Summer growth rates and annual yields of perennial ryegrass (*Lolium perenne* L.) in the Upper North Island expected to decline as a result of climate change

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Abstract
Evaluating the ability of perennial ryegrass to continue underpinning New Zealand's low-cost dairy production systems under future climate change scenarios requires a modelling approach. In this study, climate projections for different climate change scenarios were used in the BASGRA pasture model to predict changes in annual yields and seasonal pasture growth rate patterns of perennial ryegrass. These predictions, including uncertainty, were made for the years 2010-2014, 2040-2044 and 2090-2094 in 14 dairy dominant subregions in the Upper North Island of New Zealand. The suitability of perennial ryegrass is expected to decline in the future across all subregions, with worse outcomes expected under higher atmospheric greenhouse gas levels. Winter is expected to be the season least affected by climate change and summer the most. Late-winter/spring is predicted to become the main growing season, followed by late-autumn/early-winter. The ability of farmers to adapt their farming practices is essential in remaining profitable and internationally competitive.

Keywords: BASic GRAssland model, pasture yield, perennial ryegrass resilience

Introduction
The competitive advantage of New Zealand's dairy industry relies on matching the seasonal supply of pasture to the seasonal feed requirements of cows for milk production and pregnancy (Holmes *et al.,* 1987; Chikazhe *et al.,* 2017; Roche *et al.,* 2017). Changes in local climate may result in commonly-used pasture species (particularly perennial ryegrass, *Lolium perenne*) becoming more, or less, suitable for supporting livestock systems. This can occur if temperatures rise and/or rainfall patterns change (Ausseil *et al.,* 2019), for example if winters become warmer or summers become drier (Clark *et al.,* 2012).

Predicting climate change impacts on pasture growth, and persistence requires a mechanistic modelling approach to estimate the immediate and flow-on effects of local climate predictions on pasture growth and survival. Previously, the European grass model BASGRA (BASic GRAssland model; Höglind *et al.,* 2016) was adapted by Woodward *et al.* (2020) to match the pasture growth and tiller populations in the 2011-2017 grass persistence trial described by Lee *et al.* (2018). Trial sites were located in the Northland, Waikato and Canterbury regions of New Zealand. Beukes *et al.* (2021), together with the current study, utilised this work by predicting pasture responses to climate change in the Upper North Island (UNI) region of New Zealand (including the Northland and Waikato sites from the previous trial).

In the current study, historical weather data and climate projections (described below) for the Upper North Island of New Zealand from 1980 to 2100 were used as input into the BASGRA pasture model to simulate daily perennial ryegrass growth and annual yield. Results were compared for two climate change scenarios (described below) for the 2010-2014, 2040-2044 and 2090-2094 half-decades for 14 subregions of the Upper North Island of New Zealand. The 2010 half-decade was used as a baseline with which to compare the future half-decades. This allowed us to assess the suitability of perennial ryegrass for dairy farming in this region in the next 70 years.

Materials and Methods
Climate Data
Climate projections (projected daily weather data) from six general circulation models (GCMs) representing two future climate scenarios (representative concentration pathways RCP4.5 and RCP8.5) were obtained from NIWA for the 1980-2100 period for each point on a 5 km x 5 km grid covering the UNI region (NIWA 2022). Only grid points within dairy dominant districts north of Tokoroa in South Waikato (-38.22 latitude) and west of 176.975 longitude were included. Grid points were selected for using a GIS approach.

Climate for 1980-2000 was determined from historical weather data, while projections from 2010 onwards were based on the GCMs. The two concentration pathways (RCPs) represented climate scenarios in which greenhouse gas concentrations either stabilised (RCP4.5) or continued to increase at present rates (RCP8.5). The effect of greenhouse gas concentrations on climatic variables varied with region, but in general, average temperatures were expected to increase into the future, with larger increases expected under higher greenhouse gas concentrations, especially during the summer/autumn seasons. Conversely, rainfall in the UNI region was expected to decrease overall, particularly during spring.

Since the climate data did not include extreme events, the results presented only represent general climatic trends. The potential failure of a perennial ryegrass sward as a result of high temperatures, drought or flooding is not considered.

The 315 grid points (Figure 1) were grouped to represent the 14 major dairy subregions in the UNI. Grid points in the 'Other' category were not included in the analysis.

Pasture Model

Details of the New Zealand adaptation of the BASGRA pasture model are given in Woodward *et al.* (2020). The BASGRA pasture model simulates daily perennial ryegrass herbage mass and tiller population for a single grass paddock in a rotational grazing system. Other species (such as white clover) are not simulated. When calculating total dry matter cover (DM), it was assumed that the basal area not covered by perennial ryegrass was covered by other associated species, which w produced the same amount of DM per area as perennial ryegrass. Thus, total DM was a scaled-up amount of perennial ryegrass dry matter. Harvesting was assumed to occur once the total (as opposed to only perennial ryegrass) dry matter (DM) reached 2850 kg DM/ha, and the post harvesting residual was set at 1500 kg DM/ha. This regime represented a simplified grazing regime and did not simulate the complexities of harvesting decisions on a real farm (*e.g.,* Macdonald and Penno 1998).

Competition experienced by perennial ryegrass from non-sown species or weeds, which may be more resilient to extreme weather, was not included (Kalaugher *et al.,* 2017). Instead, the basal area of perennial ryegrass was simulated for each five-year period, beginning each five-year period as a newly sown 100% perennial ryegrass pasture with 100% basal coverage, and typically declining thereafter in response to climatic and harvesting stresses (Woodward et al., 2020).

As described in Woodward *et al.* (2020), Bayesian calibration was used to infer credible model parameter sets that simultaneously fitted the Northland, Waikato and Canterbury data sets described in Lee *et al.,* (2018). The single most likely parameter set (the maximum a posteriori (MAP) parameter set) was then chosen to represent perennial ryegrass swards in the simulations in the current paper.

Differences between sites were driven by latitude, soil plant available water (PAW, mm, the maximum amount of soil water accessible to plants), and daily weather data (daily rainfall, mean daily temperature, daily global solar radiation and potential evapotranspiration).

A PAW value of 60 mm (to 30 cm soil depth) was used for all simulations in the current study, representing a typical value for the Upper North Island region (based on data provided by Manaaki Whenua Landcare Research, MWLR).

Atmospheric CO_2 concentration influences leaf light-use efficiency in BASGRA, which in turn is used to calculate photosynthesis. The model was originally parameterised with an atmospheric CO_2 concentration of 350 ppm (BASGRA 2014). CO_2 fertilisation is a very complicated process and the opinions on the effects of CO_2 on plant growth in the literature are mixed (Hovenden *et al.,* 2019). Given that BASGRA does not include a soil C:N (carbon:nitrogen) component to provide potential feedbacks through progressive N limitation, CO_2 was held constant for all simulations in the current study.

Simulations

Simulations were carried out for the five-year periods (starting in May of the first year) for 1980-1984, 1990-1994, 2010-2014, 2040-2044, 2070-2074 and 2090-2094 for each grid point, climate model (GCM), and climate change scenario (RCP). Each simulation began with a newly-sown perennial ryegrass sward covering 100% of the paddock area, and simulated growth and population dynamics of the perennial ryegrass fraction of the pasture for five years (a 'half-decade'). This was based on results from Beukes *et al.* (2021), who found that the basal half-life (time in which a pasture declined from 100% basal cover to 50% basal cover) under future climates was typically around five years.

Average monthly perennial ryegrass pasture growth rate (kg DM/ha/d) and annual perennial ryegrass pasture yield (t DM/ha/y) were calculated for each half-decade. The annual pasture yields were then scaled for comparison to the baseline half-decade 2010-2014. The perennial ryegrass pasture growth rate results of each simulation were pooled across subregion, half-decade and climate model (GCM) to calculate a variety of statistical measures. The Jarque-Bera normality test (Trapletti and Hornik 2022) indicated that the results in each group were non-normal, so, the median was used as the measure of central tendency and interquartile range as the measure of uncertainty. To simplify presentation of the monthly perennial ryegrass pasture growth rates, only the results for the 2010-2014, 2040-2044 and 2090-2094 half-decades are presented. Annual pasture yield results are presented for all half-decades.

Results

Seasonal Perennial Ryegrass Pasture Growth Rate

Figure 2 shows the predicted seasonal pasture growth curves for each of the 14 subregions under climate

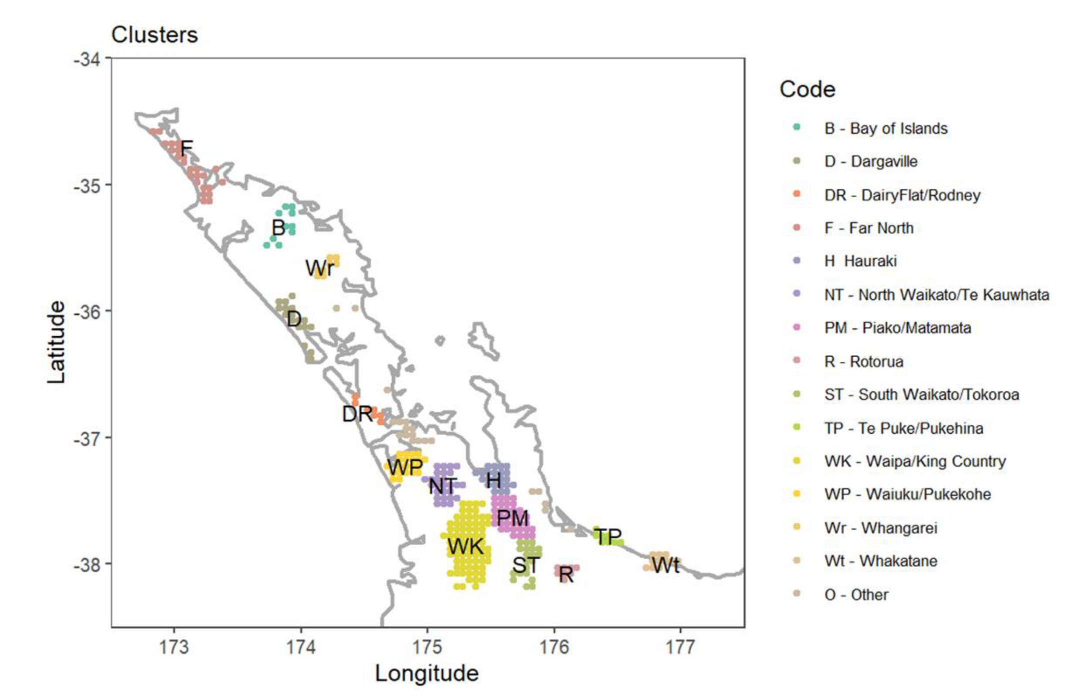


Figure 1 Map of Upper North Island climate projection locations used in this study to represent the 14 dairy subregions (Reproduced from Beukes et al., 2021)

scenarios RCP4.5 and RCP8.5 for the 2010-2014, 2040-2044 and 2090-2094 half-decades. Median monthly perennial ryegrass pasture growth rate (across GCMs and across the grid points of each subregion) is shown as a bold curve and the interquartile range (50% uncertainty range) as a shaded band.

The model predicts that median perennial ryegrass pasture growth rates will tend to become lower in the future over the spring-summer-autumn months, from September until April. For many subregions, such as South Waikato/Tokoroa, median perennial ryegrass pasture growth rates (PGRs) will tend to be marginally higher during winter, especially by the end of the century, but this is unlikely to compensate for the large losses expected during the rest of the year.

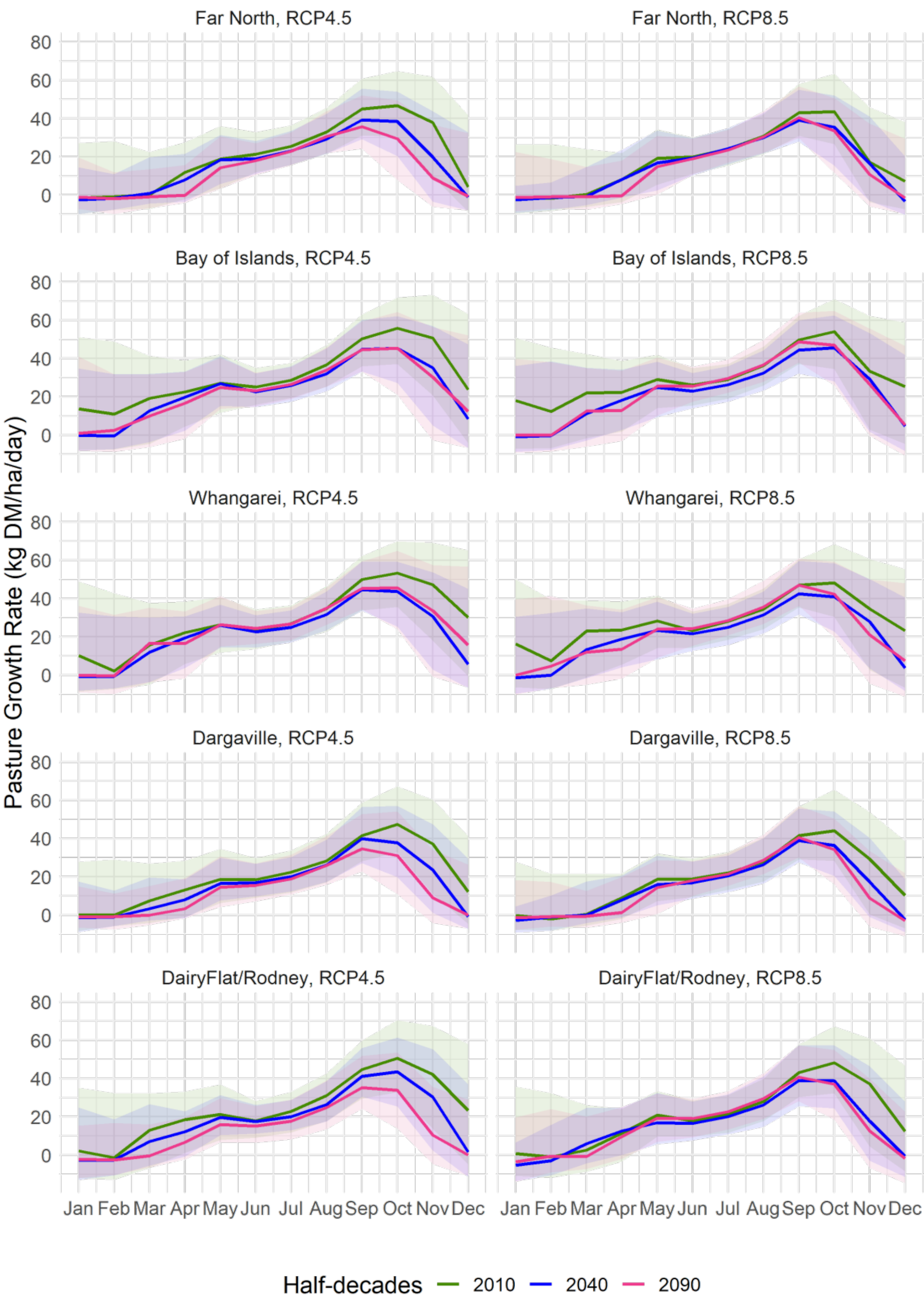
The end-of-century medians were generally lower than the mid-century medians, but there were exceptions, such as for Whangarei, where the 2090 medians were predicted to be higher than the 2040 medians. The high uncertainty around all of the predictions means that these differences may not be realised in practice.

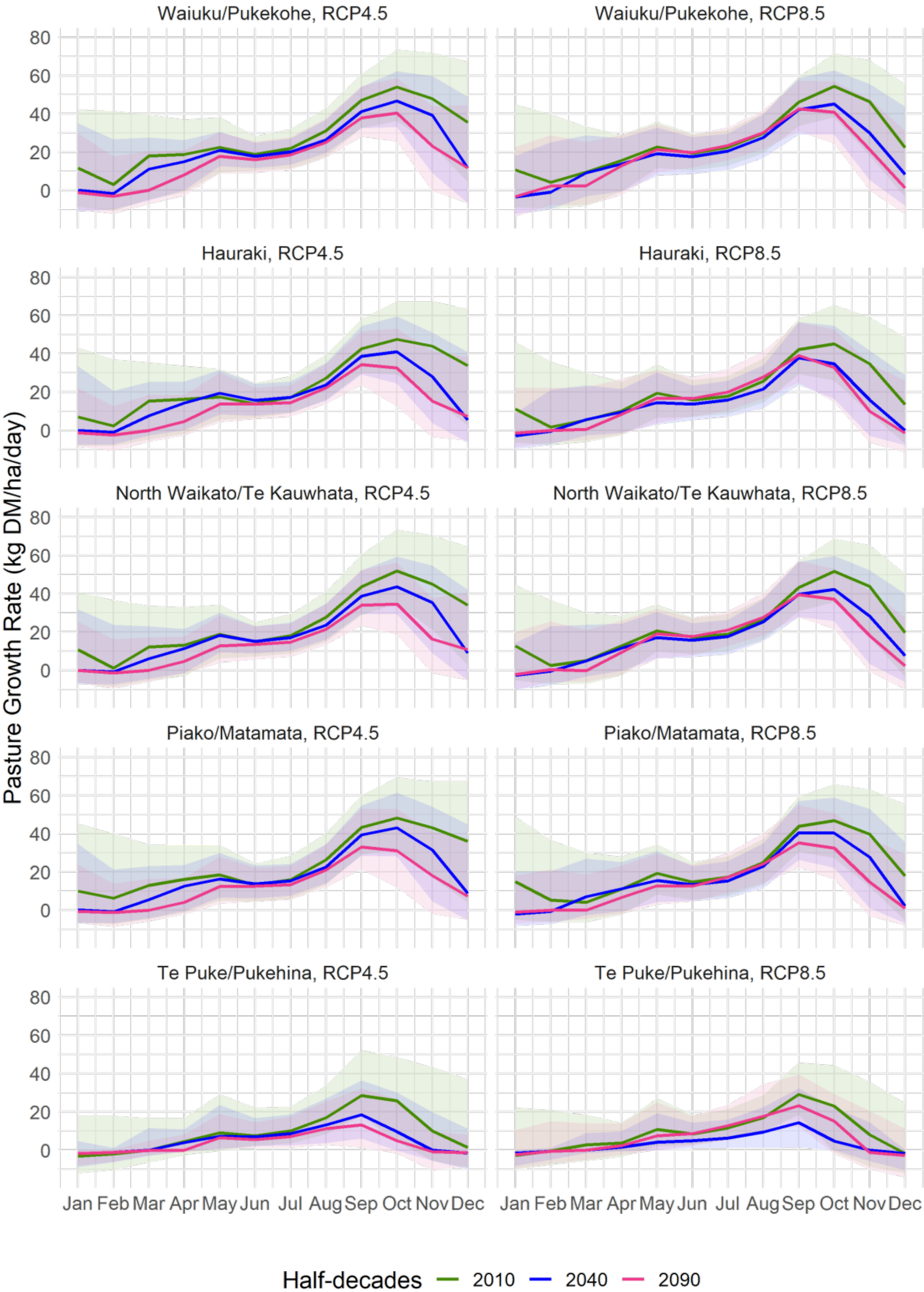
The PGR curves for Rotorua and Te Puke/Pukehina are unusual. Compared to other subregions, Rotorua was predicted to experience very high PGRs during summer, with a large dip in winter. For Te Puke/Pukehina, the curves were significantly lower and flatter than those of the other subregions, which suggested an unpromising outlook for perennial ryegrass. Future work is planned to explore the predicted climate drivers responsible for these patterns.

Annual Yield

The annual DM yield results were expressed as a percentage of the ‘baseline’ median 2010 DM yields. Using this approach, median annual yields of each period for each subregion are shown in Figure 3 for RCP4.5 and RCP8.5. In all cases, the 2040 and 2090 median annual yields were less than the 2010 yield. Predictions for past half-decades, while generally lower than the 2010 baseline, still tended to be higher than future half-decades. For RCP4.5, most subregions were predicted to have their worst future yield in the 2090 half-decade, whereas for RCP8.5, yields were predicted to decline until the 2040 half-decade and improve thereafter.

In terms of individual subregions, Rotorua fared fairly well under both RCPs, with median yield percentages staying above 70% of the 2010 baseline. In Bay of Islands and Whangarei, median annual yields remained consistently above 70% of the 2010 median annual yield under the RCP4.5 scenario, but fell below 70% in the RCP8.5 scenario. The opposite result was observed in Dargaville, Far North and North Waikato/Te Kauwhata, where median annual yields remained


Far North, RCP4.5
Far North, RCP8.5
Bay of Islands, RCP4.5
Bay of Islands, RCP8.5
Whangarei, RCP4.5
Whangarei, RCP8.5
Dargaville, RCP4.5
Dargaville, RCP8.5
DairyFlat/Rodney, RCP4.5
DairyFlat/Rodney, RCP8.5
Pasture Growth Rate (kg DM/ha/day)
0
20
40
60
80
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Half-decades
2010
2040
2090


Waiuku/Pukekohe, RCP4.5
Waiuku/Pukekohe, RCP8.5
Hauraki, RCP4.5
Hauraki, RCP8.5
North Waikato/Te Kauwhata, RCP4.5
North Waikato/Te Kauwhata, RCP8.5
Piako/Matamata, RCP4.5
Piako/Matamata, RCP8.5
Te Puke/Pukehina, RCP4.5
Te Puke/Pukehina, RCP8.5
Pasture Growth Rate (kg DM/ha/day)
80
60
40
20
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Half-decades
2010
2040
2090

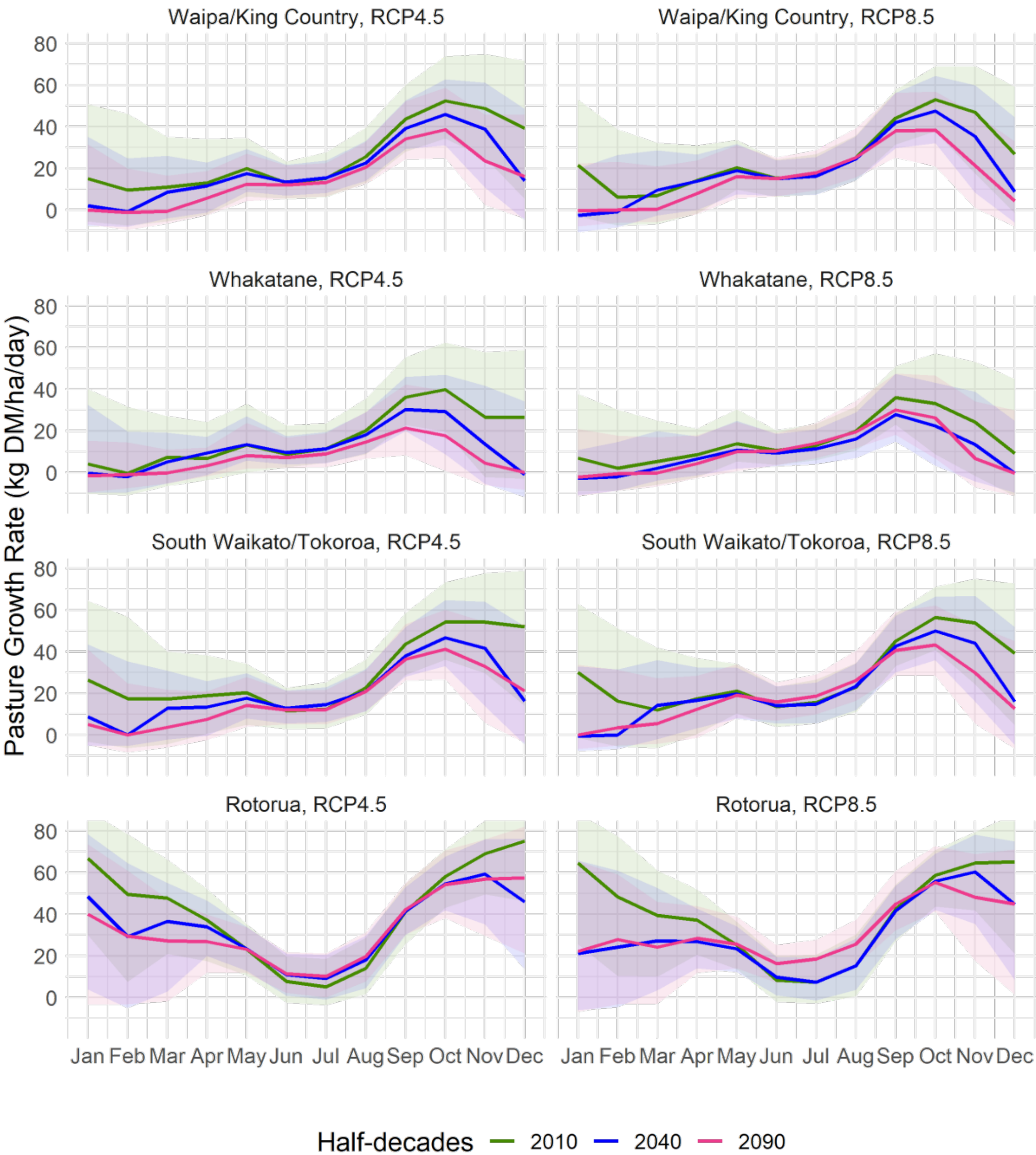


Figure 2 Predicted median monthly perennial ryegrass pasture growth rates and interquartile range over half-decades starting 2010, 2040 and 2090 for 14 subregions in the Upper North Island under two climate scenarios (RCP4.5 and RCP8.5).

above 70% of the 2010 median annual yield under the RCP8.5 scenario and fell below 70% during the RCP4.5 scenario. Annual yields in Te Puke/Pukehina and Whakatane were predicted to decrease drastically under both RCP scenarios. In Whakatane, median yields decreased to between 38-68% of the 2010 yield under RCP4.5 and to 48-59% under RCP8.5. In Te Puke/Pukehina the median annual yield decreased to 39-55% of the 2010 yield under RCP4.5 and to 30-68% under RCP8.5. In the remaining locations and scenarios, while median annual yield remained above 50%, and in some cases overtook the 70% mark, the results were not consistent over time.

Discussion

Simulation of perennial ryegrass performance in the Upper North Island of New Zealand under future climate scenarios suggested that pasture growth rates

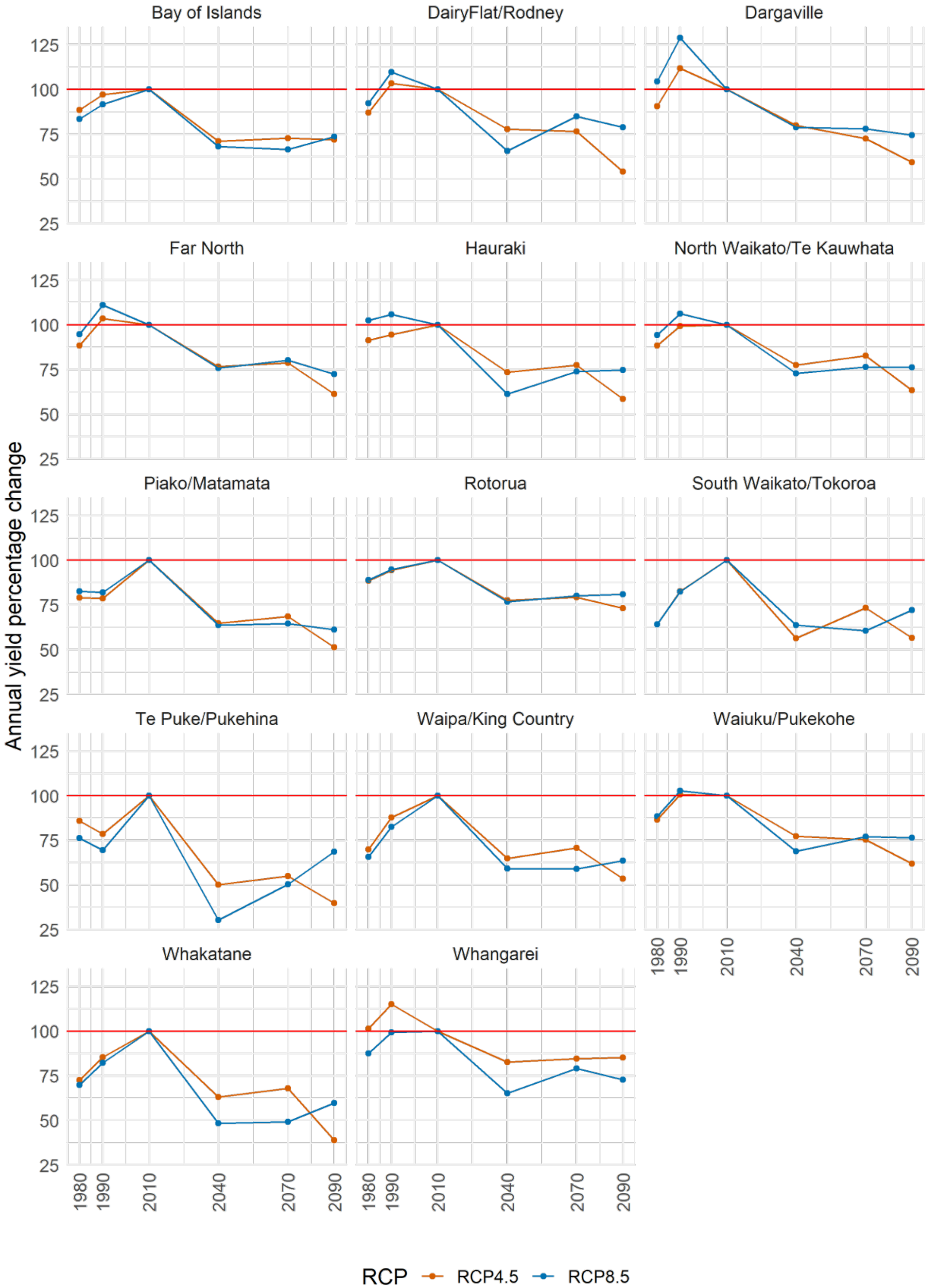


Figure 3 Median annual perennial ryegrass yield expressed as a percentage of the 'baseline' median 2010 yield (red line), for RCP4.5 (orange) and RCP8.5 (blue).

will generally decrease throughout most of the year, with possible increases only in winter. Improved winter growth rates were previously predicted by Lieffering (2016), who compared pasture growth rates from the APSIM model for the 1980–1999 and 2030–2049 periods for Southland and Hawkes Bay sites. Improved winter growth rates could potentially be taken advantage of by farmers by moving to a winter milking schedule (Chikazhe *et al.,* 2017). Several studies (Newton *et al.,* 2014; Lieffering 2016; Ausseil *et al.,* 2019) predicted higher growth rates in spring under climate change, but this was not corroborated in the current study. Their findings could have been due to the inclusion of other pasture species in their models, compensating for perennial ryegrass when growth rates are low. These studies included a CO_2 fertilisation effect, which could lead to elevated growth responses (Li *et al.,* 2013; Keller *et al.,* 2014; Hovenden *et al.,* 2019; Pers. comm. Mark Lieffering, AgResearch).

The response of perennial ryegrass pasture to changing climate is complex, since moisture, radiation, potential evapotranspiration and temperature change simultaneously and the pasture response, as modelled in BASGRA, combines these drivers in a complex way. Teasing out the contributions of individual environmental factors is difficult, and was beyond the scope of the current study.

Despite predicted improvements in perennial ryegrass pasture growth rate in winter into the future, annual yields are expected to decrease towards the end of the century, as observed in the Hawkes Bay site by Lieffering (2016). While the Southland site in Lieffering (2016) experienced an increase in annual yields into the future, it should be noted that negative daily pasture growths were not included in their calculations, which could result in an overestimation of pasture yields. An increase in annual yields was predicted by Newton *et al.* (2014); however, this was for the period 1960-2004 and is in line with the 1980, 1990 and 2010 annual yield predictions presented here. A decline in annual pasture yields could result in farm systems with lower stocking rates, lower milk production, or a greater reliance on imported feed (*e.g.,* palm kernel expeller). It could increase dependence on crops such as maize, chicory and turnips that are already widely used as supplementary feed in this region, and would be likely to reduce farm profitability (Neal and Roche 2019).

It should be noted that although yields tended to vary more in the RCP4.5 scenario, they were, nevertheless, expected to be higher than in the RCP8.5 scenario. Reductions in greenhouse gasses should therefore continue to be encouraged.

Across most subregions, mid/early-autumn to mid-spring PGR appeared to experience the least variability, while growth curves from mid-spring to mid/early-autumn had the largest variability. In agreement with this, high summer variability was predicted by Ausseil *et al.* (2019) and would likely result in this time of year becoming even more challenging for farmers than it already is, in terms of predicting the amount of feed available for their livestock (Glassey 2011). On the other hand, the lower variability of winter perennial ryegrass pasture growth rates supported the validity of the option to move to winter milking, as suggested by both Chikazhe *et al.* (2017) and Glassey *et al.* (2021). Either way, farmers will need to become more adaptable and resilient to feed supply variability changes in the future. Furthermore, thinning pastures can be subjected to weed and pest infestation requiring more intervention or complete renewal (Beukes et al., 2021). The latter is costly and increases the risk of damage to the underlying soil structures.

Based on future annual yield predictions for the RCP4.5 scenario, Bay of Islands, Rotorua and Whangarei, may be able to adapt farm systems to remain perennial ryegrass-based into the future, along with Dargaville, Far North and North Waikato/Te Kauwhata for RCP8.5, as these locations are expected to retain over 70% of their 2010 yields. Te Puke/Pukehina and Whakatane, on the other hand, may suffer catastrophic perennial ryegrass failure, in some predictions producing only up to 30% of their 2010 yields in both RCP scenarios. In these subregions, it may be best to consider alternative species to perennial ryegrass. The other subregions and scenarios modelled showed inconsistent results into the future. Yield varied from above 70% in some half-decades, to close to 50% in others. If remaining perennial ryegrass-based, these subregions and scenarios should be prepared for periods during which perennial ryegrass performs adequately, and other periods during which it does not. Alternative species may also be considered based on the individual farmer's tolerance to risk and access to external resources.

The results for Dargaville, Far North and North Waikato/Te Kauwhata for RCP8.5 differed from those predicted in Beukes *et al.* (2021), which classified these regions as becoming unsuitable for perennial ryegrass-based pastural farming into the future. In Beukes *et al.* (2021), ryegrass persistence in these three regions was predicted to fall from medium, to medium-low or low, which was reflected in a decrease in annual yield in the current study. Ryegrass suitability in Beukes *et al.* (2021) was measured, in part, by the amount of dry matter produced in each region during the five-year period. In Dargaville, Far North and North Waikato/Tokoroa, the annual yield amounts were found to be less than 10 t DM/ha and when the annual yield for the other regions were considered (which were the same regions as the ones considered here), these clusters were found to be unsuitable.

For locations expected to be able to adapt to climate change, a farm systems adaptation approach may be necessary. Although these areas (barring Rotorua) were predicted to retain over 70% of their 2010 annual yields, their perennial ryegrass growth during summer was expected to be very low, so that farm system changes may be necessary to achieve reliable profit in the future (*e.g*., moving to autumn calving, incorporating alternative crops).

As well as predicting median growth rates, this study adds to the picture of the future by estimating the variability of perennial ryegrass growth rates, providing farmers with expected ranges of pasture growth throughout the year. This is an area of interest for farmers where other modelling approaches have been lacking (Kalaugher *et al.,* 2017).

Conclusions

The mechanistic pasture model BASGRA was used with input from six NIWA climate model projections (GCMs) for two climate change scenarios (RCPs) in order to calculate future perennial ryegrass pasture growth rates for the half-decades 2010-2014, 2040-2044 and 2090-2094 in 14 dairy dominant subregions in the Upper North Island of New Zealand (UNI). The results differed from others in the literature as they included both expected median pasture growth rates as well as the variability around those medians.

In future, the main perennial ryegrass growing season can be expected to occur in late-winter/spring, with a secondary growing season in late-autumn/early-winter. The largest changes in pasture growth were predicted to occur during spring-summer-autumn and the smallest in winter. Summer was projected to experience the largest variability in expected growth rates and winter the smallest.

The current research showed a clear deterioration of perennial ryegrass pasture growth rates in the UNI as a result of climate change. Worse outcomes can be expected in the higher greenhouse gas scenario (RCP8.5) than in the lower greenhouse gas scenario (RCP4.5). For the RCP4.5 scenario, the subregions expected to remain suitable for perennial ryegrass are Bay of Islands, Rotorua and Whangarei. For the RCP8.5 scenario, Dargaville, Far North and North Waikato/Te Kauwhata are expected to remain suitable. Te Puke/Pukehina and Whakatane are expected to become unsuitable to support perennial ryegrass pastures in the future for either scenario. The remaining locations and scenarios are expected to vary in suitability over time. The results demonstrate the need for farmers to adapt their farming practices in the future in order to remain profitable and internationally competitive.

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