Climate change impacts and adaptation: a New Zealand dairy system

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Pasture-based farming systems, as in New Zealand, are susceptible to changes in the climate through feed supply variability. Future climate change will likely alter pasture growth patterns, posing opportunities and risks that farmers will have to respond to and adapt to remain profitable. Due to the heterogeneous nature of farm systems in New Zealand, adaptation strategies must be evaluated on a farm-by-farm basis.

The main objectives of this research were to use a case-study methodology to evaluate the impacts of climate change on a dairy farm system, and to investigate a range of farm management strategies aimed to maintain productivity and profitability. The study was based on the Northland Agricultural Research Farm (NARF; 35°56’39” S 173°50’34”E), using performance and farm management data over three production seasons to set up a baseline farm. Whole farm systems modelling was used to simulate climate change effects on the baseline farm in the middle and end of the 21st century. Two dynamically downscaled climate change scenarios for the baseline farm were provided by the National Institute of Water and Atmospheric Research (NIWA). These were used in the mechanistic model, DairyMod, to simulate the effects of climate change on the pasture growth rates of the baseline farm in the middle and end of the century under two warming pathways. These growth rates were used in the whole-farm systems model, Farmax, to simulate the feasibility of the farm in the middle and end of the century with altered pasture supply as impacted by climate change projections. Tactical system changes were used to match the herd’s energy demand with the altered pasture supply curves in order to re-optimise the farm system impacted by climate change. The findings of this research identified that with the use of systems changes, farms in the Northland region of New Zealand may reduce negative impacts on production and profit associated with climate change.

A second round of modelling work was completed using the strategic adaptation strategy of utilising alternative pasture species that may be better suited to the changing climate. Differences in the morphological and physiological characteristics of the baseline and adapted pasture resulted in different pasture supply curves impacted by climate change. These required more extreme system changes compared with the baseline pasture. However, with the use of system changes, production and profitability were maintained or increased compared with the baseline farm. Overall, this study showed that with the use of farm system changes farmers may be able to capitalise on the opportunities associated with climate change to offset the risks.

Keywords: whole-farm systems, pasture, pasture management, grazing, livestock, climate projections, climate impacts, plant stress, global circulation models, biophysical modelling.

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Chapter 1: Introduction

Climate change is expected to present both risks and opportunities for agriculture globally (Reisinger *et al*. 2014). Agricultural production is highly dependent on the climate and producers will have to adapt management practices to future changes (Howden *et al*. 2007). Projected changes in temperature and precipitation are expected to alter the suitability of agricultural activities for different areas, impacting production and global food security (Kalaugher 2015). Therefore, there is widespread concern over the negative effects of climate change on the stability of food availability worldwide.

Climate is a defining feature of pastoral agriculture (Kalaugher *et al.* 2017). The historically temperate climate in New Zealand and southeast Australia has enabled predominantly pasture-based dairy systems (Lee *et al.* 2013). Previous studies on the effects of climate change on New Zealand dairy farms primarily focus on pasture production, as the amount of dry matter (DM) consumed per hectare is the most influential driver of profit (Chapman *et al.* 2009). These farming systems are more vulnerable to climate fluctuations than those where livestock are housed indoors and fed purchased feeds (Clark *et al.* 2012). Therefore, evaluating the impacts of future climate change on the productivity of a range of pastures is key to maintaining a resilient dairy industry in New Zealand.

The dairy sector has experienced considerable growth from increased global demand for milk products over the last decades. Primary industries are a key component of the New Zealand economy, contributing $48 billion in total export earnings for 2020 (Ministry for Primary Industries 2021). The dairy sector contributed 41.9% of these export earnings (Figure 1.1), $20.1 billion, to the economy. As the dairy industry is a major contributor to New Zealand's economy and export trade, it is crucial to evaluate strategies that will maintain or increase its productivity in response to climate change (Kalaugher *et al*. 2017).

Figure 1.1 The proportion of individual sectors to the total export revenue for the primary industries. Data sourced from Ministry for Primary industries (2021).

New Zealand dairy farming systems are vulnerable to climate change through alterations in feed supply and quality of forage (Lee *et al.* 2013). Pasture production and quality will be affected by changes in temperature, rainfall and atmospheric carbon dioxide (CO_2) concentrations (Chappell 2016). As New Zealand's terrain gives rise to considerable regional variability, the impact of climate change is expected to differ among regions. For example, modelling by Kalaugher *et al.* (2017) showed that under a high emissions scenario, the decrease in pasture production ranged from 0 to 18% for six farms located across the major dairying regions of New Zealand. Therefore, adaptation analysis must be region-specific as the severity of climate change impacts will vary between regions.

Adapting to the environment allows farmers to take advantage of new opportunities and minimise any negative impacts associated with climate change (Howden *et al*. 2007). Several adaptation strategies for reducing climate change risk to dairy systems have been investigated such as reducing stocking rates, using supplementary feed, irrigating or using alternative pasture species with greater drought and heat tolerance. As climate variability is a significant determinant of year-to-year variation in agricultural production, utilising adaptation options is key to managing climate change risks.

Fortunately, pasture-based systems are adaptive and farmers are already accustomed to dealing with climate variability. As long-term climate projections are associated with a level of uncertainty, systems need to continue to be adaptable and resilient in response to change. However, there is a lack of research that evaluates the long-term effects of climate change on New Zealand's pasture-based dairy systems. This information is required by farmers to make informed decisions about their future and how to mitigate the effects of climate change on their farms.

1.1 Research objectives and hypothesis

A whole-farm systems model is required to compare the pasture production, milk production, and economic profitability of a dairy farm operating with a range of system changes at the middle and end of the century to evaluate the potential impacts of climate change on New Zealand pasture-based farming systems. Therefore, the objectives of this research project were:

1. To evaluate the current production and economic profitability of a standard dairy system operating with a standard pasture, forming a baseline.
2. To evaluate the effect of climate change on the production and profitability of a dairy system operating with the standard pasture at the middle and end of the 21st century. Evaluate a range of farm management changes aimed to minimise the negative impacts associated with climate change on the farm system.
3. To identify alternative species to the standard pasture that may be better suited to the future climate and how utilisation of these species impacts the dairy system's production and profitability in the middle and end of the century.

Hypotheses:

1. Future climate change will impact pasture growth rates and the productivity of the baseline dairy farm.
2. Changing the farm system in response to future climate change can mitigate negative impacts on farm performance and limit economic losses.
3. Alternative pasture species such as tall fescue, that may be better suited to the future climate, can be used as an adaptation strategy to maintain pasture production and farm performance in response to climate change.

Chapter 2: Literature review

2.1 Climate change

Climate change refers to the changes in the climate that are identified statistically by changes in the mean or variability in climate patterns that typically persist for decades or longer (IPCC 2021). Climate change is driven by natural and anthropogenic forces (Reisinger *et al.* 2014). Internal variability in weather patterns driven by El Niño/La Niña Southern Oscillation and external changes of the Earth's orbit, solar irradiance and volcanic eruptions contribute to climate change (Hegerl *et al.* 2007). Other external changes, such as the rising concentration of anthropogenic greenhouse gas (GHG) emissions in the atmosphere since the industrial revolution are also key forces for climate change. The increasing GHG (CO_2, methane (CH_4), nitrous oxide (NO_2), ozone (O_5) and halocarbon) emissions to the atmosphere cause a 'greenhouse effect' by absorbing radiation leaving Earth's atmosphere, leading to a warming of the atmosphere and surface. This warming of the atmosphere causes the evaporation of water to increase, resulting in elevated tropospheric water vapour concentrations. As water vapour is a powerful GHG, this amplifies the warming effect.

2.1.1 Global context

The Intergovernmental Panel on Climate Change (IPCC) produces a review of current scientific knowledge relevant to climate change. The scientific body reviews the work of scientists at five-yearly intervals, producing a comprehensive assessment of climate science. Key findings from the IPCC's Sixth Assessment Report (AR6) show that in 2019, atmospheric CO_2 levels were the highest in 2 million years, and CH_4 and NO_2 were the highest in 800,000 years. The increasing GHG emissions have been linked to the observed changes in the climate (IPCC 2021). For example, the global surface temperature in 2011-2020 was 1.09°C higher than 1850-1900, with a larger increase in temperature over land (1.59°C) than the ocean (0.88°C). The global mean sea-level increased by 0.20 m between 1901 and 2018. In addition, the rate of sea-level rise was 1.3 mm/year between 1901 and 1971 and increased to 3.7 mm/year between 2006 and 2018. As climate change is widespread, rapid and intensifying, there is an increasing demand for proven adaptation strategies that mitigate the effects of climate change.

2.1.2 New Zealand context

In New Zealand, the effects of climate change are already becoming apparent in the form of substantial variation in rainfall, higher average temperatures and sea-level rise (Kalaugher *et al.* 2017). Other trends include more hot extremes, fewer cold extremes and an increased frequency of drought events (Harrison *et al.* 2016). The average temperature of New Zealand increased by 1.13°C between 1909 and 2019 (StatsNZ 2020). In addition, the mean rate of sea-level rise was 1.22 mm/year between 1901 and 1960 and further increased to 2.44 mm/year between 1961 and 2018 (StatsNZ 2019). As global GHG emissions have continued to rise, warming and other changes in the climate will certainly continue in New Zealand (Ministry for the Environment 2018).

New Zealand is located in the Southwest Pacific and has a maritime environment where latitude and topography influence the climate (Clark *et al*. 2012). Large-scale atmospheric circulation interacts with the country's mountainous terrain, resulting in different regional climates across the country (Kalaugher 2015). The combination of latitude, topography and specific weather systems affect the climate on a regional basis across New Zealand. Therefore, further changes in the climate and associated adaptation options must be evaluated on a regional basis. For example, Northland (Figure 2.1) with its almost subtropical location (between 34°S and 37°S) and low elevation, has a mild and humid climate (Chappell 2016). The region's climate is affected by the high-pressure belt of the subtropics and the westerly wind belt. Northland has the highest national average temperature of 15.5°C, and this has increased by 1.4°C from 1968 to 2019 (StatsNZ 2020). High-pressure systems are prevalent during the summer months, resulting in several weeks or months of dry and hot weather (Chappell 2016). Between November 2009 and April 2010, Northland experienced the most severe drought in 60 years, with an average rainfall of only 253 mm per year compared with 748 mm in the year before (Ministry for the Environment 2018). As these challenging climatic conditions are likely to persist in the future, Northland will be the case study region for this research project.

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Figure 2.1 Map of the Northland region (Chappell 2016).

2.1.3 Projections

Climate projections for New Zealand indicate further increases in mean temperature, variation in rainfall patterns, and elevated CO_2 concentrations (Chappell 2016). Climate scenarios are projected from six General Circulation Model (GCM) simulations that provide a high resolution regional climate model (RCM) across New Zealand (Ministry for the Environment 2018). The GCMs are atmosphere-ocean climate models driven by natural climate forces such as solar irradiance coupled with anthropogenic GHG emissions based on the 1971-2005 historic period.

These six models were selected as when compared with historical climate and circulation patterns in New Zealand and the Southwest Pacific region they produced the most accurate results. RCM data is downscaled to a virtual climate station network (VCSN) of 5 km × 5 km grid cells across New Zealand for four Representative Concertation Pathway (RCP) scenarios. These RCPs include one mitigation pathway (RCP2.6) that requires zero CO_2 emissions by 2100, two intermediate stabilisation scenarios (RCP4.5 and RCP6.0) and one pathway (RCP8.5) that is 'business as usual' (IPCC 2014). A summary of the projected changes to the country's climate is displayed in Table 2.1.

Table 2.1 The main features of New Zealand's climate projections (After Ministry for the Environment 2018; Kalaugher 2015). PED = Potential Evapotranspiration Deficit.

Climate variable	Direction of change	Magnitude of change	Spatial and seasonal variation
Average temperature	Progressive increase	By 2040: 0.7°C to 1.1°C By 2090: 0.7°C to 3.0°C	Warming is greatest in summer and autumn, and least in winter/spring
Daily temperature extremes	Decrease in cold nights (<0°C) and increase in hot days (>25°C)	Cold nights: 30 to 90% decrease by 2090 Hot days: 40 to 300% increase by 2090	Cold days decrease in the coldest regions. Hot days increase in the hottest regions
Average precipitation	Increase or decrease	Substantial variation around the country	Increase in south and west and decrease in east and north for winter and spring
Drought	Increase in severity and frequency	50 mm or more increase in PED per year (Jun-Jul) by 2090	Increase in already dry areas
Average wind	Increase in westerly component	Increased westerly wind in winter (>50%) and spring (20%), and decreases in summer/autumn (20%)	Across New Zealand
Atmospheric carbon dioxide	Progressive increase	From current day levels of 410 ppm to 700 ppm by 2050	Across New Zealand
Solar radiation	Increase or decrease	5% increase in summer, 5% decrease in winter	Across New Zealand

2.2 Factors affecting plant growth processes

2.2.1 Temperature

The critical temperature range for development and growth varies between plant species (Lee *et al.* 2013). As temperatures increase to the optimal range, plant growth increases and beyond this, leaf size, tiller emergence and root growth decline (Hay & Porter 2006). The optimum temperature range for the growth of temperate (C_3) species is 15-25°C compared with 25-35°C for subtropical (C_4) species. Temperature also determines the rate of photosynthesis in C_3 and C_4 plants (Lee *et al.* 2013). In temperate grass swards, the rate of photosynthesis increases as temperatures rise from 5 to 25°C (Figure 2.2). The enzyme Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) catalyses carboxylation and oxygenation, leading to photosynthesis and photorespiration, respectively (Lee *et al.* 2013). For temperate species, higher temperatures favour oxygenation by reducing the solubility of CO_2. Long (1991) reported that as temperature increased from 0°C to 50°C, the specificity of Rubisco for CO_2 decreased by 86%, reducing the rate of photosynthesis. However, the photosynthetic pathway of C_4 plants is better adapted to higher temperatures with photosynthesis rates increasing up to 35°C (Lee *et al*. 2013). This is due to differences in plant structure as Rubisco is located in the bundle sheath of C_4 plants where it is constantly saturated with CO_2 (Hay & Porter 2006). This limits photorespiratory activity at higher temperatures, allowing photosynthesis to continue (Lee *et al.* 2013). Over the next century, as air temperatures are predicted to increase, warmer winter temperatures are likely to result in greater C_3 plant growth (Dynes *et al.* 2010). However, C_4 grasses are likely to outperform C_3 pasture grasses during summer as the number of hot (> 25°C) days are projected to increase.

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Figure 2.2 The typical temperature response curves for photosynthesis in C_3 and C_4 plants (Hay & Porter 2006).

2.2.2 Water

Water availability is the primary factor that determines plant growth and survival (Hay & Porter 2006). Low water availability limits plant growth through reductions in leaf appearance and extension rates (*Lee et al.* 2013). As plant available water becomes more difficult to extract, turgor pressure declines and cell expansion is compromised (Mills 2007). Reduced cell size results in smaller leaves and less light interception below critical leaf area index (LAI). Therefore, canopy expansion slows, and less photosynthetically active radiation is intercepted from smaller leaves on fewer tillers per unit area, reducing yield. The photosynthetic capacity of C_3 plants is reduced during a deficit by limited CO_2 diffusion into the carboxylation site (Rubisco) due to stomatal and mesophyll resistance (Lawlor & Conic 2002). In contrast, C_4 plants concentrate CO_2 in their bundle sheaths, maintaining the gradient of CO_2 concentration between intercellular spaces and the air (Hay & Porter 2006). This gradient permits the movement of CO_2 into the plant at high stomatal resistance, resulting in fewer water molecules lost per molecule of CO_2 fixed. Taylor *et al*. (2011) reported that the average water-use efficiency (WUE) of nine different C_3 and C_4 grasses was 80 and 173 µmol/mol, respectively. This suggests that subtropical species are better adapted to water stress, enabling them to maintain biomass production during water deficits. As drought is predicted to increase in frequency and intensity across the country, C_4 species are likely to outperform C_3 species due to their higher WUE.

2.2.3 Carbon dioxide

Carbon is assimilated through the phosphate reducing cycle (Calvin cycle) with the absorption of atmospheric CO_2. Rising atmospheric CO_2 levels increase the growth rates of temperate species through a process described as the 'CO_2 fertilisation effect' (Cullen *et al.* 2009). These responses are caused by increased rates of photosynthesis and reduced stomatal conductance (Lee *et al.* 2013). In C_3 plants, a greater abundance of CO_2 in the atmosphere causes increased rates of CO_2 diffusion into the mesophyll cells where Rubisco is located, increasing carboxylation, carbon assimilation and biomass production. For example, Casella & Soussana (1997) reported that under non-limiting conditions, an elevated CO_2 concentration from 350 to 700 ppm increased canopy photosynthesis of perennial ryegrass pastures by 33% over two years. Additionally, the WUE was improved as the stomata closed to regulate the flux of CO_2 molecules which subsequently reduced the amount of H_2O molecules transpired by the plant. Therefore, increased CO_2 in the atmosphere is likely to increase the performance of temperate species until the plant growth is limited by other factors (temperature, moisture). In comparison to C_3 plants, elevated CO_2 levels have little effect on the photosynthesis rates of C_4 plants (Lawlor & Conic 2002). This is due to the CO_2 concentration inside the bundle sheath cells where Rubisco is located being six to ten times higher than the CO_2 levels present in the atmosphere. Therefore, elevated atmospheric CO_2 is likely to have the greatest effect on temperate grasses. Despite this, photosynthesis and growth rates may be limited by other factors (temperature, water, nitrogen, solar radiation). As climate factors will change concurrently, further studies are required to establish the combined effect on temperate and subtropical species.

2.2.4 Nitrogen

Nitrogen is an essential macro-element that can limit the growth and development of plants (Andrews *et al.* 2013). N availability influences plant productivity indirectly through leaf size and canopy light interception, and directly by determining the amount of photosynthesis per unit leaf area (Mills *et al.* 2006). Therefore, canopies with adequate N have more leaves per unit of ground area and are taller, increasing the area available for light interception. N is integral to all biological and chemical processes in the plant as it is a component of the photosynthetic apparatus and is required for the formation of chlorophyll, Rubisco and amino acids (Peri *et al*. 2002). Nitrate (NO_3-) is the main form of N used by plants as it is readily available and assimilated by most C_3 and C_4 pasture species. Depending on the plant species and form of N, NO_3- is assimilated in either the root or shoot of the plant.

The profitability of nitrogen use depends on the pasture growth response to N, the animal response to the increase in pasture yield and the value of increased animal production. The N response is defined as: ((pasture yield (kg DM) with N – pasture yield (kg DM) without N) / amount of kg N applied) (Kopetschny 1995). Correct timing and application rate of N increase N uptake and its response while minimising N leaching. Figure 2.3 shows that following the first four days of grazing, ryegrass/white clover pastures do not take up N from the soil and instead remobilise N from reserves. After this period, pastures readily uptake mineral N from the soil including N fertiliser driven by the increasing pasture growth rate following defoliation. Therefore, applying N within 3-4 days following grazing is recommended for maximum growth response. As N is a key nutrient that determines DM production, ensuring adequate N in the sward is a vital consideration to maintain pasture production in the future. With increasing environmental legislation aimed at reducing the use of synthetic N fertiliser on farms, understanding how legume species will persist in the future is key to maintaining N delivery to the sward through N fixation.

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Figure 2.3 The N uptake and time of regrowth for perennial ryegrass (adapted from Ourry et al. 1990).

2.3 Climate change impacts on pasture production

Future changes in weather patterns may extend beyond the present range of farmers' experiences as extreme weather events become more frequent, increasing the existing pressures on the peformance of dairy systems (Kalaugher *et al*. 2017). New Zealand's historically temperate climate has allowed sufficient pasture production and year-round *in situ* grazing of forage (Chapman *et al.* 2009). However, projected changes in the climate will likely affect pasture growth, species composition and quality (Lee *et al.* 2013). As pasture forms the main component of the dairy herd's diet, further research that evaluates the effect of climate change on pasture performance in a New Zealand context is required.

The New Zealand dairy sector is primarily comprised of perennial ryegrass-based pasture (Chapman *et al.* 2009). The favourable characteristics of perennial ryegrass include its rapid establishment, tolerance to intensive grazing and high nutritive value (Lee *et al.* 2013). Nixon (2016) estimated that ryegrasses contribute $14.6 billion annually to New Zealand's gross domestic product (GDP). Although perennial ryegrass is a significant contributor to the economy, the temperate species have a higher susceptibility to drought than other pasture grasses (Chapman *et al.* 2013). In the face of climate change, there is a greater need to improve pasture performance by replacing ryegrass with other pasture species that have improved stress resistance. Further research that evaluates the performance of a range of pasture species under climate change projections is critical to provide farmers with adequate information to plan and minimise climate and economic risks in the future.

New Zealand pastures rely on a legume component to supply a low-cost source of N from N fixation to the sward and provide a high-quality feed to grazing animals (Woodfield & Clark 2009). White clover (*Trifolium repens* L.) is the main legume species used in these pastures, with growth typically peaking in spring and summer (Hofmann *et al.* 2007). However, white clover has poor performance during periods of low moisture availability compared with other deep-rooted legume species. Complementing or replacing white clover with other legume species such as lucerne (*Medicago sativa* L.) that have better drought tolerance is an effective strategy to maintain legume performance under drought conditions.

In the upper North Island (UNI) of New Zealand, changes in the local climate are already challenging perennial ryegrass-white clover performance (Beukes *et al*. 2021). Rising air temperatures and the increased number of drought events have forced the switch towards deep-rooted pasture species and annual cops. For example, Dodd *et al*. (2018) estimated that in the UNI, between 30,000 to 50,000 ha of ryegrass-based pasture for dairy farms has changed to crop and pasture rotations since 2007. In Northland, since 2010, the increased frequency and intensity of summer-autumn drought has resulted in poor pasture production and a subsequent increase in the reliance on imported feed for many farmers (McCahon *et al.* 2021). As a result, there is growing farmer interest in utilising alternative pasture species to ryegrass that can maintain year-round pasture growth.

Sub-optimal pasture growth conditions are projected to increase in frequency and intensity in the future. Modelling by Beukes *et al.* (2021) showed that, by the end of the century, the persistence of perennial ryegrass is projected to become predominantly low (0 – 2.4 years, <10 t DM/ha) in the Northland region (Figure 2.4). However, this study did not evaluate the persistence of other pasture species or include a legume component that is commonly used in the region. Further research is required to model the pasture growth rates of a range of species that may be better suited to the future climate than perennial ryegrass.

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Figure 2.4 Projected perennial ryegrass persistence for the upper North Island of New Zealand under Representative Concentration Pathway (RCP) 4.5. Persistence categories are low (0-2.4 years), medium (2.5-3.4 years), and high (3.5-6 years) (Beukes *et al*. 2021).

2.4 Climate change adaptation strategies

To minimise production losses over the coming decades, pastoral farming systems will have to adapt to the changing climate (Clark *et al.* 2012). Adaptation planning allows farmers to consider the future climate, identify and evaluate options and put them into action over time. Depending on the extent of climate risk, adaptation ranges from adopting management practices that are commonly used in other areas to the innovation of new production systems (Kalaugher *et al*. 2017). A summary of adaptation strategies investigated for New Zealand dairy farming systems in response to climate change is given in Table 2.2.

Table 2.2 A summary of published adaptations for pastoral farming systems in response to climate change in New Zealand.

Climate aspect	Impact	Adaptation	Goal	Author
Increased air temperature	Changes to seasonal/annual herbage production	Use heat-tolerant pasture species (Tall fescue, cocksfoot and C_4 species)	Extend the growing season and persistence during periods of increased temperature (autumn/summer/spring)	Lee *et al*. (2013)
		Adjust stocking rates	Lower stocking rates to match reduced pasture production	MacDonald *et al.* (2008)
		Species diversification	Utilise a mixture of species that differ in optimal heat ranges	Reich *et al.* (2001)
	An earlier peak in pasture production	Changing calving patterns	Match peak feed demand/lactation with peak pasture growth	Jarman (2020)
Low water availability	Reduced herbage yield and persistence	Use drought-tolerant/ high WUE species	Maintain pasture cover during water deficit/drought	Lee *et al*. (2013)
		Purchase supplementary feed	Maintain energy intake/milk production during feed deficit	McCahon (2019)
		Use irrigation where possible	Increase water availability to maintain pasture cover during water deficit	Kalaugher *et al.* (2017)
Increased CO_2 concentrations	Increased C_3 herbage production	Conserve feed	Make silage with high-quality pasture to offer in a feed deficit	Lee *et al*. (2013)
Warmer temperatures in winter/spring	Increased pasture production earlier in the season	Conserve feed	Make and store silage with surplus pasture to offer in feed deficit	Kalaugher *et al.* (2017)

2.4.1 Stocking rate

Stocking rate (SR) is an important management tool to manipulate the herd feed demand to match feed supply (Clark *et al.* 2012). SR is defined as the number of livestock per unit of land area (i.e., cows/ha) and is the primary driver of milk production per hectare (Lee *et al.* 2013). Implemented farm SR is usually based on the available feed, but it is key to optimising pasture production and utilisation, milk production, and profitability (Jarman 2020). For example, in areas where peak pasture growth is projected to occur earlier in the season and total pasture DM production increases, farmers may increase SR for better pasture utilisation and, hence, mitigate the economic effects of climate change through higher milk production. Modelling by Dynes *et al.* (2010) reported that under a mid-range CO_2 emission scenario, increasing SR by 8% resulted in an increase in milksolid (MS) production per cow by 25 kg and per ha by 91 kg, and improved farm profitability by $337/ha in 2080 compared with the baseline in 2000. Similarly, MacDonald *et al.* (2008) reported that when the climate was non-limiting, increasing the SR from 2.2 to 4.3 cows/ha resulted in greater pasture growth and utilisation, milk production per hectare and profit. However, in areas where pasture production is likely to decline, the SR should be reduced to maintain a sufficient amount of pasture per animal and reduce reliance on imported feed. Modelling reported by Kalaugher *et al.* (2017) for five farms across New Zealand under and a high emission scenario, showed that reducing SR by 15% reduced MS production per hectare, pasture production, and operating profit. This highlights the importance of adjusting SR based on the available pasture supply of the individual farm. SR is the most important management decision as it is the basis for all interactions between the biophysical and economic aspects of the pastoral-grazing system.

2.4.2 Calving patterns

New Zealand dairy systems calve seasonally to ensure that the herd's peak energy demand is synchronised with peak feed supply (Jarman 2020). The DM intake (DMI) of a lactating cow is maximised (up to 3.4% of live weight) at peak lactation 10 weeks post-calving (Roche *et al.* 2017). Therefore, matching this peak feed demand with peak pasture growth ensures that milk production is maximised without the use of imported feed (Spaans *et al.* 2019). In New Zealand, spring-calving is the main system used as dairy farms typically calve during late winter/ early spring to match this feed demand with peak spring pasture growth as shown in Figure 2.5. However, the combined effects of rainfall changes, warmer temperatures and increasing carbon dioxide fertilisation are likely to alter the patterns of pasture growth, shifting the seasonal peak of growth to earlier in the year (Dynes *et al.* 2010).

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Figure 2.5 Pasture growth (feed supply) curve of Ruakura and average New Zealand milk production (feed demand) per month (Shadbolt & Apparao 2016).

In areas of New Zealand, spring-calving fails to optimally align pasture supply with energy demand due to variations in the climate (Jarman *et al.* 2020). Climatic factors determine both quantity and quality of pasture, which in turn control the available dietary energy to meet animals' demand for optimal milk production. In regions such as Taranaki and Northland, recent changes in pasture growth patterns coupled with the winter milk premium have increased farmers' interest in autumn-calving systems (Spaans *et al.* 2019). In autumn-calving systems, cows calve from March-May to match feed demand with the earlier peak in pasture growth in June-July. A farm system study conducted in Taranaki by Jarman *et al* (2020) showed that MS production per cow was similar between autumn (AUT)- and spring (SPR)-calving farmlets (Table 2.3). However, the net present value of the AUT farmlet was $38,212/ha compared with $26,040/ha for the SPR farmlet due to the greater total MS production and availability of the winter milk premium. As summer-autumn drought events are predicted to increase, autumn-calving mitigates the low summer pasture growth rates and increases pasture utilisation in late winter/early spring (Lee *et al.* 2013).

Table 2.3 The number of peak cows milked, days in milk, milksolid production and supplementary feed offered in the autumn-calving (AUT) and spring-calving (SPR) farmlet dairy herds (Jarman *et al.* 2020).

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2.4.3 Alternative feeds to pasture

Pasture-based farming systems rely on the seasonal distribution of pasture growth and total production, which are both subject to variability (McCahon 2019). Increased growing degree days and elevated atmospheric CO_2 are likely to present the opportunity for surplus pasture earlier in the season to be conserved as home-grown silage (Dynes *et al.* 2010). Modelling by Kalaugher *et al.* (2017) showed that under a high emission scenario, a Northland dairy farm could increase operating profit by 150% by 2030 when surplus pasture was cut for silage and fed during periods of feed deficits. Conserving pasture has a buffering effect on the feed supply profile, and acts to match supply and demand (Roche *et al.* 2017). Considerations of the cost of silage making, labour requirements and energy inputs are required in determining whether pasture conservation is a practical option for a specific farm.

Offering supplementary feed is a strategy to increase DMI during periods of pasture deficit. However, this heightens the exposure to market risk from feed prices (McCahon 2019). In New Zealand, the cost of milk produced from pasture is low whereas the milk produced from imported feed has a high marginal cost (Spaans *et al.* 2019). Despite this, from 1991 to 2018, the quantity of imported supplements has increased on New Zealand dairy farms (e.g. +9% more palm kernel extract (PKE)/ year and +5.6% more maize silage/ year) (Neal & Roche 2019). Projections of an increase in the number of hot days (days > 25°C) and summer rainfall variability are likely to increase the reliance on purchased feed during prolonged periods of low pasture cover (Kalaugher *et al*. 2017), which will likely increase expenses associated with supplementary feed. The analysis of 12 years of DairyBase data by Neal & Roche (2019) showed that the indirect (labour, machinery, fuel) costs of supplementary feed were 53-66% of the direct (purchasing and delivering to farm) costs shown in Table 2.4. Therefore, optimising the amount of milk produced directly from pasture and reducing the amount of purchased supplementary feed is key to maintaining profitable grazing systems in the future (Roche *et al.* 2017).

Table 2.4 The direct cost (cost of purchasing and transport to the farm) of maize and pasture silage, compared with pasture (Jarman 2020).

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2.4.4 Irrigation

Irrigation use is likely to increase in many regions of New Zealand to ensure an adequate water supply is maintained for year-round pasture production and quality (Lee *et al*. 2013). As the frequency and intensity of droughts are projected to increase, the installation of irrigation infrastructure where suitable will reduce the detrimental impacts of water deficits. A modelling study by Kalaugher (2015) showed that under a high emissions scenario, operating profit was increased by 25-30% on two farms in the Bay of Plenty and Northland when irrigation was applied at 75% field capacity. However, the ability to irrigate is site-specific with rivers and lakes, aquifers and soil characteristics are not suitable for irrigation in some areas. Rivers in the northeast of the South Island and east and north of the North Island are expected to be negatively affected by climate change, reducing the viability of this adaptation option in some areas (Kalaugher 2015). Additionally, the operational and capital costs of irrigation infrastructure, especially where water storage is required, make irrigation an inaccessible option to many farmers.

2.4.5 Pasture diversity

Incorporating a diverse range of species into a sward is a strategy that aims to maintain year-round forage production and quality in response to climate change. Diversifying pastures by sowing species with differing CO_2, water and temperature requirements ensures that growth is maintained under the future climate (Lee *et al.* 2013). Reich *et al.* (2001) reported that under elevated CO_2 a single species pasture increased in biomass by 7% compared with biomass increases of 10, 18 and 22% for pastures containing four, nine and 16 plant species, respectively. This was attributed to a greater range of plant processes and traits in diverse swards that affected the carbon and N cycling. Therefore, selecting pasture species with a range of functional traits enables forage production and profitability to be maintained.

2.5 Alternative pasture species

The main source of inefficiency in temperate pastoral systems is year-to-year variation in pasture growth and quality, driven by climate variability (Chapman *et al.* 2009). Compounding current and future pasture production issues are likely to increase across New Zealand as a result of this climate variability. As a consequence, there is a need to identify species that are suited to the future climate to ensure that pasture production and quality are maintained during periods of environmental stress (Bell *et al.* 2013). Species should be selected that have a range of physiological and morphological adaptations that confer heat and drought tolerance, and a positive growth response to elevated CO_2 (Kalaugher *et al.* 2017). These traits include a deep and dense root system to increase the surface area available for water/ nutrient uptake, a high WUE to maintain a greater amount of biomass produced per molecule of water used, and a higher temperature range for growth and photosynthesis relative to ryegrass (Hay & Porter 2006). There is a range of species with these traits including subtropical grasses such as kikuyu (*Pennisetum clandestinum* Hochst), warm-temperate grasses such as tall fescue (*Festuca arundinacea* Schreb.), cocksfoot and phalaris (*Phalarisa quatica* L.) and drought tolerant legumes such as lucerne that are already present in New Zealand pastoral systems (McCahon *et al*. 2021).

2.5.1 Kikuyu

In the Northland region, increasing summer-autumn drought, summer heat, insect predation, and pugging during wet winters have already resulted in perennial ryegrass persistence issues (Ussher and Hume 2015). To maintain year-round production, many Northland dairy farms utilise the subtropical grass, kikuyu, to provide the summer and autumn pasture supply (McCahon *et al*. 2021; Jagger 2009). This C_4 grass originated from Eastern Africa and has adapted to drier conditions over time (Dodd *et al.* 2010). For example, under extreme moisture deficit, the annual yield of kikuyu was 17.0 t DM/ha compared with 12.2 t DM/ha for ryegrass (Table 2.5). Biomass production was maintained as the WUE of kikuyu was 23.2 kg DM/mm H_2O compared with 16.0 kg DM/mm H_2O for perennial ryegrass. Similarly, Fulkerson (2008) reported a 156% greater WUE for kikuyu than the ryegrass in summer. This enables kikuyu to maintain biomass production during periods of low moisture availability, providing vital summer-autumn pasture cover.

Table 2.5 The average annual yield (t DM/ha) of different forage options under and extreme irrigation treatment. The irrigation treatment was 33% of the refill point. The refill point for irrigation was 25-35 mm below field capacity in the top 0.65 m of soil (Neal *et al.* 2009).

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Kikuyu gains a productivity advantage over temperate grasses once the temperature rises above 25°C due to the more efficient carbon fixing pathway that minimises photorespiration (see also the ‘Factors affecting plant growth processes’ section above). Kikuyu has optimal growth between 20-30°C and tolerates temperatures up to 40°C (Fulkerson 2008). With the number of hot days (>25°C) projected to increase, kikuyu dominance is likely to increase and it will spread further south of New Zealand. However, kikuyu growth is severely limited when exposed to frosts and temperatures below 15°C. Due to this, Northland dairy farms generally rely on annual ryegrass (*Lolium rigidum*) to provide winter-spring pasture growth (Jager 2009; McCahon *et al*. 2021). However, this annual re-grassing process that includes mulching of kikuyu and undersowing of ryegrass is costly and labour intensive. Therefore, there is increasing interest in alternative pasture species to ryegrasses that can maintain year-round pasture production and lower the annual regressing associated with kikuyu dominance (McCahon *et al*. 2021)

2.5.2 Cocksfoot

Cocksfoot is the main dryland pasture species used in New Zealand (Mills 2007). The warm-temperate species is heat and drought tolerant with the main growth period occurring in summer (Bell *et al.* 2013). The mechanisms that allow cocksfoot to recover and maintain performance when subject to water stress include its ability to access and extract water from deep in the soil profile and its ability to recover from drought (Mills 2007). Stevens *et al.* 1992 showed that the total DM production of a dryland in Canterbury was 7.6 t DM/ha and 4.9 t DM/ha for cocksfoot and ryegrass pastures, respectively (Table 2.6). These annual differences occurred as cocksfoot produced 131% more DM in summer and 74% more DM in autumn than perennial ryegrass. Persistence during dry periods is attributed to cocksfoot's root system that forms a dense mat in the top 0.25 m of the soil profile (Mills 2007). Evans (1978) reported that in the top 0.20 m of soil, cocksfoot had 16.0 m of roots compared with 3.3 m of perennial ryegrass roots.

Table 2.6 Perennial ryegrass and cocksfoot pasture production in Canterbury (Stevens *et al*. 1992).

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The optimal temperature range of leaf photosynthesis for cocksfoot was reported as 19-23°C by Peri *et al.* (2002). This was similar to the optimal range of 20-22°C recorded in a controlled environment (Mitchell and Lunacus 1962). The higher temperature range than perennial ryegrass (18-20°C) and ability to increase water uptake through the soil profile enable cocksfoot to maintain a higher LAI intercept more solar radiation, and produce greater biomass than ryegrass (Mills 2007). However, cocksfoot has a relatively slow establishment compared to perennial ryegrass as the small-seeded grass has a thousand seed weight of 0.65-1.0 g whereas ryegrass has a thousand seed weight of 1.87-2.48 g (Lancashire and Brock 1983; Moloney 1993). Therefore, cocksfoot has fewer seed reserves to establish compared with ryegrass, resulting in a slower establishment.

N availability influences the productivity of cocksfoot under water-limiting and non-water limiting conditions (Mills *et al.* 2006). This occurs as N increases cellular division, increasing the maximum attainable leaf size and stimulates tiller production when the LAI is below critical LAI (Sanderson & Elwinger 2002). Mills *et al*. 2006 reported that cocksfoot pastures that were N deficient had a 54% lower WUE than pastures that had adequate N. This occurred as N indirectly affects WUE by influencing the photosynthetic capacity of plants. In comparison with N deficient pastures, pastures with adequate N produce more biomass per unit of water used (Peri *et al.* 2002). This highlights the importance of alleviating N deficiency to increase pasture production in areas prone to drought events.

2.5.3 Tall fescue

Tall fescue is a warm-temperate grass commonly used in areas of New Zealand where hot and dry summers limit ryegrass persistence (Milne 2011). Tall fescue has several drought avoidance mechanisms to maintain growth during soil moisture deficits. The deeper and denser fibrous root system is capable of extracting water from over 100 cm into the soil profile (Minneé *et al.* 2011). Additionally, water stress is reduced in tall fescue through leaf rolling, stomatal closure, and a reduction in transpiration rate (Renard & François 1985). Minneé *et al.* (2011) reported that continental tall fescue and Mediterranean tall fescue had a WUE of 23.5 and 21.4 kg DM/mm H_2O, respectively compared with 19.3 kg DM/mm H_2O for ryegrass during a summer field trial. This is supported by Martin *et al.* (2008) who reported a 16% increase in tall fescue DM production by using only 6% more water compared with the ryegrass. This enables tall fescue plants to accumulate a greater amount of biomass per unit of water used than ryegrass.

The optimum growth temperature of tall fescue is 26°C and it can grow at temperatures up to 35°C (Durand *et al.* 1999). Table 2.7 shows that the leaf extension rate (LER) of tall fescue leaves one and two were 60% and 76% faster at 24°C than at 14°C, respectively. Similarly, the LER of leaves three and four were 108% and 129% faster at 24°C than at 14°C. Therefore, as temperature increases to the optimum (26°C), the LER is faster and maximum LAI occurs earlier, allowing the plant to intercept maximum solar radiation for a longer amount of time. In a three-year field study in Australia, Callow *et al.* (2003) reported that tall fescue was the superior temperate species to compete with C_4 grasses in a subtropical environment. As the climate in the upper North Island of New Zealand is likely to become more subtropical in the future, further studies that evaluate the performance of tall fescue against other grasses are required to validate these results.

Table 2.7 The leaf elongation rate (LER) of tall fescue plants grown at constant temperature in a climate-controlled experiment (Durand *et al.* (1999).

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Successful establishment is critical to the productivity and persistence of tall fescue. The species is slower to establish than ryegrass due to its slow mobilisation of seed reserves and seedling growth (Wilson 2017). Once established, tall fescue becomes an important grass to provide vital summer-autumn feed supply. Brock *et al.* (1982) reported that the tall fescue cultivars ‘Roa’ and ‘S170’ produced 172% and 163% greater yields than ‘Ranui’ ryegrass, respectively. However, grazing management is a key driver of tall fescue persistence. The first grazing should occur when plants are 15-20 cm in height and should not be grazed below 7 cm (Rollo *et al.* 1998). However, grazing of tall fescue should occur frequently in spring to prevent seedhead development and stemmy pastures that lower forage quality.

2.5.4 Lucerne

Lucerne is a perennial legume used in dryland farming systems (Moot 2012). The erect growing legume has a range of drought avoidance mechanisms and consequently greater tolerance to moisture stress than other legume species. Lucerne has superior growth during periods of low soil moisture availability as its deep taproot enables a high recovery of rainfall stored in the soil profile (Brown *et al.* 2003). Moot *et al.* (2008) reported that a dryland lucerne crop extracted 328 mm of water at 2.3 m depth. Contrasting this, perennial ryegrass pasture in the same trial and soil type extracted 243 mm of water up to 1.5 m depth. Moot *et al.* 2008 showed that the spring WUE was 13, 20 and 24 kg DM/ha for a pure perennial ryegrass, ryegrass-white clover and lucerne pasture, respectively (Figure 2.6). The higher N content of legumes compared with grasses likely contributed to their higher WUE. Higher herbage N maximises photosynthesis per unit leaf area (Peri *et al.* 2002) and increases photosynthesis rates per unit of water used, resulting in an increased DM production during periods of moisture stress (Moot *et al.* 2008).

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Figure 2.6 The spring dry matter yield (t DM/ha) and water use (mm) for lucerne, perennial ryegrass-white clover, and perennial ryegrass pastures at Lincoln University (Moot *et al.* 2008).

Lucerne is suited to dryland conditions, with peak DM production occurring through late spring and summer (Brown *et al.* 2003). This provides a high-quality feed supply when other legumes and pasture species have limited growth. Moot *et al.* 2022 showed that when air temperatures were between 15°C and 22°C, the maximum daily growth rate was 206 kg DM/ha/day (Figure 2.7). However, lucerne growth rates were severely limited below 4°C, supplying low DM production in winter. The potential for stem elongation and subsequent spring DM production results from vegetative node accumulation in winter (Moot *et al*. 2003). Therefore, removal of lucerne's growing point by grazing in winter and early spring reduces the yield potential and has ongoing consequences for spring growth. As a result, it is recommended that lucerne is used to complement other pastures within dairy farm systems.

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Figure 2.7 Daily growth rates of irrigated lucerne growth (Moot *et al.* 2022).

The main factors restricting lucerne production in certain areas of New Zealand are soil type and susceptibility to hard and continuous grazing (Lambert 1967). Although healthy, established lucerne can survive flooding in moving water through permeable soils, lucerne is intolerant of waterlogged conditions (Smethurst *et al.* 2005). Areas such as valley floors that are prone to frequent flooding or sites with high annual rainfall and impermeable clay soils on flat terrain can cause anaerobic conditions that are unsuitable for lucerne production. Waterlogging causes anaerobic conditions around the rhizosphere of lucerne as oxygen is used by the roots. Additionally, there are low rates of solubility of oxygen in water (Irving *et al.* 2005). Long-term waterlogging causes a lowering of soil pH resulting in increased aluminium and magnesium solubility that are toxic to lucerne's N fixing symbionts (Smethurst *et al.* 2005). Irving *et al.* 2005 reported that a waterlogging-intolerant lucerne cultivar (Wairau) and waterlogging-tolerant lucerne cultivar (Pioneer 54Q53) both showed strong responses to waterlogging stress including reduction in photosynthetic rate, tap root weight and leaf soluble protein concentration. Therefore, sites with flat terrain, impermeable clay soils and prone to periods of high rainfall are not suitable for lucerne.

2.6 Farm systems modelling

Farm systems modelling improves the understanding of future climate impacts and the benefits or risks of adaptation options (Clark *et al.* 2012). Integrated models provide a useful basis for adaptation assessment by allowing the manipulation of management practices under future climate scenarios and providing economic and biophysical outputs (Kalaugher *et al.* 2017). Examples of such studies include Dynes *et al*. (2010) who used EcoMod to simulate pasture growth rates in the lower central North Island, which fed into a farming systems model (Farmax). The study compared a set of farm system changes (stocking rate, calving date, supplementary feeding and grazing management) under different climate change scenarios. However, the adaptation strategy of sowing alternative species better suited to the environment was not tested. Therefore, further research is required to evaluate the productivity and profitability of dairy farms operating with different pasture bases in response to climate change. Used in isolation, biophysical research has limitations of the site and temporal specificity that restrict the ability to generalise outcomes that emerge over time. Simulation modelling supports biophysical research by allowing the effects of different environments and weather patterns to be considered.

Several studies have modelled the impact of climate change scenarios on New Zealand dairy systems and evaluated a range of possible adaptation and farm management strategies (Dynes *et al.* 2010; Kalaugher *et al*. 2017; Clark *et al.* 2017; Clark *et al*. 2007). Beukes *et al.* 2021 quantified the effect of climate change on perennial ryegrass persistence at the middle and end of the century in the upper North Island. However, this study did not evaluate the persistence of a legume component such as white clover that is commonly used in dairy pastures and did not evaluate alternative pasture species to ryegrass. Published results by Kalaugher *et al.* (2012) compared perennial ryegrass and tall fescue production in response to climate change at the middle of the century. Similarly, this study used pure perennial ryegrass and tall fescue swards without including a legume species. With increasing government pressure to reduce synthetic N use on dairy farms and in areas of New Zealand where applying N fertiliser is uneconomical, legumes provide a critical N supply to dairy pastures. Therefore, quantifying the effect of climate change on pasture growth that includes legumes is important to represent New Zealand dairy pastures. Whole-farm modelling studies in Australia have evaluated the impact of climate change on the growth of a range of species such as annual ryegrass, kikuyu, tall fescue and white clover (Pembleton *et al*. 2021; Cullen *et al.* 2009; Cullen *et al.* 2008). However, there is a need to evaluate the effect of climate change on a range of grass and legume pasture species in a New Zealand context.

2.7 Conclusion

New Zealand pastoral farming systems are vulnerable to the compounding current and future changes in the climate. Climate change projections are not uniform across the country, and climate impacts and adaptation strategies must be evaluated on a regional basis. In some regions, projections of a warmer, drier climate coupled with elevated CO_2 concentrations is likely to threaten the performance of the traditional perennial ryegrass-white clover pasture base. Consequently, there is a need to identify pasture species that may be suitable for introduction on a regional basis in conjunction with climate analysis. Associated with this is the need to identify system changes that are required to facilitate their successful introduction on-farm. In order to ensure that climate change and adaptation research supports farmers and other stakeholders, quantitative research such as biophysical modelling that encompasses climate projections and farm systems is required.

Chapter 3: Effect of future climate change on a baseline dairy system

3.1 Introduction

In pasture-based farming systems, animals are typically grazed outdoors year-round with pasture being the major source of feed. However, these systems face challenges imposed by changes in pasture supply on an annual and seasonal basis (Chapman *et al.* 2013). When pasture supply is insufficient to meet animal demand, farmers adapt to maintain milk production and financial profitability. These farm system changes include supplementary feeding, reducing stocking rate or changing calving date (Dynes *et al.* 2010). The changing climate is likely to impact the pasture supply of New Zealand dairy farms. However, the impacts of climate change on New Zealand farming systems are uncertain and likely to vary regionally.

The study reported in this Chapter investigated the effects of future climate change on pasture supply in the middle and end of the 21st century. A range of farm management practices were evaluated to match animal demand with feed supply. This study used a case-study approach to first evaluate the current milk production and financial profitability of a baseline farm, and then evaluated these metrics at the middle and end of the century as impacted by climate change.

3.2 Method

3.2.1 Case study farm

The Northland Agricultural Research Farm (NARF) was the case-study farm for this modelling project. NARF is located in Dargaville (35°56’39” S 173°50’34” E, approximately 20 m above sea level), in the upper North Island of New Zealand. NARF began their ‘Future Farm Systems’ trial in June 2021, with funding from DairyNZ, Ministry for Primary Industries and the Hine Rangi Trust. This trial was established due to increasing experimental and anecdotal evidence indicating poor ryegrass performance on many Northland farms (Lee *et al.* 2013; McCahon *et al*. 2021; Jagger 2009) in response to the increasing change in the climate. The ‘Future Farm Systems’ trial aims to demonstrate strategies to help farmers adapt their farm to the changing climate and comply with environmental regulations.

The trial tests the performance of three dairy systems: a farm system that is ‘standard’ to Northland farms; a farm system using pasture species better suited to a warming climate; and a farm system designed to lower GHG emissions.

1. **Standard farmlet:** existing kikuyu and ryegrass pasture farm system with imported feed (PKE) and home-grown silage to fill feed deficits. Stocking rate of 3.1 cows/ha and up to 190 kg of applied synthetic N fertiliser per ha.
2. **Alternative Pastures farmlet**: 75% of pastures in tall fescue, cocksfoot, legumes and herbs with imported feed (PKE) to fill feed deficits. Stocking rate of 3.1 cows/ha and up to 190 kg of applied synthetic N fertiliser per ha.
3. **Low Emissions farmlet:** existing kikuyu and ryegrass pasture farm system that targets a 25% reduction in methane emissions and a 50% reduction in nitrous oxide emissions (compared with the Standard farmlet). Stocking rate of 2.1 cows/ha and no (0 kg N/ha) synthetic N fertiliser applications.

This Master's project supports this trial by modelling the effects of future climate change on the 'Standard' farmlet. The flow-on effects of changing farm management strategies and pasture species in response to changes in the climate to mitigate negative effects on production, profit, nitrate leaching and GHG emissions are evaluated.

3.2.2 Baseline farm

The "Standard farmlet" from NARF was selected as the baseline farm for this modelling study, which is representative of the current Northland dairy systems. Performance and management strategies of the "Standard farmlet" have been previously recorded at NARF for three production seasons (2018-19, 2019-20 and 2020-21). Average data across these three production seasons was used to form the baseline farm.

Physical summary

The baseline farm had an effective area of 28 ha and flat terrain. Poorly drained Kaipara Clay Loam soil comprised 25 ha and very poorly drained Te Kopuru Sand comprised 3 ha of the area (Northland Regional Council 2018). To maintain year-round pasture production, the farm was kikuyu dominant (45-70% of herbage DM from early summer to autumn, and ryegrass dominant (33-55% of herbage DM) from autumn to late spring. Legumes and herbs generally contributed 5 -15% of the herbage DM of these pastures (Table 3.1). Annual pasture transitioning between these species occurred with autumn mulching of kikuyu from mid-March to mid-May after each paddock had been grazed to remove the kikuyu stem/stolon below the growing point. This reduced the growth of kikuyu and allowed remaining ryegrass plants in the pasture to re-establish while temperatures and soil moisture were sufficient for ryegrass growth before winter (Jagger 2009). On 10-20% of the farm area, mulching was followed by under sowing of ryegrass to re-establish ryegrass in the pasture on paddocks with low plant numbers.

Table 3.1 The average seasonal botanical composition (%) of the baseline farm over three (2018-2019, 2019-2020, 2020-2021) production seasons. Winter (June-August), Spring (September-November), Summer (December-February), Autumn (March-May).

	Italian ryegrass	Perennial ryegrass	Kikuyu	Legume	Other
Winter	33%	31%	11%	5%	20%
Spring	55%	24%	5%	5%	12%
Summer	20%	13%	45%	8%	15%
Autumn	1%	3%	73%	14%	9%

To boost ryegrass growth, synthetic N fertiliser was applied following the mulching of kikuyu paddocks. Further N fertiliser was applied from June until December, and then again in April and May (Table 3.2). To avoid excessive growth beyond demand and the loss of quality, fertiliser was not applied during January, February and March when kikuyu became the dominant pasture species. The total average annual N fertiliser applied over the three production seasons was 177 kg N/ha.

Table 3.2 The average synthetic N applications for the baseline farm over three (2018-2019, 2019-2020, 2020-2021) production seasons per month and per annum.

Month	Average N application (Kg N/ha)
June	12.6
July	32.2
August	17.7
September	41.9
October	29.4
November	9.0
December	13.0
April	7.1
May	13.6
Total	176.6

Monthly pasture growth rates were calculated based on changes in pasture cover using a rising plate meter. The average monthly growth rates of pasture peaked in late September and October, and decreased to the lowest period of growth in March and April. The 2019-20 and 2020-21 seasons experienced a prolonged drought in summer and autumn (Figure 3.1). This resulted in the 2018-19 season having the greatest yield (15.4 t DM) compared with the 2019-20 (13.4 t DM) and 2020-21 (14.8 t DM) seasons. The average yield of the three production seasons was 14.5 t DM.

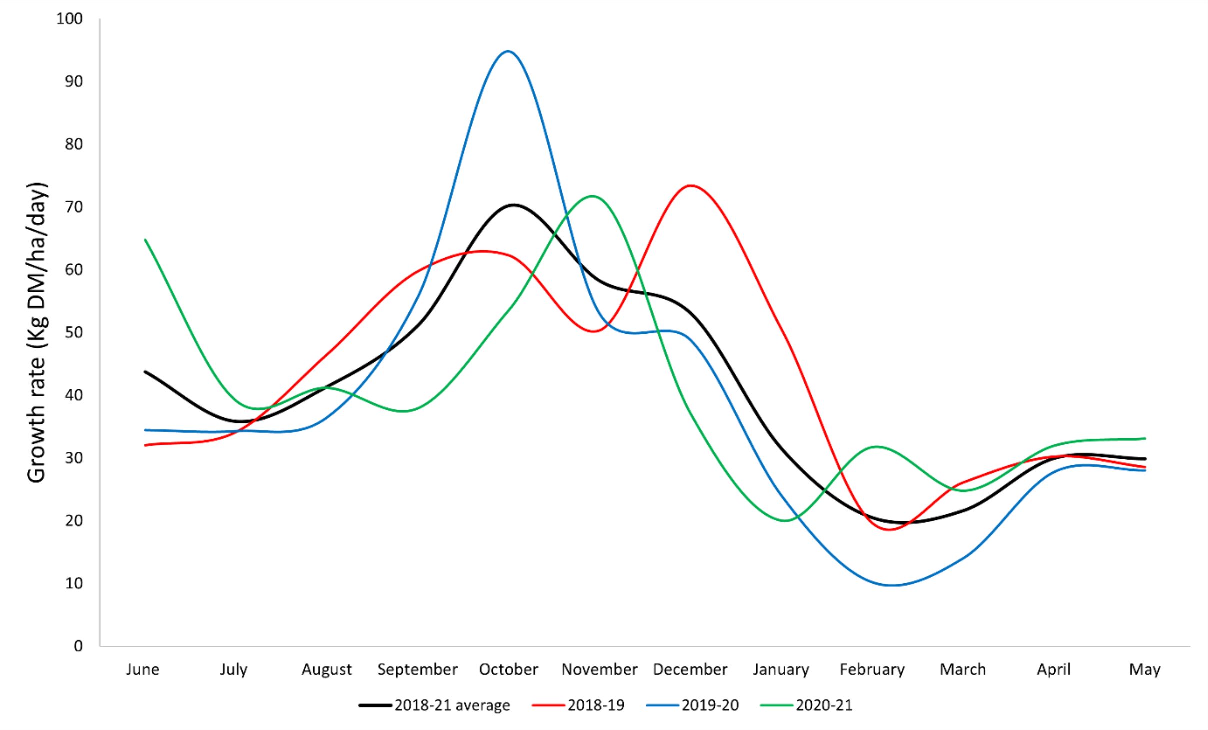

Figure 3.1 The average monthly pasture growth rates of the baseline farm for each of the three (2018-2019, 2019-2020, 2020-2021) production seasons and the average.

The supplements fed to the dairy herd on the baseline farm over the three seasons consisted of PKE and home-grown silage. Pasture silage was cut when there was surplus pasture growth and fed during periods of feed deficit or carried through to the next season. An annual average of 253 kg DM/cow of silage and 837 kg DM/cow of PKE was fed over the three production seasons (Table 3.3).

Table 3.3 The amount of pasture silage and palm kernel expeller (PKE) fed per cow (kg DM fed/cow) over three production seasons (2018-2019, 2019-2020 and 2020-2021) and average. All silage was made on farm.

	Supplements fed (kg DM/cow)	
	Silage	**PKE**
2018-19	247	978
2019-20	197	784
2020-21	316	748
Average	253	837

Stock numbers and MS production

The stock management followed a rotational grazing system with an average rotation length of 60 days in winter and 28 days in summer. Over the three production seasons, the number of cows at the start of the production season was 89 cows with an average stocking rate of 3.1 cows/ha. Calving began on July 7th and all cows were lactating by early October (Table 3.4).

Table 3.4 The monthly average number of non-lactating cows, lactating cows and total cow numbers for the baseline farm over three production seasons (2018-2019, 2019-2020 and 2020-2021).

	Non-lactating	Lactating	Total
June	89	0	89
July	64	25	89
August	17	71	88
September	2	85	87
October	0	87	87
November	0	87	87
December	0	87	87
January	0	87	87
February	0	86	86
March	3	78	82
April	15	60	79
May	29	57	86

The average annual MS production across the three production seasons was 1,209 kg/ha and 389 kg/cow (Table 3.5). Average daily MS production peaked at 1.89 kg/cow in September, decreasing to 0.9 kg/cow/day in May (Figure 3.2). Overall, the average amount of milk collected by Fonterra over the three seasons was 357,423 L per annum.

Table 3.5 The milk price ($ /kg MS), amount of milksolid (MS) produced per ha and milksolid produced per cow per production season and averages across three seasons (2018-2019, 2019-2020 and 2020-2021).

Production season	Milk price ($ /kg MS)	Kg MS/ha	Kg MS/cow
2018-19	6.35	1225	403
2019-20	7.14	1129	359
2020-21	7.55	1272	405
Average	7.01	1209	389

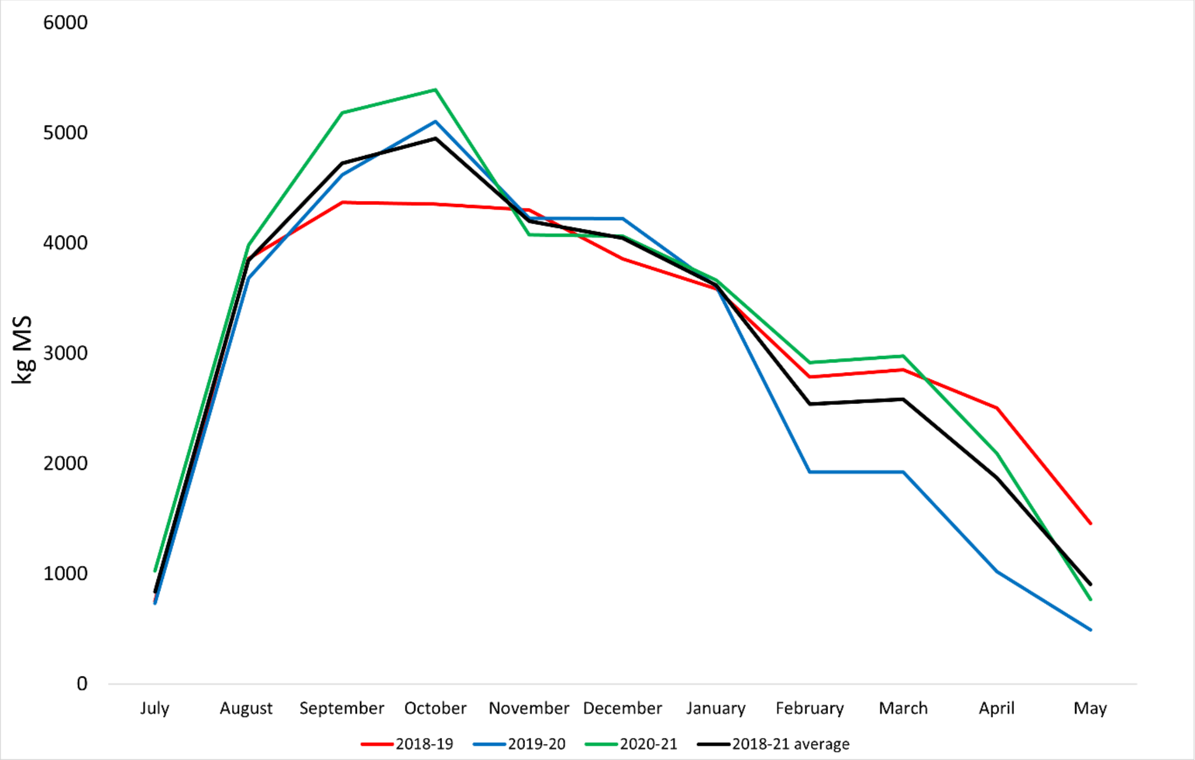

Figure 3.2 Total monthly milksolid production (kg MS) for the baseline farm for the three (2018-2019, 2019-2020, 2020-2021) production seasons and averaged across the seasons.

Financial profitability

The price of MS increased over the three production seasons with an average milk price of $7.01/kg MS (Table 3.5). At this price, the total average operating profit of the baseline farm was $85,482 (Table 3.6).

Table 3.6 The average financials of the baseline farm over the three production seasons (2018-2019, 2019-2020 and 2020-2021) at a milk price of NZD 7.1 per kg milksoild.

Income	**Total**	**$/ha**	**$/kg MS**	**$/cow**
Income from milk	$237,223	$8,472	$7.01	$2,727
Dividend Ballance	$1,065	$38	$0.03	$12
Income from stock sales	$14,654	$523	$0.43	$168
Total Income	$252,943	$9,034	$7.47	$2,907
Expenses				
Wages	$43,926	$1,569	$1.30	$505
Animal Health	$6,447	$230	$0.19	$74
Breeding Expenses	$7,526	$269	$0.22	$87
Shed expenses	$3,319	$119	$0.10	$38
Electricity	$5,848	$209	$0.17	$67
Grazing	$14,093	$503	$0.42	$162
Calf rearing	$1,447	$52	$0.04	$17
Feed				
Home Made Silage	$2,864	$102	$0.08	$33
PKE	$25,659	$916	$0.76	$295

Nitrogen fertiliser	$8,780	$314	$0.26	$101
Re-grassing (Italian & Perennial ryegrass)	$3,760	$134	$0.11	$43
Weed and Pest	$2,318	$83	$0.07	$27
Vehicle Expenses	$5,788	$207	$0.17	$67
Repairs and Maintenance	$12,049	$430	$0.36	$138
Effluent	$1,774	$63	$0.05	$20
Administration	$3,813	$136	$0.11	$44
Insurance	$2,123	$76	$0.06	$24
Rates	$3,879	$139	$0.11	$45
Farm Working Expenses	$155,414	$5,551	$4.59	$1,786
Vehicle & Equipment Depreciation	$12,047	$430	$0.36	$138
Total Operating Expenses	$167,461	$5,981	$4.95	$1,925
Operating Profit	$85,482	$3,053	$2.53	$983

Co-development

As the Northland Dairy Development Trust (NDDT) conducts research and makes management decisions at NARF, co-development of scenarios to model was instigated with this group to remain relevant with their farmlet trial. On March 10th 2022, there was a NARF site visit and workshop with the NDDT farm management group to discuss their interest in the research project and ideas for adaptation to climate change. The farm management group consists of local farmers and rural professionals. Three other farms across the Northland regions were visited to gain local knowledge on farming in the region and to gain real-time insights into the effect of current and future climate change on dairy systems in the region. Additionally, this visit was used to gain farmer input/evaluation of farm management changes that have worked, are currently working, and will likely be required in the future. Regular communication with the science adviser at NARF was maintained throughout the duration of this study to ensure that this Master's project was relevant, needed, and insightful for farmers.

3.2.3 Climate data

To evaluate the effect of climate change at NARF, climate data was sourced from NIWA's VCSN. Climate data was generated from a suite of six ranked GCMS that were chosen to validate well on present climate data (Ministry for the Environment 2018). These GCMs were selected for 'dynamical downscaling' that combined large-scale circulation with high-resolution orography and surface features (land-sea interface, vegetation cover, mountains, lakes etc.) to drive an RCM across New Zealand. This dynamical downscaling approach aims to reduce bias in the RCM data and improve confidence in regional climate impact studies by forming a set of temporally and spatially highly resolved fields. This VCSN provides climate data for 315 cells in the upper North Island (Figure 3.3), including Dargaville. In this research project, the daily climate data for 2011-2091 was sourced from the VCSN for Dargaville for all six GCMs. The GCMs provided data for the maximum and minimum temperature, rainfall, solar radiation, wind and vapour pressure.

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Figure 3.3 The location of the National Institute of Water and Atmospheric Research's (NIWA's) virtual climate station network (black dots) with ≥75% area occupied by land ≤7° slope in the Upper North Island, New Zealand (Beukes *et al*. 2021).

Of the four RCPs, two climate scenarios of possible greenhouse gas trajectories were selected to represent future climate. Capellán-Pérez *et al.* (2016) reported that the likelihood of exceeding each RCP by 2100 was 100% (RCP2.6), 92% (RCP4.5), 42% (RCP6.0), and 12% (RCP8.5). Therefore, in this research project, RCP4.5 and RCP8.5 were used as the two scenarios to estimate the 90% and 10% confidence intervals for climate change (Beukes *et al.* 2021). To model future climate change, the six GCMS representing RCP4.5 and the six GCMS representing RCP8.5 were used, totalling 12 climate files.

Uncertainty associated with climate change projections arises from scenario uncertainty, model uncertainty and internal climate variability (Gao *et al.* 2020). Scenario uncertainty is due to the assumptions of future GHG emissions and limited knowledge of future anthropogenic activities that influence the climate system (Ministry for the Environment 2018). Model uncertainty is caused by the physical and numerical equations that are used to reflect the actual climate system. Internal climate variability accounts for the dynamic processes of the ocean, atmosphere and coupled ocean-atmosphere systems (Gao *et al.* 2020).

In climate modelling, it is recommended to use all six GCMs for each RCP, and then report the average or median output rather than using only one GCM (NIWA 2021). Using the ensemble average or median is deemed a 'better representation' of the climate signal as this process reduces the uncertainty of the climate models and the internal variability of the climate system. Due to this, the GCMs are used to predict the gradual changes in the climate rather than capturing extreme events.

Climate projections for NARF

The magnitude of change in rainfall, temperature and CO_2 concentration projections for NARF vary with RCP and the GCM used. The historical average total rainfall and temperature were 1258 mm/year and 15.9°C, respectively for the baseline. There is little variation in the total annual rainfall projected from 2025 to 2040 as rainfall decreases by 1% under RCP4.5 and 3% under RCP8.5 projections (Figure 3.4). RCP4.5 projections to 2040 show minimal changes within 5% (increase or decrease) in each season whereas RCP8.5 projections show up to 10% less rainfall in spring with minimal change in other seasons. From 2025 to 2090, total annual rainfall is projected to increase by 2% under RCP4.5 and decrease by 15% under RCP8.5 projections for NARF. At RCP4.5, rainfall decreases by 5% in spring but is projected to increase by 5% in winter and autumn. However, under RCP8.5 projections, rainfall decreases by 15% in spring, 5% in winter and minimal changes in the other seasons.

Overall, the temperature change is more extreme than the changes in rainfall projected for NARF (Figure 3.5). These temperature changes are projected to occur on an annual and seasonal basis. For example, in 2040, the average air temperature is 16.2°C under RCP4.5 and 16.3°C under RCP8.5 projections. Warming is uniform in all seasons at RCP4.5 whereas, under RCP8.5 projections, warming is greatest in summer, autumn, and winter but lowest in spring. In 2090, the average air temperature is 16.6°C under RCP4.5 and 18.0°C under RCP8.5 projections. By 2090, warming is projected to be greatest in autumn and summer with uniform warming in winter and spring at RCP4.5. The number of hot days (days >25°C) is projected to increase from 25 to 55 days per year under RCP4.5 with the majority occurring in summer and autumn. However, under RCP8.5 projections, warming is the most severe in summer, uniform in winter and autumn, and lowest in spring. The number of hot days is projected to increase to 99 days per year with most hot days occurring in summer.

The climate variable that is projected to have the greatest change over time is atmospheric CO_2 levels. The observed CO_2 concentration for 2020 was 413 ppm, which is projected to rise to 950 ppm and 540 ppm, for RCP4.5 and RCP8.5, respectively in 2100 (Figure 3.6).

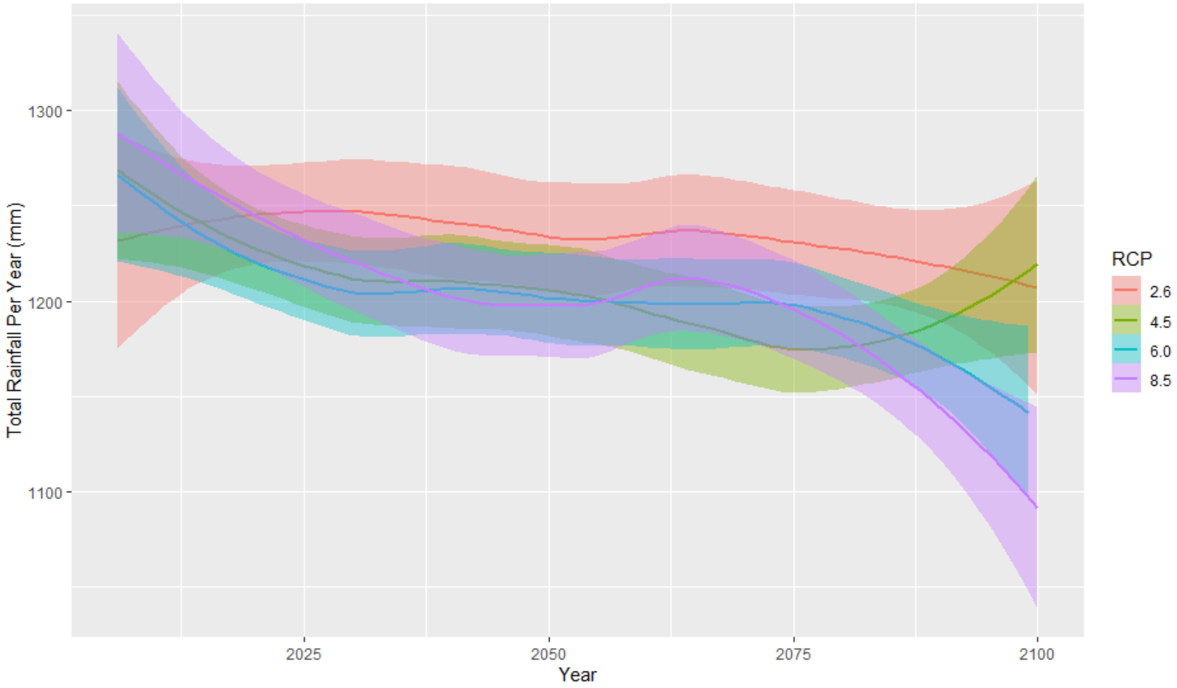

Figure 3.4 The total annual rainfall projected for the Northland Agricultural Research Farm for each representative concentration pathway (RCP) with lines of best fit and error margins.

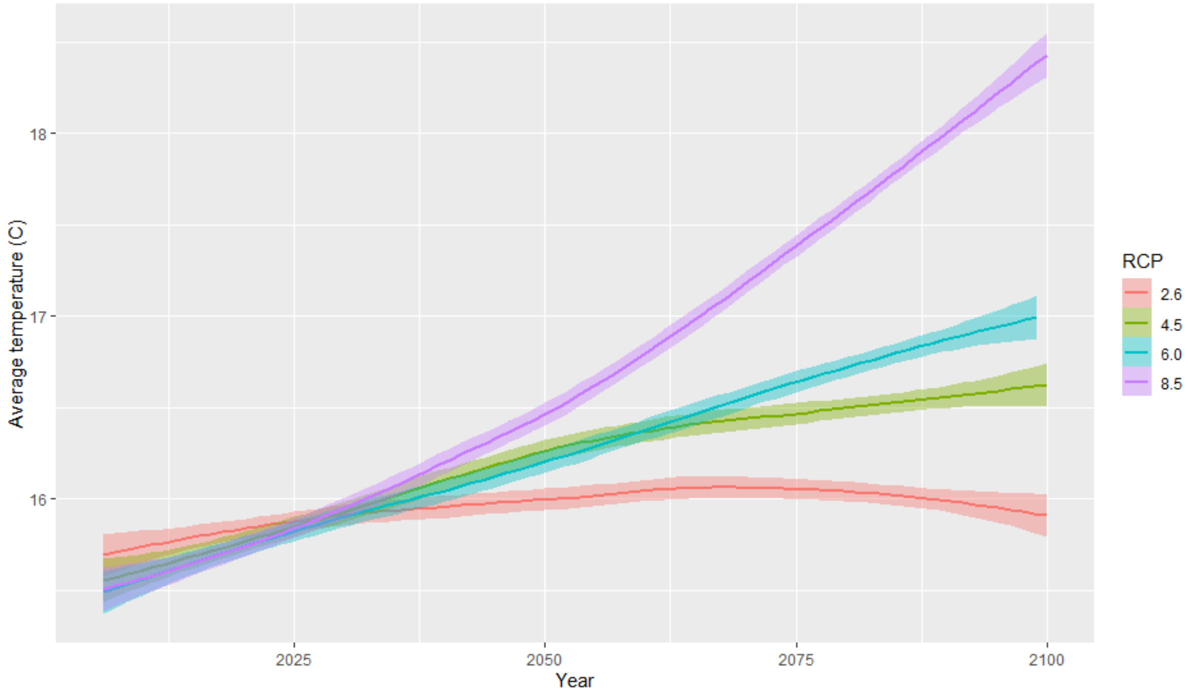

Figure 3.5 Projected average air temperature for the Northland Agricultural Research Farm for each representative concentration pathway (RCP) with lines of best fit and error margins.

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Figure 3.6 The projected future change in carbon dioxide concentration (ppm) in the atmosphere for each representative concentration pathway (RCP) (IPCC 2018).

3.2.4 Baseline modelling

Farmax

In this research project, Farmax Dairy Pro was used to replicate the baseline farm. Farmax Dairy Pro simulation model is a pastoral grazing model used as a management support tool to assist the decision-making of a dairy system, estimating the impact of management strategies on animal performance and economic outputs (Bryant *et al.* 2010). The model uses monthly estimates of pasture growth, farm, and herd information to determine the milk production and financial outcomes of managerial decisions. All scenarios were run in the "long term" mode. This ensures that the model is "balanced" regarding pasture covers, stock reconciliations, animal liveweight gains, and supplements.

Farmax was used to simulate the environmental characteristics of the farm, including N surplus and greenhouse gas (GHG) emissions. N surplus is calculated as the difference between N input (imported to farm such as fertiliser, imported PKE) and N output (N exported off farm such as milk, cull cows, sold silage). GHG emissions are calculated as the amount of methane, nitrous oxide and carbon dioxide from the farm system. Methane emissions are determined by the number of animals and feed intake, nitrous oxide emissions by animal excreta and synthetic N fertiliser, and carbon dioxide by urea applications.

Management assumptions

The baseline Farmax file used the details in section 3.2.2 to replicate the baseline farm. These include the farm area, average pasture growth rates, total number of cows and stocking rate. The planned calving start date was July 7th, with cows achieving peak MS production in spring. Dry off date was on May 14th, resulting in an average lactation length of 266 days.

In Farmax, the N response is defined as the additional amount of DM produced per kg of N. In the baseline Farmax file, the N response of the fertiliser applications was defined based on the pasture growth rates as shown in Table 3.7 following the DairyNZ Facts & Figures (DairyNZ 2021). The resulting response of pasture growth was 15 kg DM/ kg applied N from September until December. The total N applications, rate and response used in Farmax are shown in Table 3.8. In Farmax, N is not applied over the area allocated for silage conservation. As a result, the area set aside for silage making received no N, decreasing the average N used in the model to 166 kg N/ha compared with the 176.6 kg N/ha used on the baseline farm at NARF. The type of N fertiliser used was urea.

Table 3.7 The nitrogen (N) default response values associated with the amount of pasture grown used in Farmax (DairyNZ 2021).

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Table 3.8 The timing and rate (kg N/ha) of the N fertiliser applications of the baseline farm and response (kg DM/kg N) used in modelled Farmax farm.

Month	Rate (kg N/ha)	Response (kg DM/kg N)	Area (ha)
June	13	10	28
July	32	10	28
August	18	10	28
September	42	15	22
October	29	15	24
November	9	15	28
December	13	15	28
April	9	10	28
May	14	10	28
Total	**166**		

In Farmax, the utilisation rate is the amount of feed eaten compared with the amount offered (Bryant *et al.* 2010). The utilisation rates were higher in spring, summer and autumn compared with those in winter (Table 3.9). These utilisation rates were based on default values in Farmax. Additionally, the metabolisable energy of the pasture was based on the monthly pasture samples collected at the baseline farm at NARF (Table 3.9).

Table 3.9 The monthly recorded metabolisable energy (ME) of the baseline pasture over the three (2018-2019, 2019-2020, 20202-2021) production seasons and the default utilisation rates used in Farmax.

Month	Metabolisable energy (MJ ME/kg DM)	Utilisation %
June	11	80
July	11	80
August	12	80
September	12	85
October	12	90
November	11	90
December	10	95
January	10	95
February	10	95
March	10	95
April	10	95
May	11	95

Feeding regime

The feeding regime consisted of pasture and PKE throughout the season, and home-grown pasture silage in late summer/early autumn. The crude protein in pasture silage was set at 15% and the crude protein in PKE was 14% (DairyNZ 2021). The average PKE fed was 837 kg DM/cow in accordance with the supplement used in the baseline (Section 3.2.2). However, for the farm to be considered feasible in Farmax, additional supplementary feeds were required. The maximum amount of 3 kg DM PKE/cow/day, to comply with Fonterra's milk fat evaluation index (FEI) limit, was already being fed from January until April. Therefore, an additional 10 kg DM /cow/year of home-grown silage was fed from January until April.

Financial assumptions

The MS payout for the financial projections was based on the average milk price of \$7.01/kg MS. The average budgeted expenditure of the baseline farm over the three production seasons (Section 3.2.2) was used for fixed costs such as administration, rates, insurance, wages, animal health, re-grassing and livestock sales. The non-fixed costs were PKE (\$331/t), home-grown silage (\$127/t DM) and N fertiliser (\$1.78 / kg N or \$819 /t urea). These costs were based on the average cost recorded at NARF over the three production seasons (Table 3.6).

3.2.5 Future scenarios modelling

DairyMod

DairyMod was the model selected to simulate the effect of future climate change on pasture growth rates in this study. DairyMod is a biophysical simulation model that uses both mechanistic and empirical relationships for daily time-step predictions (Johnson *et al*. 2008). The multi-paddock simulation model was developed specifically for dairy farm systems with a pasture model that encompasses the whole soil-plant-water system (Johnson *et al.* 2016). Calculations of light interception, photosynthesis, growth and maintenance respiration, development, senescence, and the influence of CO_2 on growth are included in the pasture growth model.

DairyMod was selected for several reasons. Firstly, the model allows up to five pasture species in any simulation; these can be annual or perennial, C_3 or C_4, and legumes. For each of these, default parameter settings are given for a range of species including perennial ryegrass, annual ryegrass, kikuyu, tall fescue, white clover, plantain, chicory and generic C_3 and C_4 grasses. There is also an option to define a new species. Additionally, the biophysical model runs climate data from 1901 until 2099 with daily climate variables for rainfall, maximum and minimum air temperature, solar radiation, vapour pressure, wind speed and atmospheric CO_2 concentration. DairyMod is an Australian model, and it has been used to represent herbage accumulation rates with reasonable accuracy in New Zealand (Cullen *et al.* 2008; Chapman *et al.* 2008).

3.2.5..1 Baseline setup

DairyMod was used to replicate the baseline farm outlined in section 3.2.2, and to achieve this, a multi-paddock simulation was selected with heavy clay soils for 25 ha and light soils for 3 ha.

Within the paddock model, annual ryegrass was used to represent Italian ryegrass along with kikuyu and white clover to comprise the baseline pasture (KIK-RG-WC). To minimise the complexity of this pasture system, perennial ryegrass was not included in the pasture mix as the dominant ryegrass species in the baseline farm was Italian ryegrass (Table 3.1). Smith *et al.* (2019) reported that to accurately represent the growth of kikuyu and Italian ryegrass in the mixed pasture and overcome phenology limitations in DairyMod, it was necessary to modify the growth cycles to mimic field observations. This was achieved by defining emergence and anthesis dates to enable the two pasture species to grow in a relay with their dormant growth period at two different times of the year. In the biophysics section of DairyMod, the establishment date for annual ryegrass was set in accordance with NARF's practice following the mulching of kikuyu paddocks from the 15th of March. The date of anthesis was based on the observed botanical composition (Table 3.1) for the baseline period. These modifications are displayed in Table 3.10.

Table 3.10 The modified emergence and anthesis dates of annual ryegrass used in DairyMod.

Growth characteristics	Default	Modified
Date of emergence	1 April	15 March to 15 May
Date of anthesis	1 December	15 November

To simulate the annual pasture transitioning from kikuyu to ryegrass, the model was based on NARF pasture preparation practices. The kikuyu pastures were cut immediately after grazing to 0 t/ha from the 15th of March until the 15th of May, annually. This meant that ryegrass was able to emerge after the growing point of kikuyu was damaged, allowing growth to occur while temperature and moisture levels were adequate. Following the systems at NARF, paddocks were grazed on a rotational basis with pre- and post-grazing herbage mass of 2.5 t DM/ha and 1.8 t DM/ha, respectively. Similar values of pre- and post-herbage mass were used by Smith *et al.* (2019). During periods of surplus in spring, summer and autumn, pasture was cut and conserved as silage. This is a common management practice to maintain pasture quality (Kalaugher 2015; Dynes *et al*. 2010). During periods of surplus, pasture in paddocks with high mass (3.4 t /ha) was cut to 1.8 t/ha.

Scenarios

DairyMod was run with continuous climate data for 10 production seasons (June 1st - May 31st) over three time periods. This provided current (Current; 2011-2021), middle (Mid-century; 2041-2051) and end (End-century; 2081-2091) of the century scenarios. Climate data for 10 consecutive production seasons was chosen instead of one season for each period to reduce year-to-year variation in climate data and represent the average climate trend (NIWA 2021). As all six GCMs are required to represent the climate projections for each RCP, these were run for RCP4.5 and RCP8.5 over the three periods. As climate data used for NARF is historic prior to 2005 and projected thereafter, the projected climate data for the Current scenario was different at RCP4.5 and RCP8.5. Therefore, the Current scenario was run for RCP4.5 and RCP8.5. In summary, DairyMod was used to create 36 files (six GCMs x 2 RCPs x 3 periods (2011-2021 = Current, 2041-2051 = Mid-century, 2081-2091 = End-century)).

The daily growth rates simulated for each scenario over the 10 production seasons were handled in R-Studio. All pasture growth rates simulated by DairyMod for the Current, Mid-and End-century scenarios at RCP4.5 and RCP8.5 were tested for normality using a Shapiro Wilk test. Results showed that the monthly growth rates had P-values ≤ 0.05, indicating that the data was not normally distributed across the months. Therefore, the median was selected as the most appropriate measure of central tendency. The median is less sensitive to the influence of outliers and as this project focuses on the gradual trend of climate change, rather than the extremes, selecting the median reduced the skew from intense weather events (Harrison *et al.* 2016; Ehrhardt *et al.* 2017). These were used to calculate median monthly growth rates for one production season for each scenario (Current RCP4.5, Current RCP8.5, Mid-century RCP4.5, Mid-century RCP8.5, End-century RCP4.5, End-century RCP8.5). This provided one monthly pasture curve for each scenario.

Scaling

The observed baseline growth rates (average for 2018-2021 production seasons; Figure 3.1) were scaled by those simulated by DairyMod to estimate future growth rates. This allowed the changes in pasture growth to be related to the baseline farm system. The relative change in pasture growth was calculated between the Current, Mid- and End-century scenarios at RCP4.5 and RCP8.5. This was used to capture the percentage change in growth modelled by DairyMod in response to the climate data projections (Riedo *et al.* 2001).

The observed monthly growth rates for the baseline farm (averages for the 2018-2021 production seasons) were multiplied by the relative percentage change ((new value / reference value) + 1) to calculate the monthly growth rates at the middle and end of the century. The ‘reference value’ is the monthly growth rate in the Current scenario, and the ‘new value’ is the monthly growth rate in either the Mid- or End-century scenario. In this process, growth rates were compared for the same RCP e.g., Current RCP4.5 with Mid-century RCP4.5. This gave the relative change in monthly growth rates at the middle and end of the century compared with the Current monthly growth rates.

Farm performance modelling

To evaluate the effect of future climate change on dairy farm performance, the scaled monthly growth rates, for each RCP and time period, were input to the baseline Farmax file (Section 3.2.4) to create four future scenarios (Mid-century and End- century at RCP4.5 and RCP8.5). This enabled the changes in pasture supply and feasibility of the baseline farm in the future to be evaluated. The only initial changes to these Farmax scenarios were the use of the scaled growth rates and the N response of each fertiliser application associated with the growth rate (Table 3.8).

Once pasture growth rates are entered, pasture covers are predicted. Pasture cover is a proxy used by Farmax to measure the farm's feasibility, if pasture cover is below the minimum cover to meet desired animal performance, the farm will not be feasible (Byrant *et al.* 2010). Modifications are then required to ensure the farm is biologically feasible such as changing pasture intake, supplementary feed offered and altering stocking rate or calving patterns.

Farm system changes

To make the future scenarios feasible, a range of farm management practices were applied. Strategies for each scenario were evaluated on an individual basis, based on the changes in the feed supply and the feasibility of the modelled farm in response to climate change. All scenarios were modelled to maintain annual MS production per cow at 389 kg/cow, and system changes were implemented to optimise economic profitability. A range of management strategies (described in the literature review) were used to manage pasture deficits and general farm feasibility. These strategies included common farm practices of conserving pasture during periods of pasture surplus, feeding home-grown or imported supplement during periods of feed deficits and changing calving dates. Farm scenarios were ranked by profit expressed as earnings before tax.

3.2.6 Modelling assumptions

In this Chapter, fixed milk price (averaged over the three production seasons 2018/2019, 2019/2020, and 2020/2021) was assumed in all the scenarios. Thus, the response in operating profit from climate change reflected variability in climate through changes in physical inputs such as pasture growth, rather than variability caused by temporal price fluctuations from year to year. The influence of variation in milk price and feed costs over time should be considered in future work. In the modelled scenarios, costs (e.g., fertiliser and supplementary feeds) and profit were not inflation adjusted.

As the aims of this study were to model the impact of climate change on pasture growth patterns, the metabolisable energy (ME) of the pasture remained the same for all scenarios. Monthly ME values were based on those measured on the baseline farm. However, it is likely that higher temperatures coupled with moisture stress would encourage the growth of subtropical species such as kikuyu, which reduces pasture digestibility and ME (Bell *et al.* 2013; Howden *et al.* 2008). Additionally, Bell *et al.* (2013) reported that the ME of perennial ryegrass, a temperate species, plateaued or declined when the average air temperature increased by 2°C from a 1971-2000 baseline. Thus, further research on the effect of future climate change should take into account the effect on pasture quality.

It was assumed that future increases in temperature would not affect the heat stress of dairy cows. Both DairyMod and Farmax do not directly model the effect of increased temperature on the performance of dairy cows. However, increased heat stress is likely to reduce the amount of DM intake, total milk production and farm profitability (Harrison *et al.* 2016).

3.2.7 Statistics

Accuracy of fit

A range of methods were used to evaluate the accuracy of fit between predicted and observed data (Aizimu *et al.* 2021; Van Housen 2015). Chai and Draxler (2014) reported that using only a single statistical measure of data provides only one estimation of the model errors. Therefore, multiple metrics should be used to determine the 'goodness of fit' between the predicted and observed data. Thus, multiple statistical parameters were calculated, including the coefficient of determination (R^2), the root mean square error (RMSE), the normalised RMSE (NRMSE) and the mean absolute error (MAE) (Van Housen 2015; Li *et al.* 2011; Aizimu *et al.* 2021). The RMSE provides a measure of the absolute deviation between the simulated and observed data, and the NRMSE provides the relative deviation of the simulated from the observed data. The NRMSE is used to compare data with different scales (Mills 2007) with an NRMSE value of zero representing a perfect fit between the observed and simulated values.

To test the accuracy of fit of the model, DairyMod was run with historic climate data for NARF from 2018, 2019, 2020 and 2021 that was obtained from the National Climate Database (NIWA). The simulated growth rates were compared with those observed on the baseline farm (Figure 3.1). A linear regression was used in GenStat to evaluate the R^2 and significance of differences between the data sets. Following this, Lin's concordance test was used to measure the correspondence between observed and simulated growth rates. R-Studio was then used to calculate the RMSE (Equation 1), NRMSE (Equation 2) and MAE (Equation 3) for the observed and simulated data for 2018-21.

The deviation of the observed pasture growth rates (O_i) from those simulated (S_i) by the model was quantified using the following equations (Aizimu *et al.* 2021):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \quad (Equation\ 1)$$

$$NRMSE = \frac{RMSE}{mean(O)} \quad (Equation\ 2)$$

$$MAE = \left(\frac{\sum_{i=1}^{n}|O_i - S_i|}{n}\right) \quad (Equation\ 3)$$

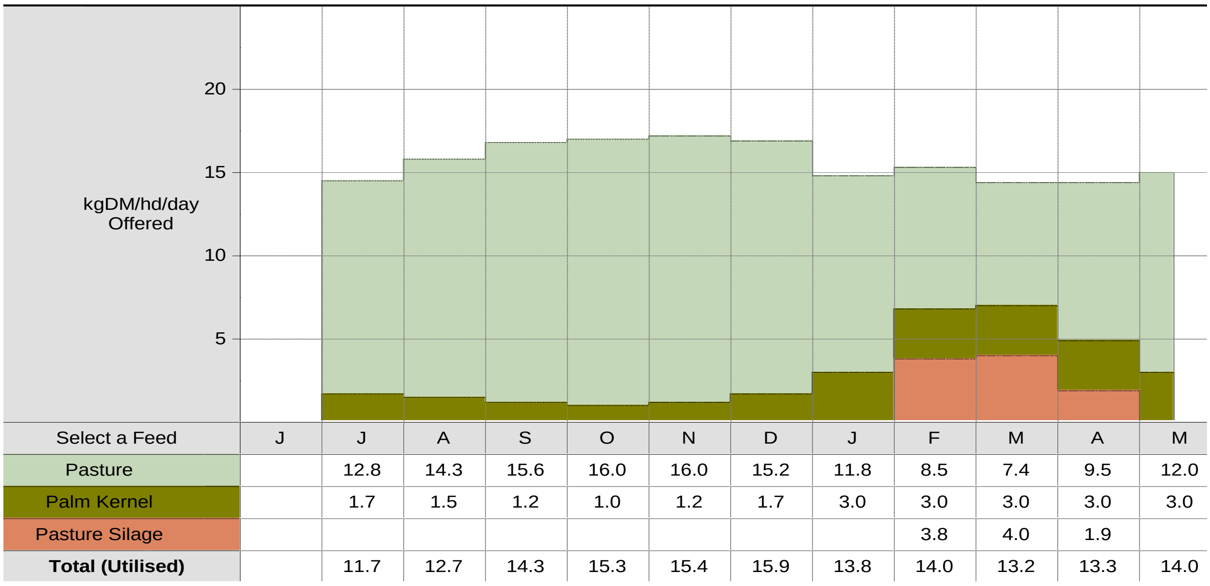
Statistical analysis

Simulated pasture growth rates (kg DM/ha/day) were analysed for each scenario using an ANOVA as the dependent variable's residuals were normally distributed. The model included GCM, RCP, Decade, Month and all their interactions as fixed effects, nested to reflect the hierarchical structure of the design: GCM nested within RCP, Decade nested within GCM, Year nested within Decade, and Month nested within year to establish the significance of differences. The Tukey post-hoc test was conducted to identify statistical difference between all possible pairs of groups. Significance was declared if P ≤ 0.05.

3.3 Results

3.3.1 Baseline modelling

The allocation of feed offered per day to the lactating cows to produce a feasible baseline farm in Farmax (based on the information in Section 3.2.4), is shown in Figure 3.7. The total supplement fed was 837 kg PKE DM/cow and 263 kg silage DM/cow, which is comparable to the annual average of 837 PKE DM/cow and 253 kg silage DM/cow observed in the baseline farm.



Select a Feed	J	J	A	S	O	N	D	J	F	M	A	M
Pasture		12.8	14.3	15.6	16.0	16.0	15.2	11.8	8.5	7.4	9.5	12.0
Palm Kernel		1.7	1.5	1.2	1.0	1.2	1.7	3.0	3.0	3.0	3.0	3.0
Pasture Silage									3.8	4.0	1.9	
Total (Utilised)		11.7	12.7	14.3	15.3	15.4	15.9	13.8	14.0	13.2	13.3	14.0

Figure 3.7 The amount of feed offered per day (kg DM/cow/day) to the lactating cows in the modelled baseline farm.

A total of 89 cows were milked for 266 days, producing 389 kg MS/cow and 1,209 kg MS/ha (Table 3.11) as per the observed baseline farm information in Section 3.2.2. The total amount of feed offered per cow was 5.6 t DM, comprising 1.1 t of supplement and 4.4 t pasture offered. Overall, 15% of the total feed offered was purchased.

The baseline modelled farm profit was $87,463 (Table 3.11). This was 2.3% more than the observed baseline farm (Table 3.6). These differences in operating profit were caused by the 6% reduction in the cost of N fertiliser as 10.6 kg N /ha/year less was applied in the modelled farm as N was not able to be applied over the silage area compared with the observed baseline. This was partly offset by the $201 extra cost associated with producing 1.6 t DM of silage. Overall, the financial analysis of the modelled baseline farm was comparable to the observed baseline and, therefore, provided a benchmark in Farmax to compare with future scenarios.

Table 3.11 Summary of the baseline farm modelled in Farmax.

Category	Description	Value	Units
Farm	Stocking rate	3.1	Cows/ha
	Days in milk	266	days
	BCS at calving	5.5	BCS
	MS per ha	1,209	kg/ha
	MS per cow	389	kg/cow
Feeding	Pasture offered per cow	4.4	t DM/cow
	Supplement offered per cow	1.1	t DM/cow
	Pasture offered per ha	13.7	t DM/ha
	Supplement offered per ha	3.7	t DM/ha
Revenue	Milk sales	8,462	$/ha
Expenses	Pasture conserved	109	$/ha
	Bought feed	861	$/ha
Profit	Total farm profit	87,463	$ total
	Profit per ha	3,124	$/ha

3.3.2 Future scenario modelling

The effects of the experimental factors and interactions on simulated pasture growth rates are presented in Table A.4. Month had a significant (P<0.0001) effect on simulated pasture growth rates. Figure 3.8 shows that pasture growth patterns followed similar trends in all scenarios, with peak growth occurring in October and declining in December-January before reaching a second peak in March. Peak pasture growth was highest (64 kg DM/ha/day) in October for the End-century RCP8.5 scenario compared with other scenarios. Monthly average growth rates were significantly different in seven out of the twelve months (June, August, September, October, November, December and February; P<0.05) between simulated scenarios. The pasture growth curve of the End -century scenario at RCP8.5 shifted to the left compared with other scenarios.

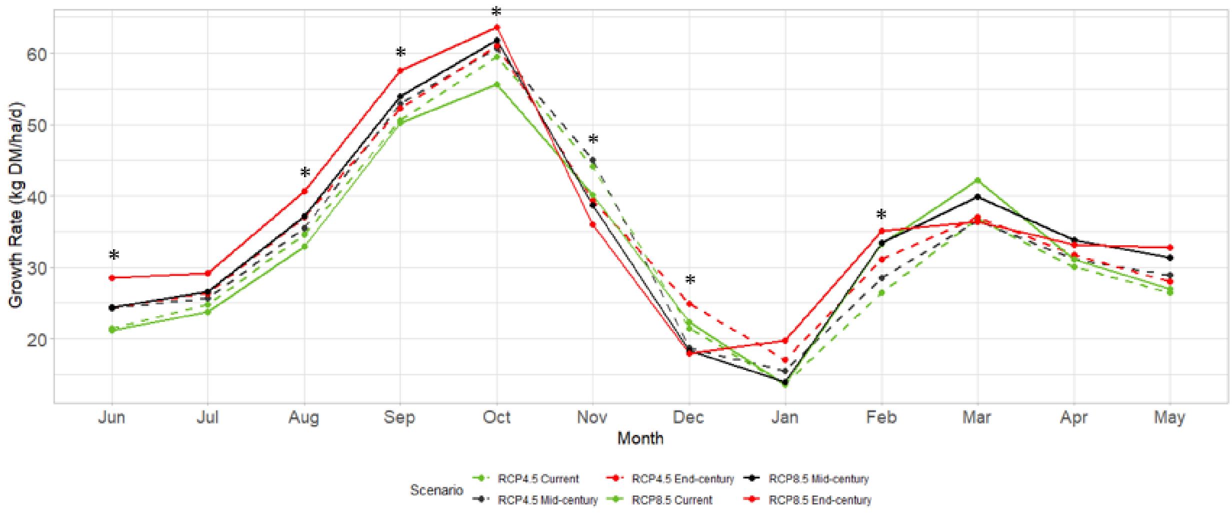


Figure 3.8 **The monthly pasture growth rates simulated by DairyMod for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5.**

Pasture growth rates for the End-century decade were greater (P<0.05) than the Current decade in June, August, September and October under RCP8.5 climate projections (Figure 3.9). Decade (P<0.0001) and RCP (P=0.0469) had a significant impact on pasture growth rates. Additionally, the two-way interaction between Month and Decade was significant (P<0.001). This indicates pasture growth rates increased from the Current decade to the end of the century in winter and early spring under RCP8.5 climate projections.

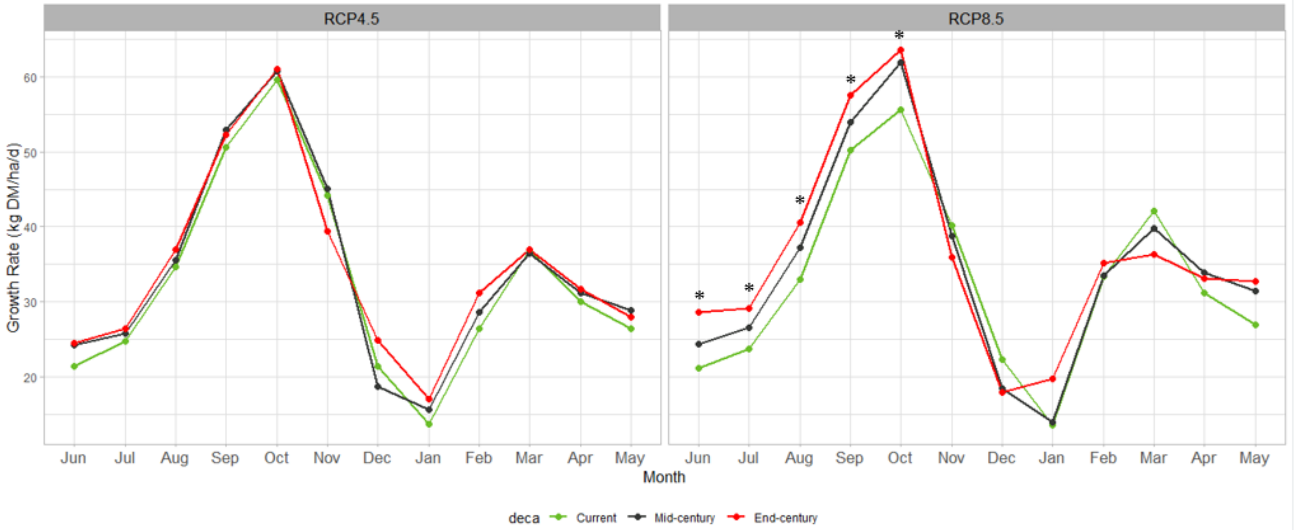


Figure 3.9 **The monthly pasture growth rates simulated by DairyMod for kikuyu, ryegrass and white clover (KIK-RG-WC) pasture for each Representative Concentration Pathway (RCP) in the Current, Mid-century and End-century scenarios.**

RCP had a significant impact (P<0.0469) on pasture growth rates. There was a two-way (Month x RCP; P<0.001) and three-way (Month x RCP x GCM; P<0.0001) interaction effect on pasture growth rates. Figure 3.10 shows that in the Current decade, the pasture growth rate in February was greater (P<0.05) at RCP8.5 than at RCP4.5. Conversely, in the End-century decade, the pasture growth rate in

December was greater (P<0.05) for RCP4.5 than RCP8.5. To illustrate the spread in simulated growth rates over time, Figure 3.10 shows the 25th and 75th percentiles of modelled monthly data. The spread of data between the 25th and 75th percentile was greatest in the End-century RCP8.5 scenario from December to April. This reflects the variability in pasture growth rates between GCMs as changes in climate variables (rainfall, temperature, carbon dioxide) become more extreme (Section 3.2.3) compared with RCP4.5.

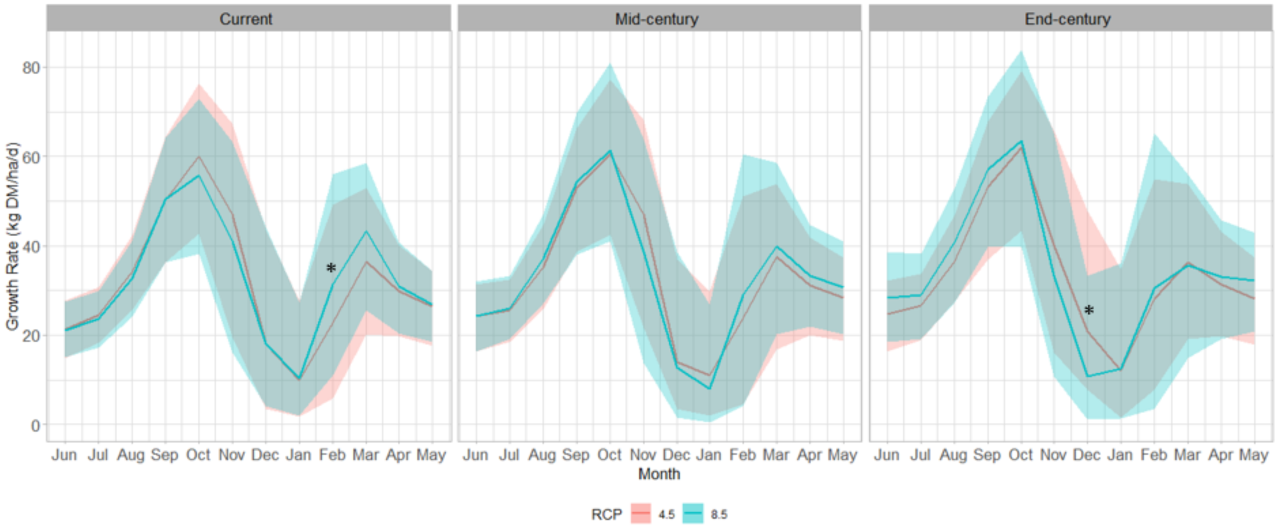


Figure 3.10 The monthly pasture growth rates simulated by DairyMod for the kikuyu, ryegrass and white clover (KIK-RG-WC) in the Current, Mid-century and End-century scenarios at each Representative Concentration Pathway (RCP; 4.5, 8.5). The shaded area represents the 25th and 75th percentiles.

Botanical composition

The seasonal botanical composition of the pasture simulated by DairyMod is shown in Table 3.12. Overall, across all scenarios and the baseline, annual ryegrass was the dominant species in winter and spring whereas kikuyu was dominant in summer and autumn. Under the RCP4.5 climate projections, in the End-century scenario, annual ryegrass presence in the sward increased by 11% in winter and 5% in spring, however, declined by 31% in summer compared with the Current scenario. Conversely, kikuyu presence declined by 18% in winter and increased by 14% in summer. To offset this, white clover presence increased by 29% in summer and 15% in autumn.

Under the RCP8.5 climate projections, in the Mid-century scenario, the ryegrass content increased by 14% in winter and 5% in spring with kikuyu content decreasing by 24% and 23%, respectively compared with the Current scenario. In the End-century scenario, the proportion of annual ryegrass in the sward increased by 27% in winter and 10% in spring compared with the Current. This resulted in a 55% and 46% reduction in the proportion of kikuyu in the sward in winter and spring, respectively. However, in summer, kikuyu presence increased by 18% whereas ryegrass presence declined by 40%. Overall, the changes in botanical composition were more extreme for the End-century than Mid-century and for RCP8.5 than RCP4.5.

Table 3.12 The seasonal botanical composition of the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture simulated by DairyMod for RCP4.5 and RCP8.5 in Current, Mid-century and End-century scenarios. Winter (June-August), spring (September-November), summer (December-January) and autumn (February-May).

	RCP4.5			RCP8.5		
	Annual ryegrass (%)	**Kikuyu (%)**	**White clover (%)**	**Annual ryegrass (%)**	**Kikuyu (%)**	**White clover (%)**
Current						
Winter	63	28	9	63	29	8
Spring	78	12	10	79	13	8
Summer	36	50	14	35	51	14
Autumn	23	64	13	22	65	13
Mid-century						
Winter	67	26	7	72	22	6
Spring	80	11	9	83	10	7
Summer	30	55	15	27	56	17
Autumn	22	65	13	22	63	15
End-century						
Winter	70	23	7	80	13	7
Spring	82	10	8	87	7	6
Summer	25	57	18	21	60	19
Autumn	22	63	15	21	61	18

Relative change in growth rates

The relative change in pasture growth rate between the Current, Mid-century and End-century scenarios under RCP 4.5 and RCP 8.5 projections are shown in Table 3.13. In comparison with the Current RCP4.5 scenario, monthly pasture growth declined in December (-23%) but increased or remained the same in all other months in the Mid-century RCP4.5 scenario. In the End-century RCP4.5 scenario monthly pasture growth declined in November (-14%) but increased in all other months, except for March where it didn’t change, compared with the Current. The seasonal pasture growth increased by 10% in winter and 20% in summer compared with the Current RCP4.5 scenario (Table 3.14).

The RCP8.5 scenarios had the greatest change (increase and decrease) in average monthly pasture growth compared with RCP4.5. In comparison with the Current RCP 8.5 scenario, the RCP 8.5 Mid-century scenario showed that the greatest increase in the monthly average pasture growth occurred in June and May (+15%), and the greatest decline occurred in December (-30%). The seasonal change in pasture growth was +13% in winter and -20% in summer for Mid-century RCP 8.5 compared with the Current RCP 8.5 scenario. In the RCP 8.5 End-century scenario, the greatest increase in the average growth occurred in June (+35%), while the greatest decline occurred in December (-41%)

compared with the Current RCP8.5 scenario. Overall, the change in monthly pasture growth rate was most severe under the End-century RCP8.5 scenario compared with the other future scenarios. This severe effect was more pronounced on the seasonal growth pattern (+27% in winter vs -8% in summer in End-century RCP 8.5 compared with the Current RCP 8.5 scenario) than the annual pasture yield.

Table 3.13 The calculated monthly relative change (%) in pasture growth modelled by DairyMod for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture between Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5.

	Relative change (%)			
	Mid-century		End-century	
Month	RCP4.5	RCP8.5	RCP4.5	RCP8.5
June	13	15	15	35
July	4	10	8	23
August	3	13	7	25
September	5	8	6	13
October	1	10	3	14
November	0	-6	-14	-19
December	-23	-30	15	-41
January	11	-22	22	20
February	5	-8	23	-3
March	3	-8	0	-18
April	4	7	5	7
May	8	15	7	19

Table 3.14 The calculated seasonal relative change (%) in pasture growth modelled by DairyMod for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture between the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5. Winter (June-August), spring (September-November), summer (December-January) and autumn (February-May).

	Relative difference (%)			
	Mid-century		End-century	
Season	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Winter	7	13	10	27
Spring	1	4	-2	3
Summer	-2	-20	20	-8
Autumn	5	5	4	3

Scaled growth rates

The baseline and scaled growth rates for the Mid-and End-century scenarios at RCP4.5 and RCP8.5. Peak pasture growth occurred in October across all scenarios (Table 3.15 and Figure 3.11). In the Mid-century scenario, the growth rates modelled with the RCP4.5 climate projections were comparable to the baseline in all months, except for December when pasture growth declined by 12 kg DM/ha/day compared to the baseline. In contrast, in the Mid-century RCP8.5 scenario pasture growth rates were greater than the baseline from June to October, lower than the baseline from December to March, and comparable to the baseline in April and May. In the End-century RCP4.5 scenario, the pasture growth rate was higher than the baseline from June until October. Pasture growth decreased in November before peaking again (60 kg DM/ha/day) in December and maintained greater growth rates than the baseline until March. The highest (80.0 kg DM/ha/day) and lowest (17.8 kg DM/ha/day) pasture growth rates occurred in the End-century RCP8.5 scenario.

Table 3.15 The baseline and scaled growth rates for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture in the Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5.

	Growth rate (kg DM/ha/day)				
	Baseline	**Mid-century**		**End-century**	
Month		**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
June	43.7	49.5	50.5	50.4	58.9
July	35.8	37.3	39.5	38.9	44.0
August	41.4	42.6	46.9	44.2	51.6
September	51.1	53.8	55.1	54.0	57.8
October	70.2	70.8	77.3	72.5	80.0
November	58.2	58.4	54.8	50.0	47.3
December	53.1	41.0	37.0	61.2	31.6
January	31.5	35.1	24.5	38.3	37.9
February	20.5	21.4	18.9	25.2	20.0
March	21.6	22.3	19.9	21.5	17.8
April	30.0	31.2	32.1	31.5	31.9
May	29.9	32.2	34.2	31.8	35.7

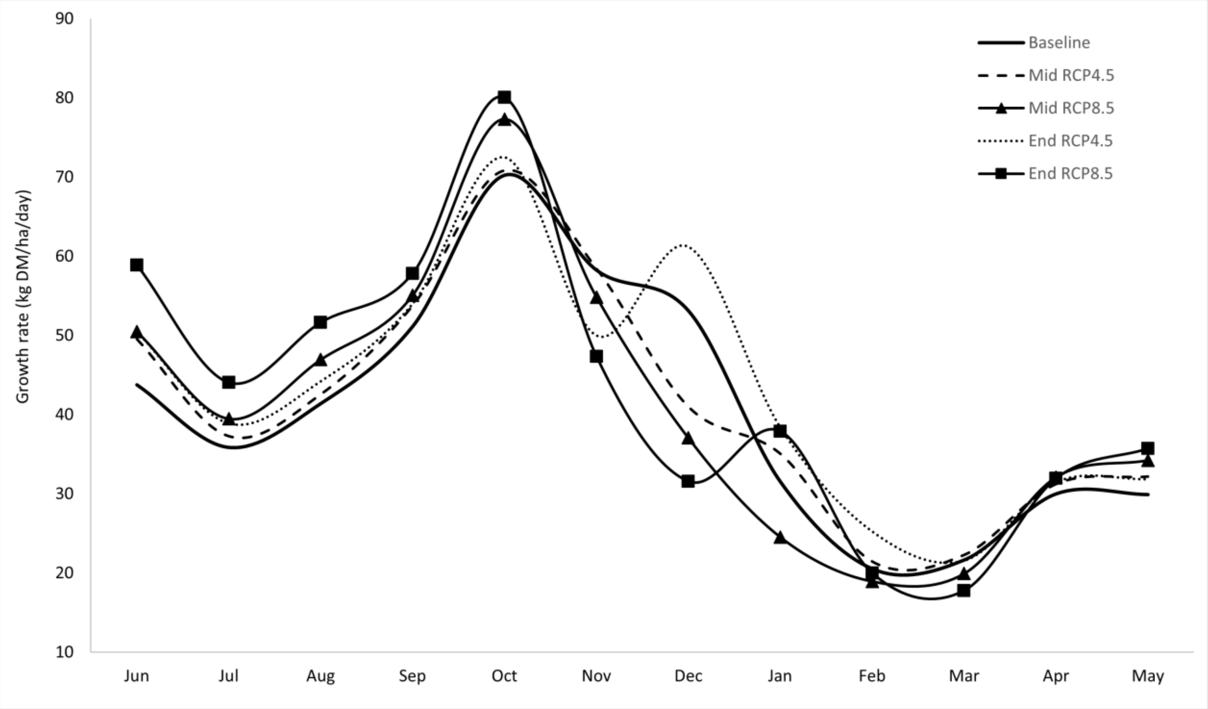


Figure 3.11 The monthly scaled pasture growth rates for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture in the Mid-century and End-century scenarios at

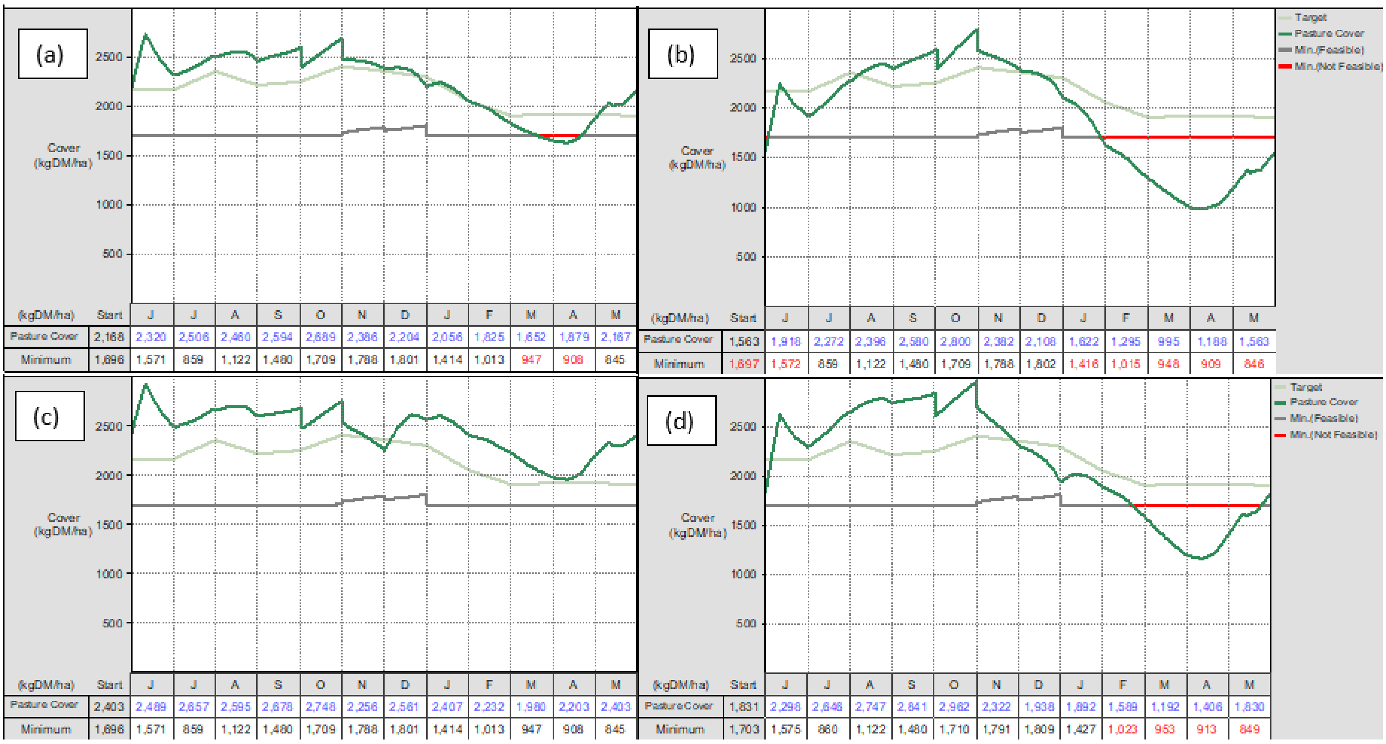
Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline growth rate.

In addition to the pasture growth rates, the total yield corresponding to each scenario was calculated from the monthly average pasture growth rates. The total annual yield of the observed baseline was 14.6 t DM/ha, compared with 14.9 and 14.7 t DM/ha at RCP4.5 and RCP8.5, respectively in the Mid-century scenario. At the End-century period, the total annual yield was 15.6 t DM/ha at RCP4.5 compared with 15.4 t DM/ha at RCP8.5.

Farm performance modelling

Pasture cover (average pasture mass DM/ha on total farm effective pasture area) was modelled in the baseline Farmax file for the four future scenarios based on their respective growth rates. The Mid-and End-century scenarios at RCP4.5 and RCP8.5 all resulted in a greater average pasture cover than the baseline from mid-July until November (Figure 3.12). Contrasting this, from November to April, all scenarios had a lower pasture cover than the baseline except for the End-century RCP4.5 scenario (Figure 3.12c).

With the same management assumptions as the baseline, the change in pasture supply caused the farm to be unfeasible in all future scenarios except for End-century at RCP4.5. The greatest decrease in pasture cover across all scenarios occurred in the Mid-century RCP8.5 scenario with the farm becoming unfeasible from January to March (Figure 3.12b; average pasture cover kg DM/ha (dark green line) is lower than the minimum (red line)). This resulted from low pasture growth in winter-spring, coupled with the 30% lower growth in December and subsequent lower pasture growth rates until March. The End-century scenario at RCP4.5 resulted in a higher pasture cover than the baseline throughout the production season, providing a pasture supply greater than the target cover (Figure 3.12c). Pasture cover was highest in the End-century RCP8.5 than all other scenarios from July until November. However, the average pasture cover decreased from November to May, causing the farm to be in an unfeasible state from February to March (Figure 3.12d).



(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	2,168	2,320	2,506	2,460	2,594	2,689	2,386	2,204	2,056	1,825	1,652	1,879	2,167
Minimum	1,696	1,571	859	1,122	1,480	1,709	1,788	1,801	1,414	1,013	947	908	845

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,563	1,918	2,272	2,396	2,580	2,800	2,382	2,108	1,622	1,295	995	1,188	1,563
Minimum	1,697	1,572	859	1,122	1,480	1,709	1,788	1,802	1,416	1,015	948	909	846

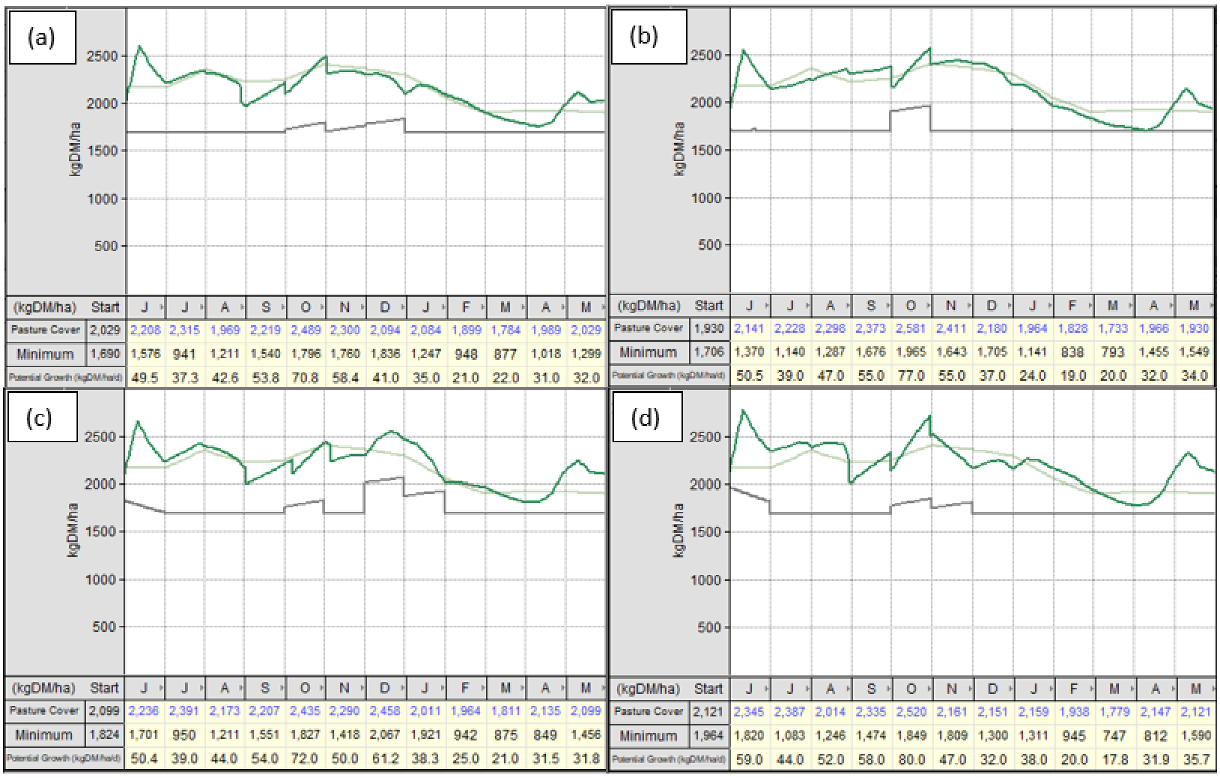
(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	2,403	2,489	2,657	2,595	2,678	2,748	2,256	2,561	2,407	2,232	1,980	2,203	2,403
Minimum	1,696	1,571	859	1,122	1,480	1,709	1,788	1,801	1,414	1,013	947	908	845

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,831	2,298	2,646	2,747	2,841	2,962	2,322	1,938	1,892	1,589	1,192	1,406	1,830
Minimum	1,703	1,575	860	1,122	1,480	1,710	1,791	1,809	1,427	1,023	953	913	849

Figure 3.12 The modelled kikuyu, ryegrass and white clover (KIK-RG-WC) pasture cover in Farmax with the scaled pasture growth rates in the Mid-century RCP4.5 (a), Mid-century RCP8.5 (b), End-century RCP4.5 (c) and End-century RCP8.5 (d) scenarios. Average pasture cover (kg DM/ha; dark green line), minimum pasture cover (kg DM/ha; grey line), baseline pasture cover (kg DM/ha; light green line) and not feasible when average cover is lower than minimum pasture cover (kg DM/ha; red line).

Farm system changes

System changes were made in Farmax to make the future farms feasible with a similar average pasture cover across the months as the baseline. This was mainly achieved by feeding out supplement during periods of pasture deficit and conserving pasture as silage during periods of pasture surplus. All scenarios were evaluated on an individual basis with the aim to match the MS production per cow to the baseline (389 kg MS/cow) and to minimise additional costs to the farm by capitalising on periods of increased pasture supply. The resulting average pasture covers are shown in Figure 3.13.



(a)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	2,029	2,208	2,315	1,969	2,219	2,489	2,300	2,094	2,084	1,899	1,784	1,989	2,029
Minimum	1,690	1,576	941	1,211	1,540	1,796	1,760	1,836	1,247	948	877	1,018	1,299
Potential Growth (kgDM/ha/d)		49.5	37.3	42.6	53.8	70.8	58.4	41.0	35.0	21.0	22.0	31.0	32.0

(b)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,930	2,141	2,228	2,298	2,373	2,581	2,411	2,180	1,964	1,828	1,733	1,966	1,930
Minimum	1,706	1,370	1,140	1,287	1,676	1,965	1,643	1,705	1,141	838	793	1,455	1,549
Potential Growth (kgDM/ha/d)		50.5	39.0	47.0	55.0	77.0	55.0	37.0	24.0	19.0	20.0	32.0	34.0

(c)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	2,099	2,236	2,391	2,173	2,207	2,435	2,290	2,458	2,011	1,964	1,811	2,135	2,099
Minimum	1,824	1,701	950	1,211	1,551	1,827	1,418	2,067	1,921	942	875	849	1,456
Potential Growth (kgDM/ha/d)		50.4	39.0	44.0	54.0	72.0	50.0	61.2	38.3	25.0	21.0	31.5	31.8

(d)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	2,121	2,345	2,387	2,014	2,335	2,520	2,161	2,151	2,159	1,938	1,779	2,147	2,121
Minimum	1,964	1,820	1,083	1,246	1,474	1,849	1,809	1,300	1,311	945	747	812	1,590
Potential Growth (kgDM/ha/d)		59.0	44.0	52.0	58.0	80.0	47.0	32.0	38.0	20.0	17.8	31.9	35.7

Figure 3.13 The modelled kikuyu, ryegrass and white clover (KIK-RG-WC) pasture cover in Farmax with the scaled pasture growth rates for the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture with farm system changes in the Mid-century RCP4.5 (a), Mid-century RCP8.5 (b), End-century RCP4.5 (c) and End-century RCP8.5 (d) scenarios. Average pasture cover (kg DM/ha; dark green line), minimum pasture cover (kg DM/ha; grey line), baseline pasture cover (kg DM/ha; light green line) and not feasible when average cover is lower than minimum pasture cover (kg DM/ha; red line).

Mid-century RCP4.5

In this scenario, supplement allocation was altered to make the farm feasible. The strategy of conserving surplus pasture and feeding this during a deficit was applied. The increase in pasture supply from June to September was conserved as silage and offered during the March and April deficit. The total amount of home-grown silage offered was 36 t DM, increasing the amount offered to the herd by 50% compared with the baseline (Table 3.16). Subsequently, this allowed the farm to reduce its reliance on PKE by 19%.

Mid-century RCP8.5

To better match peak milk production with feed supply, the calving date was changed to June 7th, with dry-off occurring a month earlier than the baseline (Table 3.16) to reduce the animal feed requirements during the summer-autumn deficit. To make the farm feasible, an extra 2 t DM of pasture silage was produced compared with the baseline farm. However, this was not adequate to fulfil the animal demand for feed and as a result, the amount of PKE purchased increased to 75 t DM compared with 73 t DM in the baseline. Daily PKE offered did not exceed 3.0 kg DM/cow, but the duration it was fed for was extended. Overall, the amount of supplement (PKE and home grown silage) offered to cows in this scenario was 6% greater than in the baseline.

End-century RCP4.5

In this scenario, the farm was in a feasible state with greater pasture growth than the baseline farm across all months except for November. Therefore, for this scenario more pasture could be utilised, reducing the reliance on PKE. The amount of pasture silage produced increased by 66% and the amount of PKE offered decreased by 45% compared with the baseline. Overall, this scenario had the least amount of supplement offered to cows (80 t DM) compared to all other scenarios.

End-century RCP8.5

To match the greater supply of pasture with peak milk production earlier in the season, the calving date was brought back a week to July 1st. Subsequently, the dry off date was changed to May 8th. In addition, the greatest amount of home-grown pasture silage offered to the herd occurred in this scenario (43 t DM). There was a 17% decrease in the PKE offered to cows, however, the total amount of supplement offered to cows was greater than the baseline (103 t DM) due to the increase in home-grown silage offered.

Table 3.16 Summary of the farm system changes used in the Mid-century and End-century kikuyu, ryegrass and white clover (KIK-RG-WC) scenarios farm at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		End-century	
Farm system changes	**Baseline**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Supplement					
Area conserved for silage (ha)	9.7	14.9	10.7	16.7	17.8
Home-grown pasture silage (t DM)	24	36	28	40	43
PKE (t DM)	73	59	75	40	60
Total supplement fed (t DM)	97	95	103	80	103
Dates					
Calving date	July 7th	July 7th	June 7th	July 7th	July 1st
Dry-off date	May 14th	May 14th	April 14th	May 14th	May 8th
Days in milk	266	266	264	266	260

Physical summary and profit

Across all scenarios, the farm area, stocking rate, total N fertiliser used and the amount of MS per cow remained the same as the baseline (Table 3.17). MS per ha was greatest in the Mid-century RCP8.5 scenario (1,222 kg/ha, or 34,226 kg in total). This scenario had the greatest amount of PKE (75 t DM) and total supplement (103 t DM) fed, and the earliest calving and dry-off date than all other scenarios. All other scenarios had similar total and per ha MS production as the baseline farm.

As stock numbers, total supplement used and fertiliser applied remained the same between scenarios, the total GHG emissions per ha was similar compared with the baseline (Table 3.17). However, the N surplus decreased by 18% for the End-century RCP4.5 scenario. This reduction in N surplus was due to the 33 t DM less imported PKE fed compared with the baseline.

Table 3.17 The physical summary of each future scenario in the Mid-century and End-century kikuyu, ryegrass and white clover (KIK-RG-WC) scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		**End-century**	
	Baseline	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Farm					
Area (ha)	28	28	28	28	28
Stocking rate (cows/ha)	3.1	3.1	3.1	3.1	3.1
Cow numbers (July 1)	89	89	89	89	89
N use (kg N/ha)	166	166	166	166	166
Potential growth (t DM/ha)	14.9	15.1	14.9	15.8	15.7
Production					
Milksolid per ha (MS/cow)	389	389	389	389	389
Milksolid per ha (MS/ha)	1,207	1,208	1,224	1,209	1,207
Total milksolid (kg)	33,800	33,821	34,264	33,850	33,809
Avg BCS at caving	5.5	5.4	5.4	5.4	5.4
Feeding					
Pasture offered per cow (t DM/cow)	4.4	4.4	4.3	4.5	4.4
Supplements offered per cow (t DM/cow)	1.1	1.1	1.2	0.9	1.2
Total feed offered per ha (t DM/cow)	5.6	5.6	5.6	5.6	5.7
Environmental					
Total kg GHG* per ha (kg GHG/ha)	644	645	651	643	652
N surplus* (kg N/ha)	117	109	116	96	109

*Greenhouse gas (GHG) emissions are calculated as the amount of methane, nitrous oxide and carbon dioxide emitted in each scenario with the main influencing factors being animal intake and fertiliser.
*N surplus is calculated as the difference between total N in (N fertiliser, incoming stock, purchased feed) and total N out (milk, outgoing stock, sold feed).

The financial profitability of each scenario was impacted by variable costs that fluctuate depending on the farm system. The fixed costs remained the same. In this modelling, the variable costs were associated with the amount of pasture conserved and bought feed. These costs coupled with the net milk sales were the key determinants of the changes in profitability between scenarios. Farm profit before tax was greater in all four future scenarios than the baseline (Table 3.18). This was due to the reduced amount of imported supplements offered to the herd in all scenarios except for Mid-century RCP8.5. In this scenario, the 2.4% increase in profit compared with the baseline was due to the greater amount of milk sales.

Within each Decade, the RCP4.5 scenarios had a higher farm profit per ha compared with the RCP8.5 scenarios. The End-century scenario at RCP4.5 had the greatest farm profit across all scenarios of

$96,773, this was 11% and 8% higher than the baseline and End-century RCP8.5, respectively. Despite the End-century RCP4.5 costing $1991 more in pasture conservation than the baseline, the increase in farm profit was due to the largest decrease in bought feed, costing $13,161 compared with $24,095 for the baseline.

Table 3.18 The profit ($) and loss ($) of the Mid-century and End-century kikuyu, ryegrass and white clover (KIK-RG-WC) scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		End-century	
	Baseline	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Revenue					
Net milk sales	236,938	237,088	240,188	237,290	236,998
Livestock sales	14,650	14,650	14,650	14,650	14,650
Total	251,588	251,738	254,838	251,941	251,649
Expenses					
Pasture conserved	3,065	4,558	3,543	5,056	5,419
Bought feed	24,095	19,671	24,801	13,163	19,751
Other *	136,975	136,975	136,975	136,975	136,975
Total	164,135	161,203	165,319	155,194	162,145
Farm profit					
Total profit before tax	87,453	90,535	89,519	96,746	89,504
Profit per ha before tax	3,123	3,233	3,197	3,455	3,197

* Costs associated with wages, animal health and breeding, grazing, working farm expenses and overheads.

3.3.3 Statistics

Accuracy of fit

The accuracy of fit between the observed pasture growth rates of the baseline farm and those simulated by DairyMod for the baseline period using historic climate data was tested. Figure 3.14 shows the average simulated and observed pasture growth rates from the 2018-2021 production seasons. A linear regression showed a moderate correlation (R^2 = 66%, $P < 0.001$) between observed and simulated pasture growth rates. Additionally, Lin's concordance correlation was high (0.726) between simulated and observed data (Table 3.19), suggesting a high accuracy of fit between observed and simulated pasture growth rates and, thus, supporting the ability of DairyMod to predict the effect of climate change on growth of pasture.

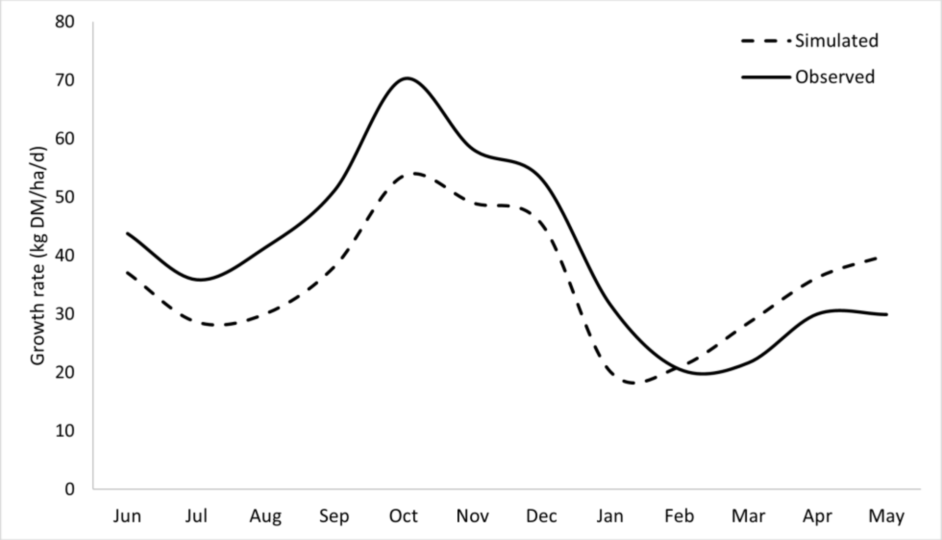


Figure 3.14 The observed pasture growth rates from the baseline farm and those simulated by DairyMod for the baseline period (2018-2021) using historic climate data at the Northland Agricultural Research Farm (NARF).

Table 3.19 Measures of deviation between observed and simulated growth rates for correlation (R2), Lin's concordance (concordance) coefficient, Pearson's correlation (correlation) coefficient, root mean square error (RMSE), normalised root mean square error (NRMSE).

Measure of model fit	**Value**
R^2	66%
Concordance	0.726
Correlation	0.833
RMSE	9.8 kg DM/ha/d
NRMSE	0.24
NSE	0.55

An initial test was run with projected climate data for NARF to evaluate DairyMod's ability to simulate pasture growth in response to changing climate variables. The six GCMs for RCP4.5 were run in DairyMod for 2018-19, 2019-20 and 2020-21. Figure 3.15 shows the variation in pasture growth patterns caused by the different climate variables within each GCM. However, a similar trend for average pasture growth curve was shown across the three production seasons, suggesting that ensemble averaging reduces the effect of extreme climate events.

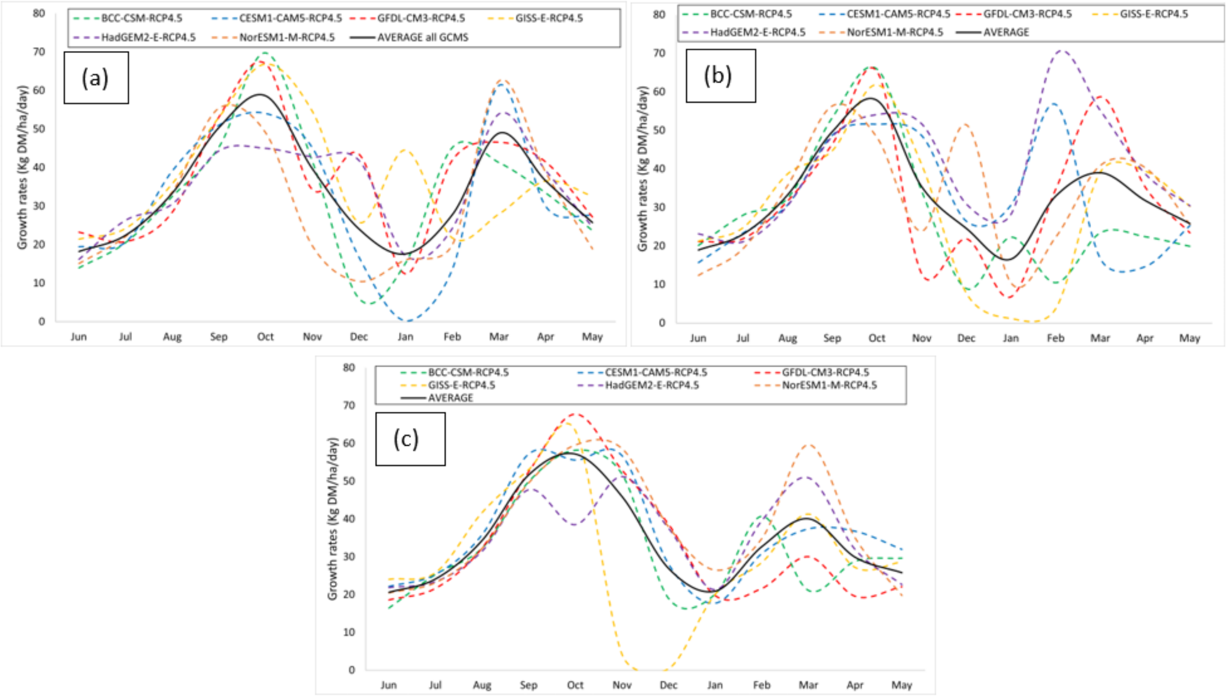


Figure 3.15 The kikuyu, ryegrass and white clover (KIK-RG-WC) pasture growth rates simulated with the climate data for the six GCMs at RCP4.5 for the production seasons (a) 2018-2019, (b) 2019-2020, (c) 2020-2021 production season.

3.4 Discussion

3.4.1 Growth rates and botanical composition

This Chapter indicated that kikuyu, Italian ryegrass and white clover may be a suitable pasture base for future dairy systems in the Northland region of New Zealand. Modelled future scenarios displayed elevated pasture growth rates in winter and early spring (June-September), and reduced growth from Mid-spring to summer (October-December) compared with the Current scenario. These trends were amplified as the severity of climate change increased from RCP4.5 to RCP8.5 with elevated CO_2 levels combined with higher temperatures causing greater growth in winter while the water deficit and higher temperatures depressed summer growth (Harrison *et al.* 2017; Harrison *et al*. 2016). This is consistent with modelling studies in New Zealand (Kalaugher *et al.* 2017; Dynes *et al.* 2010) and Australia (Harrison *et al.* 2017) that predicted a shift in pasture growth pattern with increased winter and early spring pasture growth coupled with increased summer-autumn shortfalls and shorter spring growing seasons.

RCP4.5

Future changes in the climate will influence pasture productivity. Due to the complex interactions between temperature, water availability and atmospheric CO_2 concentration, it is difficult to determine the direct effect of individual climate variables on pasture growth (Lee *et al.* 2013). In the RCP4.5 scenarios, there were no significant effects of climate projections on pasture growth rates.

This was likely due to the mild changes in climate variables projected for the RCP4.5 scenarios in the future compared with the RCP8.5 scenarios. Under RCP4.5 climate projections, the temperature is projected to increase by 0.50°C, total annual rainfall is projected to decrease by 1% and atmospheric CO_2 is projected to increase by ~80 ppm (Section 3.2.3) in the middle of the century compared with current levels.

Comparably, by the end of the century, the average air temperature is projected to increase by 0.70°C, total annual rainfall to decrease by 4% and CO_2 concentration is projected to increase by 100 ppm from current levels. The End-century RCP4.5 scenario had greater winter (10%) and summer (20%) pasture growth than the Current scenario. This was likely caused by the projected increase in rainfall from 1175 mm per year in 2075 to 1225 mm per year in 2100 (Figure 3.4). The 20% increase in summer pasture growth was due to the 14% increase in kikuyu presence in the mixed sward as this C_4 grass is more heat-tolerant and deep-rooted than Italian ryegrass, a C_3 grass (Bell *et al.* 2013). As the number of hot days (days > 25°C) is predicted to be 55 days per year by the end of the century (NIWA 2016), this likely caused an increase in competition from kikuyu, subsequently reducing ryegrass presence by 9%. During warmer months and as temperature increases, kikuyu's adventitious root structure can help extract soil nutrients and water (Bell *et al.* 2013; Cullen *et al.* 2009) and, therefore, maintain a higher growth compared to ryegrass. However, in winter kikuyu is temperature limited and the 10% increase in winter growth in the End-century scenario compared with the Current scenario was due to the 7% greater ryegrass presence in the sward. Ryegrass presence likely increased due to a combination of adequate water availability (1180 mm/year), optimal temperatures and the 100 ppm increase in CO_2 resulting in CO_2 fertilisation. Overall, these results are supported by Cullen *et al.* (2009) who concluded that pastoral systems based on C_3 and C_4 species mixtures are resilient to the projected increase in air temperature. This was due to the shortened C_3 species' growing season in summer and autumn being compensated by a longer C_4 growing season. Furthermore, Cullen *et al.* (2009) reported that under moderate climate projections, annual pasture production may increase in high rainfall areas, but may remain unchanged in lower rainfall temperate regions.

RCP8.5

Under the RCP8.5 climate projections, the change in pasture growth patterns was more extreme than under RCP4.5. In the Mid-century scenario, pasture growth increased by 13% in winter and decreased by 20% in summer compared with the Current scenario. In the middle of the century, average air temperature is projected to increase by 4%, total annual rainfall is projected to decline by 3% and atmospheric CO_2 is projected to increase by 25% compared with current levels.

In the End-century scenario, pasture growth increased by 28% in winter and 14% in early spring but decreased by 8% in summer (41% reduction in December month) compared with the Current scenario. This was a result of an increase in average air temperature by 16%, total annual rainfall declining by 10%, and CO_2 concentration increasing by 104% compared with levels. While a decline in annual rainfall and an increase in temperature favour C_4 species rather than C_3 species, the opposite is true for increased CO_2 levels (Bell *et al.* 2013; IPCC 2021). The 28% increase in pasture growth in winter and 14% in early spring were due to the 27% and 10% increase in ryegrass growth, respectively. These changes in seasonal pasture growth patterns likely reflected the warmer winter temperatures, adequate soil moisture and increase in CO_2 in the atmosphere, which result in an increase in C_3 growth through CO_2 fertilisation (Cullen *et al.* 2009). However, the spring growing season was shortened due to higher temperatures and reduced spring rainfall. The 8% decrease in summer growth was likely due to the increase in the number of hot days and reduced rainfall projected to occur in summer-autumn (Chappell 2016). Bell *et al.* (2013) reported that kikuyu is a useful source of green feed under high RCP climate projections during December–March as long with adequate rainfall. Additionally, with warming occurring uniformly across all seasons, cool temperature limitations may be overcome, and kikuyu growth would extend beyond summer months. This would likely result in increased kikuyu dominance in the sward and increased pasture management required to prohibit Italian ryegrass from being outcompeted as temperatures rise.

Overall, results from this study indicate that the current combination of a temperate and subtropical species may provide a suitable pasture base in the future. Cullen *et al.* (2009) reported that C_4 species are likely to increase production (at expense of pasture quality) with higher temperatures. Under climate change conditions, kikuyu and other species that form a component of New Zealand pastures in drier areas, such as Paspalum, may become more ecologically competitive than ryegrass, altering the balance of pasture composition (Kalaugher 2015).

3.4.2 Farm system changes

This study showed that changes in management strategies have the potential to compensate for the impacts of climate change on dairy farm performance. A range of strategies have previously been trialled on-farm and modelled (Table 2.2). In this study, conserving more pasture as silage during periods of surplus and shifting calving dates were used as management strategies to mitigate negative climate change impacts and to better match supply with demand. As a result, farm profit was increased in all future scenarios compared with the baseline.

Modelling by Kalaugher *et al.* (2017) showed that under a high emission scenario, a Northland dairy farm could increase operating profit by 150% by 2030 when surplus pasture was cut for silage and fed during feed deficits. Conserving pasture has a buffering effect on the feed supply profile, and acts to match supply with animal demand (Roche *et al.* 2017). However, several considerations of the practical application of this strategy need to be accounted for on a farm-by-farm basis. While the cost of silage making was included in the modelling of this Chapter, other factors such as availability of staff and machinery, labour inputs and slope suitability are key determinants of whether this option is practical for an individual farm (Kalaugher *et al.* 2017). Additionally, the different silage making technologies and how long it can be stored without degrading in quality should be considered. Overall, the tactical strategies were shown to mitigate the impacts of future climate variability in the Northland region of New Zealand. It should be recognised that each set of farm system changes were specific to the context of the case-study farm (NARF). Therefore, care must be taken when extrapolating these results.

3.4.3 Limitations

Limitations of modelling

As with all modelling studies, this research was limited by the capacity of the model and data inputs (Kalaugher 2015). In this thesis, monthly pasture growth rates were modelled to simulate gradual climate change effects on pasture growth rates. However, the frequency and intensity of extreme climate events may be more important to farmers than changes in average temperature and precipitation. Additionally, this study used the median as the statical measure of central tendency rather than the mean. This may have further reduced the pull of outliers and extreme weather parameters. This approach likely reduced the effect of extreme events such as heatwaves, droughts and flooding (Harrison *et al. 2016*). The IPCC has documented significant increases in global extreme climate events, regional trends towards more severe and longer droughts, and high certainty that heat waves will increase in frequency and magnitude during the 21st century (IPCC 2021). Therefore, further research should aim to quantify the impacts of extremes on farm systems.

There are also biophysical uncertainties, as DairyMod is unable to model a comprehensive range of dynamic biophysical processes such as pests and diseases, pasture species competition and heat stress in animals. For example, it has been reported that black beetle predation will increase in intensity and frequency in the upper North Island as the temperature rises (Bell *et al.* 2011; Mansfield *et al.* 2021). As black beetle is the second most economically damaging pasture pest in New Zealand due to its impact on pasture growth, future climate-related beetle life cycle changes should be investigated in Northland at the farm level. Additionally, the incursion of kikuyu that occurs over time on Northland farms (McCahon *et al.* 2021) was not simulated by DairyMod. It is likely that the annual cut of kikuyu in DairyMod reduces the reinvasion of kikuyu in ryegrass paddocks that is observed at NARF. Furthermore, the incursion of other grasses such as paspalum that may outcompete ryegrass is not simulated in the model. Additionally, DairyMod does not report the dead plant component in the sward. Therefore, the accuracy of the botanical composition simulated by DairyMod may be limited by the fact that the invasion of kikuyu and other weed grasses may outcompete ryegrass and there is a dead plant component in the sward.

Another key limitation of this modelling study was the case-study approach. This methodology limits the ability of results to be extrapolated to a national scale of the climate impacts on New Zealand dairy farms as modelling was completed for one farm. To build a more comprehensive understanding of climate change impacts on farm systems a broader approach that models multiple farms across the country is necessary.

Conclusions

This Chapter evaluated the impacts of future climate change on the performance of the kikuyu, ryegrass and white clover pasture in the middle and end of the 21st century. Changes in future pasture growth patterns were amplified with increasing RCP intensity and time period. Future pasture growth scenarios displayed elevated winter to mid-spring growth, enabled by warmer winter temperatures coupled with adequate rainfall and elevated CO_2 levels. During these months, ryegrass was the dominant species and likely increased due to CO_2 fertilisation and enhanced growing conditions. This illustrates that climate change may increase pasture growth earlier in the season, and kikuyu, ryegrass and white clover pasture mixtures may be a suitable pasture base in the future.

Utilisation of tactical farm management strategies (cutting surplus pasture for silage, feeding out in periods of shortage and earlier calving) were able to mitigate the changes in pasture growth patterns on farm performance. Tactical changes in farm management practices to synchronise the herd’s energy demand with pasture supply enabled milk production and profit per hectare to be maintained or increased in the future scenarios compared with the baseline. This implies that farmers need to be adaptive and flexible in response to climate change to ensure resilient pasture-based farm systems are maintained in the future.

It should be recognised that the frequency and intensity of extreme climate events such as droughts and flooding may have greater impacts on farm performance than the modelled gradual changes over time. In addition, climate projections are non-uniform across New Zealand due to the country’s diverse topography and localised climate. Therefore, care must be taken when extrapolating these results.

Chapter 4: Effect of future climate change on an alternative pasture type: tall fescue and white clover

4.1 Introduction

Compounding current and future pasture production issues are likely to increase across New Zealand as a result of climate change. There is growing interest by both researchers and farmers to identify pasture species that may be better suited to the future climate than those currently used (McCahon *et al.* 2021; Lee *et al.* 2013; Kalaugher *et al.* 2017). The value of pasture species and or mixes (e.g. annual ryegrass, kikuyu, white clover and tall fescue) may increase under climate change, as plant traits such as WUE, drought and heat tolerance, and response to elevated atmospheric CO_2 are likely to become more important.

This Chapter aimed to investigate the impacts of future climate change on an alternative pasture type, tall fescue and white clover (TF-WC), in the middle and end of the 21st century. This used the same modelling approach in Chapter 3 to evaluate the pasture growth rates of TF-WC in response to climate change projections. These were compared to the future monthly KIK-RG-WC pasture growth rates to evaluate the variation in growth patterns caused by morphological and physiological differences between the pasture species.

4.2 Method

4.2.1 Future scenario modelling

DairyMod setup

DairyMod was used to simulate future growth rates of tall fescue and white clover (TF-WC) mixed pasture in the middle and end of the century at RCP4.5 and RCP8.5. The DairyMod file outlined in section 3.2.5.1 was used but with TF-WC being the pasture base instead of KIK-RG-WC. Within the paddock module, the tall fescue and white clover default species were selected to comprise the pasture in all paddocks, with annual cutting practices that enabled the transition from kikuyu to ryegrass to be removed from the management module. However, the cutting policy was triggered during periods of pasture surplus, and the herbage mass of 3.4 t /ha was cut to 1.8 t/ha. Additionally, the rotational grazing remained the same with a pre-and post-grazing herbage mass of 2.5 t DM/ha and 1.8 t DM/ha, respectively.

Scenarios

The DairyMod file was run with the same climate data over the 10 production seasons (June 1st - May 31st) in three time periods as explained in Section 3.2.5.1 to simulate TF-WC growth rates for current

(Current; 2011-2021), middle (Mid-century; 2041-2051) and end (End-century; 2081-2091) of the century scenarios. In total, DairyMod was used to create 36 files (six GCMs x 2 RCPs x 3 time periods). The daily growth rates simulated for each scenario over the 10 production seasons were handled in R-Studio using the same processes as outlined in Section 3.2.5.

4.2.2 Statistics

The ANOVA outlined in Section 3.2.7 was used to evaluate the statistical differences between the simulated growth rates for the TF-WC mix in the Current, Mid-and End-century scenarios at RCP4.5 and RCP8.5. The model included GCM, RCP, Decade, Month and all their interactions as fixed effects, nested to reflect the hierarchical structure of the design. The Tukey post-hoc test was conducted to identify statistical difference between all possible pairs of groups. Significance was declared if $P \leq 0.05$.

Another ANOVA was run with all KIK-RG-WC and TF-WC simulated growth rates from DairyMod. In this statistical analysis, the model included GCM, RCP, Decade, Month as well as Species being TF-WC and KIK-RG-WC. This was used to evaluate the differences in the pasture growth rates between the two pasture types in response to climate change.

4.2.3 Modelling assumptions

In this Chapter, several modelling assumptions defined in Section 3.2.5 were used to simulate future pasture growth rates. Further modelling assumptions were made as the pasture type changed from KIK-RG-WC in Chapter 3 to TF-WC in Chapter 4.

Several pasture management practices were assumed from Chapter 3. In DairyMod, the fertiliser regime used for the KIK-RG-WC pasture (Table 3.8) was implemented for the TF-WC pasture. This was assumed as NARF did not have an established TF-WC fertiliser regime, and to limit changes in the farm system that may have impacted on growth rates. However, this likely did not optimise tall fescue growth as this fertiliser regime only applies N from April to December to limit excessive kikuyu growth over summer. Hendericks *et al.* (2016) reported that tall fescue pasture should be managed according to its specific growth habits to maximise productivity and persistence. Hume *et al.* (2009) reported that Northland tall fescue pastures should receive up to 30 kg N/ha after each grazing to encourage maximum pasture yield. Therefore, utilisation of a fertiliser regime based on tall fescue's phenology and morphology may improve the performance of the TF-WC pasture in the future more than presented in this study.

Grazing rotations were assumed to be the same for the TF-WC pasture as for KIK-RG-WC (Section 3.2.5). This was assumed as NARF did not have an established grazing regime for TF-WC pastures, and to limit farm system changes that may have an impact on future growth rates. However, a field study in the Manawatū reported that tall fescue pastures had the greatest growth and quality when pastures were rotationally grazed at the leaf stage of 2-3 leaves per tiller compared with the 4-4.5 leaf stage for kikuyu (Hendericks *et al.* 2016). Therefore, further modelling studies should utilise correct grazing management practices specific to the species' plant morphology to optimise productivity.

4.3 Results

4.3.1 Future scenario modelling

Results from the statistical analysis (Table A.8) showed that the three-way interaction between RCP, Decade and Month was significant (P<0.001). This indicates that climate projections impacted the monthly growth rates of the TF-WC pasture differently between scenarios. The TF-WC pasture growth patterns followed similar trends for all simulated scenarios with peak pasture growth occurring in October (60-68 kg DM/ha/day) except for the End-century RCP8.5 scenario (Figure 4.1). In the end-century RCP8.5 scenario, pasture growth peaked one month earlier, in October, with the highest growth rate of 73 kg DM/ha/day. Additionally, the pasture growth curve of the End-century RCP8.5 scenario shifted to the left with greater growth rates from June to October compared with the other scenarios. Figure 4.1 shows that monthly average growth rates were significantly different in all months except for May (P<0.05) between simulated scenarios.

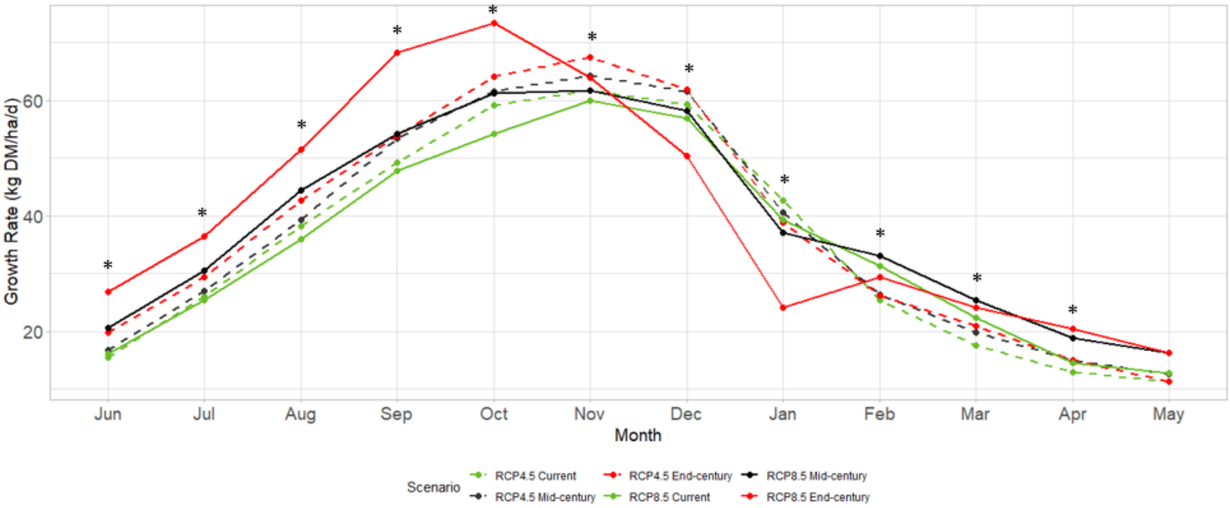


Figure 4.1 The monthly tall fescue and white clover (TF-WC) pasture growth rates simulated by DairyMod in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5.

Figure 4.2 shows that there were no differences in monthly TF-WC growth rate between decades under the RCP4.5 climate projections except for November, where the monthly growth rate was significantly higher (P<0.05) in the End-century scenario compared with the Current. However, under RCP8.5 climate projections, pasture growth rates were higher for the Mid-century scenario in August and October compared with the Current. In the End-century RCP8.5 scenario, monthly growth rates were greater than the Current scenario during the months from June to October (winter to mid-spring; P<0.005). Conversely, pasture growth declined (P<0.005) in December and January for the End-century decade compared with the Current RCP8.5 scenario. This indicates that monthly pasture growth rates were most impacted (increase and decrease) under RCP8.5 projections in the End-century scenario.

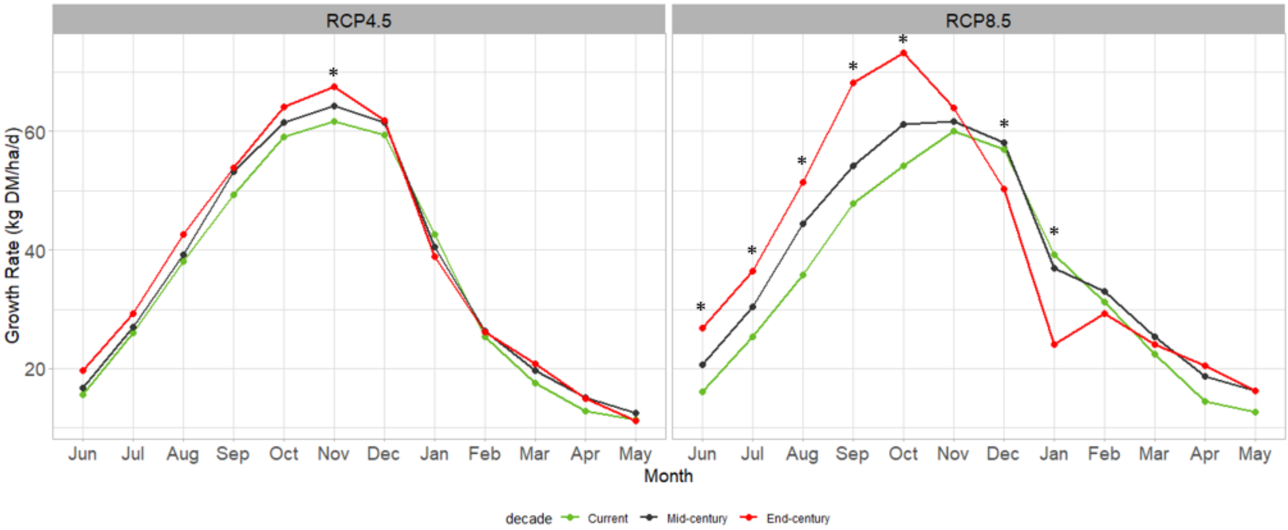


Figure 4.2 The monthly tall fescue and white clover (TF-WC) pasture growth rates simulated by DairyMod in the Current, Mid-century and End-century scenarios for each Representative Concentration Pathway (RCP) 4.5 and 8.5.

Figure 4.3 shows that there were no significant differences in monthly growth rates between RCP4.5 and RCP8.5 climate projections for the Current and Mid-century scenarios. In the End-century scenario, monthly pasture growth rates were greater under RCP8.5 scenario from June to October, and lower in December and January than under RCP4.5 projections. To illustrate the spread in simulated growth rates over time, Figure 4.3 shows the 25th and 75th percentiles of modelled monthly data. In the End-century decade, RCP8.5 pasture growth curve shifted to the left compared with RCP4.5, indicating a shift in pasture growth pattern to earlier in the season.

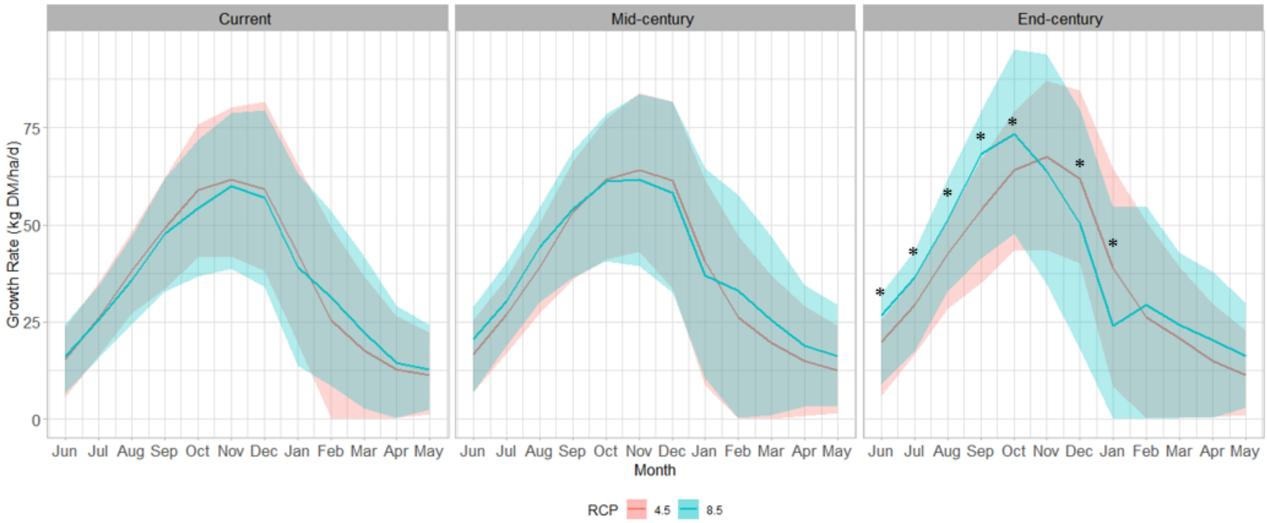


Figure 4.3 The monthly tall fescue and white clover (TF-WC) pasture growth rates simulated by DairyMod in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5. The shaded area represents the 25th and 75th percentiles of the data range.

The relative changes in monthly TF-WC pasture growth rates between Current, Mid-century and End-century scenarios are shown in Table 4.1. Compared with the Current scenario, monthly growth rates increased in all months except for January and February (where pasture growth declined) in the Mid-century under RCP4.5 and RCP8.5. In the End-century RCP4.5 scenario, pasture growth rates increased in all months except for January, February and May where the pasture growth declined relative to the Current. Changes in monthly pasture growth were most extreme for the End-century RCP8.5 scenario relative to the Current. This scenario had the greatest increase in pasture growth from June to October compared with the other scenarios, and a 60% increase in June growth compared with the Current. Conversely, this scenario had the greatest reduction in growth rates from December to March, with a 67% reduction in January growth.

Seasonal TF-WC pasture growth increased in winter, spring and autumn but declined in summer (Table 4.2). In Mid-century, growth rate increased by 5% and 22% in winter, 5% and 10% in spring, 31% and 23% in autumn, and declined by -3% and -5% in summer under RCP4.5 and RCP8.5, respectively, compared with the Current scenario. In End-century, pasture growth rates increased by 15% and 48% in winter, 10% and 27% in spring, 12% and 17% in autumn, and declined by -2% and -36% in summer under RCP4.5 and RCP8.5, respectively, compared with the Current scenario.

Table 4.1 **The monthly relative change in growth rates simulated by DairyMod for the tall fescue and white clover (TF-WC) pasture between the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and RCP8.5.**

	Relative change (%)			
	Mid-century		End-century	
Month	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
June	5	26	19	60
July	6	15	15	40
August	4	24	11	44
September	10	12	12	37
October	3	14	8	35
November	4	5	10	9
December	1	4	5	-13
January	-9	-8	-12	-67
February	-1	-10	0	-27
March	44	6	22	-4
April	33	38	19	41
May	14	25	-4	15

Table 4.2 **The seasonal relative change in growth rates simulated by DairyMod for the tall fescue and white clover (TF-WC) pasture in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) 4.5 and RCP8.5. Winter (June-August), spring (September-November), summer (December-January) and autumn (February-May).**

	Mid-century		End-century	
Season	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Winter	5	22	15	48
Spring	5	10	10	27
Summer	-3	-5	-2	-36
Autumn	31	23	12	17

Botanical composition

The seasonal botanical composition of the TF-WC pasture simulated by DairyMod is shown in Table 4.3. Under the RCP4.5 climate projections, tall fescue was the dominant species across all seasons and scenarios. Compared with the Current scenario, under RCP4.5 climate projections, tall fescue presence declined in winter (-10%, -7%), spring (-9%, -5%), summer (-5%, -3%) and autumn (-11%, -7%) for the Mid-century and End-century scenarios, respectively. The Mid-century RCP4.5 scenario displayed greater reductions in tall fescue presence than the End-century scenario.

Under RCP8.5 climate projections, tall fescue presence in the sward was lower for all scenarios compared with those under RCP4.5. Compared with the Current scenario, under RCP8.5 projections, tall fescue presence declined in winter (-6%, -37%), spring (-7%, -32%), summer (-7%, -15%) and autumn (-8%, -37%) for the Mid-century and End-century scenarios, respectively. Tall fescue content was lowest in all seasons for the End-century scenarios and white clover content increased by 167%

in winter, 233% in spring, 175% in summer and 229% in autumn compared with the Current. This highlights that white clover may be more competitive in the sward in response to climate change. Overall, the changes in botanical composition were more extreme for the RCP8.5 scenarios than for the RCP4.5 scenarios.

Table 4.3 The botanical composition of the simulated tall fescue and white clover (TF-WC) pasture in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP) RCP4.5 and RCP8.5.

	RCP4.5		**RCP8.5**	
	Tall fescue (%)	**White clover (%)**	**Tall fescue (%)**	**White clover (%)**
Current				
Winter	92	8	82	18
Spring	95	5	88	12
Summer	94	6	92	8
Autumn	92	8	86	14
Mid-century				
Winter	83	17	77	23
Spring	86	14	82	18
Summer	89	11	86	14
Autumn	81	19	79	21
End-century				
Winter	86	14	52	48
Spring	90	10	60	40
Summer	91	9	78	22
Autumn	86	14	54	46

4.3.2 Sward comparison

Results from the statistical analysis (Table 4.4) comparing pasture types (KIK-RG-WC vs TF-WC) showed that the three-way interactions between Species, RCP and Month, and Species, Decade and Month were highly significant (P<.0001). This indicates that the two pasture types (KIK-RG-WC and TF-WC) exhibited different pasture growth responses to climate projections over time. Under the Current scenario, the exhibited pasture growth pattern was different between pasture types (Figure 4.4). In addition, the changes in the future pasture growth patterns in response to climate change projections differed between pasture types. However, for both pasture types, pasture growth rates tended to increase in winter-to mid-spring for the End-century RCP8.5 scenario compared with the Current RCP8.5 scenario.

Table 4.4 **The effect of the factors: Species, Representative Concentration Pathway (RCP), Global circulation model (GCM), Decade and Month on simulated pasture growth rates for the tall fescue and white clover (TF-WC), and kikuyu, ryegrass and white clover (KIK-RG-WC) pasture types.**

Source	**P value**
Species*Decade	0.0012***
Species*Month	<.0001***
Species*RCP*Month	0.0017***
Species*GCM*Month	0.0319*
Species*Decade*Month	<.0001***

* P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001

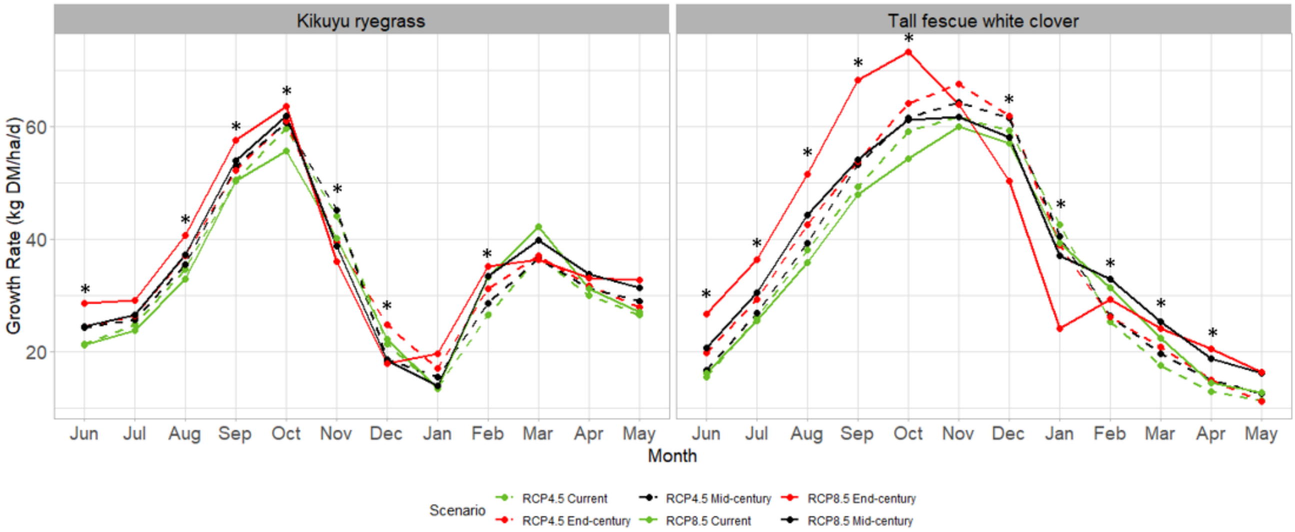


Figure 4.4 **The monthly pasture growth rates simulated by DairyMod for the kikuyu ryegrass (KIK-RG-WC) and tall fescue white clover (TF-WC) pasture in the Current, Mid-century and End-century scenarios at Representative Concentration Pathway (RCP; 4.5 and 8.5).**

4.4 Discussion

4.4.1 Growth rates and botanical composition

This Chapter evaluated the climate change impacts on TF-WC pasture growth rates. Modelled future scenarios showed that pasture growth rates were impacted by climate change projections every month except for May compared with the Current scenario (Figure 4.1). TF-WC pastures displayed elevated monthly growth rates in winter and early spring compared with the Current scenario. This trend was amplified as the severity of climate change increased from RCP4.5 to RCP8.5, likely due to the elevated CO_2 levels and warmer winter temperatures causing CO_2 fertilisation and favourable growing conditions (Harrison *et al.* 2017; Harrison *et al*. 2016). This is consistent with modelling studies in New Zealand (Kalaugher *et al.* 2017; Dynes *et al.* 2010) that reported increased winter and early spring pasture growth for temperate species.

RCP4.5

In the RCP4.5 Mid-century scenario, there were no significant effects of climate projections on monthly TF-WC pasture growth rates. This is likely due to the mild changes in climate variables projected in the middle of the century as a result of RCP4.5 being an 'intermediate stabilisation' pathway (Chappell 2016). Compared with current levels, in the middle of the century, there is a 0.50°C projected increase in air temperature, a 1% increase in total annual rainfall and ~80 ppm increase in atmospheric CO_2 concentration (Section 3.2.3). However, in the End-century scenario, monthly pasture growth was significantly higher in November than the Current scenario (Figure 4.2). In this scenario, tall fescue was the dominant species across all seasons with spring (90%) and summer (91%) having the highest tall fescue proportions in the sward. Pasture growth likely increased in November due to a combination of optimal temperatures and the 100 ppm increase in atmospheric CO_2 compared with current levels, causing CO_2 fertilisation (Cullen *et al.* 2009; Harrison *et al*. 2016). Additionally, physiological characteristics such as tall fescue's ability to extract water from 100 cm in the soil profile (Minneé *et al.* 2011) and ability to grow at temperatures up to 35°C (Durand *et al.* 1999) likely enabled the grass to increase its November growth compared with the Current scenario.

RCP8.5

Future changes in temperature, water availability and atmospheric CO_2 concentration may influence pasture productivity (Harrison *et al.* 2017). These changes are likely to be most severe under RCP8.5 climate projections as this pathway has the greatest change in climate variables over time (Chappell 2016). In the Mid-century scenario, monthly pasture growth was higher in August and October than the Current scenario (Figure 4.1) likely due to the projected ~25% increase in atmospheric CO_2 levels (Figure 3.6).

In the End-century scenario, the pasture growth curve was shifted to the left, with peak growth occurring in October compared with November in the Current RCP8.5 scenario. Overall, monthly pasture growth rates increased from June to October compared with the Current (Figure 4.1). This increase in growth from winter to mid-spring was likely due to enhanced growing conditions (Harrison *et al.* 2016; Dynes *et al.* 2010). Climate projections for NARF showed that the average annual air temperature is likely to increase by 16% and rainfall is to decrease by 5% in winter and 15% in spring (Section 3.2.3). Despite the reduction in winter and spring rainfall, CO_2 levels were estimated to increase by 104% compared with current levels, which likely increased carbon assimilation through the Calvin cycle, increasing spring biomass production (Cullen *et al.* 2009). Conversely, the simulated pasture growth decline in December and January was likely due to the projected reduction in summer rainfall combined with the increase in number of hot days (days >25°C) from 25 to 99 days per year, with most occurring in summer (Chappell 2016).

Similar to the botanical composition of the RCP4.5 scenarios, the greatest proportion of tall fescue in the sward was shown in spring (82%, 60%) and summer (86%, 78%) for the RCP8.5 Mid- and End-century scenarios, respectively. However, the proportion of tall fescue was lowest and white clover was highest in the End-century RCP8.5 scenario compared with all other scenarios. This suggests that white clover is more competitive or less affected under the RCP8.5 climate projections and towards the end of the century compared with tall fescue. Allard *et al.* (2003) and Hebeisen *et al.* (1997) reported that the proportion of legumes in the sward, such as white clover, may increase as they positively respond to rising CO_2 levels. However, this is dependent on the strength of the competition from other pasture species (Lee *et al*. 2013).

4.4.2 Growth rates between pasture types

In comparison to the KIK-RG-WC pasture (Chapter 3), the TF-WC pasture exhibited different growth rates in response to climate change over time, mainly due to differences in the morphological and physiological characteristics of the plant species between the two pasture types (Lee *et al*. 2013). This indicates that climate change will impact pasture types differently as each plant species has unique traits and optimum growth thresholds (Kalaugher 2015).

However, in response to climate change projections, the KIK-RG-WC and TF-WC pastures followed similar trends in growth for winter and spring. During these months, annual ryegrass and tall fescue were the dominant species in the KIK-RG-WC and TF-WC swards, respectively. As these species are temperate C_3 grasses, growth rates likely increased from the Current to the End-century RCP8.5 scenarios due to warmer winter temperatures and elevated CO_2 levels (Cullen *et al.* 2009). Similarly, in Tasmania, the southernmost state of Australia, DairyMod modelling predicted an earlier start to the C_3 growing season and greater production in winter to mid-spring (Holz *et al.* 2010). For C_3 plants, a greater abundance of CO_2 in the atmosphere results in an increased rate of CO_2 diffusion into plant cells, increasing carboxylation, carbon assimilation and biomass production (Casella & Soussana 1997; Lee *et al*. 2013).

Trends in pasture growth patterns for summer and autumn differed between pasture types. For the TF-WC pasture, early summer (December and January) growth rates declined in the End-century RCP8.5 scenario compared with the Current. In all TF-WC scenarios, tall fescue was the dominant species in summer and autumn. The decline in the growth of tall fescue was due to the dry conditions, low water availability and sub-optimal temperatures in December and January for the End-century RCP8.5 scenario (Holz *et al.* 2010). Lee *et al.* (2013) and Minneé *et al. (*2011) reported a reduction in leaf size, tiller emergence and photosynthesis when temperature and rainfall were outside of tall fescue's optimum threshold and near the extreme end of its functional range. These results are supported by Cullen *et al.* (2009) who reported a reduction in C_3 growth in summer due to increased temperatures and low rainfall projections. However, in a three-year field study in Australia, Callow *et al.* (2003) reported that tall fescue was the superior temperate species to compete with C_4 grasses in a subtropical environment. Therefore, tall fescue may be a suitable pasture grass species for the Northland region of New Zealand.

This reduction in summer growth was not observed for the KIK-RG-WC pasture as the C_4 grass, kikuyu, was dominant in the sward and exhibits greater heat and drought tolerance than other temperate species such as tall fescue (Fulkerson 2007). As outlined in Section 2.5.1, kikuyu is a deep rooting species with several drought avoidance mechanisms and an optimum temperature of 26°C (Milne 2011; Durand *et al.* 1999). This superior tolerance of summer-autumn conditions for kikuyu is shown in Figure 4.4 where monthly KIK-RG-WC pasture growth during the period from December to May were similar between End-century RCP8.5 and Current RCP8.5 scenario. This illustrates the differences in the ability of temperate and subtropical species to cope with extreme weather events (Lee *et al*. 2013). Cullen *et al.* (2009) reported that the C_4 growing season was extended under the climate change scenarios, with a reduction in the C_3 growing season, leading to a change in species composition. As C_3 species are expected to have higher forage quality than C_4 species at elevated CO_2 concentrations, this shift towards C_4 dominance could reduce forage quality (Cullen *et al*. 2009; Dynes *et al.* 2010). Therefore, mixtures of C_3 species could be the most suitable pasture type for the future.

4.4.3 Modelling limitations

The modelling limitations outlined in Section 3.4.3 apply to this Chapter. In addition, there are several modelling limitations associated with changing the pasture species and their mixtures in this Chapter. The key limitations include DairyMod lacking the capability to model biophysical processes that are important in the analysis of tall fescue performance.

Changing the pasture species on-farm requires consideration of growth patterns and their management, as successful management practices can vary between species (Lee *et al*. 2013; Kalaugher 2015). For example, tall fescue requires careful management during establishment, and this can be slower than other grasses such as ryegrass (Lee *et al.* 2013; Kalaugher. 2015). It is slower to establish than ryegrass due to its slow mobilisation of seed reserves and slow seedling growth (Wilson 2017). Tharmaraj *et al.* (2008) reported that slow establishment can result in low pasture DM during its first year, and pasture yield during the successive years will greatly depend on pasture management. Rollo *et al.* (1998) stated that rhizome development didn’t begin until 2 years after autumn sowing of tall fescue and can be reduced by poor grazing management. Therefore, the first grazing should occur when plants are 15-20 cm in height and should not be grazed below 7 cm. However, grazing of tall fescue should occur frequently in spring to prevent excessive seedhead development and stemmy pastures that lower its feed quality. However, these biophysical interactions between establishment, pasture management and production are not reflected in DairyMod. Further research is required to understand the optimal grazing management of tall fescue pastures and to build the capacity to model the impacts of management on pasture productivity effectively.

Farmers in the Northland region of New Zealand using tall fescue rely on endophyte (MaxP) protection to reduce damage from insect pests such as Black Beetle (Hume *et al.* 2009). DairyMod is unable to represent the endophyte status of pasture species, including tall fescue. However, while DairyMod does not account for biotic limitations to plant growth such as insect predation, it can be assumed that the simulations represent endophyte positive effect on pastures (Prembleton *et al.* 2021).

It should be recognised that this modelling study was undertaken for the Northland region of New Zealand. This was the only quantitative modelling that could have been completed within the time frame stipulated for this thesis. However, the used modelling approach could be extended readily to other regions where farm data are available, and to investigate other alternative pasture species such as cocksfoot.

Conclusions

This Chapter evaluated the impacts of future climate change on the performance of the TF-WC pasture in the middle and end of the 21st century. The modelled future pasture growth rate scenarios displayed elevated monthly growth rates in winter and early spring compared with the Current. This trend was amplified as the severity of climate change increased from RCP4.5 to RCP8.5, likely due to the elevated CO_2 levels and warmer winter temperatures causing CO_2 fertilisation and favourable growing conditions for the pasture. However, pasture growth declined in early summer for the End-century RCP8.5 scenario compared with the Current as a result of increasing summer-dry conditions. Therefore, future farm systems utilising this pasture should consider utilising strategies that aim to match animal demand with pasture supply.

Monthly TF-WC pasture growth rates and patterns differed compared with the KIK-RG-WC pasture modelled in Chapter 3. This reflected the different species used in each of the pastures, and their morphological and physiological characteristics. Both pasture types displayed increased growth rates in winter to mid-spring caused by climate projections as C_3 grasses were the dominant species in the sward. However, the KIK-RG-WC pasture maintained the same future growth rates over summer and autumn compared with the Current as the subtropical species, kikuyu, was dominant. This highlights the ability of subtropical (kikuyu) species to cope with summer-dry conditions compared with temperate (tall fescue) species.

Chapter 5: Effect of future climate change on the performance of a tall fescue and white clover-based dairy system

5.1 Introduction

Alternative pasture species have been suggested as a viable adaptation option to mitigate the impacts of climate change on the performance of pasture-based dairy farms (Lee *et al.* 2013). Successful utilisation of different pasture species requires changes in farm management practices to maximise productivity and ensure that animal demand is matched with pasture supply (Jarman 2020). The farm system study established at NARF in 2021 (outlined in Section 3.3.1) aims to evaluate the performance of alternative pasture species to the common kikuyu-ryegrass pasture mix used by dairy farms in the Northland region of New Zealand. To ensure future resilience of Northland dairy farms, the NARF field study was complemented with a modelling exercise evaluating the impact of future climate change on dairy farm systems operating with alternative pasture species.

This Chapter aimed to investigate the effects of climate change on the performance of a farm system operating with TF-WC pasture in the middle and end of the 21st century compared with the baseline (KIK-RG-WC farm explained in Section 3.3.1). In this Chapter, the use of an alternative pasture type was the main adaptation strategy evaluated, however, other farm system changes were also implemented to match the dairy herd's energy demand with pasture supply patterns. The same case-study approach explained in Chapter 3 was used to evaluate future milk production and financial profitability of a dairy system operating with TF-WC pasture. The simulated TF-WC pasture growth rates used in the farm performance modelling are outlined in Chapter 4.

5.2 Methods

5.2.1 Farm performance modelling

Farm performance modelling in Farmax followed the same process outlined in Section 3.2.5. To evaluate the effect of future climate change on dairy farm performance, the simulated TF-WC growth rates outlined in Chapter 4 were entered into the baseline Farmax file (KIK-RG-WC-based farm; Section 3.2.4) to create four future scenarios (Mid-century and End-century at RCP4.5 and RCP8.5). This enabled the changes in pasture supply associated with TF-WC on the feed availability and overall farm feasibility of the modelled scenarios to be evaluated assuming that the management practices remained the same as the baseline.

Farm system changes

In this Chapter, utilising an alternative pasture type (TF-WC) was the main adaptation strategy tested. However, further tactical and strategic management strategies were required to make each Farmax scenario feasible. Management strategies for each scenario were evaluated on an individual basis based on the changes in the feed supply and the feasibility of the modelled farm. A range of strategies (described in the literature review) were used to manage the change in pasture growth patterns and general farm feasibility. These strategies included practices of conserving pasture during periods of pasture surplus, feeding home-grown or imported supplement during periods of feed deficits, changing calving dates and reducing stocking rate. Farm scenarios were ranked and compared by profit expressed as earnings before tax.

5.2.2 Modelling assumptions

In this Chapter, modelling assumptions outlined in Sections 3.2.6 and 4.2.3 were used to model future farm performance in Farmax. Further modelling assumptions were made as the pasture type changed from KIK-RG-WC in Chapter 3 to TF-WC in Chapter 4.

The effect of climate change on pasture quality was not simulated and the ME values used in Chapter 3 were also used for the TF-WC pasture. Hence, the Farmax modelling did not account for differences in ME between the mixtures. Tall fescue is a C_3 species with an average ME value of ~11.7 MJ ME/kg DM (Hendricks *et al*. 2016) which is higher than the pasture quality values used (Table 3.13). Cullen et al. (2009) reported that C_3 species, such as tall fescue, are expected to have higher forage quality than C_4 species under elevated CO_2 concentrations. This suggests that pasture quality in the future scenarios may be better than the values used in the TF-WC scenarios, with the potential to increase milk yield and profit. Kalaugher *et al.* (2017) also used perennial ryegrass quality data while modelling tall fescue in response to climate change projections.

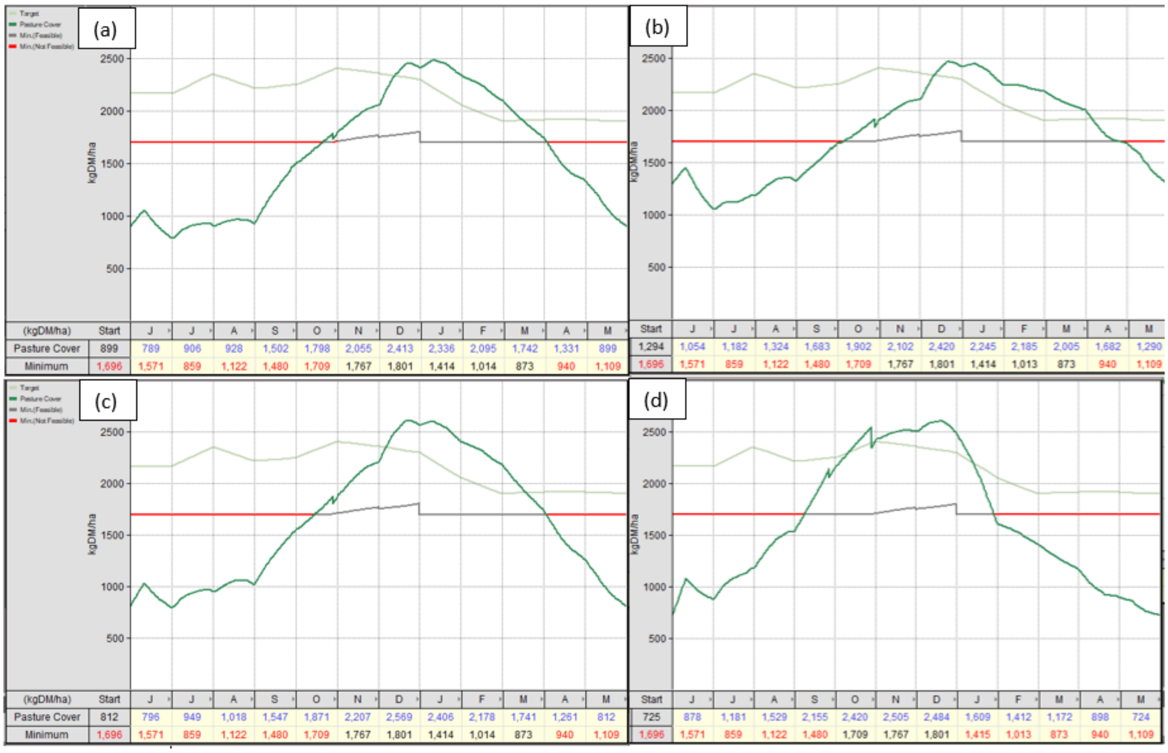
Scaling of future simulated KIK-RG-WC growth rates was used in Chapter 3 to relate the simulated changes in pasture growth caused by climate change projections to actual growth rates measured on the baseline farm. However, there were no observed pasture growth data for TF-WC pastures at NARF, so the simulated TF-WC pasture growth rates in this Chapter were not scaled. Further research using observed tall fescue growth rates from NARF is required for a better comparison between kikuyu-and tall fescue-based dairy systems. However, pasture growth curves of the tall fescue in the middle and end of the century (Figure 4.1) were comparable to those modelled by Kalaugher *et al.* (2017) for the Northland region.

5.3 Results

5.3.1 Future scenario modelling

Farm performance modelling

Pasture cover was modelled in Farmax for the four future scenarios based on their respective simulated TF-WC growth rates. With the same management assumptions as the baseline, the change in TF-WC pasture growth patterns caused all future scenarios to become unfeasible (Figure 5.1). Figures 5.1a, 5.1b and 5.1c show that the modelled farm systems were generally unfeasible (average pasture mass DM per ha (dark green line) is greater than the minimum feasible pasture mass (red line) in winter, spring and autumn. The End-century RCP8.5 scenario (Figure 5.1d) was unfeasible in all months except from September to January. Overall, the modelled TF-WC farm systems generally had lower pasture cover than the baseline (light green line; KIK-RG-WC-based farm in Section 3.3.1) farm in winter, spring and autumn. This indicates that with the same management practices as the baseline farm, the pasture cover of all future TF-WC scenarios tended to be lower than the baseline across the production season except for summer. As the modelled farm systems were unfeasible in Farmax (Figure 5.1), this highlighted the need to change management practices in response to the TF-WC pasture growth patterns (Figure 4.1) to optimise performance of the dairy system.



(a)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	899	789	906	928	1,502	1,798	2,055	2,413	2,336	2,095	1,742	1,331	899
Minimum	1,696	1,571	859	1,122	1,480	1,709	1,767	1,801	1,414	1,014	873	940	1,109

(b)

Start	J	J	A	S	O	N	D	J	F	M	A	M
1,294	1,054	1,182	1,324	1,683	1,902	2,102	2,420	2,245	2,185	2,005	1,682	1,290
1,696	1,571	859	1,122	1,480	1,709	1,767	1,801	1,414	1,013	873	940	1,109

(c)

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	812	796	949	1,018	1,547	1,871	2,207	2,569	2,406	2,178	1,741	1,261	812
Minimum	1,696	1,571	859	1,122	1,480	1,709	1,767	1,801	1,414	1,014	873	940	1,109

(d)

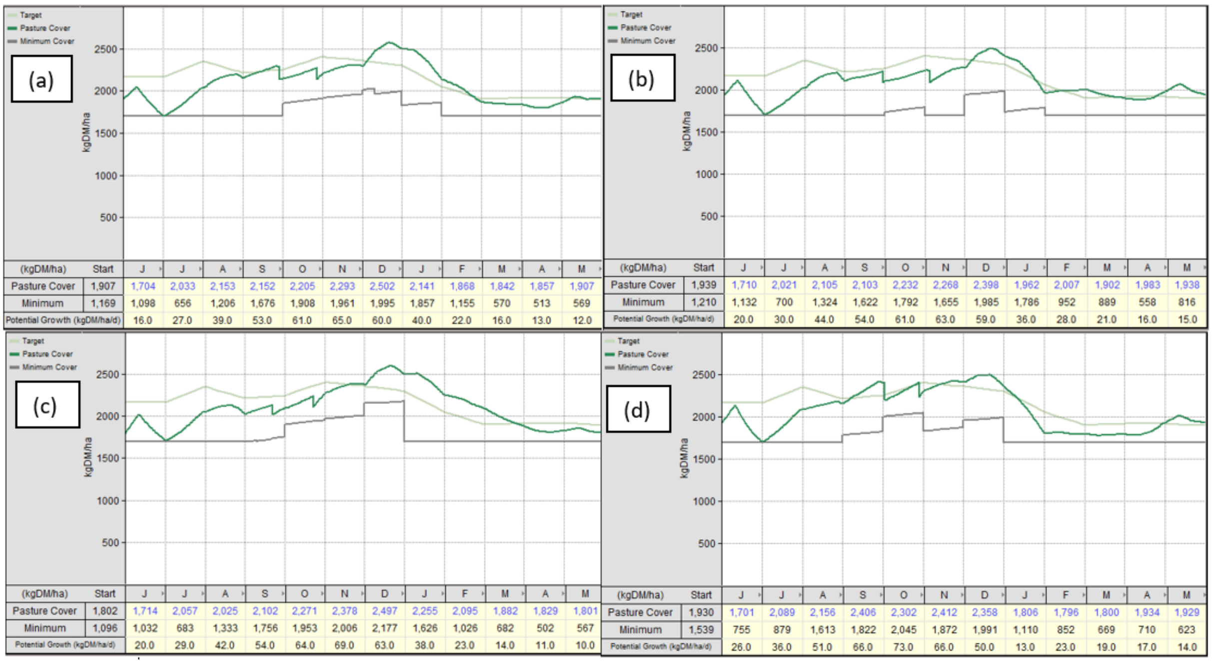
Start	J	J	A	S	O	N	D	J	F	M	A	M
725	878	1,181	1,529	2,155	2,420	2,505	2,484	1,609	1,412	1,172	898	724
1,696	1,571	859	1,122	1,480	1,709	1,767	1,801	1,415	1,013	873	940	1,109

Figure 5.1 The pasture cover modelled in Farmax with the tall fescue and white clover (TF-WC) pasture growth rates for Mid-century at RCP4.5 (a) and RCP8.5 (b), End-century at RCP4.5 (c) and RCP8.5 (d). Average pasture cover (kg DM/ha; dark green line), minimum pasture cover (kg DM/ha; grey line), baseline pasture cover (kg DM/ha; light green line)

and not feasible when average cover is lower than minimum pasture cover (kg DM/ha; red line).

Farm system changes

System changes were made in Farmax to respond to changes in the TF-WC pasture growth patterns (Figure 4.1) and make the farm systems feasible. A summary of the system changes utilised is shown in Table 5.1. All scenarios were evaluated on an individual basis with the aim to match milk production and optimise farm profitability compared with the baseline. The resulting average pasture covers are shown in Figure 5.2.



(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,907	1,704	2,033	2,153	2,152	2,205	2,293	2,502	2,141	1,868	1,842	1,857	1,907
Minimum	1,169	1,098	656	1,206	1,676	1,908	1,961	1,995	1,857	1,155	570	513	569
Potential Growth (kgDM/ha/d)		16.0	27.0	39.0	53.0	61.0	65.0	60.0	40.0	22.0	16.0	13.0	12.0

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,939	1,710	2,021	2,105	2,103	2,232	2,268	2,398	1,962	2,007	1,902	1,983	1,938
Minimum	1,210	1,132	700	1,324	1,622	1,792	1,655	1,985	1,786	952	889	558	816
Potential Growth (kgDM/ha/d)		20.0	30.0	44.0	54.0	61.0	63.0	59.0	36.0	28.0	21.0	16.0	15.0

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,802	1,714	2,057	2,025	2,102	2,271	2,378	2,497	2,255	2,095	1,882	1,829	1,801
Minimum	1,096	1,032	683	1,333	1,756	1,953	2,006	2,177	1,626	1,026	682	502	567
Potential Growth (kgDM/ha/d)		20.0	29.0	42.0	54.0	64.0	69.0	63.0	38.0	23.0	14.0	11.0	10.0

(kgDM/ha)	Start	J	J	A	S	O	N	D	J	F	M	A	M
Pasture Cover	1,930	1,701	2,089	2,156	2,406	2,302	2,412	2,358	1,806	1,796	1,800	1,934	1,929
Minimum	1,539	755	879	1,613	1,822	2,045	1,872	1,991	1,110	852	669	710	623
Potential Growth (kgDM/ha/d)		26.0	36.0	51.0	66.0	73.0	66.0	50.0	13.0	23.0	19.0	17.0	14.0

Figure 5.2 The pasture cover modelled in Farmax with the tall fescue and white clover (TF-WC) pasture growth rates with management changes for Mid-century at RCP4.5 (a) and RCP8.5 (b), End-century at RCP4.5 (c) and RCP8.5 (d). Average pasture cover (kg DM/ha; dark green line), minimum pasture cover (kg DM/ha; grey line), baseline pasture cover (kg DM/ha; light green line) and not feasible when average cover is lower than minimum pasture cover (kg DM/ha; red line).

Mid-century RCP4.5

In this scenario, animal demand was altered in response to the changed pasture growth curve compared with the KIK-RG-WC baseline. Pasture cover was the lowest from spring to summer (June-December) in Mid-century RCP4.5 compared with baseline and other scenarios (Figure 5.2). To reflect the low pasture supply, animal demand was reduced by reducing stocking rate from 3.1 (baseline) to 2.9 cows/ha (Table 5.1). As the number of cows declined, the amount of pasture available per cow increased, resulting in 5% less total supplement fed compared to baseline.

Mid-century RCP8.5

In this scenario, peak milk production occurred from September to December during peak pasture supply (Figure 4.1). Stocking rate was maintained at 3.1 cows/ha, however, dry-off started 6 days earlier than the baseline to respond to the low pasture supply in autumn (Table 5.1). To maintain an adequate feed supply throughout the year, the total amount of supplement fed remained the same as the baseline (97 t DM).

End-century RCP4.5

To match pasture supply with animal demand in this scenario, the planned start of calving was shifted one week earlier (from July 7th to July 1st) and the stocking rate was reduced (3.1 to 2.9 cows/ha) compared with the baseline. These changes were made in response to the lower pasture cover from spring to summer (June-December) compared with the RCP8.5 scenarios and the baseline (Figure 5.2). As this scenario had the lowest growth rates in autumn compared with all other scenarios (Figure 4.1), dry-off took place on May 6th, reducing the number of days in milk by 6 days compared with the baseline.

End-century RCP8.5

Due to the earlier peak in pasture growth compared with other scenarios and the baseline (Figure 4.1), the calving date in this scenario was shifted to June 1st. Pasture growth was greater from mid-winter to late spring (July – November) than the baseline, resulting in greater pasture supply over these months, reducing the total supplement fed by 6% compared with the baseline. However, pasture cover was lowest from December to May compared with all other scenarios and the baseline (Figure 5.2). As a result, dry-off occurred on April 6th.

Table 5.1 Summary of the farm system changes used in the Mid-century and End-century tall fescue and white clover (TF-WC) scenarios farm at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		End-century	
Farm system changes	**Baseline**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Supplement					
Area conserved for silage (ha)	9.7	9.4	10.4	9.9	10.1
Pasture silage (t DM)	24	24	27	26	26
PKE (t DM)	73	68	70	68	65
Total supplement (t DM)	97	92	97	94	91
Dates					
Planned start of calving	July 7th	July 7th	July 7th	July 1st	June 1st
Dry-off date	May 14th	May 14th	May 8th	May 6th	April 6th
Days in milk	266	266	260	260	266
Stocking rate (cows/ha)	3.1	2.9	3.1	2.9	3.1

Physical summary and profit

The physical farm summary of the TF-WC farms modelled in Farmax is shown in Table 5.2. As the number of cows per ha was lower in the RCP4.5 scenarios, more pasture was available per cow, increasing MS production from 389 kg/cow in the baseline to 414 kg/cow in both RCP4.5 scenarios. This increase in per cow production in the RCP4.5 scenarios compensated for the lower stocking rate and enabled the per ha MS production to be maintained at a similar level to baseline (average 1207 vs 1199 kg MS/ha for the baseline and RCP4.5 scenarios, respectively). The RCP4.5 scenarios had 8% and 6% less total feed offered per ha in the Mid- and End-century scenarios, respectively as stocking rate was lowered. The total GHG emissions per ha were 5% and 4% less in the Mid- and End-century scenarios than the baseline due to the lower cow numbers and less PKE fed.

In the RCP8.5 scenarios, stocking rate and MS production per cow were maintained at 3.1 cows/ha and 389 kg MS/cow, respectively as in the baseline. MS production per ha increased in the End-century RCP8.5 scenario (1,222 kg/ha) compared to baseline (1,207 kg/ha) and other scenarios. This was due to the cows consuming a greater amount of pasture during peak pasture supply, maximising milk production before early dry-off. Total GHG emissions per ha were 10% and 13% less than the baseline for the Mid- and End-century RCP8.5 scenarios, respectively.

Table 5.2 The physical summary of each future scenario in the Mid-century and End-century tall fescue and white clover (TF-WC) scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		**End-century**	
	Baseline	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Farm					
Area (ha)	28	28	28	28	28
Stocking rate (cows/ha)	3.1	2.9	3.1	2.9	3.1
N use (kg N/ha)	166	166	166	166	166
Potential growth (t DM/ha)	14.9	12.9	13.6	13.3	13.8
Production					
Milksolid per cow (MS/cow)	389	414	389	414	389
Milksolid per ha (MS/ha)	1,207	1,199	1,208	1,198	1,221
Total milksolids (kg)	33,800	33,561	33,818	33,555	34,192
Liveweight (kg/ha)	1,389	1,307	1,393	1,304	1,366
Avg BCS at caving	5.5	5.1	5.1	5.1	5.2
Feeding					
Pasture offered (t DM/ha)	13.7	12.3	13.1	12.6	12.9
Supplements offered (t DM/ha)	3.6	3.5	3.7	3.5	3.6
Total feed offered (t DM/ha)	19.2	17.6	18.6	18.0	18.5
Environmental					
Total kg GHG* (kg GHG/ha)	644	613	634	618	631
N surplus* (kg N/ha)	117	115	116	114	112

*Greenhouse gas (GHG) emissions are calculated by Farmax as the amount of methane, nitrous oxide and carbon dioxide emitted in each scenario with the main influencing factors being animal intake and fertiliser.

*N surplus is calculated in Farmax from the N balance where total N in (N fertiliser, incoming stock, purchased feed) - total N out (milk, outgoing stock, sold feed) = N surplus.

The financial profitability of each scenario was based on variable costs that have fluctuations dependent on the farm system. In this modelling, these variable costs were associated with the amount of pasture conserved and bought feed. These costs coupled with the net milk sales were the key determinants of the profitability of each scenario. Table 5.3 shows that the farm profit before tax of all four future scenarios was similar to the baseline (average 3,123/ha) except for the End-century RCP8.5 scenario which had a farm profit of $3,285/ha. This 6% increase in profit was mainly caused by the combination of the increase in net milk sales and the reduction in purchased feed compared with the baseline.

Table 5.3 The profit ($) and loss ($) of the Mid-century and End-century tall fescue and white clover (TF-WC) scenarios at Representative Concentration Pathway (RCP) 4.5 and 8.5 compared with the baseline.

		Mid-century		End-century	
	Baseline	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Revenue					
Net milk sales	236,938	235,261	237,067	235,221	239,683
Livestock sales	14,650	14,650	14,650	14,650	14,650
Total	251,588	249,911	251,718	249,870	254,333
Expenses					
Pasture conserved	3,065	3,082	3,424	3,269	3,344
Bought feed	24,095	22,569	23,212	22,534	22,023
Other *	136,975	136,975	136,975	136,975	136,975
Total	164,135	162,625	163,11	162,778	162,342
Farm profit					
Total profit before tax	87,453	87,286	88,107	87,093	91,991
Profit per ha before tax	3,123	3,117	3,147	3,110	3,285

5.4 Discussion

5.4.1 Future farm performance

This Chapter showed that by tactically and/or strategically managing the changes in the patterns of pasture supply, TF-WC may be a suitable pasture type for future Northland dairy farm systems. By responding to the changes in the pasture curve, the negative impacts of climate change on dairy farm performance may be mitigated. Tactical and strategic strategies such as supplementary feeding, reducing stocking rate and shifting calving date were utilised in the modelled scenarios to produce feasible farm systems in Farmax that maintained profit per hectare compared with the baseline.

RCP4.5

Under RCP4.5 climate projections, to manage the low pasture supply at the beginning and end of the production season (Figure 5.1a and 5.1c), the stocking rate was reduced from 3.1 in the baseline to 2.9 cows/ha. Stocking rate is an important management tool to manipulate the herd feed demand to match feed supply (Clark *et al.* 2012). In these scenarios where pasture supply was insufficient for the herd's energy requirements, the stocking rate was lowered to optimise milk production, and profitability (Jarman 2020). Due to the stocking rate being reduced in the RCP4.5 scenarios to a slightly greater extent than needed relative to feed supply, hence resulting in a higher feed supply per cow, MS production per cow was increased to 414 kg MS/cow compared with 389 kg MS/cow in the baseline. As a result, profit per ha in the Mid-century ($3117/ha) and End-century ($3110/ha) scenarios were similar to the baseline ($3,123 per ha). This contrasts with results by Dynes *et al.* (2010) who reported under a mid-range emission scenario, increasing stocking rate by 8% increased MS production by 25 kg per cow, and improved farm profitability by $337/ha for 2080 compared with the 2000 baseline. However, in this study pasture production was increased under climate projections due to the dairy farm being located in the Manawatu, hence experiencing different climate projections compared with Northland. This highlights the importance of adjusting stocking rate based on the available pasture supply of the individual farm.

RCP8.5

Under RCP8.5 climate projections, in the Mid-century scenario, the modelled farm was not feasible from June-November and in May (Figure 5.1b). To match the total feed demand with pasture supply, calving date was shifted to synchronise peak milk production in September to December with peak pasture supply. Stocking rate was maintained at 3.1 cows/ha, however, dry-off occurred on May 8th compared with May 14th in the baseline. This aimed to maximise MS production per day during peak pasture supply and to dry off earlier to reduce the animal demand during the autumn pasture deficit. This resulted in a total of 389 kg MS/cow and the total profit per ha ($3,147/ha) being comparable to the baseline ($3,124/ha).

In the End-century RCP8.5 scenario, pasture supply peaked earlier than the other scenarios (October vs November; Figure 4.1). To match peak pasture supply with peak animal demand, the calving date shifted from July 7th in the baseline to June 1st. Matching the pasture growth curve with animal feed demand ensured that milk production and profitability were optimised by ensuring that pasture was the main source of feed supplied (Clark *et al.* 2007). This is illustrated by the reduced reliance on supplementary feeds and increase in net milk sales. Resulting profit was $3,321/ha for the End-century RCP8.5 scenario compared with $3,124/ha for the baseline. Similarly, Tharmaj *et al.* (2008) reported that tall fescue dominant pastures increased returns by $127 to 256/ha compared with ryegrass pastures in the Waikato region.

Overall, the results indicate that the TF-WC mix is a suitable pasture base for future Northland dairy farm systems. Responding to the changes in pasture growth patterns by using tactical and strategic management practices to match pasture supply with animal demand enabled the productivity and profitability of the TF-WC-based farm to be maintained at a similar level to the 'standard' baseline KIK-RG-WC-based farm. However, TF-WC pastures do not require the annual, labour-intensive re-grassing practices that are common on kikuyu and ryegrass-based farms in Northland, thus TF-WC may be a more attractive pasture option to farmers.

5.4.2 Limitations

The modelling limitations outlined in Section 4.4.3 apply to this Chapter. In addition, it should be recognised that modelling the performance of future dairy systems utilising a range of pasture species (e.g. cocksfoot, paspalum, lucerne) or mixtures would provide a more comprehensive assessment of suitable pasture species in response to climate change. However, evaluating the performance of farm systems operating with a TF-WC pasture impacted by climate change was the only quantitative modelling that could have been completed within the time frame stipulated for this thesis. This modelling approach could be extended to other species.

A key limitation of this modelling was the use of fixed expenditure such as wages and re-grassing costs that was based on observed costs of the baseline farm (Section 3.3.2) at NARF. In Chapter 3, annual mulching of kikuyu and sowing of ryegrass seed in autumn was required to allow ryegrass to emerge and to provide winter and spring pasture cover. However, this annual transition is not required for TF-WC pastures. Therefore, total farm expenditure presented in this Chapter (Table 5.3) likely overestimates the wages and re-grassing costs assumed from the baseline farm. Further research is required to estimate costs associated with tall fescue management to include in total farm profit associated with changing species.

Conclusions

This Chapter evaluated the performance of farm systems using the TF-WC pasture in the middle and end of the 21st century. In order to ensure the farms were feasible, several tactical and strategic strategies were used to synchronise animal demands with pasture supply such as changing calving dates and reducing the stocking rates. This enabled milk production and financial profitability to be maintained in all future scenarios compared with the baseline farm. Therefore, with a range of farm management practices, TF-WC may provide a suitable pasture mixture for farmers in the Northland region of New Zealand in the future.

Chapter 6: General Discussion

The objectives of this thesis were to evaluate the effect of gradual climate change on the performance of a typical Northland dairy farm using a standard KIK-RG-WC and TF-WC pasture. Impact and adaptation were evaluated by comparing the farm's performance under the projected climate in the middle and end of the 21st century with a baseline farm. This involved using a range of farm management strategies aimed to synchronise the dairy herd's energy demand with peek feed supply to optimise milk production and limit economic losses (Jarman 2020).

Northland farmers have already adapted to climate change

Due to Northland's unique, sub-temperate climate, pastures typically comprise of annual ryegrass to provide winter-spring growth and kikuyu to provide summer-autumn growth (Jagger 2009). This mixture has been used as traditional perennial ryegrass-based pastures have struggled to persist and maintain pasture production year-round (McCahon *et al.* 2021). Therefore, it is important to note that adaptation is already occurring in Northland through the use of kikuyu-ryegrass mixtures as an alternative pasture sward to the traditional pastures. As farmers are already responding to the climate, it is likely that they will readily adapt to further climate change.

Pasture species for the future

There is growing interest from both researchers and farmers to identify pasture species that are suited to the future climate (McCahon *et al.* 2021; Lee *et al.* 2013; Kalaugher *et al.* 2017). As traits such as tolerance of drought and heat, WUE and a positive response to rising atmospheric CO_2 become more important, utilisation of a range of pasture species and mixtures (e.g. Italian ryegrass, kikuyu, white clover and tall fescue) becomes valuable. Results in Chapters 3 and 4 illustrate differences in pasture growth patterns between the KIK-RG-WC and TF-WC pasture in response to climate change. Both pasture types displayed an increase in growth rates in winter to mid-spring caused by climate projections as C_3 grasses were the dominant species in the sward. However, the KIK-RG-WC pasture maintained similar monthly growth rates over summer and autumn in the future scenarios compared with the Current as the subtropical species, kikuyu, was dominant. This is due to morphological and physiological differences between the C_3 and C_4 pasture grass species (Lee *et al.* 2013). Therefore, pastures that contain a mixture of species with different plant growth characteristics are likely to maintain pasture covers year-round and allow pasture-based dairy farming systems to be resilient.

Adapting to climate change

Evaluation of climate change adaptation strategies is complex as farm systems and the climate are both dynamic (Kalaugher 2015). As New Zealand dairy farms are predominantly pasture-based, the farm system changes used in Chapters 3 and 5 focused on matching animal demand with pasture supply. Results from Chapter 5 showed that in response to climate change, the TF-WC pasture required different system changes compared with the KIK-RG-WC pasture such as reducing stocking rate to better match supply with feed demand. It is important to note that the TF-WC pasture only had one grass species, and therefore does not require annual pasture transitioning between grass species as the KIK-RG-WC pasture. This will likely result in less farm expenditure associated with re-grassing, wages and establishment. Therefore, several considerations need to be accounted for when selecting pasture species, such as the pattern of pasture supply, optimal pasture management, and associated costs and labour requirements.

Future farm systems

This study illustrates that with the use of adaptation and farm management strategies, future dairy farms in the Northland region of New Zealand may be as productive and profitable as at present. Future farm systems will need to be adaptive and match the pasture species to the farm system, climate and soils. As changes in the climate will differ across New Zealand on a regional basis, pasture species mixtures used for farms will also differ across regions. Utilising the most suitable pasture type on a farm-by-farm basis combined with changes in strategic and tactical management practices will ensure that farm systems remain predominantly pasture-based, and that economic losses associated with pasture deficits and supplementary feed costs are limited.

For farmers contemplating alternative pasture species, several pieces of information are useful (Lee *et al.* 2013), including comparisons of seasonal trends in plant nutritive value and yield for many pasture species in a range of environments, most suitable calving and drying-off patterns, resulting seasonal milk production, and costs of pasture establishment and management and supplementary feeds. Modelling alongside biophysical research in the field is required to provide this information.

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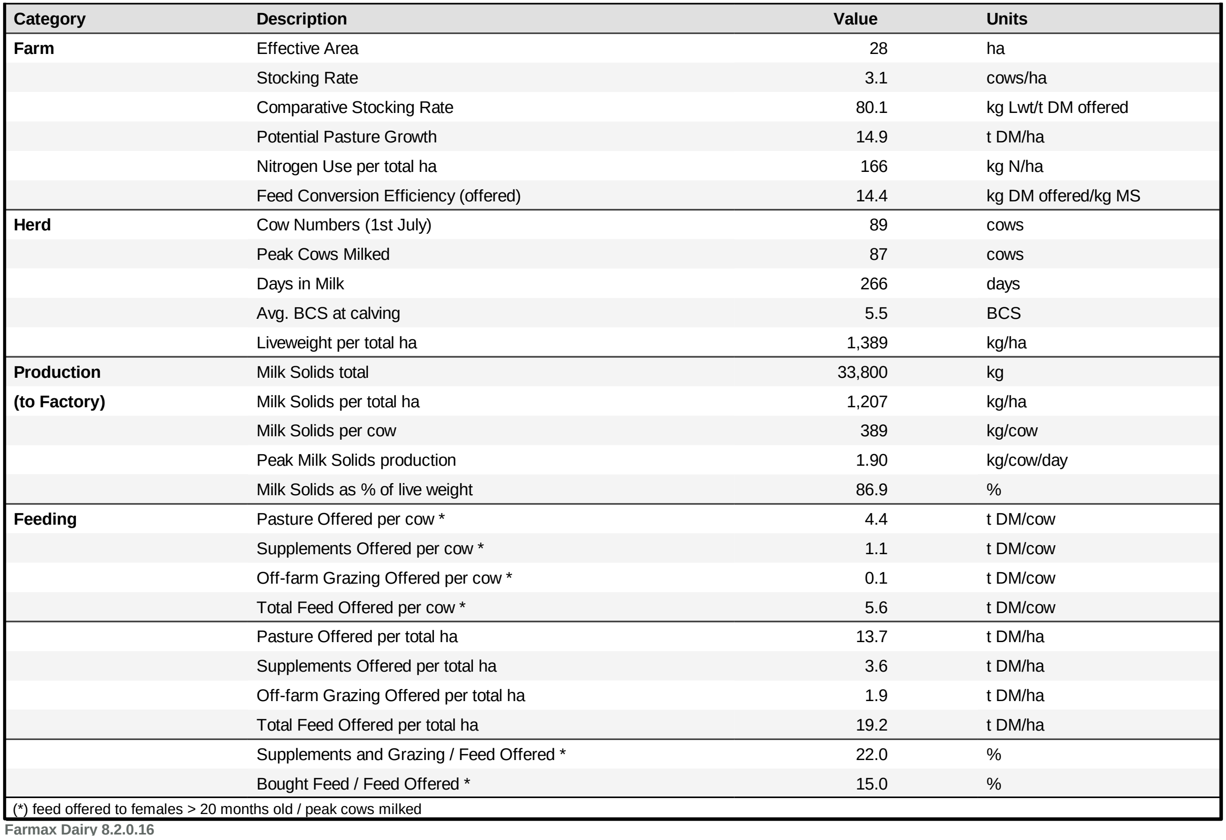
Appendix A: Chapter 3

Table A. 1 The physical summary of the baseline farm modelled in Farmax (average of 2018-19, 2019-20, 2020-21 production seasons).



Category	Description	Value	Units
Farm	Effective Area	28	ha
	Stocking Rate	3.1	cows/ha
	Comparative Stocking Rate	80.1	kg Lwt/t DM offered
	Potential Pasture Growth	14.9	t DM/ha
	Nitrogen Use per total ha	166	kg N/ha
	Feed Conversion Efficiency (offered)	14.4	kg DM offered/kg MS
Herd	Cow Numbers (1st July)	89	cows
	Peak Cows Milked	87	cows
	Days in Milk	266	days
	Avg. BCS at calving	5.5	BCS
	Liveweight per total ha	1,389	kg/ha
Production (to Factory)	Milk Solids total	33,800	kg
	Milk Solids per total ha	1,207	kg/ha
	Milk Solids per cow	389	kg/cow
	Peak Milk Solids production	1.90	kg/cow/day
	Milk Solids as % of live weight	86.9	%
Feeding	Pasture Offered per cow *	4.4	t DM/cow
	Supplements Offered per cow *	1.1	t DM/cow
	Off-farm Grazing Offered per cow *	0.1	t DM/cow
	Total Feed Offered per cow *	5.6	t DM/cow
	Pasture Offered per total ha	13.7	t DM/ha
	Supplements Offered per total ha	3.6	t DM/ha
	Off-farm Grazing Offered per total ha	1.9	t DM/ha
	Total Feed Offered per total ha	19.2	t DM/ha
	Supplements and Grazing / Feed Offered *	22.0	%
	Bought Feed / Feed Offered *	15.0	%

(*) feed offered to females > 20 months old / peak cows milked

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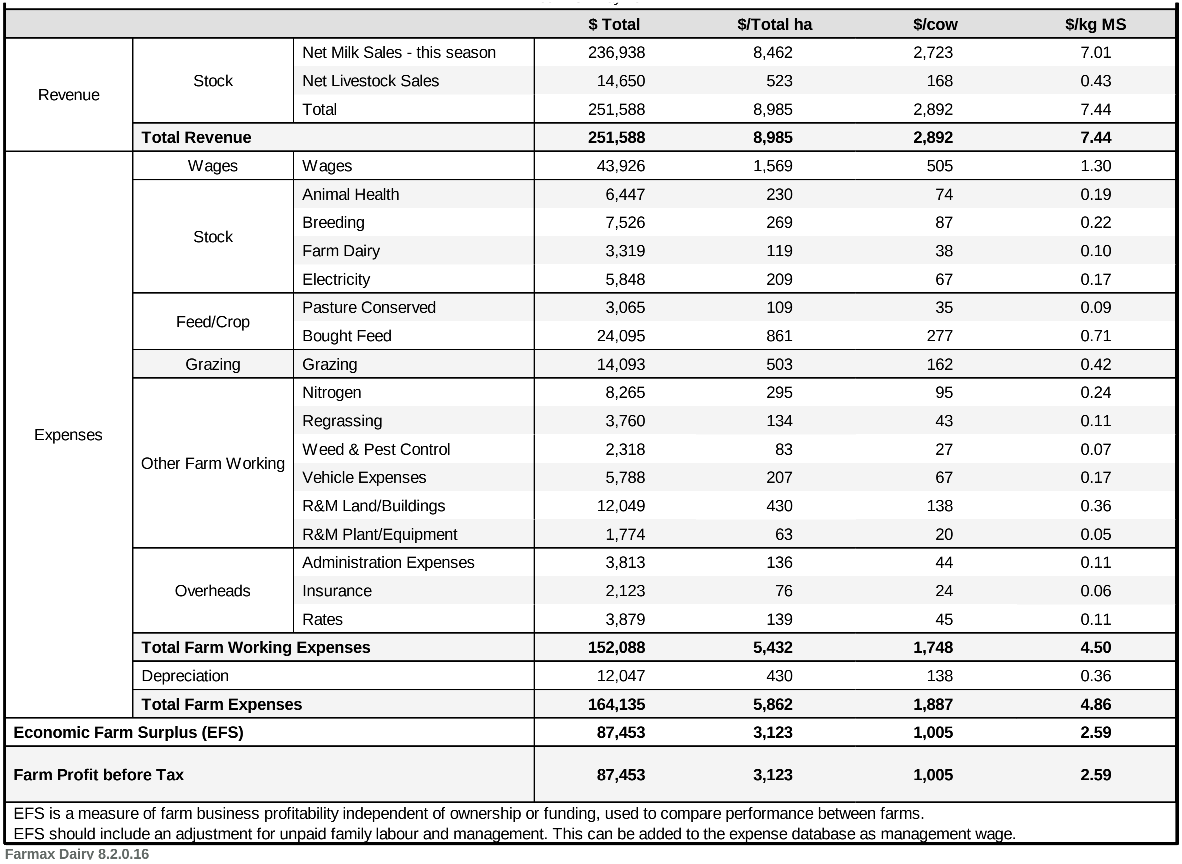
Table A. 2 The profit and loss of the baseline farm modelled in Farmax (average of 2018-19, 2019-20, 2020-21 production seasons).



			$ Total	$/Total ha	$/cow	$/kg MS
Revenue	Stock	Net Milk Sales - this season	236,938	8,462	2,723	7.01
		Net Livestock Sales	14,650	523	168	0.43
		Total	251,588	8,985	2,892	7.44
	Total Revenue		**251,588**	**8,985**	**2,892**	**7.44**
Expenses	Wages	Wages	43,926	1,569	505	1.30
	Stock	Animal Health	6,447	230	74	0.19
		Breeding	7,526	269	87	0.22
		Farm Dairy	3,319	119	38	0.10
		Electricity	5,848	209	67	0.17
	Feed/Crop	Pasture Conserved	3,065	109	35	0.09
		Bought Feed	24,095	861	277	0.71
	Grazing	Grazing	14,093	503	162	0.42
	Other Farm Working	Nitrogen	8,265	295	95	0.24
		Regrassing	3,760	134	43	0.11
		Weed & Pest Control	2,318	83	27	0.07
		Vehicle Expenses	5,788	207	67	0.17
		R&M Land/Buildings	12,049	430	138	0.36
		R&M Plant/Equipment	1,774	63	20	0.05
	Overheads	Administration Expenses	3,813	136	44	0.11
		Insurance	2,123	76	24	0.06
		Rates	3,879	139	45	0.11
	Total Farm Working Expenses		**152,088**	**5,432**	**1,748**	**4.50**
	Depreciation		12,047	430	138	0.36
	Total Farm Expenses		**164,135**	**5,862**	**1,887**	**4.86**
Economic Farm Surplus (EFS)			**87,453**	**3,123**	**1,005**	**2.59**
Farm Profit before Tax			**87,453**	**3,123**	**1,005**	**2.59**

EFS is a measure of farm business profitability independent of ownership or funding, used to compare performance between farms.
EFS should include an adjustment for unpaid family labour and management. This can be added to the expense database as management wage.

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Table A. 3 Simulated monthly kikuyu, ryegrass and white clover (KIK-RG-WC) pasture growth rates by DairyMod showing the mean, median and quantiles (25th and 75th) calculated in R-Studio for the Current (2011-2021), Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5.

		Growth rate (kg DM/ha/day)							
		RCP4.5				RCP8.5			
Scenario	**Month**	**Mean**	**Median**	**25th quantile**	**75th quantile**	**Mean**	**Median**	**25th quantile**	**75th quantile**
Current	January	19.0	9.9	1.7	27.6	18.6	10.3	2.0	27.2
	February	30.0	22.8	5.8	49.1	35.6	31.3	11.0	55.9
	March	37.3	36.5	20.1	53.0	42.5	43.3	25.6	58.7
	April	29.7	29.9	19.8	40.1	30.9	31.0	20.5	40.8
	May	25.8	26.3	17.6	34.3	26.6	26.9	18.5	34.2
	June	21.3	21.3	14.8	27.7	21.1	21.0	15.1	27.4
	July	24.4	24.5	18.2	30.7	23.3	23.7	17.1	29.8
	August	33.9	34.1	25.5	42.4	32.5	32.6	24.0	40.9
	September	49.9	50.3	36.3	64.2	49.8	50.4	36.4	64.1
	October	59.0	60.0	42.8	76.3	55.5	55.7	38.1	72.8
	November	45.9	46.9	19.6	67.4	42.2	41.0	16.1	63.4
	December	26.3	18.1	3.4	43.6	26.8	18.1	4.1	44.3
Mid-century	January	19.9	11.0	1.9	29.8	18.6	8.0	0.4	26.9
	February	31.1	23.9	4.4	51.1	35.7	28.9	4.1	60.4
	March	37.0	37.6	16.8	53.7	40.1	39.9	20.1	58.6
	April	31.0	31.1	20.0	41.8	33.4	33.2	22.0	44.6
	May	28.0	28.3	18.6	37.3	30.3	30.8	20.2	41.1
	June	24.0	24.2	16.4	31.4	24.3	24.2	16.3	32.1

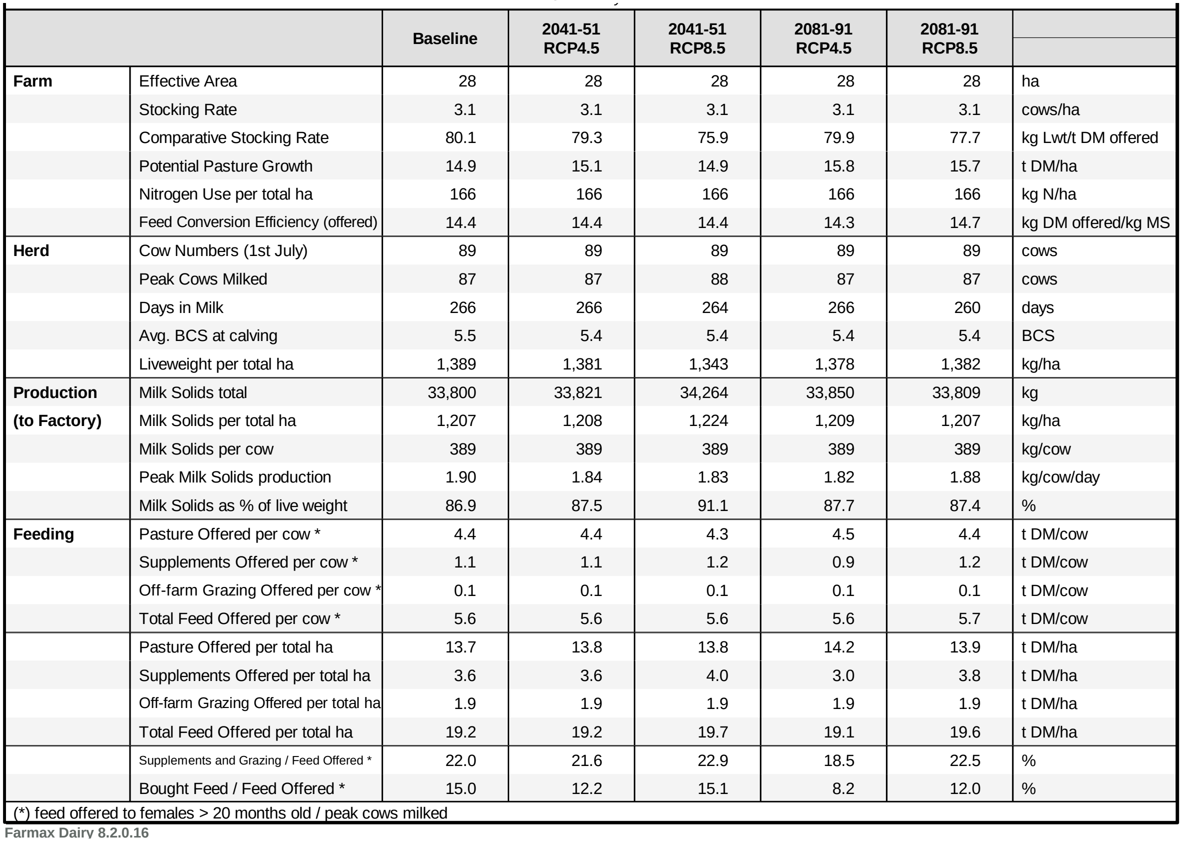
	July	25.4	25.5	18.6	32.4	26.2	26.1	19.1	33.3
	August	35.2	35.1	25.7	44.5	36.8	37.0	26.9	47.0
	September	52.3	52.9	38.5	66.3	53.7	54.3	38.0	69.6
	October	59.3	60.6	42.6	77.2	61.0	61.4	41.0	80.9
	November	46.8	47.0	21.7	68.3	41.5	38.6	13.7	63.8
	December	24.0	14.0	3.5	36.8	23.8	12.6	1.5	38.7
End-century	January	22.6	12.0	1.6	34.8	24.3	12.4	1.2	36.1
	February	33.8	28.0	7.8	54.9	38.4	30.5	3.6	65.2
	March	37.5	36.4	19.0	53.8	37.1	35.5	14.9	56.1
	April	31.2	31.4	19.8	43.1	32.5	33.0	19.2	45.7
	May	27.7	28.0	17.8	37.3	31.7	32.1	20.8	43.0
	June	24.4	24.6	16.3	32.1	28.3	28.3	18.4	38.5
	July	26.1	26.6	18.8	33.7	28.8	29.1	19.1	38.2
	August	37.0	36.4	27.6	46.8	40.2	40.7	27.2	52.8
	September	52.2	53.1	36.9	67.7	56.5	57.1	39.7	73.4
	October	60.6	62.0	43.3	79.0	62.3	63.5	39.7	83.8
	November	43.1	40.2	16.0	65.8	39.9	33.3	10.7	65.1
	December	29.2	20.9	7.7	47.8	22.3	10.8	1.1	33.2

Table A. 4 The effect of the factors: Representative Concentration Pathway (RCP), Global circulation model (GCM), Decade and Month on the kikuyu, ryegrass and white clover (KIK-RG-WC) pasture growth rates (kg DM/ha/day). Displaying the degrees of freedom (DF), Type I sum of squares (type I SS) ANOVA, Mean square, F values and P values.

Source	DF	Type I SS	Mean square	F value	P value
RCP	1	1038.5	1038.5	6.88	0.0469*
GCM	5	340.2	68.0	0.35	0.8684
RCP*GCM	5	754.9	151.0	0.79	0.5830
Decade	2	4623.5	2311.7	13.86	<.0001***
RCP*Decade	2	388.3	194.2	1.16	0.3159
Decade*GCM	10	766.9	76.7	0.46	0.9123
RCP*Decade*GCM	10	1922.6	192.3	1.13	0.3350
Month	11	728541.0	66231.0	389.27	<.0001***
RCP*Month	11	6669.2	606.3	3.56	<.0001***
GCM*Month	55	14563.0	264.8	1.56	0.0055***
Decade*Month	22	9552.1	434.2	2.55	<.0001***
RCP*GCM*Month	55	19044.0	346.2	2.04	<.0001***
RCP*Decade*Month	22	4799.7	218.2	1.28	0.1697
Decade*GCM*Month	110	17682.0	160.7	0.94	0.6439
RCP*Decade*GCM*Month	110	18342.0	166.7	0.98	0.5414

* P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001

Table A. 5 The physical summary of the kikuyu, ryegrass and white clover (KIK-RG-WC) based farm with system changes in the Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5 compared with the baseline modelled in Farmax.

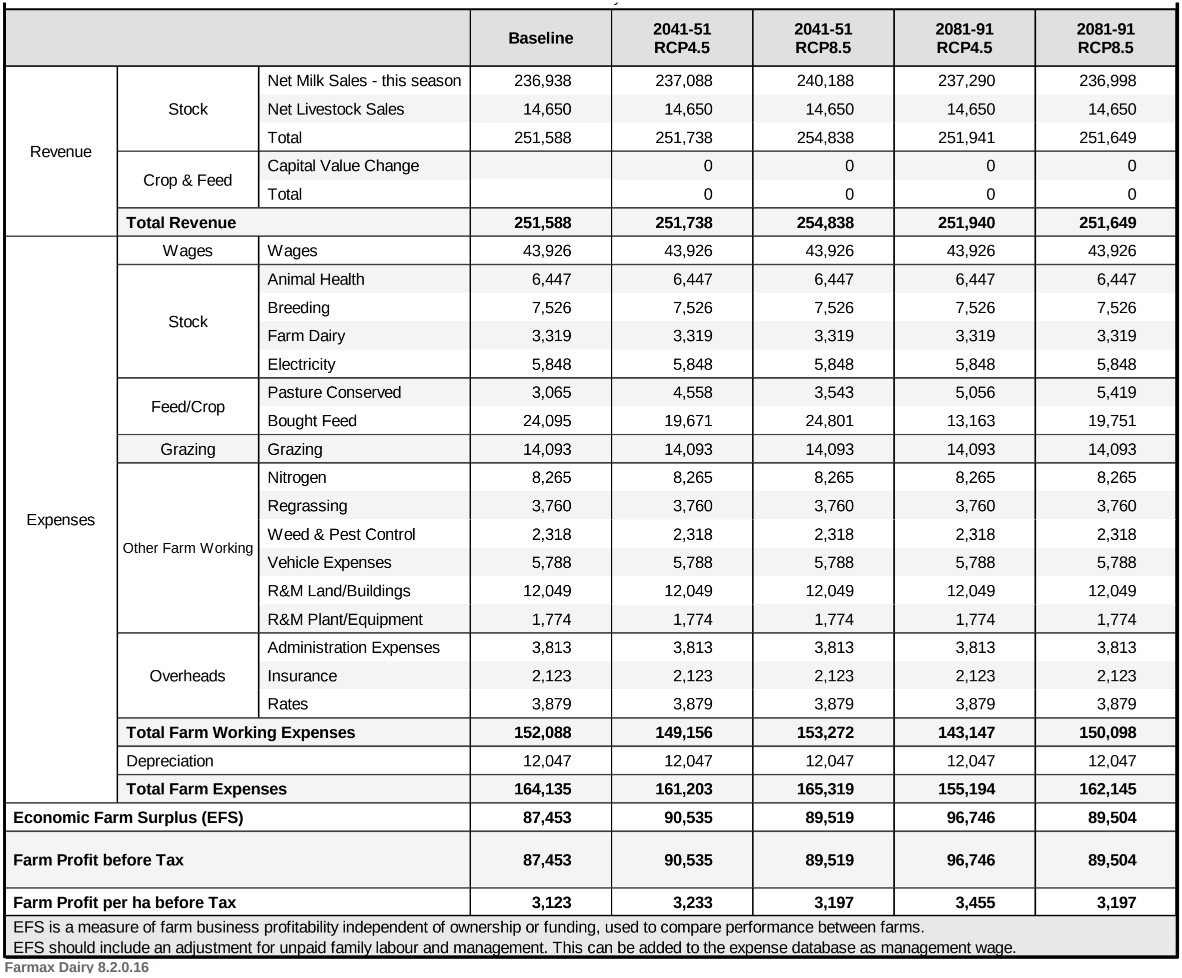


		Baseline	2041-51 RCP4.5	2041-51 RCP8.5	2081-91 RCP4.5	2081-91 RCP8.5	
Farm	Effective Area	28	28	28	28	28	ha
	Stocking Rate	3.1	3.1	3.1	3.1	3.1	cows/ha
	Comparative Stocking Rate	80.1	79.3	75.9	79.9	77.7	kg Lwt/t DM offered
	Potential Pasture Growth	14.9	15.1	14.9	15.8	15.7	t DM/ha
	Nitrogen Use per total ha	166	166	166	166	166	kg N/ha
	Feed Conversion Efficiency (offered)	14.4	14.4	14.4	14.3	14.7	kg DM offered/kg MS
Herd	Cow Numbers (1st July)	89	89	89	89	89	cows
	Peak Cows Milked	87	87	88	87	87	cows
	Days in Milk	266	266	264	266	260	days
	Avg. BCS at calving	5.5	5.4	5.4	5.4	5.4	BCS
	Liveweight per total ha	1,389	1,381	1,343	1,378	1,382	kg/ha
Production	Milk Solids total	33,800	33,821	34,264	33,850	33,809	kg
(to Factory)	Milk Solids per total ha	1,207	1,208	1,224	1,209	1,207	kg/ha
	Milk Solids per cow	389	389	389	389	389	kg/cow
	Peak Milk Solids production	1.90	1.84	1.83	1.82	1.88	kg/cow/day
	Milk Solids as % of live weight	86.9	87.5	91.1	87.7	87.4	%
Feeding	Pasture Offered per cow *	4.4	4.4	4.3	4.5	4.4	t DM/cow
	Supplements Offered per cow *	1.1	1.1	1.2	0.9	1.2	t DM/cow
	Off-farm Grazing Offered per cow *	0.1	0.1	0.1	0.1	0.1	t DM/cow
	Total Feed Offered per cow *	5.6	5.6	5.6	5.6	5.7	t DM/cow
	Pasture Offered per total ha	13.7	13.8	13.8	14.2	13.9	t DM/ha
	Supplements Offered per total ha	3.6	3.6	4.0	3.0	3.8	t DM/ha
	Off-farm Grazing Offered per total ha	1.9	1.9	1.9	1.9	1.9	t DM/ha
	Total Feed Offered per total ha	19.2	19.2	19.7	19.1	19.6	t DM/ha
	Supplements and Grazing / Feed Offered *	22.0	21.6	22.9	18.5	22.5	%
	Bought Feed / Feed Offered *	15.0	12.2	15.1	8.2	12.0	%

(*) feed offered to females > 20 months old / peak cows milked

Farmax Dairy 8.2.0.16

Table A. 6 The profit and loss of the kikuyu, ryegrass and white clover (KIK-RG-WC) based farm with system changes in the Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5 compared with the baseline modelled in Farmax.



			Baseline	2041-51 RCP4.5	2041-51 RCP8.5	2081-91 RCP4.5	2081-91 RCP8.5
Revenue	Stock	Net Milk Sales - this season	236,938	237,088	240,188	237,290	236,998
		Net Livestock Sales	14,650	14,650	14,650	14,650	14,650
		Total	251,588	251,738	254,838	251,941	251,649
	Crop & Feed	Capital Value Change		0	0	0	0
		Total		0	0	0	0
	Total Revenue		**251,588**	**251,738**	**254,838**	**251,940**	**251,649**
Expenses	Wages	Wages	43,926	43,926	43,926	43,926	43,926
	Stock	Animal Health	6,447	6,447	6,447	6,447	6,447
		Breeding	7,526	7,526	7,526	7,526	7,526
		Farm Dairy	3,319	3,319	3,319	3,319	3,319
		Electricity	5,848	5,848	5,848	5,848	5,848
	Feed/Crop	Pasture Conserved	3,065	4,558	3,543	5,056	5,419
		Bought Feed	24,095	19,671	24,801	13,163	19,751
	Grazing	Grazing	14,093	14,093	14,093	14,093	14,093
	Other Farm Working	Nitrogen	8,265	8,265	8,265	8,265	8,265
		Regrassing	3,760	3,760	3,760	3,760	3,760
		Weed & Pest Control	2,318	2,318	2,318	2,318	2,318
		Vehicle Expenses	5,788	5,788	5,788	5,788	5,788
		R&M Land/Buildings	12,049	12,049	12,049	12,049	12,049
		R&M Plant/Equipment	1,774	1,774	1,774	1,774	1,774
	Overheads	Administration Expenses	3,813	3,813	3,813	3,813	3,813
		Insurance	2,123	2,123	2,123	2,123	2,123
		Rates	3,879	3,879	3,879	3,879	3,879
	Total Farm Working Expenses		**152,088**	**149,156**	**153,272**	**143,147**	**150,098**
	Depreciation		12,047	12,047	12,047	12,047	12,047
	Total Farm Expenses		**164,135**	**161,203**	**165,319**	**155,194**	**162,145**
Economic Farm Surplus (EFS)			**87,453**	**90,535**	**89,519**	**96,746**	**89,504**
Farm Profit before Tax			**87,453**	**90,535**	**89,519**	**96,746**	**89,504**
Farm Profit per ha before Tax			**3,123**	**3,233**	**3,197**	**3,455**	**3,197**

EFS is a measure of farm business profitability independent of ownership or funding, used to compare performance between farms.
EFS should include an adjustment for unpaid family labour and management. This can be added to the expense database as management wage.

Farmax Dairy 8.2.0.16

Appendix B: Chapter 4

Table A. 7 Simulated monthly tall fescue and white clover (TF-WC) pasture growth rates by DairyMod showing the mean, median and quantiles (25th and 75th) calculated in R-Studio for the Current (2011-2021), Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5.

		Growth rate (kg DM/ha/day)							
		RCP4.5				RCP8.5			
Scenario	Month	Mean	Median	25th quantile	75th quantile	Mean	Median	25th quantile	75th quantile
Current	January	44.3	43.6	19.7	65.5	41.1	39.5	13.7	63.4
	February	29.3	22.8	0.4	49.4	34.1	31.3	8.7	53.7
	March	19.9	11.2	0.0	36.8	24.4	19.8	2.8	41.9
	April	15.1	9.4	0.2	26.4	16.5	11.8	0.2	29.0
	May	12.9	10.4	1.3	22.2	14.3	12.1	2.6	24.3
	June	15.4	15.5	5.7	23.4	16.3	16.2	6.8	24.4
	July	25.4	25.5	16.3	35.0	25.0	25.7	15.7	34.3
	August	37.2	37.6	27.1	48.1	35.6	35.5	24.5	47.1
	September	47.6	48.7	33.5	62.2	46.8	48.0	32.7	62.0
	October	57.9	59.3	41.6	75.8	53.6	53.8	36.8	71.9
	November	60.7	62.2	41.8	80.4	58.9	60.0	38.8	78.9
	December	59.9	60.1	38.2	81.7	56.4	56.8	34.0	79.6
Mid-century	January	42.5	39.9	8.8	61.7	40.2	36.3	10.6	64.6
	February	29.4	22.5	0.0	47.3	34.3	28.1	0.2	57.6
	March	22.7	16.3	0.1	37.0	27.3	20.9	1.0	46.9
	April	17.2	12.6	0.8	29.1	20.7	16.3	3.2	34.6
	May	14.0	11.8	1.5	23.9	17.6	15.1	3.4	29.5
	June	16.5	16.3	6.9	25.5	21.2	20.4	7.0	29.0
	July	26.5	26.9	17.0	36.3	30.9	30.2	18.8	40.5
	August	38.6	39.1	27.3	50.5	43.7	44.2	30.1	54.6
	September	51.9	53.4	36.1	66.4	52.8	53.8	36.4	69.0
	October	60.0	61.0	41.2	77.4	60.3	61.1	40.7	78.6
	November	63.5	64.6	43.2	83.9	62.0	62.9	39.5	83.7
	December	61.7	60.5	33.5	81.8	58.3	58.9	32.7	81.8
End-century	January	41.5	38.2	8.4	64.5	30.2	12.9	0.0	54.6
	February	30.1	22.9	0.2	50.8	32.7	23.0	0.0	54.8
	March	23.2	13.6	0.4	39.2	26.9	18.9	0.3	42.8
	April	17.3	11.2	0.4	29.6	21.9	16.6	0.2	37.9
	May	13.6	9.9	1.1	22.9	17.6	13.9	2.9	30.0
	June	20.2	18.5	6.0	25.5	28.3	26.0	9.0	32.3
	July	28.9	29.2	16.6	36.5	34.7	35.9	17.5	43.4
	August	41.8	41.9	28.3	51.5	50.8	51.2	33.1	62.0
	September	52.6	54.3	35.1	66.7	65.5	65.7	41.4	79.3
	October	63.1	64.1	43.4	79.3	71.1	72.8	47.7	95.2
	November	66.5	68.6	43.5	87.0	65.3	65.7	34.8	94.0
	December	62.8	62.9	40.2	84.7	52.4	49.6	18.0	79.8

Table A. 8 **The effect of the factors: Representative Concentration Pathway (RCP), Global circulation model (GCM), Decade and Month on the tall fescue and white clover (TF-WC) pasture growth rates (kg DM/ha/day). Displaying the degrees of freedom (DF), Type I sum of squares (type I SS) ANOVA, Mean square, F values and P values.**

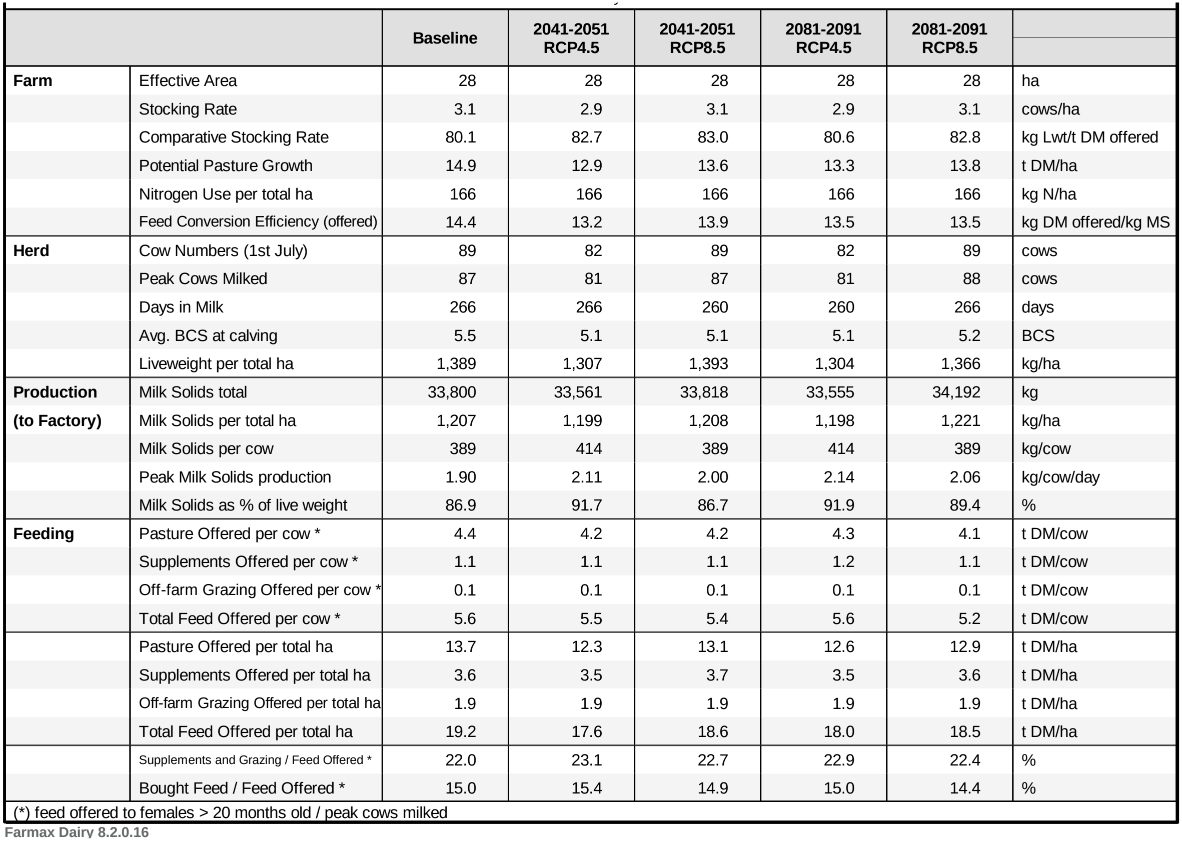
Source	DF	Type I SS	Mean square	F value	P value
RCP	1	2718.3	2718.3	4.84	0.0790
GCM	5	3530.4	706.1	1.69	0.2251
RCP*GCM	5	2806.9	561.4	1.34	0.3231
Decade	2	14221.0	7110.4	35.55	<.0001***
RCP*Decade	2	1874.8	937.4	4.69	0.0111**
Decade*GCM	10	2053.9	205.4	1.03	0.4257
RCP*Decade*GCM	10	4185.3	418.5	2.29	0.0113**
Month	11	1492599.0	135691.0	741.87	<.0001***
RCP*Month	11	19934.0	1812.2	9.91	<.0001***
GCM*Month	55	42174.0	766.8	4.19	<.0001***
Decade*Month	22	31041.0	1410.9	7.71	<.0001***
RCP*GCM*Month	55	24872.0	452.2	2.47	<.0001***
RCP*Decade*Month	22	15450.0	702.3	3.84	<.0001***
Decade*GCM*Month	110	20058.0	182.3	1.00	0.4917
RCP*Decade*GCM*Month	110	21999.0	200.0	1.09	0.2400

Table A. 9 **The effect of the factors: Species, Representative Concentration Pathway (RCP), Global circulation model (GCM), Decade and Month on the tall fescue and white clover (TF-WC) and kikuyu, ryegrass and white clover (KIK-RG-WC) pasture growth rates (kg DM/ha/day). Displaying the degrees of freedom (DF), Type I sum of squares (type I SS) ANOVA, Mean square, F and P values.**

Source	DF	Type I SS	Mean square	F value	P value
Species	1	23933.6	23933.6	120.73	0.0578
Species*RCP	1	198.2	198.2	0.37	0.5705
Species*GCM	5	1257.7	251.5	0.85	0.5477
Species*RCP*GCM	5	2692.7	538.5	1.81	0.1985
Species*Decade	2	1322.7	661.4	7.18	0.0012***
Species*RCP*Decade	2	330.8	165.4	1.80	0.1708
Species*Decade*GCM	10	1056.9	105.7	0.60	0.8162
Species*RCP*Decade*GCM	10	2975.2	297.5	1.69	0.0778
Species*Month	11	612348.6	55668.1	315.36	<.0001***
Species*RCP*Month	11	5253.5	477.6	2.71	0.0017***
Species*GCM*Month	55	13433.1	244.2	1.38	0.0319*
Species*Decade*Month	22	18536.7	842.6	4.77	<.0001***
Species*RCP*GCM*Month	55	6236.0	113.4	0.64	0.9818
Species*RCP*Decade*Month	22	4847.1	220.3	1.25	0.1947
Species*Decade*GCM*Month	110	12320.1	112.0	0.63	0.9990
Species*RCP*Decade*GCM*Month	110	10130.5	92.1	0.52	1.0000

Appendix C: Chapter 5

Table A. 9 The physical summary of the tall fescue and white clover (TF-WC) based farm with system changes in the Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5 compared with the baseline modelled in Farmax



		Baseline	2041-2051 RCP4.5	2041-2051 RCP8.5	2081-2091 RCP4.5	2081-2091 RCP8.5	
Farm	Effective Area	28	28	28	28	28	ha
	Stocking Rate	3.1	2.9	3.1	2.9	3.1	cows/ha
	Comparative Stocking Rate	80.1	82.7	83.0	80.6	82.8	kg Lwt/t DM offered
	Potential Pasture Growth	14.9	12.9	13.6	13.3	13.8	t DM/ha
	Nitrogen Use per total ha	166	166	166	166	166	kg N/ha
	Feed Conversion Efficiency (offered)	14.4	13.2	13.9	13.5	13.5	kg DM offered/kg MS
Herd	Cow Numbers (1st July)	89	82	89	82	89	cows
	Peak Cows Milked	87	81	87	81	88	cows
	Days in Milk	266	266	260	260	266	days
	Avg. BCS at calving	5.5	5.1	5.1	5.1	5.2	BCS
	Liveweight per total ha	1,389	1,307	1,393	1,304	1,366	kg/ha
Production	Milk Solids total	33,800	33,561	33,818	33,555	34,192	kg
(to Factory)	Milk Solids per total ha	1,207	1,199	1,208	1,198	1,221	kg/ha
	Milk Solids per cow	389	414	389	414	389	kg/cow
	Peak Milk Solids production	1.90	2.11	2.00	2.14	2.06	kg/cow/day
	Milk Solids as % of live weight	86.9	91.7	86.7	91.9	89.4	%
Feeding	Pasture Offered per cow *	4.4	4.2	4.2	4.3	4.1	t DM/cow
	Supplements Offered per cow *	1.1	1.1	1.1	1.2	1.1	t DM/cow
	Off-farm Grazing Offered per cow *	0.1	0.1	0.1	0.1	0.1	t DM/cow
	Total Feed Offered per cow *	5.6	5.5	5.4	5.6	5.2	t DM/cow
	Pasture Offered per total ha	13.7	12.3	13.1	12.6	12.9	t DM/ha
	Supplements Offered per total ha	3.6	3.5	3.7	3.5	3.6	t DM/ha
	Off-farm Grazing Offered per total ha	1.9	1.9	1.9	1.9	1.9	t DM/ha
	Total Feed Offered per total ha	19.2	17.6	18.6	18.0	18.5	t DM/ha
	Supplements and Grazing / Feed Offered *	22.0	23.1	22.7	22.9	22.4	%
	Bought Feed / Feed Offered *	15.0	15.4	14.9	15.0	14.4	%

(*) feed offered to females > 20 months old / peak cows milked

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Table A. 10 The profit and loss of the tall fescue and white clover (TF-WC) based farm with system changes in the Mid-century (2041-2051) and End-century (2081-2091) scenarios at RCP4.5 and RCP8.5 compared with the baseline modelled in Farmax.

			Baseline	2041-2051 RCP4.5	2041-2051 RCP8.5	2081-2091 RCP4.5	2081-2091 RCP8.5
Revenue	Stock	Net Milk Sales - this season	236,938	235,261	237,067	235,221	239,683
		Net Livestock Sales	14,650	14,650	14,650	14,650	14,650
		Total	251,588	249,911	251,718	249,870	254,333
	Crop & Feed	Capital Value Change		0	0	0	0
		Total		0	0	0	0
	Total Revenue		**251,588**	**249,911**	**251,718**	**249,871**	**254,334**
Expenses	Wages	Wages	43,926	43,926	43,926	43,926	43,926
	Stock	Animal Health	6,447	6,447	6,447	6,447	6,447
		Breeding	7,526	7,526	7,526	7,526	7,526
		Farm Dairy	3,319	3,319	3,319	3,319	3,319
		Electricity	5,848	5,848	5,848	5,848	5,848
	Feed/Crop	Pasture Conserved	3,065	3,082	3,424	3,269	3,344
		Bought Feed	24,095	22,569	23,212	22,534	22,023
	Grazing	Grazing	14,093	14,093	14,093	14,093	14,093
	Other Farm Working	Nitrogen	8,265	8,265	8,265	8,265	8,265
		Regrassing	3,760	3,760	3,760	3,760	3,760
		Weed & Pest Control	2,318	2,318	2,318	2,318	2,318
		Vehicle Expenses	5,788	5,788	5,788	5,788	5,788
		R&M Land/Buildings	12,049	12,049	12,049	12,049	12,049
		R&M Plant/Equipment	1,774	1,774	1,774	1,774	1,774
	Overheads	Administration Expenses	3,813	3,813	3,813	3,813	3,813
		Insurance	2,123	2,123	2,123	2,123	2,123
		Rates	3,879	3,879	3,879	3,879	3,879
	Total Farm Working Expenses		**152,088**	**150,578**	**151,564**	**150,731**	**150,295**
	Depreciation		12,047	12,047	12,047	12,047	12,047
	Total Farm Expenses		**164,135**	**162,625**	**163,611**	**162,778**	**162,342**
Economic Farm Surplus (EFS)			**87,453**	**87,286**	**88,107**	**87,093**	**91,991**
Farm Profit before Tax			**87,453**	**87,286**	**88,107**	**87,093**	**91,991**
Farm Profit per ha before Tax			**3,123**	**3,117**	**3,147**	**3,110**	**3,285**

EFS is a measure of farm business profitability independent of ownership or funding, used to compare performance between farms.
EFS should include an adjustment for unpaid family labour and management. This can be added to the expense database as management wage.

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