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

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Additional File 1: Appendices 1-5, Figures A1-A3 and Table A1.

Appendix 1. APSIM

The daily time-step Agricultural Production Systems Simulator (APSIM, Holzworth et al. 2014) was used to simulate pasture growth. To simulate pasture production under past and future climates, we used the multi-species AgPasture module in APSIM (v. 7.10). APSIM links AgPasture to other modules which provide climate data, soil water and nutrient dynamics, plant and animal organic matter returns, and manipulation of grazing management. The main processes used to simulate plant growth in AgPasture are given in detail in Li et al. (2011); this paper also demonstrates the module's ability to simulate pasture systems in New Zealand accurately across a wide range of soil types and climates. In addition, AgPasture has been validated using data from a long-running free-air CO_2 enrichment (FACE) experiment and has been shown to adequately simulate both intra- and inter-annual variations in response to elevated CO_2 concentration (Li et al. 2014). The effects of increasing atmospheric CO_2 concentration are included in AgPasture by re-parameterising three key functions: plant photosynthesis and respiration, plant nitrogen (N) demand and plant stomatal conductance. The parameter values, which depend on the atmospheric CO_2 concentration, were taken from relevant literature (Li et al. 2014).

For all point locations, the pastures were modelled as a mixed pasture of *Lolium perenne* (perennial ryegrass) and *Trifolium repens* (white clover). Default parameter values for both species were used. For each location two soils were modelled; these were parameterised using APSIM-ready S-map files provided by Manaaki Whenua Landcare Research (https://smap.landcareresearch.co.nz/). Pasture management was the same for the three locations: the pasture was grazed when the standing pasture biomass reached 2500 kg DM/ha for all months except in winter (May, June and July) when the target was set to 2000 kg DM/ha. The simulated animals were removed when pasture biomass was grazed down to 1400 kg DM/ha in all months except in winter when it was set to 1700 kg DM/ha. In all cases the stocking rate was the equivalent of pasture being consumed at the rate of 350 kg DM/ha/d. This protocol approximates that used by farmers to maximise both pasture productivity and quality. Simulated nutrient return through deposition of dung and urine was evenly spread across the pasture; note that as is usual for New Zealand hill country farms, the only *de novo* input of N in the model is from N fixation by clovers. Also, P was not explicitly modelled and was assumed to be non-limiting.

Appendix 2. Biome-BGC

The Biome-BGC model v4.2 (Thornton et al. 2002; Thornton & Rosenbloom 2005) was used to model point location and regional pasture productivity for New Zealand managed grassland systems under future climate change scenarios. The Biome-BGC model is an ecosystem process model that simulates the biological and physical processes controlling fluxes of carbon, N and water in vegetation and soil in terrestrial ecosystems. The model includes the CO_2 fertilization effect that enhances both the rate of photosynthesis and reduces water loss in plants under elevated atmospheric CO_2 concentrations. Climate inputs include daily minimum and maximum air temperature, precipitation, vapour pressure deficit, wind, and solar radiation. Soil is modelled as a single layer with site-specific texture and rooting depth inputs. The model runs at a daily time step.

We adapted Biome-BGC to represent two typical New Zealand managed grassland systems: "Sheep & Beef" (low intensity) and "Dairy" (high intensity). Although the Biome-BGC model does not explicitly simulate managed grasslands or animal grazing, we modified and re-interpreted key ecological parameters from the model's default C_3 grasslands parameterization to represent the effects of management and the presence of grazing animals on pasture productivity (Keller et al. 2014). Dairy systems receive more N inputs (to simulate more fertiliser use), more grass is eaten (in the form of increased whole-plant mortality), and more animal products (i.e., carbon in milk or meat) are extracted and removed from the system. Irrigation and nitrate leaching are not simulated in either system. Model parameters were calibrated using observations of pasture growth and historic climate at six locations in New Zealand and validated for both dairy and sheep systems (Keller et al. 2014).

In this paper, all results shown use the Sheep & Beef parameterization. This is likely an underestimate of productivity in the areas that are dominated by intense dairy farming. However, our results are given in terms of change in productivity relative to present-day (RCP past), thus minimizing the effect of biases in the absolute levels of pasture growth. This also allows us to better isolate the climate effect on pasture growth without the effect of management interventions. The reference or 'baseline' pasture production for each GCM is an average over the nominal years 1986–2005. For all future scenarios, the model was first 'spun up' to an equilibrium steady state using RCP past climate, and then restarted and run as a transient simulation from 2005 to 2100 using each model- and RCP-specific projected climate.

Appendix 3. WATYIELD

The Water-Balance model is designed for calculating the water deficit in soil for crop growth. It is developed based on the WATYIELD (Fahey et al. 2010) (a water balance bucket model developed by Manaaki Whenua – Landcare Research, FAO-56 (Guidelines for computing crop water requirements) report as well as the SWAT model (developed by USDA)).

- Soil Moisture Deficit (SMD) – the amount of rain needed to bring the soil moisture content back to field capacity.

The SMD on day i is given by the difference between field capacity and soil water content (SWC) at that day:

$$SMD_i = TAW - SWC_i$$

where TAW = total available water. When SWC_i is at field capacity, the minimum value for SMD_i is 0. When SWC_i reaches the wilting point (WP), the SMD_i will have its maximum value TAW. Therefore, the limits on SMD_i are:

$$0 \leq SMD_i \leq TAW$$

- Evapotranspiration Deficit (ET_cD) - is the total amount of water that is not available for a crop to have an unstressed transpiration process.

The ET_cD is the difference between the demand and the available water. It is calculated by comparing the difference between the crop evapotranspiration under standard conditions (ET_c) and the actual crop evapotranspiration (AET_c).

$$ET_cD_{\ i} = ET_{c\ i} - AET_{c\ i}$$

The limits on $ET_cD_{\ i}$ are:

$$0 \le ET_cD_{\ i} \le ET_{c\ i}$$

The parameterisation of WATYIELD includes the soil properties (TAW and readily available water (RAW)), interception fraction and the crop coefficients. For pasture, the values are as follows: Crop coefficient (K_c) = 1, Interception Fraction (IF) = 0, and Interception Storage Capability (ISC) = 0.5.

Appendix 4. Model Uncertainty

The spread or standard deviation among the results with the six GCMs that we have used as inputs can be considered one measure of uncertainty. Figures A1-A3 show the standard deviation for mean annual pasture production among the six GCMs for RCP 2.6, 4.5, and 8.5 at mid-century and end-of-century.

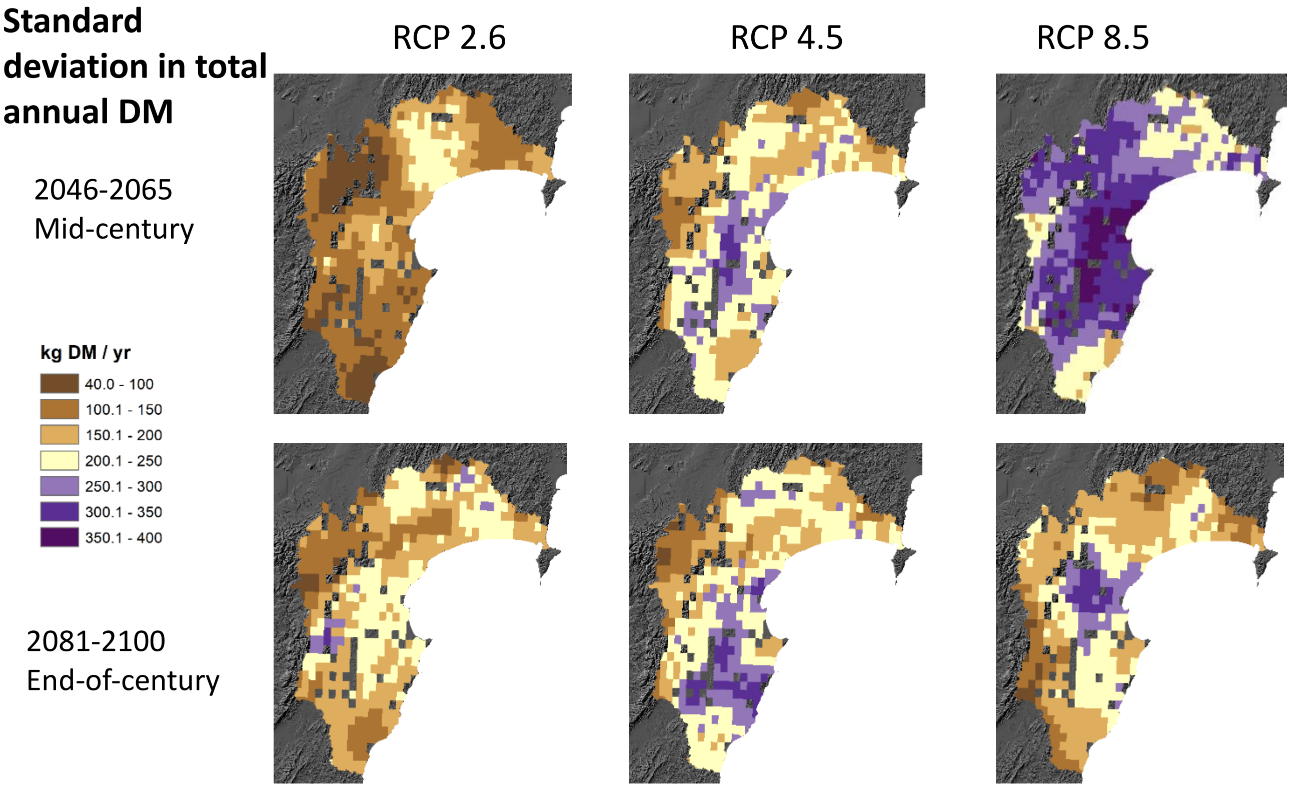

Figure A1 Biome-BGC standard deviation of modelled mean annual pasture production among the six different GCMs for the Hawke's Bay region.

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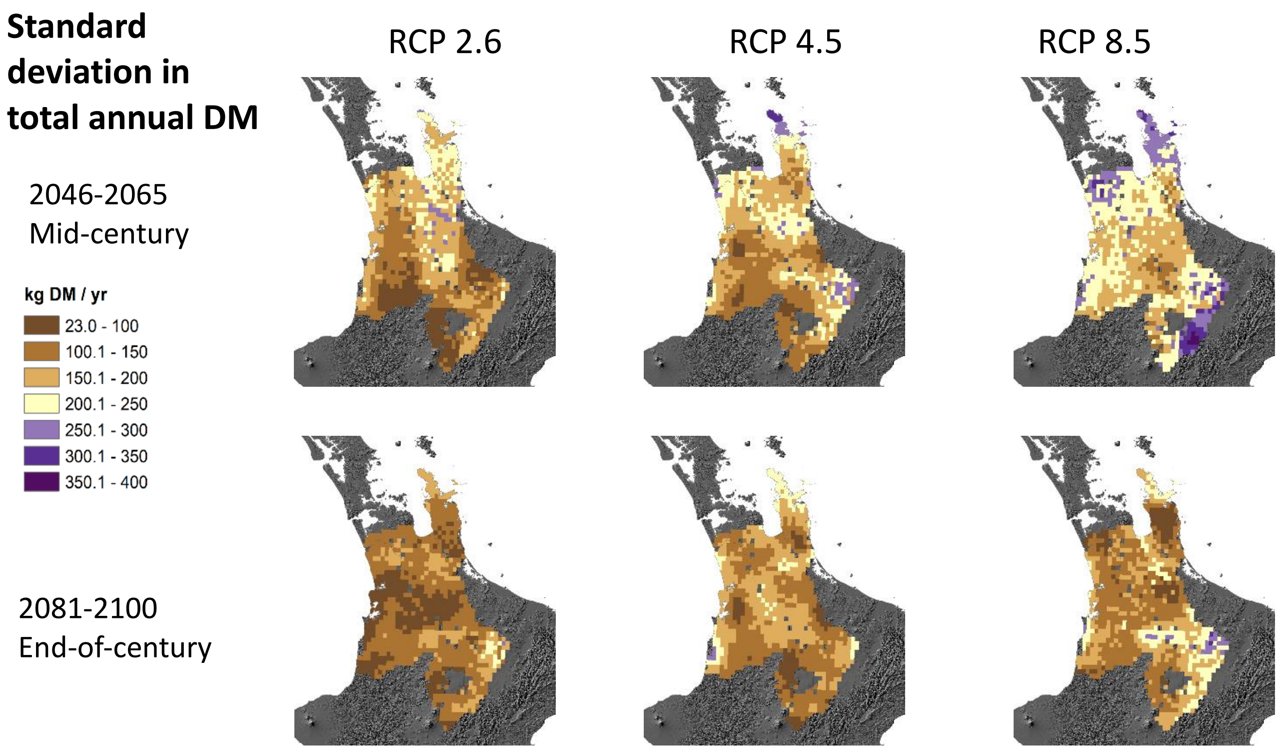

Figure A2 Biome-BGC standard deviation of modelled mean annual pasture production among the six different GCMs for the Waikato region.

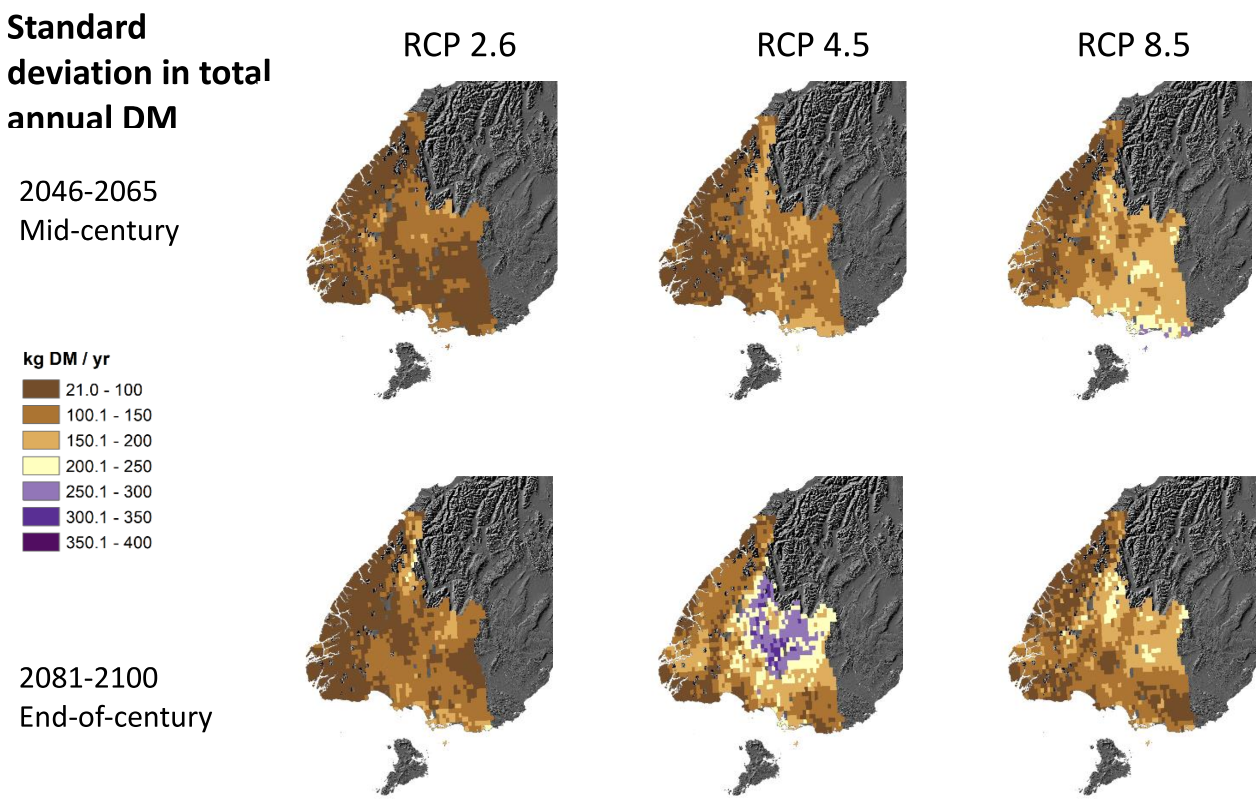

Figure A3 Biome-BGC standard deviation of modelled mean annual pasture production among the six different GCMs for the Southland region.

Appendix 5. Inter-annual variability

Table A1 Coefficient of variation calculated for each month from the individual data points (all GCMs and years) in Figure 7. Entries are expressed in kg DM/ha/d.

Month	Past	Mid	End
January	44	52	92
February	66	67	127
March	86	77	114
April	76	84	94
May	48	61	85
June	41	48	70
July	35	34	42
August	27	22	27
September	18	13	19
October	16	11	14
November	13	13	14
December	21	27	37

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