Modelling perennial ryegrass (*Lolium perenne*) persistence and productivity for the Upper North Island under current and future climate

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Abstract

The objective of this study was to predict the future performance of perennial ryegrass in the Upper North Island, New Zealand. The Basic Grassland model, BASGRA, was used with historic, current and future daily climate data as input, and soil water holding capacity, to predict changes in perennial ryegrass performance in space and time. The study focussed on land of ≤7° slope north of the town of Tokoroa and considered two potential warming pathways to the end of the 21st century. Persistence was defined as the time in years for the ryegrass sward to decline to 50% ground cover. The results for the two climate pathways were largely consistent with each other. Persistence should remain in the medium category (2.5-3.4 years, 10-12 t DM/ha) for the rest of this century for Bay of Islands, Whangarei, South Waikato/Tokoroa, and Rotorua. Persistence is predicted to change from medium to predominantly low (0-2.4 years, <10 t DM/ha) for Far North, Dargaville, DairyFlat/Rodney, Waiuku/Pukekohe and northern and central parts of Waikato. Coastal regions of Bay of Plenty were predicted to be poorly suited to perennial ryegrass and to remain so into the rest of the century. Large parts of the Upper North Island that are currently borderline for perennial ryegrass are predicted to become unsuitable for the species.

Keywords: basal cover, BASGRA model, climate change, pasture yield, perennial ryegrass suitability

Introduction

There is mounting concern about the increased incidence of perennial ryegrass (*Lolium perenne*) failure in the Upper North Island (UNI) of New Zealand. Dodd et al. (2018) estimated that between 30000 and 50000 ha of perennial dairy pasture in the UNI has changed to annual crop/pasture rotations since 2007, some of which is expected to be a response to on-going persistence problems. Reduced perenniality of pastures can result in increased pasture management costs (Brazendale et al. 2011), greater risk of nutrient losses to the environment (Betteridge et al. 2011), and higher rates of depletion of soil carbon stocks (Rutledge et al. 2017).

Persistence failure may be associated with an increase in the frequency and intensity of summer-autumn drought across the region, which is consistent with successive projections of how climate change will affect drought in New Zealand (Ministry for the Environment 2018). These projections show that the severity of drought will increase in most areas, with both the frequency and intensity of meteorological drought in already drought-prone regions expected to increase (Mullan et al. 2005; Clark et al. 2011). Potentially, the largest impact will not be the effect of drought in isolation, but the cumulative impacts of back-to-back extreme climatic events (Clark et al. 2011; Chang-Fung-Martel et al. 2017).

From the perspective of farm production and profit, persistence is best defined as the continuity of a forage yield advantage, where the yield advantage may arise from the replacement of an old pasture with a new pasture (e.g., Parsons et al. 2011) or a genetic advantage in yield of one cultivar over others (e.g., Ludemann & Chapman 2019). In this context, persistence failure may result from yield decline of the newly sown sward over time with no, or minimal, change in population density, or reduction of population density to the point where size/density compensation can no longer sustain canopy cover and competitive dominance necessary to sustain the yield differential (Parsons et al. 2011). Thus, both physiological (plant growth) and demographic (plant population) factors are involved.

Previous modelling studies of climate-driven pasture performance have used the AgPasture model as part of

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the APSIM (Agricultural Production System Simulator) suite in New Zealand (Li et al. 2011) and the DairyMod model in Australia (Harrison et al. 2016). Although both models were available for our study, neither of them account for population dynamics nor, therefore, ground cover as an important measure of persistence. For this reason the Basic Grassland Model (BASGRA) was our model of choice. More detail on BASGRA is given in the Materials and Methods section.

The objective of this study was to define perennial ryegrass 'suitability zones' at a sub-regional scale based on recognition that there is spatial and temporal variation across the UNI in the conditions for perennial ryegrass growth, related to local soil type and climate. The concept is that there will be a gradation of ryegrass suitability, from 'highly suited' where solutions such as adapting grazing management could ensure ryegrass resilience to future climate stress, to 'poorly suited' where the forage base may need to change to other, better-adapted species to sustain forage production. Re-framing the problem this way means that a platform can be created for: 1) better characterisation of the physical environments for pasture growth in the UNI; 2) better knowledge of what plants require in order to persist and produce in these environments; and 3) estimating, using well-proven farm systems models, the impacts of future climate on production costs and profitability of pastoral businesses within different suitability zones and, by amalgamation, across the entire UNI.

Materials and Methods

Modelling approach

This study focussed on evaluating ryegrass persistence on land ≤7° slope in the UNI, where pastoral agriculture is dominant and where pasture persistence affects the financial viability of these businesses. The area was defined as north of the town of Tokoroa in South Waikato (-38.22 latitude) and west of 176.975 longitude (i.e., excluding the mountainous East Cape). A GIS approach was then used to identify pasture-dominated, low-lying land (0-7^{o} slope) in this area (Figure 1).

Climate data for the decades starting 1980, 1990, 2010, 2040, 2070, and 2090 were generated from a suite of six ranked General Circulation Model (GCM) simulations (Ministry for the Environment 2018) that were selected to drive a higher resolution regional climate model (RCM) over New Zealand. The output data fields from the RCM were bias-corrected relative to a 1980-1999 climatology, and subsequently further downscaled to a virtual climate station network (VCSN) of approximate 5 km ×5 km grid cells (Sood 2014). The GCMs are coupled atmosphere-ocean climate models driven by natural climate forcing (solar irradiance, volcanic emissions, aerosols) and anthropogenic emissions of greenhouse gases and aerosols based on observations for the 1971-2005 historic period, and four 'future' Representative Concentration Pathway scenarios (RCPs 2.6, 4.5, 6.0, and 8.5 W/m^2 as a possible range of greenhouse gas concentration trajectories to the year 2100) for the 2006-2100 period (Van Vuuren et al. 2011). Capellán-Pérez et al. (2016) estimated that the likelihood of exceeding each RCP level by 2100 was 100% (RCP2.6), 92% (RCP4.5), 42% (RCP6.0) and 12% (RCP8.5). Considering this, RCP4.5 and RCP8.5 were selected to approximate the 90% and 10% confidence intervals for climate change. The climate variables required as input to the Basic Grassland model (BASGRA) were daily global radiation (MJ/m^2/day), minimum and maximum temperatures (°C), rainfall (mm), and potential evapotranspiration (PET, mm). These data were produced as historic climate for 1971 to 2005 and as 'future' climate for 2006 to 2100 for all selected VCSN sites on land of ≤7° slope in the UNI (black dots in Figure 1).

Soil water holding capacity across the region was obtained from Manaaki Whenua Landcare Research (MWLR) and is reproduced with their permission. MWLR calculates profile available water (PAW) to 30, 60 cm or 1m depth. Because ryegrass root mass is concentrated in the top 30 cm of the soil (Wedderburn et al. 2010), PAW_{30} was used in this study, and scaled to the modelled maximum root depth (ROOTDM), which was very similar in this case, at 0.31 m. Data for PAW_{30} were provided for 242 of the 315 VCSN cells in Figure 1, and each VCSN site exhibited soil differences reflected in the different PAW values and the areas they covered. Values for PAW_{30} ranged between 25 mm and 205 mm (median = 53 mm). About half of the values (representing 53% of the study area) fell in the range 55-65 mm therefore an intermediate value of 60 mm was used for all simulations. This simplification was made to avoid including multiple soil effects, which would have confounded results and hindered interpretation.

Pasture persistence under grazing was simulated using BASGRA, which is one of the few pasture models that explicitly includes sward population dynamics (Woodward et al. 2020). BASGRA simulates soil and plant processes with a daily time step. Input and output align with commonly available weather information and pasture sampling methods. BASGRA includes a single layer soil water balance model where soil water content is updated daily based on rainfall and irrigation, evaporation and transpiration, surface runoff and drainage below the root zone, to a maximum of the PAW parameter value. Plant access to this water is mediated by simulated root mass and root depth as described in Woodward et al. (2020) and drives water stress effects on growth. The basal area sub-model, BASAL, was particularly important for the current study, and simulates the changing proportion of pasture

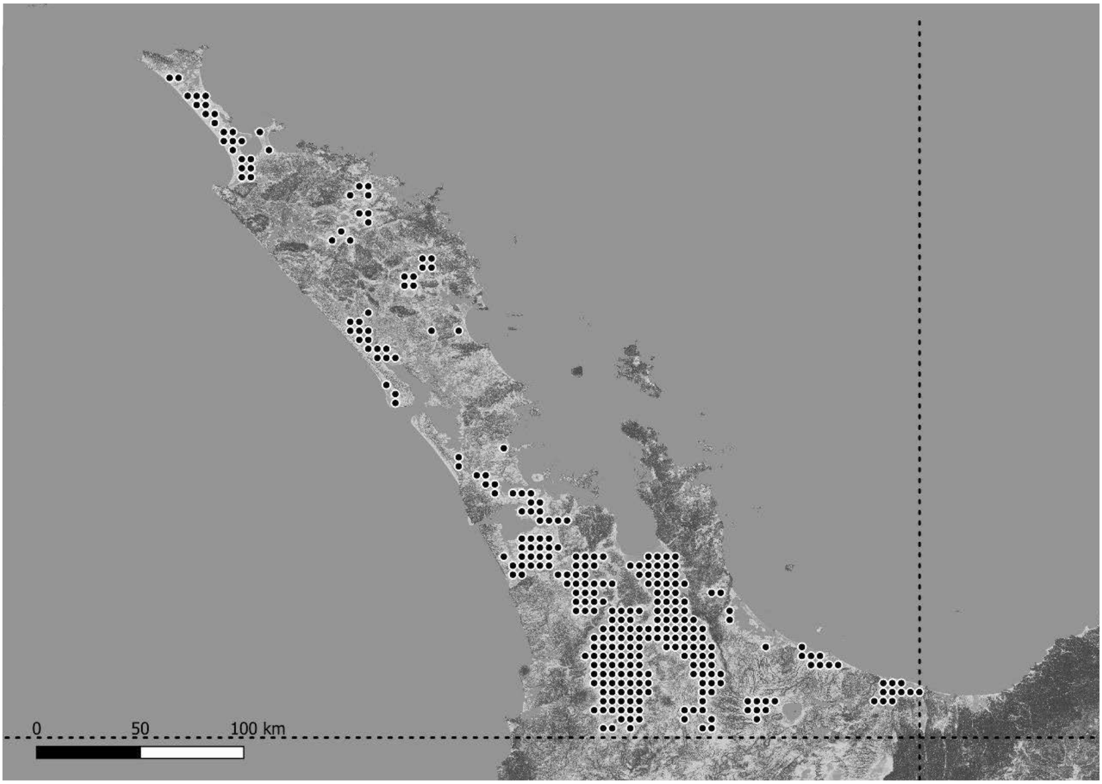

Figure 1 Location of the National Institute of Water and Atmospheric Research's virtual climate station network (black dots at the centre of 5 km × 5 km cells) with ≥75% area occupied by land ≤7° slope in the Upper North Island, New Zealand, north of Tokoroa (-38.225) and west of 176.975 longitude (broken lines).

area occupied by ryegrass rather than other pasture species. The uncertainty of the model was quantified by Woodward et al. (2020) showing that the 90% credible intervals of annual yield and basal area were 3.4 t dry matter (DM)/ha and 0.18, respectively. In the current study, the uncertainty of the predictions made was likely to be similar. Nitrogen cycling was not modelled in this study.

A harvesting policy was implemented in BASGRA that triggered a grazing/cutting event every time the above-ground standing total DM reached 2850 kg DM/ha, leaving 1500 kg DM/ha (post-grazing residual). These pre- and post-grazing DMs (covers) are within the range of optimum management of ryegrass pastures for achieving the best balance between pasture and animal performance (Macdonald & Penno 1998) and were implemented as grazing rules in the experiments that were used by Woodward et al. (2020) to parameterise the model (see further description below). They were applied across all simulated sites, seasons and years. It is a simplification of what happens in reality, where there might be considerable variation around these covers depending on the individual farm situation and season. However, that was deemed an acceptable simplification considering the scale at which this study was done.

Predictions under climate change are always extrapolations from existing data and cannot be 'validated' in the traditional sense. Data sets on tiller population dynamics and pasture persistence are extremely rare, and the data set described in Lee et al. (2018) is uniquely rich in this regard. Rather than divide the data set into calibration and validation subsets, Woodward et al. (2020) used a Bayesian calibration approach to infer the set of "models" (i.e., parameter sets) that is consistent with the data set. The given model equations and priors in this approach represent prior scientific knowledge about the underlying processes. Validation was then carried out by (1) checking the posterior model residuals matched the assumptions of independence and normality, (2) checking the posterior parameter distributions were consistent with proposed priors, and (3) sensibility checking of additional model predictions where no data were available (Woodward et al. 2020). Because the calibration data set included a wide range of soils, latitudes, years, management regimes, pests and weeds, we can have some confidence when predicting pasture performance for other sites and future climates.

The BASGRA calibrations carried out by Woodward et al. (2020) derived *maximum a priori* (MAP) parameter sets based on assuming a default CO_2 concentration of 350 ppm during the 2011-2017 period (Hansen et al. 2008). In BASGRA, the assumed CO_2 atmospheric concentration affects photosynthesis. Some climate change studies simulate a 'CO_2 fertilisation' effect of increased atmospheric CO_2 concentrations with changing climate. However, empirical studies on the magnitude of the effects of raised CO_2 concentrations on plant production have been equivocal (Hovenden et al. 2019). In particular, there is a strong risk that models may over-predict the effect for years with a small or negative response to CO_2 (Li et al. 2014). For this reason, simulations in this study were carried out with the MAP parameters from Woodward et al. (2020) assuming no effect of increased CO_2.

The warm climate of the UNI permits invasion of less desirable grass and broadleaf species (Tozer et al. 2011), which were passively represented in the model as reductions in ryegrass basal area. Additionally, insect pests, including clover root weevil, cystoid nematodes, grass grub and black beetle can have a significant impact on pasture persistence (Lee et al. 2017). Weed and pest pressures are not modelled explicitly in BASGRA, but their effects are included implicitly via parameter calibration to actual pasture data that have been subject to these stresses, for example, affecting the leaf and tiller death parameters (Woodward et al. 2020).

Simulations and data manipulation

Following Woodward et al. (2020), BASGRA was initialized as a mature ryegrass sward at the start of each run on 1 May. This date was selected to align with the official start of winter for the UNI and to align with common establishment practices (e.g., Lee et al. 2018).

In developing metrics for pasture persistence, we considered that farmer expectation of ryegrass persistence is around 6-10 years (Dodd et al. 2018). There is also a need to relate persistence metrics to DM production, which is not represented in the most agronomically robust measures of persistence like tiller density and basal cover. In BASGRA, basal cover (BASAL) is a smoothed and more stable representation of total tiller density. Basal cover (%) was therefore chosen to represent population persistence, and annual DM yield (t DM/ha/yr) to represent persistence of growth potential. Predicted daily basal cover and annual pasture yield were extracted for every 10-year time slice for the six GCM-generated climates. For basal cover, the daily output was tracked over time and when it reached a value of 50%, the number of days since the start of simulation was recorded and divided by 365 for an index of pasture 'half-life'. The basal cover of 50% was chosen because this is the point where ryegrass tiller density reaches approximately 2000 tillers/m^2, from where the sward is unlikely to recover (Lee et al. 2018; Woodward et al. 2020). For annual yield, the average for the first 5 years of every 10-year time slice was calculated to separate longevity and yield effects. These two metrics were obtained per GCM model, with the average then calculated across the six models. The basal half-life data were categorised by taking the minimum and maximum values across all simulations which had a range of 1.6-6 years. This was used to develop three categories of persistence: low = 0-2.4 years; medium = 2.5-3.4 years; high = 3.5-6 years. Indices of pasture half-life were compared across space and time using maps with colour coding for categories. Yield data are only reported in the text. The following results and discussion focus on the dairy-dominant sub-regions or zones (clusters of cells) identified in Figure 2.

Results

A very basic climate analysis for Hamilton city, as a representative site for the Waipa/King Country region, shows that mean annual daily temperatures are projected to increase throughout the rest of this century, with RCP8.5 diverging from RCP4.5 around mid-century (Figure 3a). Mean daily maximum temperatures for RCP8.5 are projected to remain below 25°C by the end of the century (data not shown).

Annual rainfall for Hamilton throughout the 21st century is predicted to decrease <2% from 2000 to 2100, with very little difference between RCP4.5 and 8.5. Total summer-autumn rainfall (December to April inclusive) is also projected to remain constant, with no difference between the two RCP scenarios. Furthermore, there is no clear evidence of a consistent increase in variability of annual rainfall (Figure 3b).

Figures 4 and 5 show predicted ryegrass population persistence (basal half-life) across the UNI in each modelled decade. For both RCPs, predictions for historic (1980- and 1990-) and current (2010-) decades show medium to high persistence for most clusters in UNI. The exception is the striking pattern for ryegrass pastures in the Bay of Plenty (BOP) coastal areas (Te Puke/Pukehina and Whakatane) where low persistence for historical, current, and future decades was predicted under both RCPs. In contrast, model results suggest persistence will remain high for BOP inland areas (Rotorua) for the rest of the century.

There is reasonable consistency in terms of the patterns of change predicted for the current (2010-) and future (2040-, 2070-, 2090-) decades using climates for the two RCPs (Figures 4 and 5). Relatively positive outcomes are predicted for Bay of Islands, Whangarei, Waiuku/Pukekohe and South Waikato/Tokoroa clusters where the current medium-high persistence status declines to predominantly medium persistence by the

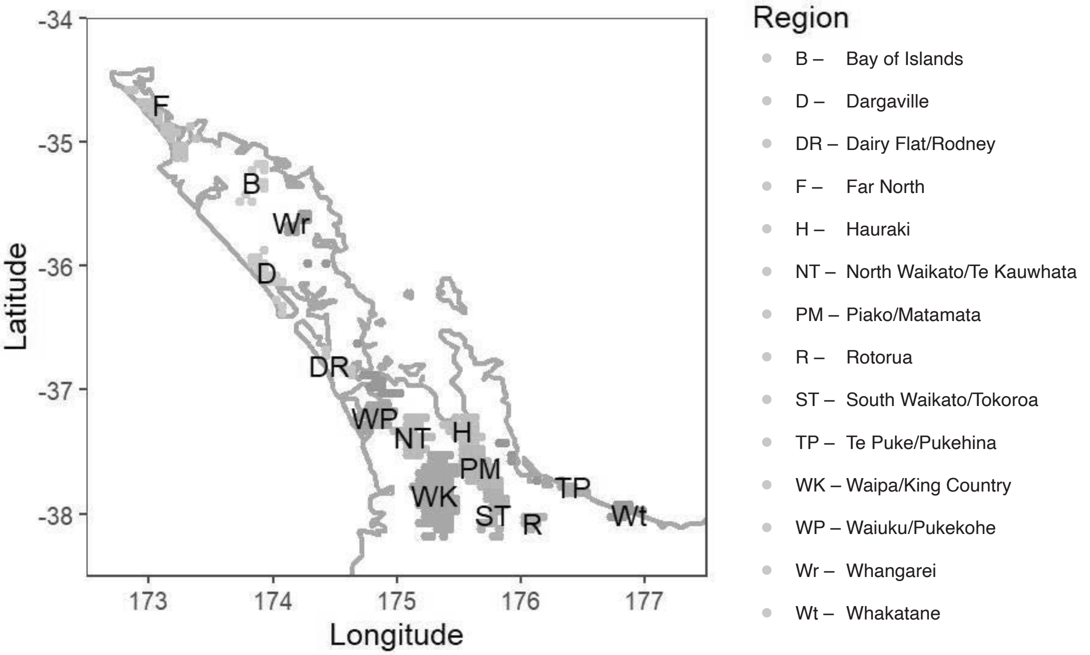

Figure 2 Regions/districts/towns and surrounding areas covered in this study in the Upper North Island, New Zealand, where pastoral agriculture dominates and where pasture persistence is of particular interest.

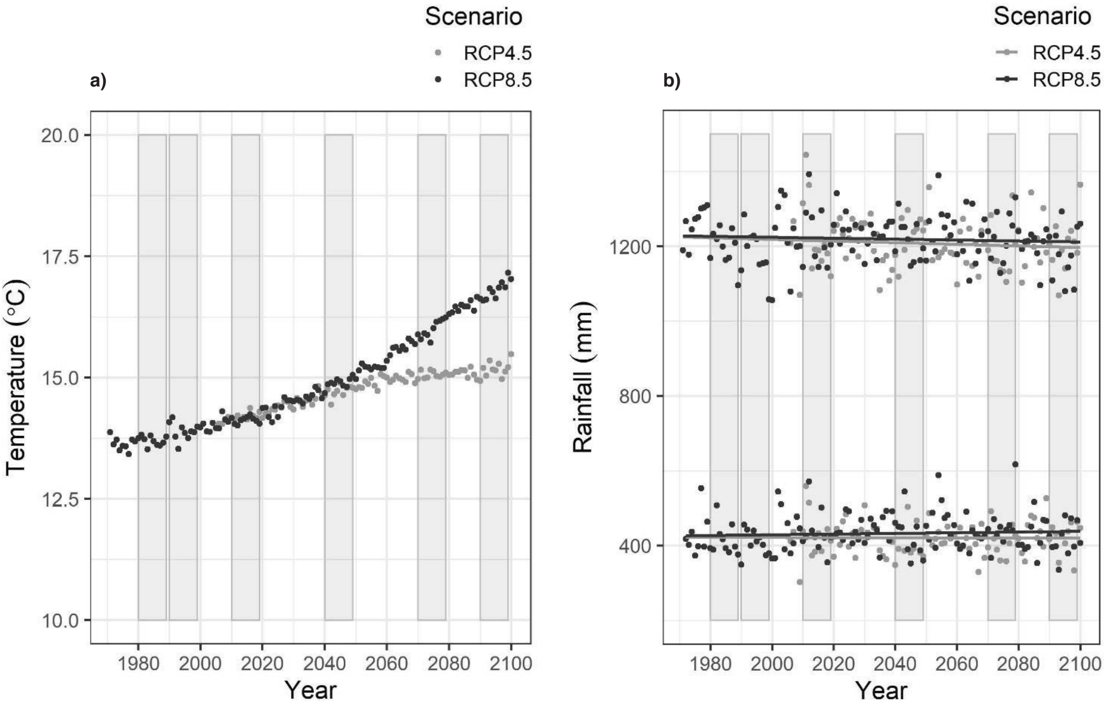

Figure 3 Mean annual daily temperature (a) and total annual (top cloud) and total December-April (bottom cloud) rainfall (b) for historic and projected climates for Hamilton city, New Zealand. Means are for six General Circulation Models for Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5. BASGRA-modelled decades are grey shadowed.

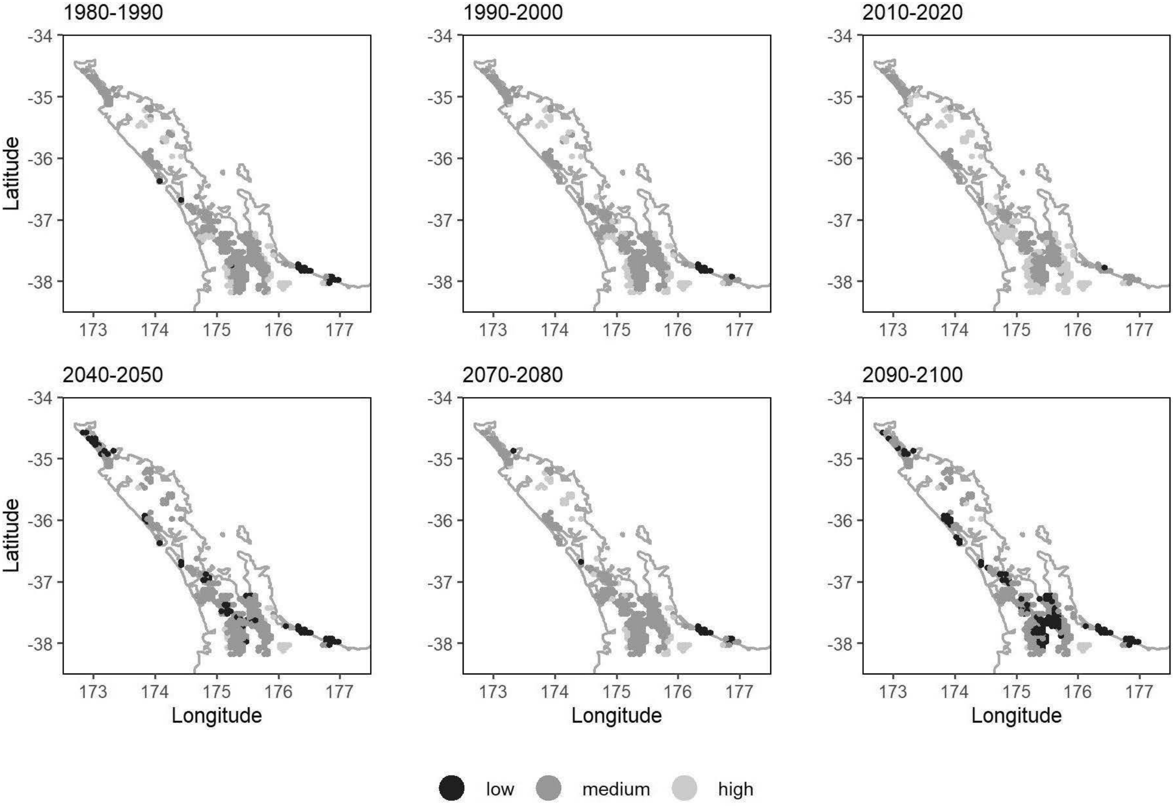

Figure 4 Predicted ryegrass persistence based on basal cover half-life as affected by historical and projected climate for Representative Concentration Pathway 4.5 for the Upper North Island, New Zealand. A profile available water of 60 mm was assumed for all sites. Persistence categories are 0-2.4 years (low), 2.5-3.4 years (medium), 3.5-6 years (high).

middle and end of the century. Less positive outcomes are predicted for Far North, Dargaville, DairyFlat/Rodney, North Waikato/Te Kauwhata, Waipa/King Country, Hauraki, and Piako/Matamata. In these clusters the decrease is from predominantly medium to medium-low persistency by the end of the century. It should be considered that this may only apply to sub-regions where soil profile available water for the top 30 cm is in the order of 55-65 mm, as used in this study.

Current ryegrass annual yields were predicted in the range of 10-12+ t DM/ha for most of the UNI, except Te Puke/Pukehina and Whakatane where yields of less than 10 t DM/ha were predicted. Future yields were predicted to remain above 10 t DM/ha for predominant parts of Bay of Islands, Whangarei and Rotorua; less than 10 t DM/ha were predicted for Far North, Dargaville, DairyFlat/Rodney, Waiuku/Pukekohe and large parts of Waikato and King Country.

Discussion

The overall picture that emerges is that pastoral regions north of the Bombay Hills will exhibit ryegrass persistence that sits between medium and high throughout the 21st century. The exception is the trend towards low persistence for Far North and Dargaville and maybe also DairyFlat/Rodney sub-regions. The biggest shift in persistence is predicted for Waikato and King Country, where persistence is currently sitting at medium to high. The prediction is that this will gradually shift to predominantly medium by mid-century, and then to predominantly low by the end of the century. The exceptions here are western, southern and eastern boundaries of this mega-region (e.g., western parts of Waipa/King Country, South Waikato/Tokoroa, and Rotorua in the south) where persistence appears to remain better throughout the century compared to the central parts. This is an interesting trend observed in both RCPs and could be a topographically driven phenomenon, where low mountain ranges surrounding the Waikato basin, e.g., Pirongia and the hill country towards Kawhia in the west and the Kaimai Range in the east, affect rainfall patterns.

This apparent shift in ryegrass persistence for the Waikato mega-region is hard to explain, considering that temperature projections appear to be well within the range of tolerance of perennial ryegrass,

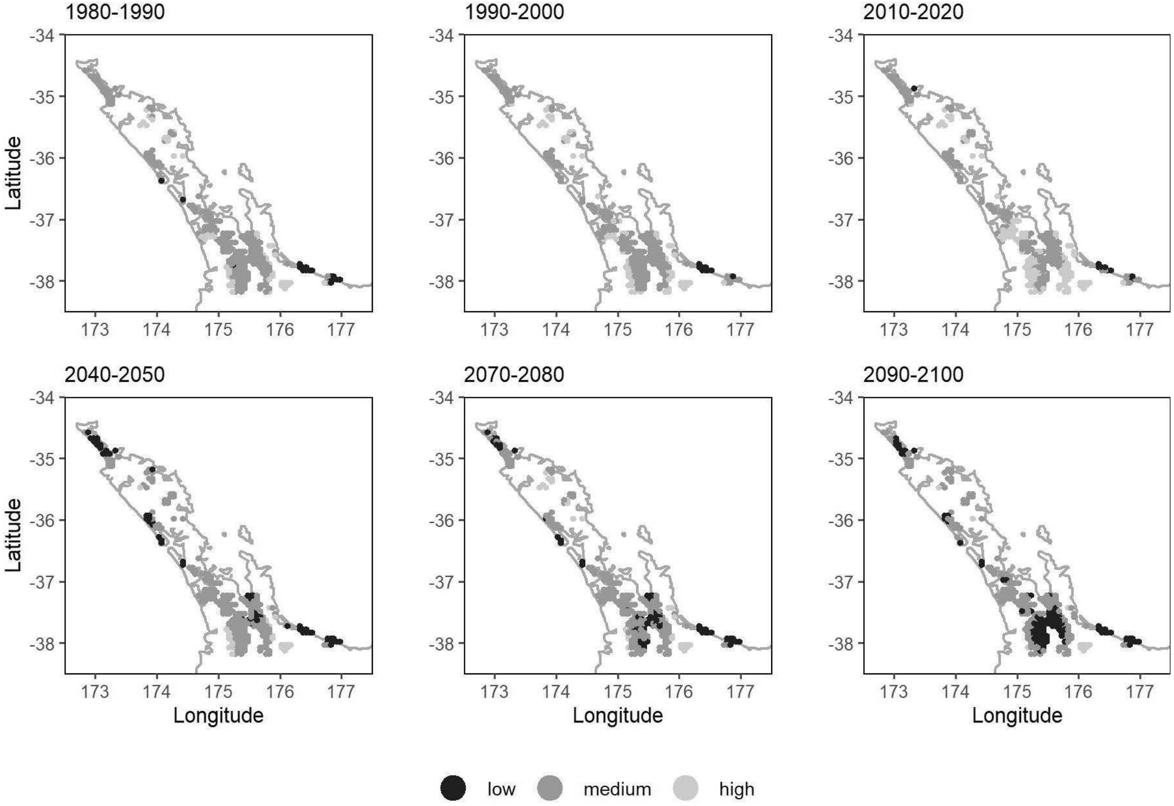

Figure 5 Predicted ryegrass persistence based on basal cover half-life as affected by historical and projected climate for Representative Concentration Pathway 8.5 for the Upper North Island, New Zealand. A profile available water of 60 mm was assumed for all sites. Persistence categories are 0-2.4 years (low), 2.5-3.4 years (medium), 3.5-6 years (high).

where the optimum day time temperature for leaf growth is 20-25°C (Parsons & Chapman 2000). Furthermore, annual rainfall and variability appear to be fairly stable throughout the century. One possible explanation is that higher temperatures will drive higher evapotranspiration rates that will result in more frequent and deeper summer/autumn soil moisture deficits. This implies that plants could experience resource limitations for longer periods than currently. The importance of soil moisture deficits for ryegrass persistence was demonstrated in a modelling study by Woodward et al. (2020), who used BASGRA to explore the causes of production and population loss of ryegrass pastures at three sites (dryland in Northland and Waikato, and irrigated in Canterbury). They suggest that increased tiller mortality associated with drought was the main cause of persistence failure at dryland sites. They propose that decreasing grazing pressure or breeding for tolerance to higher temperatures may not be successful in preventing this persistence failure. Perennial ryegrass is moderately to poorly adapted to low soil moisture availability. Water shortage limits leaf appearance, leaf expansion and tiller initiation irrespective of availability of other resources, and largely explains inter-annual variability in pasture growth rate (Chapman et al. 2011). For instance, in a study of Waikato pastures over 31 years, Glassey (2011) found that rainfall during the months December to April inclusive, had a significant positive effect on herbage accumulation, with an extra 850 kg DM/ha for every additional 100 mm rainfall.

In this study, predicted ryegrass persistence (based on basal half-life) ranged between 1.6 and 6 years. Since the BASGRA model was initialised to represent a pasture at peak tiller density, an additional 0.5 to 1 year could be added to this range to allow for the time taken after sowing to attain this state in the UNI (Lee et al. 2018). These numbers align relatively well with the limited data available for pasture renewal rates in the region. Kelly et al. (2011) conducted a survey of 717 dairy farmers in Waikato and BOP in which respondents were asked to estimate what proportion of the pasture area on their farms had been renewed in the previous 12 months. According to their data, the weighted mean rate of renewal was 21%, equating to a 5-year cycle of pasture replacement. The length of the renewal cycle will vary with decadal variation in climate (e.g., Glassey et al. 2021) and shifts in farm system strategies (e.g., Clark 2011), but the half-lives predicted here appear reasonable.

Considering both persistence and yield then suitable zones for perennial ryegrass pastoral farming into the rest of this century are predicted for Bay of Islands, Whangarei, Rotorua, and to a large extent also South Waikato/Tokoroa. However, if climate change continues to track between RCP4.5 and 8.5 for the rest of this century, the trend towards poor persistence (<2.5 years) and annual yield (<10 t DM/ha) for several regions in the UNI could be of concern. Regions that are currently considered relatively suitable for perennial ryegrass-based pastoral farming, e.g., Far North, Dargaville and Central Waikato could see changes to becoming unsuitable. Our simulations predict that BOP coastal areas are currently unsuitable, with this situation remaining for the rest of this century.

One caveat for our results is that only one soil water holding capacity was modelled. This is clearly a simplification, as Nie et al. (2004) found that pasture persistence in southern Australia was poorer on light-textured than heavier soil due to moisture deficit being a major limiting factor in the former. Future studies should explore the sensitivity of our results to a much wider range of profile-available water. Flooding effects on pasture persistence were also beyond the scope of this study. Another caveat is the omission of management strategies that could benefit ryegrass performance. Glassey (2011) points to the importance of pre- and post-grazing residuals during dry spells, whereas Lane (2011) presents anecdotal evidence that low-stocked farms have less persistence issues than intensively farmed pastures. Lane (2011) also suggests that management for maintaining soil structure and the pasture establishment process are important factors.

It is possible that the predicted poor performance of perennial ryegrass into the rest of this century for large parts of the UNI highlights that this species is near its limit of adaption to high temperatures and periodic droughts commonly experienced in this region. Alternative pasture species should be considered for parts of UNI. In a study near Camden, New South Wales, Australia, Neal et al. (2012) showed that two temperate grasses (phalaris and tall fescue), two tropical grasses (kikuyu and paspalum), two herbs (chicory and plantain), and lucerne were able to generate and maintain stronger soil water deficits to 150 cm than perennial ryegrass, meaning they are better extractors of water. They suggest that these species are better suited to growing under water deficit conditions because they can access stored soil water from greater depth and in greater amounts compared with perennial ryegrass.

Conclusions

The persistence of perennial ryegrass on land of ≤7° slope in the UNI was predicted to fall predominantly in the medium bracket (2.5-3.4 years, or 3.5-4.4 years if establishment time is included), with this situation remaining largely unchanged since the 1980s until the present. Future predictions with two climate change pathways showed fairly similar changes in a pattern developing from the middle of this century onwards. Based on persistence and annual yield, zones in the UNI that are likely to remain suitable for ryegrass-based pastoral farming are Bay of Islands, Whangarei, Rotorua, and potentially also South Waikato/Tokoroa. In these zones, alternative grazing and soil management may be sufficient to maintain the performance of perennial ryegrass. Zones that are predicted to become progressively unsuitable for ryegrass-based farming are Far North, Dargaville, DairyFlat/Rodney, Waiuku/Pukekohe and northern and central parts of the Waikato region. Coastal areas of Bay of Plenty fall into the same category. For major parts of the UNI, persistence is predicted to be <2.5 years and/or yield <10 t DM/ha by the end of the century. Solutions, like better adapted pasture species, will have to be found for developing a more resilient pastoral industry that is better able to cope with the challenges of future climate change.

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