used as a proxy for shallower topsoil in areas prone to erosion. Soil characteristics were varied spatially according to the Fundamental Soil Layers database (Landcare Research). Nitrogen inputs are given by a constant rate of N fixation, calibrated to present-day rates.

WATYIELD is another relatively simple model designed for calculating the water deficit in soil for crop growth that is easy to implement on a broad regional scale. It calculates PED, which is the difference between estimated evapotranspiration and rainfall and is used as an indicator of "water demand" in plants. We used WATYIELD to simulate the water balance under several different types of land cover (pasture, crops, and forest) at point locations in Hawke's Bay, Waikato and Southland. Although not a pasture growth model, WATYIELD is included in this study because of the importance of water-related variables to pasture production. It also shows the contrasting demands of different land covers and the increased pressure on resources in water-limited regions such as Hawke's Bay, providing some insight into the benefits and trade-offs of land-use change.

The models are described in more detail (Ausseil et al. 2019; Additional online file: Appendices 1-3), including references to calibration and validation for New Zealand systems.

Statistical analysis

To understand which climate attributes are most significant to pasture production, we applied multiple regression to correlate the selected attributes (Beare et al. 2017) to modelled yields from APSIM and Biome-BGC. This analysis tells us what portion of the variance in production can be explained by each attribute. The model results were treated as independent variables, although it should be noted that the models used some of the same inputs and are therefore correlated with each other.

Stepwise selection of variables was performed in JMP v14.3 (SAS Institute, USA). A full suite of available metrics was entered into backwards stepwise regression for selection at a stringent P-value of 10^{-15} to minimise the number of and correlation between selected parameters for the final multiple regression. The multiple regression results were used to attribute explained variance.

From this analysis, we found that several water-related indices were most influential in terms of explaining the variance in biomass production and/or pasture growth, particularly annual PED (or ET – PET) and Standardised Precipitation-Evapotranspiration Index (SPEI) calculated over the summer months. The SPEI is a measure of drought severity based on precipitation and temperature data (Vicente-Serrano et al. 2010). The number attached to the index indicates how many months prior have been averaged, i.e., SPEI2.Jan = SPEI index averaged over the two months December-January. It is calculated from the regionally downscaled outputs of the six GCMs. We were able to explain 79% of the variance of the APSIM results and 89% of the Biome-BGC results with the selected variables (which also included non-climatic attributes such as soil type and GCM; see Table 2). For APSIM, 20% of the variance could be attributed to basic climate indices, and 29% to water indices derived from Biome-BGC. Of the model-derived water indices, Biome-BGC's annual and summer ET-PET were most important. For climate indices, SPEI2 for January was most important (9%). For Biome-BGC, model-derived water indices explained 39% of the variance in production, with 29% explained by annual ET-PET. Basic climate indices explained 28%, led by SPEI2 for February at 15%.

Note, however, that the water indices are model outputs themselves and therefore cannot be considered independent of the modelled pasture yield. Eliminating the model-derived variables (the water indices from Biome-BGC) and focusing only on the climate indices

Table 2 Variables explaining APSIM- and Biome-BGC-modelled pasture production. The top predictors of production in the last row of the table take into account all variables (both climate indices and model-derived variables).

Variable	APSIM (% of variation explained)	Biome-BGC (% of variation explained)
Total	79.0	89.1
GCM	4.4	1.9
Soil	26.1	19.8
Modelled water	28.4	39.4
Climate Index	20.0	28.3
Top predictors	Biome-BGC ET Annual	Biome-BGC ET Annual
	Biome-BGC ET Summer	Biome-BGC ET Annual
	SPEI2 January	SPEI2 February

(Table 3), we find that SPEI2 in Jan/Feb is the most influential in explaining pasture production in both models, followed by annual temperature (APSIM) and GDD7 (Biome-BGC; GDD7 = growing degree days or accumulated number of days above a base temperature of 7°C). Other months and combinations of SPEI are also significant in both models, although it must be acknowledged that some of these attributes overlap in time (covering 1-3 months prior). It is clear, however, that water availability in summer is very important to overall yields. Annual temperature, growing degree days (GDD7/GDD10 annual) and number of hot days (>25°C; Nbhotdays25) are also significant, though less so than water availability.

As the climate gets hotter and drier in many regions of New Zealand over the new century, this will have clear implications for farm management.

Impacts on pasture production

Overall annual production and growth rates are projected to increase with increasing RCP scenario (increasing emissions). This is partially a result of warmer temperatures in winter and spring, which makes up for declines in summer. In addition, enhanced atmospheric CO_2 concentrations increase photosynthesis rates and water use efficiency, boosting modelled plant growth. Note, however, that models tend to overestimate the positive effects of CO_2 fertilization so these results could overstate the increase (Li et al. 2014). Both APSIM point-scale results and Biome-BGC regional model runs show increasing trends in total annual yield for mid-century and end-of-century time slices in all three regions (Figures 3-6). Warmer winter and spring temperatures make the most difference in Southland, where it is currently too cold to grow pasture year-round. Waikato experiences more modest gains since the winter is already relatively mild.

Table 3 Ranking of top eight key climate attributes influencing pasture production where production was modelled using APSIM and Biome-BGC. Note that model-derived variables have been excluded here because they cannot be considered independent variables.

APSIM		Biome-BGC	
Climate variable	**% of variation explained**	**Climate variable**	**% of variation explained**
SPEI2.Jan	34	SPEI2.Feb	48
Temp annual	14	GDD7annual	16
SPEI3.Nov	11	SPEI2.Dec	10
SPEI1.Feb	10	SPEI3.Jun	9
Nbhotdays25	8	PCP	4
GDD10annual	5	SPEI2.Jan	4
PET	5	Temp autumn	4
SPEI2.Apr	4	Nbhotdays25	3

The standard deviation among the results using the individual GCMs as input is one indicator of model uncertainty (Additional online file: Appendix 4). Biome-BGC results all show the same general trend (not shown), giving some confidence in this positive outcome. The spread among GCMs tends to increase with RCP scenario (except in Southland), showing that there is more uncertainty inherent in the high emissions scenario, as it deviates more from present-day conditions. By this metric, Hawke's Bay shows the most uncertainty, whereas Southland shows the least. However, it is important to note that the largest uncertainties come not from the climate projections but from the emissions pathways and human activity, which is extremely hard to quantify.

Although overall annual total yields increase with increasing emissions scenario, summer yields decline significantly in many regions of the country, including western Hawke's Bay, most of Waikato, and east Southland (Figures 7-10). The decline is most pronounced inland and is correlated with declines in precipitation (not shown). Presently, pasture production typically peaks in late spring and early summer (November and December). Under projected climate change, this peak increases in magnitude and shifts earlier to mid-spring, declining sharply towards summer (Figure 7). The shorter, sharper peak in pasture production will require careful farm management to ensure a constant feed supply during the summer months.

There is a substantial increase in year-to-year variability in pasture production by the end of the century in our model simulations (Figures 3 and 7). In APSIM, variability of monthly pasture growth rates (as expressed by the coefficient of variation) across all GCMs was similar for the past, mid-century, and end-of-century time slices in spring (calculated from data in Figure 7; Additional online file: Table A1). However, in summer, the "end" period was nearly as twice as variable than the "past", while in autumn and winter, variability was about 40% and 30% higher, respectively. Such variability will make it harder to predict in advance the amount of pasture available for grazing livestock. Variability is closely linked to water availability in the Waikato and Hawke's Bay regions, with extremes in precipitation (heavy rain and drought) predicted to increase in frequency and duration. There is less variability in Southland, likely because the region is not under as much pressure from drought and has enough water to meet demand even in relatively dry years. Note, however, that our models are currently not able to capture the impact of extreme events on plant senescence and mortality in perennial grasses, so the full extent of damage from these events cannot be assessed.

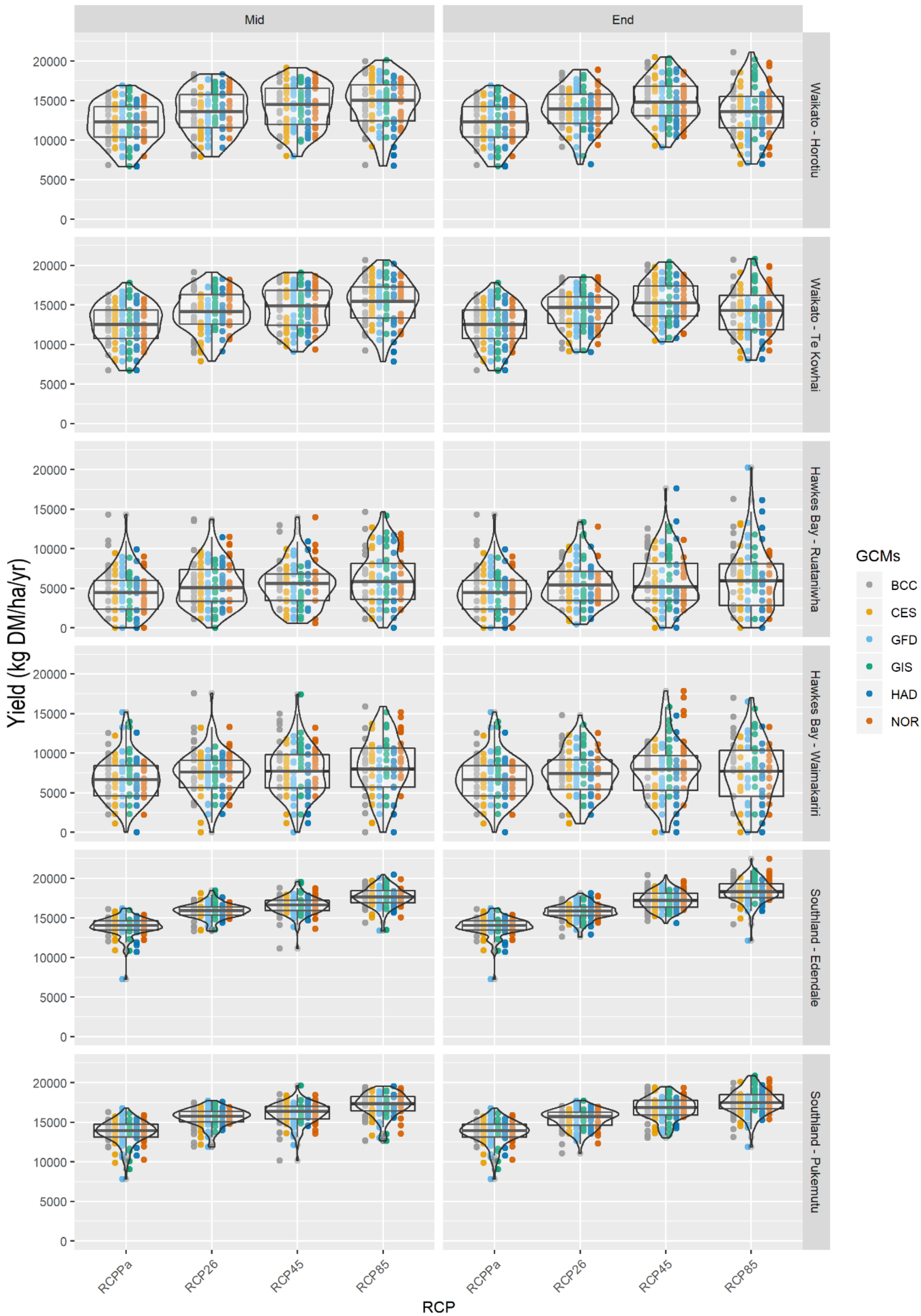

Figure 3 APSIM-modelled annual pasture production for three locations (Waikato, Hawke's Bay and Southland) and two soils at each location under RCP past (RCPPa) and three RCPs at mid- and end-of-century. Dots represent the six GCMs ("columns") and 20 years ("rows"). The box shows the 25th and 75th percentile range, with the median indicated by the thick middle horizontal line. The "violin" outline reflects the distribution of the data across all percentiles.

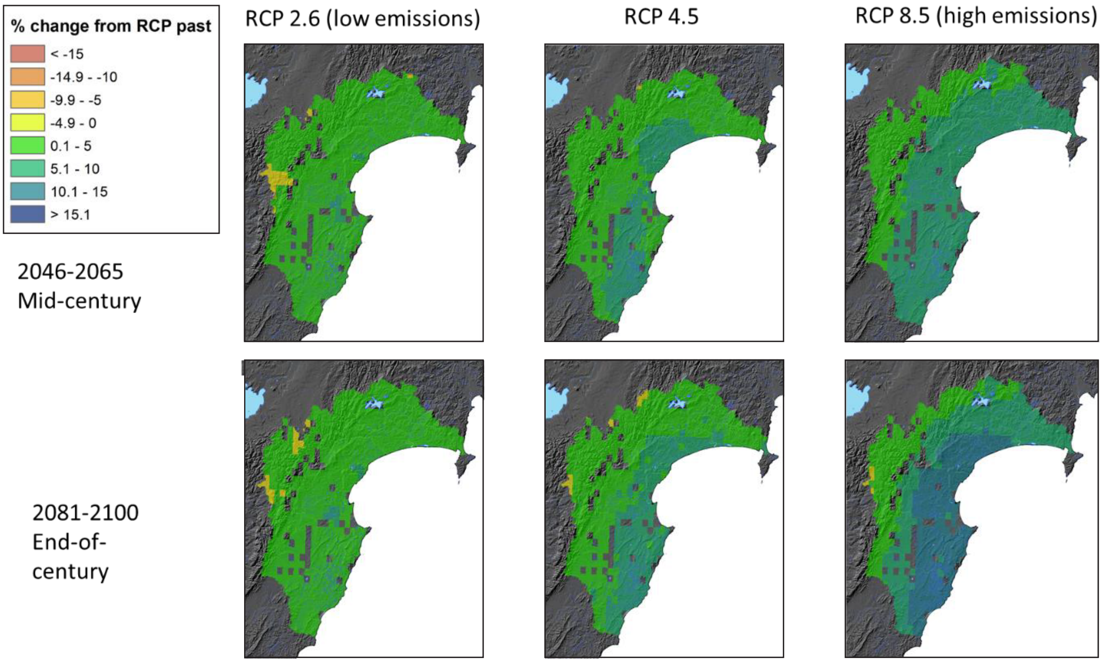

Figure 4 Biome-BGC model ensemble mean annual pasture yield for the Hawke's Bay region, as percentage change from RCP past (1971-2005). Two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100) are shown for RCP 2.6 (left), RCP 4.5 (middle), and RCP 8.5 (right). All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

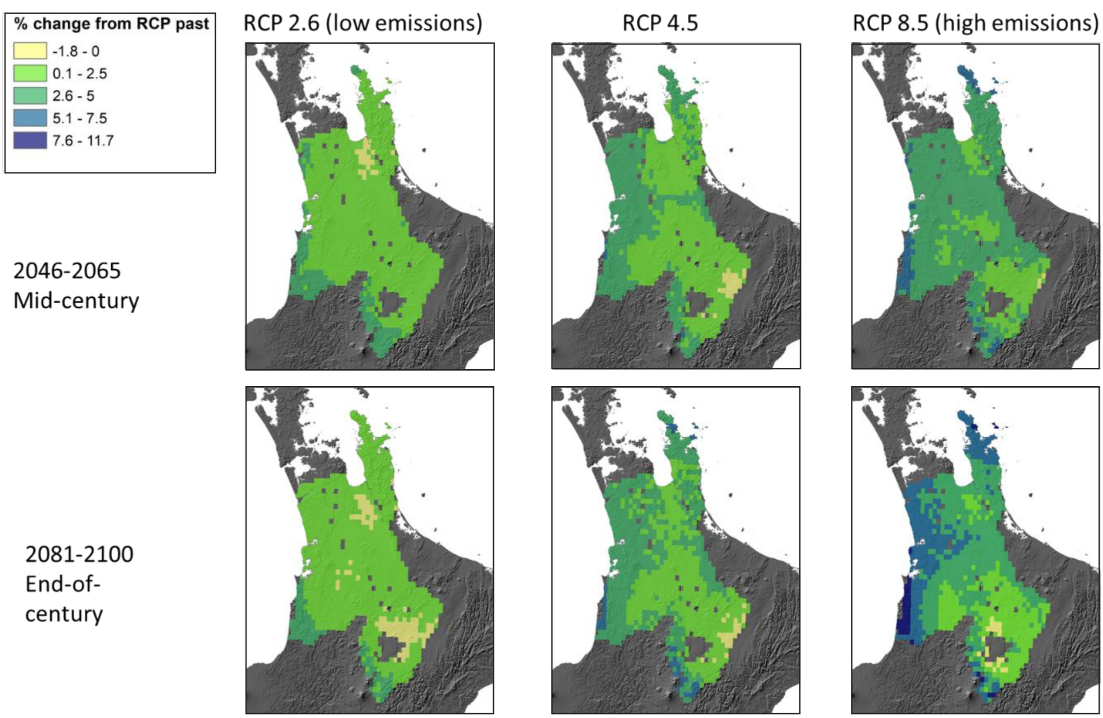

Figure 5 Biome-BGC model ensemble mean annual pasture yield for the Waikato region, as percentage change from RCP past (1971-2005). Two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100) are shown for RCP 2.6 (left), RCP 4.5 (middle), and RCP 8.5 (right). All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

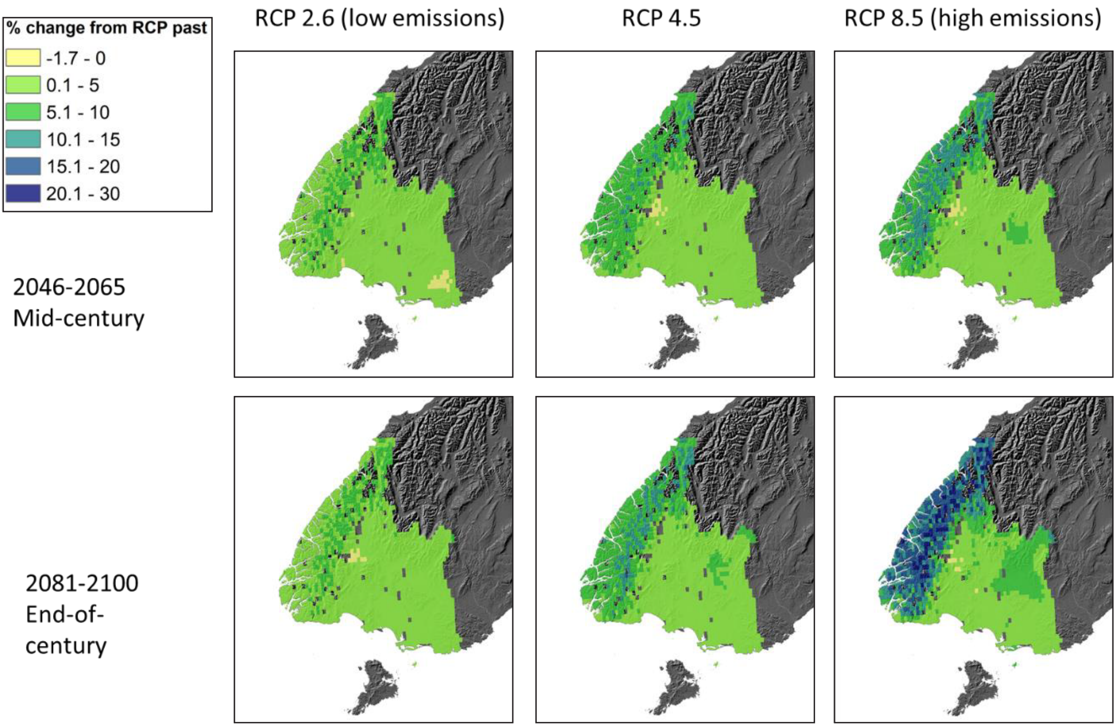

Figure 6 Biome-BGC model ensemble mean annual pasture yield for the Southland region, as percentage change from RCP past (1971-2005). Two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100) are shown for RCP 2.6 (left), RCP 4.5 (middle), and RCP 8.5 (right). All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

Water limitation emerges as a key issue for future pasture resilience, highlighting the importance of seasonal climate patterns and increased periods of prolonged drought. Our analysis showed that the SPEI is a significant predictor of pasture production in dry regions such as Hawke's Bay (Ausseil et al. 2019) although it is less significant for other regions that are not water-limited. SPEI is based on the concept of water demand and quantifies the anomaly in precipitation and PET from the long-term mean. A general negative trend in the SPEI for the 3 months before February under scenario RCP 8.5 with six different GCMs is shown in Figure 11, highlighting that the severity of summer drought will increase in the majority of projections. Biome-BGC and WATYIELD results both show increases in PED for pasture under the high-emissions RCP 8.5 scenario (results not shown; see Ausseil et al. 2019), indicating that plant water demand is not met by rainfall alone.

This highlights future challenges that farmers will confront with respect to water availability. Some areas will manage with relatively minor disruptions; however, in other areas, conditions might affect the economic and/or environmental viability of pastoral agriculture and other land uses.

Adaptation of pastoral farm systems to climate change

The evidence presented here suggests that while annual pasture yields will increase modestly on average, pasture production will become more variable and unpredictable both seasonally and inter-annually over the course of this century. While the overall picture is positive, particularly for southern regions like Southland, pastoral farms will increasingly need to plan for both shortages and surpluses in feed supply. Farmers in many regions already have strategies to deal with significant seasonal and year-to-year variability; our work suggests that more of this type of forward planning will be necessary in the future. Successful adaptation strategies will most likely include a combination of short- and long-term management interventions (Lieffering et al. 2016; Nettier et al. 2017; Cradock-Henry et al. 2020). Intensively managed dairy systems likely have a higher capacity for adaptive interventions (Lee et al. 2013), whereas with many extensively managed sheep and beef systems in hill country, options for adaptation are more limited.

Short-term tactical interventions such as importing feed, moving stock between regions, strategic timing of fertiliser application or lowering stock numbers in

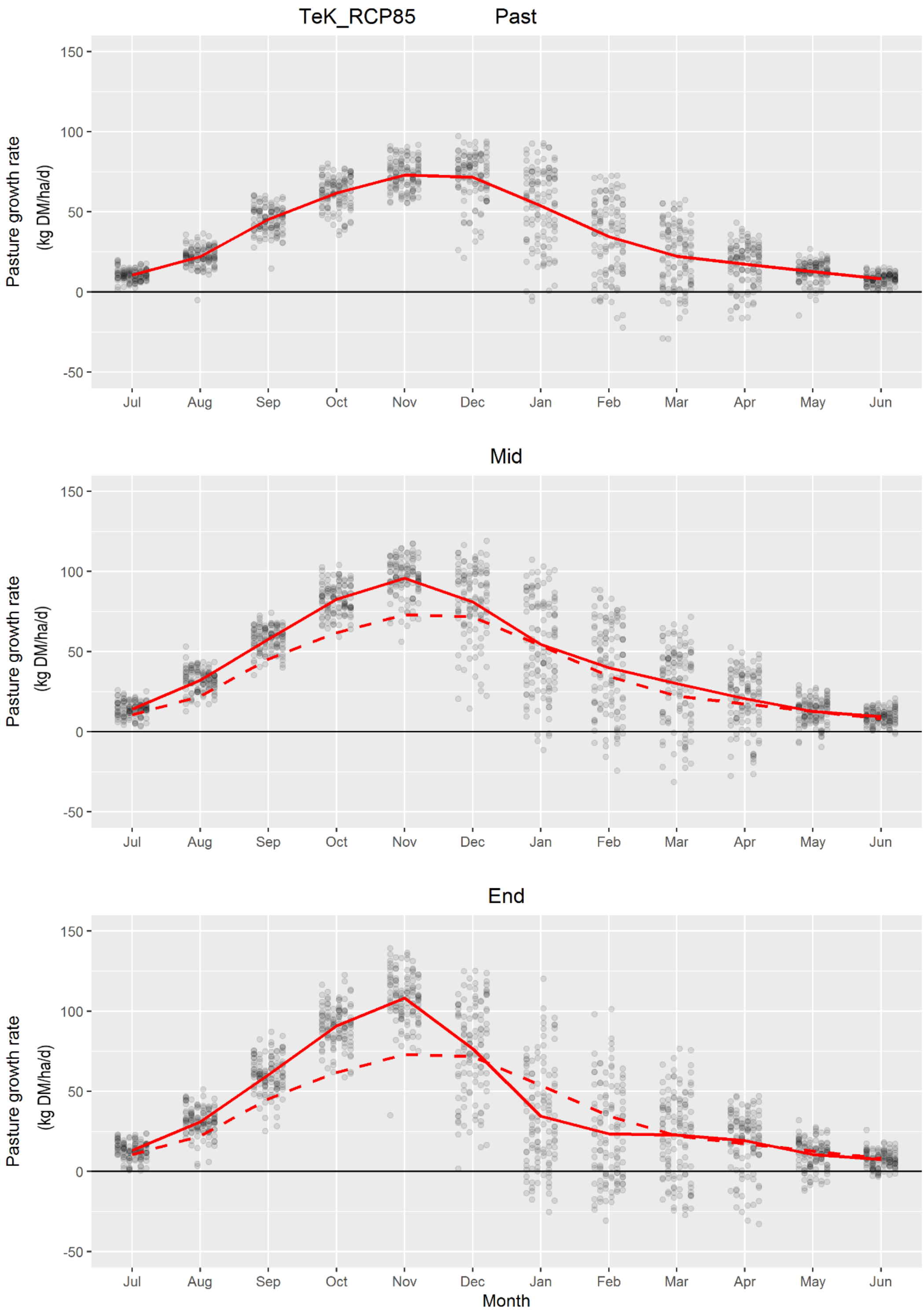

Figure 7 APSIM-modelled representative current (Past), mid-century (Mid) and end-of-century (End) monthly pasture growth curve changes in one of the locations/soils (Waikato/Te Kowhai soil) under RCP 8.5. Dots represent the six GCMs ("columns") and 20 years ("rows") with no colour coding. Solid red line shows the mean of all six GCMs and 20 years. Dashed lines in Mid and End panels are the current mean growth curve.

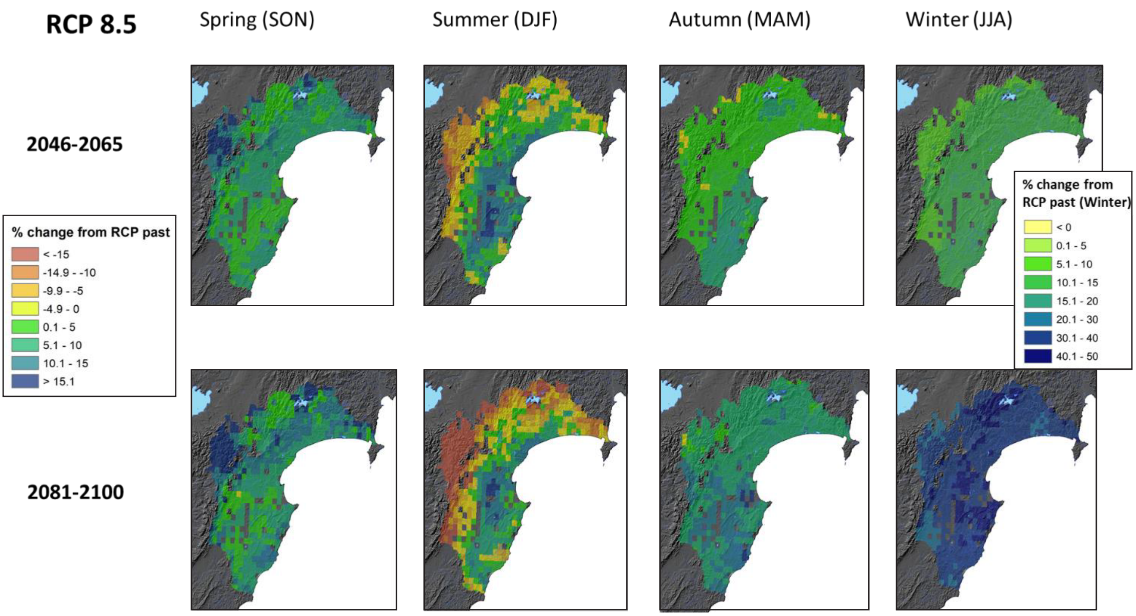

Figure 8 Biome-BGC model ensemble mean seasonal pasture growth rate for the Hawke's Bay region under RCP 8.5, as percentage change from RCP past (1971-2005), for two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100). Note that winter is shown on a different scale. All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

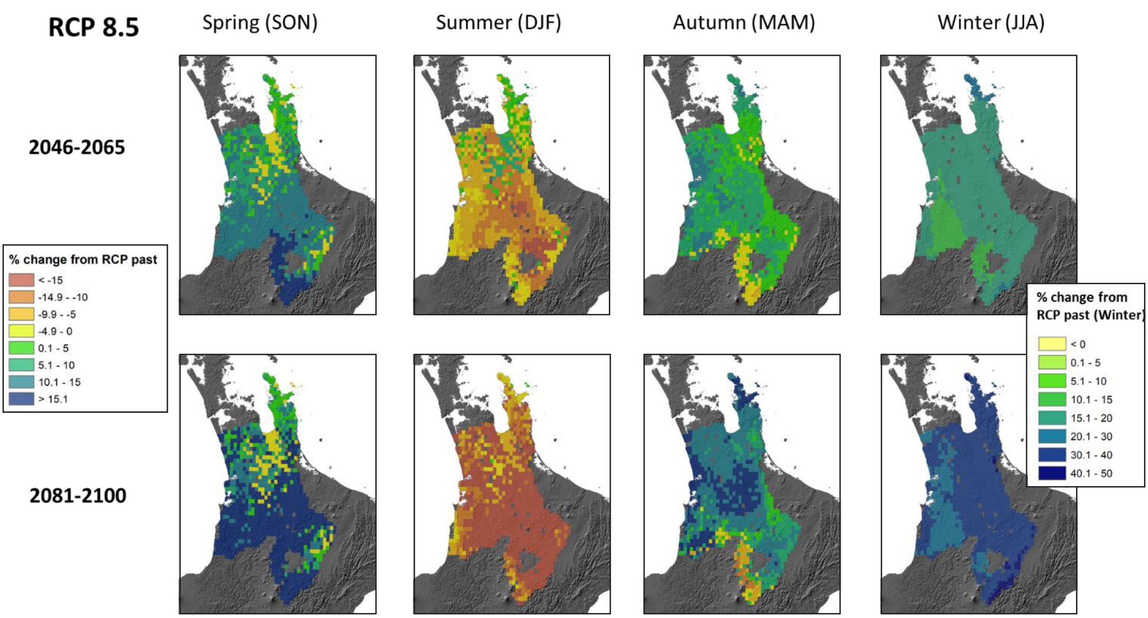

Figure 9 Biome-BGC model ensemble mean seasonal pasture growth rate for the Waikato region under RCP 8.5, as percentage change from RCP past (1971-2005), for two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100). Note that winter is shown on a different scale. All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

response to temporary shortages due to an unusually dry summer, for example, can be done relatively quickly and easily without long-term investment, and indeed are already done in many parts of New Zealand. It is often possible to harvest and store extra pasture and/or forage crop produced in spring or buy imported feed to cover shortages later in the year in summer or autumn. Our results suggest that more of

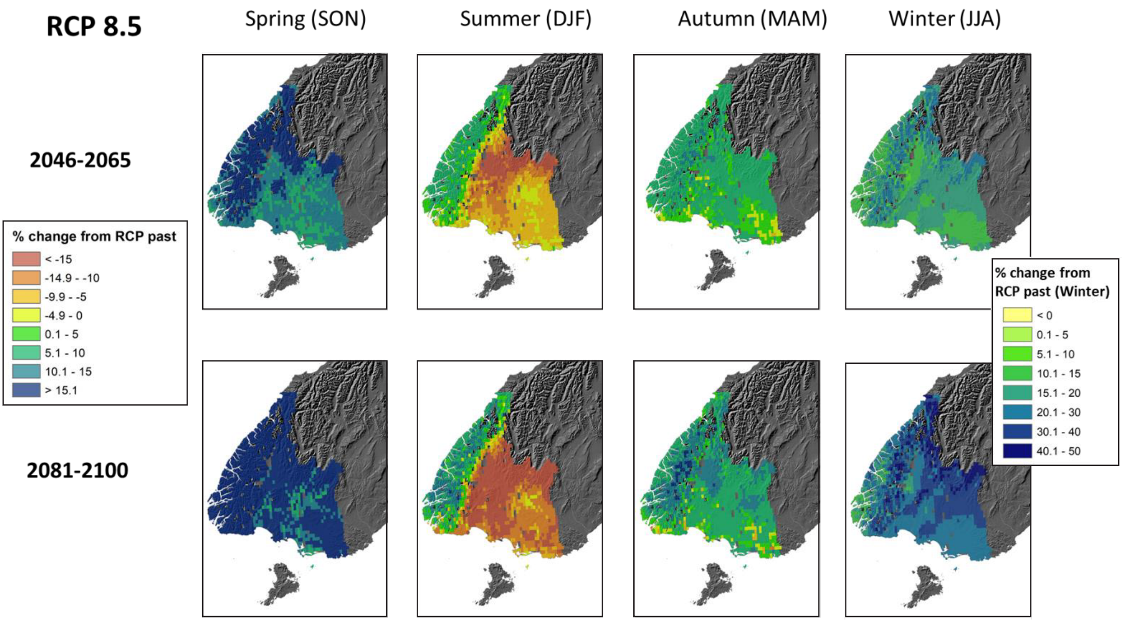

Figure 10 Biome-BGC model ensemble mean seasonal pasture growth rate for the Southland region under RCP 8.5, as percentage change from RCP past (1971-2005), for two time slices, mid-century (top: 2046-2065) and end-of-century (bottom: 2081-2100). Note that winter is shown on a different scale. All land is modelled as pasture, regardless of actual land use, and might be unrealistic for some locations (particularly mountainous terrain).

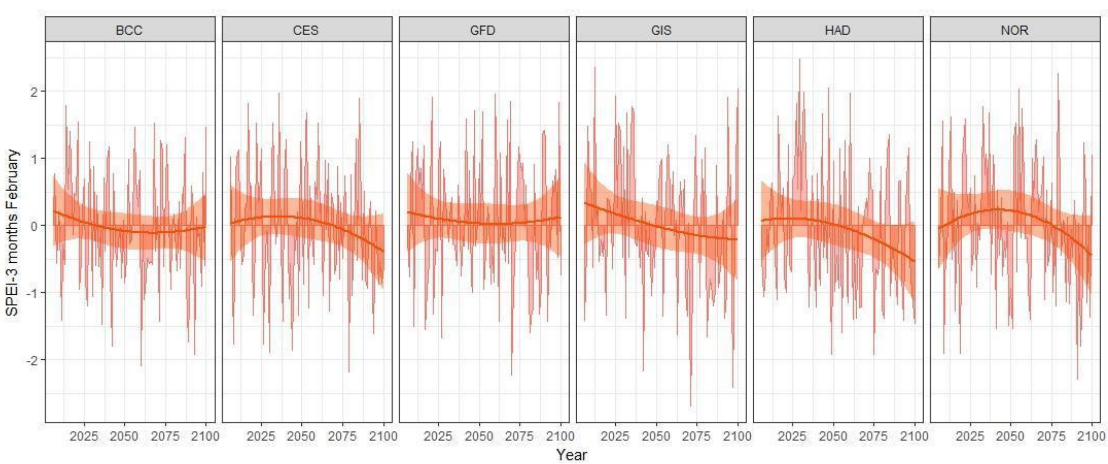

Figure 11 Standardised precipitation-evapotranspiration index (SPEI) for six different GCMs in Hawke's Bay, cumulated over 3 months before February. A negative value indicates drier than average conditions.

these types of existing interventions will be necessary in the future. However, as disruptions become more frequent and climate conditions depart dramatically from those experienced in the past, short-term solutions will become less attractive and perhaps economically unviable (Cradock-Henry et al. 2020).

Longer-term, strategic decisions such as introducing irrigation, changing the pastoral system or type of animal grazed or shifting into another land use altogether must be considered if climate change continues on its present trajectory. Changes in seasonality and water demand in particular will be a challenge for pastoral agriculture. Although pasture growth in winter and early spring will benefit from warmer temperatures and more favourable growing conditions, water shortages could become more severe in summer and autumn. Irrigation is an option in some regions, but much of New Zealand pasture is in steep hill country, where traditional irrigation systems

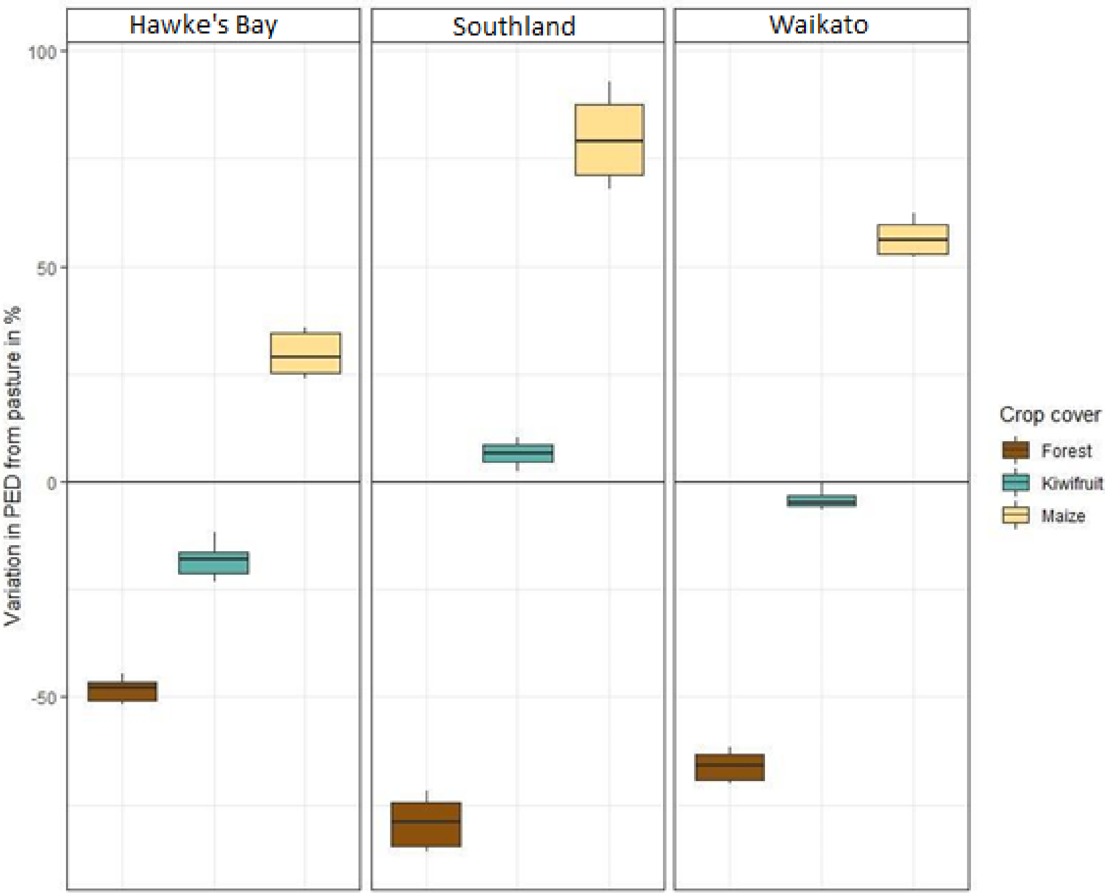

Figure 12 Variation in annual potential evapotranspiration deficit (PED) of other land covers from pasture cover under present-day conditions (RCP past) at point locations in Hawke's Bay, Southland and Waikato. Kiwifruit tends to have a similar amount of PED compared to pasture in the three locations. PED from maize cover is on average higher than PED from pasture cover, whereas forest has much lower PED (< -50%). The box represents the second and third quartile (25%-75% range). The black vertical lines extend to the minimum and maximum of the data. The black horizontal line represents the median.

cannot be implemented (Lieffering et al. 2016). Other management options could involve changing the ratio of sheep to cattle, changing the timing of lambing or calving, diversification of pasture composition (Skinner et al. 2006; Rojas-Downing et al. 2018) or introducing species of grass that are more drought-tolerant. More transformational options involving land-use change, for example, partial conversion of pasture to forest, could offer dual benefits of lower water demand and diversification of income from timber and carbon sequestration credits. Note however that commercial forestry has additional, controversial impacts on the landscape, as recent flooding and erosion triggered by clear-cutting on the east coast of the North Island have demonstrated (Hall 2018).

When considering strategic land-use change, it is important to note that the land cover affects evapotranspiration rates and PED/water demand. WATYIELD was used to quantify the percentage difference in PED among three common land uses (kiwifruit, maize, and forest) relative to a present-day baseline pasture cover in Hawke's Bay, Waikato, and Southland (Figure 12). In all three regions, pasture requires less water to meet growth and maintenance demands than rotation crops or horticulture, but more water than forest. The relative difference between kiwifruit and pasture varies according to region. WATYIELD predicts that water demand will increase under all four scenarios and in all three regions studied, with more substantial changes in Southland and Waikato (results not shown; see Ausseil et al. 2019). Adding irrigation is possible in some areas but not all, particularly the majority of hill country, and requires significant investment. Where irrigation is physically possible (i.e., flat or gently rolling land), high-value rotational crops and horticulture tend to offer a better return on investment, but place even more pressure on strained water resources. A study in Australia has suggested that adaptive management measures such as reducing stock numbers are more cost-effective in the long run than changes in land-use (Thamo et al. 2017). While it is out of scope of this study, analysis of the complex interactions between environmental and economic factors should be undertaken before management decisions such as land-use change are made.

Successful adaptation to climate change depends in large part on the willingness of individual farmers to implement new strategies. Dynamic adaptive pathways (DAP) is one approach that has been used to help communities plan for an uncertain future climate and identify adaptation options for agriculture in Hawke's Bay (Lawrence et al. 2019; Cradock-Henry et al. 2020). The options identified ranged from optimising current practices to whole-scale land-use change. The range of DAP options reflected the diversity of the sector in Hawke's Bay but should apply broadly to New Zealand's other regions as well. The emphasis of most of the participants was on adaptation involving incremental changes in optimisation and efficiency, in line with current practice, while keeping options open for more transformational change over time. The use of DAP methodology highlights that there is no universal, one-size-fits-all solution to climate change.

Conclusions and future implications

Overall, annual pasture yields in New Zealand are projected to be robust to a changing climate due to more favourable growing conditions in winter and early spring and increased plant efficiencies from the CO_2 fertilization effect. However, growth is also expected to become more variable and unpredictable, and particular attention must be paid to the sustainability of water demand. Some regions that are already relatively dry, such as Hawke's Bay, will experience even warmer, drier summers, which could put pressure on water resources and create seasonal feed shortages. While farmers in these regions already adapt and plan for seasonal feed deficits and inter-annual variability to some extent, more severe, prolonged droughts and seasonal shifts in peak production might require even more forward planning to ensure a steady feed supply for animals.

Regional differences in projected climate will require more adaptation in some places than others. Our knowledge of local climate change impacts is limited by the relatively coarse resolution of models, and small-scale spatial variation in precipitation, soil properties, and existing land management will affect the degree of resilience to climate change on individual farms. Complex and uncertain interactions between environmental conditions, international economic markets, and local policy regulations will dictate which adaptation options are available and feasible to implement. For example, introducing new irrigation systems will depend on the available water supply and competing demands from other sectors, which in turn are also affected by climate change. Incremental adaptive changes (which are already in use in New Zealand) are likely to be most practical and cost-effective in the near term.

While we considered the impact of drought, we have not looked into the implications of increased episodes of heavy rain and flooding. Soils can be damaged and pasture yields reduced if cattle tread on water-logged areas, resulting in pugging and compaction. Heavy rain can also trigger erosion e.g., landslides and inundate lowland pasture with sediment. The former damages the land and reduces potential long-term pasture growth, while the latter has severe short-term consequences, and both commonly damage infrastructure such as fencing. With both episodes of drought and flooding projected to increase, the contrast between extremes will present new challenges for pastoral agriculture. The impact of such extremes should be a priority for future research.

We also did not attempt to quantify changes in pasture quality. Our results are based on C_3 grasses, but many pastures in Northland and other North Island regions contain C_4 grasses. C_4 grasses are better adapted to higher temperatures but are generally of lower feed quality (Barbehenn et al. 2004), and elevated atmospheric CO_2 concentration does not convey the same boost to growth as it does for C_3 grasses (Crush & Rowarth 2007). Management can to some extent improve the nutritional value of C_4 grasses; nevertheless, there could be a trade-off between pasture resilience to higher temperatures and pasture quality. Pests also have potential to impact pasture quality. This is a critical topic for more research and the subject of another article in this issue.

It is important to consider the interactions of climate with the receiving environment, for example, soil characteristics and N leaching. Nitrogen leaching is likely to increase under future climate change (Ausseil et al. 2019), which might make the higher N load of beef and dairy cattle production untenable in some locations. This topic is beyond the scope of this paper, but any management decisions will have to contend with water quality issues and potential environmental policies and regulations. Future research priorities include a closer examination of the impact of climate change on N leaching and other aspects of the receiving environment, including the influence of extreme events on environmental degradation.

Projections are dominated by uncertainty not only in future climate but also in political and economic factors, societal response to climate change and new technological developments. In the short term, adaptation involving incremental changes in optimisation and efficiency and relatively inexpensive management interventions already in use will allow farmers to mitigate risk while leaving options open for more transformational change at a later stage.

ACKNOWLEDGEMENTS

This work was supported by the New Zealand Government and the Our Land and Water and Deep South National Science Challenges. The authors would like to thank the entire research team for their contributions: Tony van der Weerden, Mike Beare, Edmar Teixeira, Iris Vogeler, Stephen Flood, Nicholas Cradock-Henry, Richard Law, Alasdair Noble, and Andrew Sturman. We also thank three anonymous referees whose comments have improved this manuscript.

SUPPLEMENTARY MATERIAL

Additional Online File 1: Appendices 1-3–Descriptions of models; Appendix 4–Model uncertainty; Figures A1-A3–Standard deviation of modelled pasture production in three regions; Appendix 5–Inter-annual variability; Table A1–Coefficient of variation for pasture growth rate. https://www.nzgajournal.org.nz/index.php/rps/article/view/3458

REFERENCES

Ausseil A-G, van der Weerden T, Beare M, Teixeira E, Baisden WT, Lieffering M, Guo J, Keller E, Law R, Noble A. 2019. *Climate change impacts on land use suitability* [Contract Report LC3573]. Manaaki Whenua-Landcare Research, New Zealand. 78 p. https://ourlandandwater.nz/wp-content/uploads/2019/11/LUS_Ausseil_Land-Use_Final-Report_FINAL-30-June-2019-1.pdf.

Baars J, Radcliffe J, Rollo M. 1990. Climatic change effects on seasonal patterns of pasture production in New Zealand. *Proceedings of the New Zealand Grassland Association 51*: 43-46. https://doi.org/10.33584/jnzg.1990.51.1913

Barbehenn RV, Chen Z, Karowe DN, Spickard A. 2004. C_3 grasses have higher nutritional quality than C_4 grasses under ambient and elevated atmospheric CO_2. *Global Change Biology 10*: 1565-1575. https://doi.org/10.1111/j.1365-2486.2004.00833.x

Beare M, van der Weerden T, Ausseil A-G, Baisden WT, Teixeira E, Vogeler I, Keller E, de Klein C. 2017. *Identifying climate attributes that impact on land use suitability* [Contract Report 34484, SPTS No. 15283]. Plant and Food Research Ltd, Auckland, New Zealand. 32 p.

Clark H, Mitchell N, Newton P, Campbell B. 2001. The sensitivity of New Zealand's managed pastures to climate change. Chapter 6. In: Warrick RA, Kenny GJ & Harman JJ. Eds. *The effects of climate change and variation in New Zealand: An assessment using the CLIMPACTS system*. Hamilton, New Zealand: International Global Change Institute, The University of Waikato, pp. 65-76.

Cradock-Henry NA, Blackett P, Hall M, Johnstone P, Teixeira E, Wreford A. 2020. Climate adaptation pathways for agriculture: Insights from a participatory process. *Environmental Science & Policy 107*: 66-79. https://doi.org/10.1016/j.envsci.2020.02.020

Craine JM, Nippert JB, Elmore AJ, Skibbe AM, Hutchinson SL, Brunsell NA. 2012. Timing of climate variability and grassland productivity. *Proceedings of the National Academy of Sciences 109*: 3401-3405. https://doi.org/10.1073/pnas.1118438109

Crush JR, Rowarth JS. 2007. The role of C_4 grasses in New Zealand pastoral systems. *New Zealand Journal of Agricultural Research 50*: 125-137. https://doi.org/10.1080/00288230709510287

De Keersmaecker W, van Rooijen N, Lhermitte S, Tits L, Schaminée J, Coppin P, Honnay O, Somers B. 2016. Species-rich semi-natural grasslands have a higher resistance but a lower resilience than intensively managed agricultural grasslands in response to climate anomalies. *Journal of Applied Ecology 53*: 430-439. https://doi.org/10.1111/1365-2664.12595

Dodd MB. 2013. Elevated CO_2 impacts on grazed pasture: long-term lessons from the New Zealand FACE. *Proceedings of the 22nd International Grassland Congress*, Sydney, Australia, 15-19 September.

Fahey B, Ekanayake J, Jackson R, Fenemor A, Davie T, Rowe L. 2010. Using the WATYIELD water balance model to predict catchment water yields and low flows. *Journal of Hydrology (New Zealand) 49*: 35-58.

Giridhar K, Samireddypalle A. 2015. Impact of climate change on forage availability for livestock. In: Sejian V, Gaughan J, Baumgard L & Prasad C. Eds. *Climate change impact on livestock: adaptation and mitigation*. New Delhi, India: Springer India, pp. 97-112. https://doi.org/10.1007/978-81-322-2265-1_7

Hall D. 2018, 7 Jun 2018. Clear-cut forestry might make a profit, but local communities pay the price. *The Dominion Post*. Wellington, New Zealand.

Harrison MT, Cullen BR, Rawnsley RP. 2016. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. *Agricultural Systems 148*: 135-148. https://doi.org/10.1016/j.agsy.2016.07.006

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S, Keating BA. 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software 62*: 327-350. https://doi.org/10.1016/j.envsoft.2014.07.009

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland. 151 p.

Kalaugher E, Beukes P, Bornman JF, Clark A, Campbell DI. 2017. Modelling farm-level adaptation of temperate, pasture-based dairy farms to climate change. *Agricultural Systems 153*: 53-68. https://doi.org/10.1016/j.agsy.2017.01.008

Keller ED, Baisden WT, Timar L, Mullan B, Clark A. 2014. Grassland production under global change scenarios for New Zealand pastoral agriculture. *Geoscientific Model Development 7*: 2359-2391. https://doi.org/10.5194/gmd-7-2359-2014

Kenny GJ, Ye W, Flux T, Warrick RA. 2001. Climate variations and New Zealand agriculture: The CLIMPACTS system and issues of spatial and temporal scale. *Environment International 27*: 189-194. https://doi.org/10.1016/S0160-4120(01)00081-2

Kimball BA, Kobayashi K, Bindi M. 2002. Responses of agricultural crops to free-air CO_2 enrichment. *Advances in Agronomy 77*: 293-368. https://doi.org/10.1016/S0065-2113(02)77017-X

Lawrence J, Bell R, Stroombergen A. 2019. A hybrid process to address uncertainty and changing climate risk in coastal areas using dynamic adaptive pathways planning, multi-criteria decision analysis & real options analysis: a New Zealand application. *Sustainability 11*: 406. https://doi.org/10.3390/su11020406

Leakey ADB, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany 60*: 2859-2876. https://doi.org/10.1093/jxb/erp096

Lee JM, Clark AJ, Roche JR. 2013. Climate-change effects and adaptation options for temperate pasture-based dairy farming systems: a review. *Grass and Forage Science 68*: 485-503. https://doi.org/10.1111/gfs.12039

Li FY, Newton PC, Lieffering M. 2014. Testing simulations of intra-and inter-annual variation in the plant production response to elevated CO_2 against measurements from an 11-year FACE experiment on grazed pasture. *Global Change Biology 20*: 228-239. https://doi.org/10.1111/gcb.12358

Lieffering M, Newton PCD, Vibart R, Li FY. 2016. Exploring climate change impacts and adaptations of extensive pastoral agriculture systems by combining biophysical simulation and farm system models. *Agricultural Systems 144*: 77-86. https://doi.org/10.1016/j.agsy.2016.01.005

Lieffering M, Newton PCD, Brock SC, Theobald PW. 2019. Some effects of topographic aspect on grassland responses to elevated CO_2. *Plant Production Science 22*: 345-351. https://doi.org/10.1080/1343943X.2019.1587301

Manderson A, Hoogendoorn C, Newsome P. 2019. *Grassland Improvement Mapping using Innovative Data Analysis (IDA) Techniques* [Contract Report LC3373]. Manaaki Whenua – Landcare Research, Wellington, New Zealand. 39 p.

Moore AD, Ghahramani A. 2013. Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. *Global Change Biology 19*: 1440-1455. https://doi.org/10.1111/gcb.12150

Mullan B, Sood A, Stuart S, Carey-Smith T. 2016. *Climate change projections for New Zealand: atmosphere projections based on simulations from the IPCC fifth assessment, 2^nd^ edition*. Ministry for the Environment, Wellington, New Zealand. 131 p.

Nettier B, Dobremez L, Lavorel S, Brunschwig G. 2017. Resilience as a framework for analyzing the adaptation of mountain summer pasture systems to climate change. *Ecology and Society 22*: 25. https://doi.org/10.5751/ES-09625-220425

Nowak RS, Ellsworth DS, Smith SD. 2004. Functional responses of plants to elevated atmospheric CO_2 – do photosynthetic and productivity data from FACE experiments support early predictions? *New Phytologist 162*: 253-280. https://doi.org/10.1111/j.1469-8137.2004.01033.x

Pembleton KG, Cullen BR, Rawnsley RP, Ramilan T. 2020. Climate change effects on pasture-based dairy systems in south-eastern Australia. *Crop and Pasture Science 72*: 666-677. https://doi.org/10.1071/CP20108

Rojas-Downing MM, Nejadhashemi AP, Abouali M, Daneshvar F, Al Masraf SAD, Herman MR, Harrigan T, Zhang Z. 2018. Pasture diversification to combat climate change impacts on grazing dairy production. *Mitigation and Adaptation Strategies for Global Change 23*: 405-431. https://doi.org/10.1007/s11027-017-9740-5

Skinner RH, Sanderson MA, Tracy BF, Dell CJ. 2006. Above- and belowground productivity and soil carbon dynamics of pasture mixtures. *Agronomy Journal 98*: 320-326. https://doi.org/10.2134/agronj2005.0180a

Sood A. 2015. *Improved Bias Corrected and Downscaled Regional Climate Model data for Climate Impact Studies: Validation and Assessment for New Zealand*. National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand. 43 p.

Soussana J-F, Graux A-I, Tubiello FN. 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. *Journal of Experimental Botany 61*: 2217-2228. https://doi.org/10.1093/jxb/erq100

Tait A. 2008. Future projections of growing degree days and frost in New Zealand and some implications for grape growing. *Weather and Climate 28*: 17-36. https://doi.org/10.2307/26169696

Tait A, Henderson R, Turner R, Zheng X. 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology 26*: 2097-2115. https://doi.org/10.1002/joc.1350

Tait A, Liley B. 2009. Interpolation of daily solar radiation for New Zealand using a satellite data-derived cloud cover surface. *Weather and Climate 29*: 70-88. https://doi.org/10.2307/26169706

Tait A, Sturman J, Clark M. 2012. An assessment of the accuracy of interpolated daily rainfall for New Zealand. *Journal of Hydrology (New Zealand) 51*: 25-44.

Tait A, Sood A, Mullan B, Stuart S, Bodeker G, Kremser S, Lewis J. 2016. *Climate Changes, Impacts and Implications for New Zealand to 2100. Synthesis Report: RA1. Updated Climate Change Projections for New Zealand for Use in Impact Studies* [MBIE contract C01X1225]. 18 p.

Thamo T, Addai D, Pannell DJ, Robertson MJ, Thomas DT, Young JM. 2017. Climate change impacts and farm-level adaptation: Economic analysis of a mixed cropping-livestock system. *Agricultural Systems 150*: 99-108. https://doi.org/10.1016/j.agsy.2016.10.013

Thornton PE, Law BE, Gholz HL, Clark KL, Falge E, Ellsworth DS, Goldstein AH, Monson RK, Hollinger D, Falk M, Chen J, Sparks JP. 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. *Agricultural and Forest Meteorology 113*: 185-222. https://doi.org/10.1016/S0168-1923(02)00108-9

Thornton PE, Rosenbloom N. 2005. Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model. *Ecological Modelling 189*: 25-48. https://doi.org/10.1016/j.ecolmodel.2005.04.008

Thornton PK, Ericksen PJ, Herrero M, Challinor AJ. 2014. Climate variability and vulnerability to climate change: a review. *Global Change Biology 20*: 3313-3328. https://doi.org/10.1111/gcb.12581

Tubiello FN, Soussana J-F, Howden SM. 2007. Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences 104*: 19686-19690. https://doi.org/10.1073/pnas.0701728104

Vicente-Serrano SM, Beguería S, López-Moreno JI. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate 23*: 1696-1718. https://doi.org/10.1175/2009JCLI2909.1

Vogel A, Scherer-Lorenzen M, Weigelt A. 2012. Grassland resistance and resilience after drought depends on management intensity and species richness. *PloS ONE 7*: e3699. https://doi.org/10.1371/journal.pone.0036992

Zhang B, Valentine I, Kemp PD. 2007. Spatially explicit modelling of the impact of climate changes on pasture production in the North Island, New Zealand. *Climatic Change 84*: 203-216. https://doi.org/10.1007/s10584-007-9245-4