

# Long-term climate variability in Waikato and Manawatu: Have conditions for pasture growth, performance, and resilience changed?

J. Eruera TAIT-JAMIESON, Daniel J. DONAGHY\*, Andrew D. CARTMILL and Jonathan PROCTER

*School of Agriculture and Environment, Massey University,  
Private Bag 11-222, Palmerston North 4440, New Zealand*

\*Corresponding author: [d.j.donaghy@massey.ac.nz](mailto:d.j.donaghy@massey.ac.nz)

## Highlights

- Available climate data (1940-2024) from Grasslands, Palmerston North and Ruakura, Hamilton weather stations in Aotearoa-New Zealand (A-NZ), show a strong warming trend across all seasons.
- Rainfall, while highly variable, has remained largely unchanged throughout the same period, however due to increased temperatures, a general trend of greater drought severity and duration has emerged.
- Severe summer droughts have become one of the defining features of the A-NZ pastoral growing season, as have warmer winters.
- Farm resilience to drought, particularly in the dairy sector, has been diminished by structural and operational changes since the 1990s, leading to an amplified perception of drought intensity, which is compounded by underlying climatic changes.

**Keywords:** climate change, drought, grazing management, warming

## Background

Increasing awareness of climate change throughout the Aotearoa-New Zealand (A-NZ) pastoral sector has been accompanied by frequent discussion of how contemporary seasonal weather conditions are different or less predictable than those usually experienced by current and previous generations of farmers. Perception of climate change is a complex phenomenon, mediated by both lived experience and social learning (Sugerman et al. 2021). Increased occurrence of climate-driven extreme weather events, higher seasonal temperatures, and prolonged periods of drought have focused the general public's concerns around climate change, adaption, and mitigation (Dessai and Sims 2010; Sloggy et al. 2021; Soni and Mistur 2022). In contrast with the general public, A-NZ farmers, despite expecting greater drought frequency and severity in the future, have not strongly associated past experiences of drought with this belief, suggesting that climate change perception within the farming community is more strongly influenced by demography, education, and trusted information sources (Arbuckle et al.

2013; Nguyen et al. 2023). Perception of climate change to date has also been found to be at odds with instrumental climate records in some cases, in part because of low rates of change which can be difficult to detect within a highly variable local climate and also due to infrastructure investments that can buffer farm sensitivity to meteorological stresses (Hopkins et al. 2015; Niles and Mueller 2016). This discordance between observation and perception of climate change suggests that the lived experience of these changes cannot be relied upon solely to motivate or guide adaptation and mitigation strategies into the future. We suggest that a data driven approach to monitoring and managing climate change effects within the A-NZ pastoral industry is needed.

This paper describes trends in seasonal rainfall and air temperature patterns from 1940 to 2024 in A-NZ, focusing on daily data available from Grasslands and Ruakura agricultural research stations in Palmerston North and Hamilton, respectively. Weather stations at these two sites form part of the eleven-station series identified by the National Institute of Water and Atmospheric Research (NIWA) as being among the most stable, with no significant site shifts within the period in question. As a young nation A-NZ has relatively few sources of long-term daily climate records, and fewer still that are not influenced by major site shifts that make construction of a suitable reference series challenging (Mullan 2010; NIWA 2012). The Grasslands and Ruakura weather stations offer a unique opportunity to examine daily weather records at specific locations of historical significance for agricultural research, nested within districts of economic significance for agricultural production, and answer the question; Have climatic conditions for pastoral productivity in A-NZ changed or is it just our perception?

## Climatic Trends

Daily temperature (minimum, maximum, and average) and rainfall records from Palmerston North and Hamilton stations identified in the NIWA eleven-station series were obtained from the NIWA DataHub climate

**Table 1** Weather station details for Palmerston North and Hamilton sites from the National Institute of Water and Atmospheric Research (NIWA) eleven-station series.

Location	Station Identifier	Start Date	End Date	Location (long/lat)	Elevation (m)
Grasslands, Palmerston North	3238	1928/01/01	2001/06/30	175.6092,	21.0
	21963	2001/03/30	-	-40.3820	
Ruakura, Hamilton	2101	1905/07/01	2005/10/01	175.3125,	40.0
	12616	1996/10/23	2007/02/21	-37.7791	
	26117	2005/11/08	-	175.3052,	45.0
				-37.7739	

data catalogue (<https://data.niwa.co.nz>). Continuous series for each location were constructed by appending the records from successive stations without adjustment. Where multiple stations operated concurrently at a location the mean of daily observations was used.

Daily records from each site were truncated to remove data from outside the target analysis window and processed using the Climact R library (version 3.3) to generate distribution and continuity quality control plots. Both sites contained intermittent short data 'dropouts,' particularly in temperature data from Ruakura from 1940 to 1946. Major discontinuities included no temperature data recorded at the Grassland site between 16<sup>th</sup> December 2013 and 13<sup>th</sup> February 2014, and no rainfall recorded for the periods from 19<sup>th</sup> February 2016 to 28<sup>th</sup> March 2016 and 15<sup>th</sup> December 2017 to 20<sup>th</sup> January 2018 at the Ruakura site.

## Air Temperature

### Seasonal Temperatures

Warming trends were observed at both sites with the greatest increase in temperature occurring in summer at Ruakura and the smallest increase occurring in spring at Grasslands (Figure 1), each of these seasons varied significantly ( $p < 0.001$ ) from the overall warming trends at their respective locations.

Other than these two exceptions, significant differences in the warming trends were not observed between seasons within the same site. This suggests that perceptions of pronounced changes in temperature seasonality are not well supported by the climate records from these sites.

At an annual level the Grasslands and Ruakura sites warmed by an average of 1.1°C and 1.7°C, respectively, from 1940 to 2024; continuing within the range of trends previously described at these locations (Withers et al. 2009) and across A-NZ in general (Caloiero 2017). Distinct changes in diurnal temperature variation were not observed, suggesting uniform increases in daily minimum, maximum, and average air temperatures for any given season, albeit with the average degree of warming between months within a season varying by

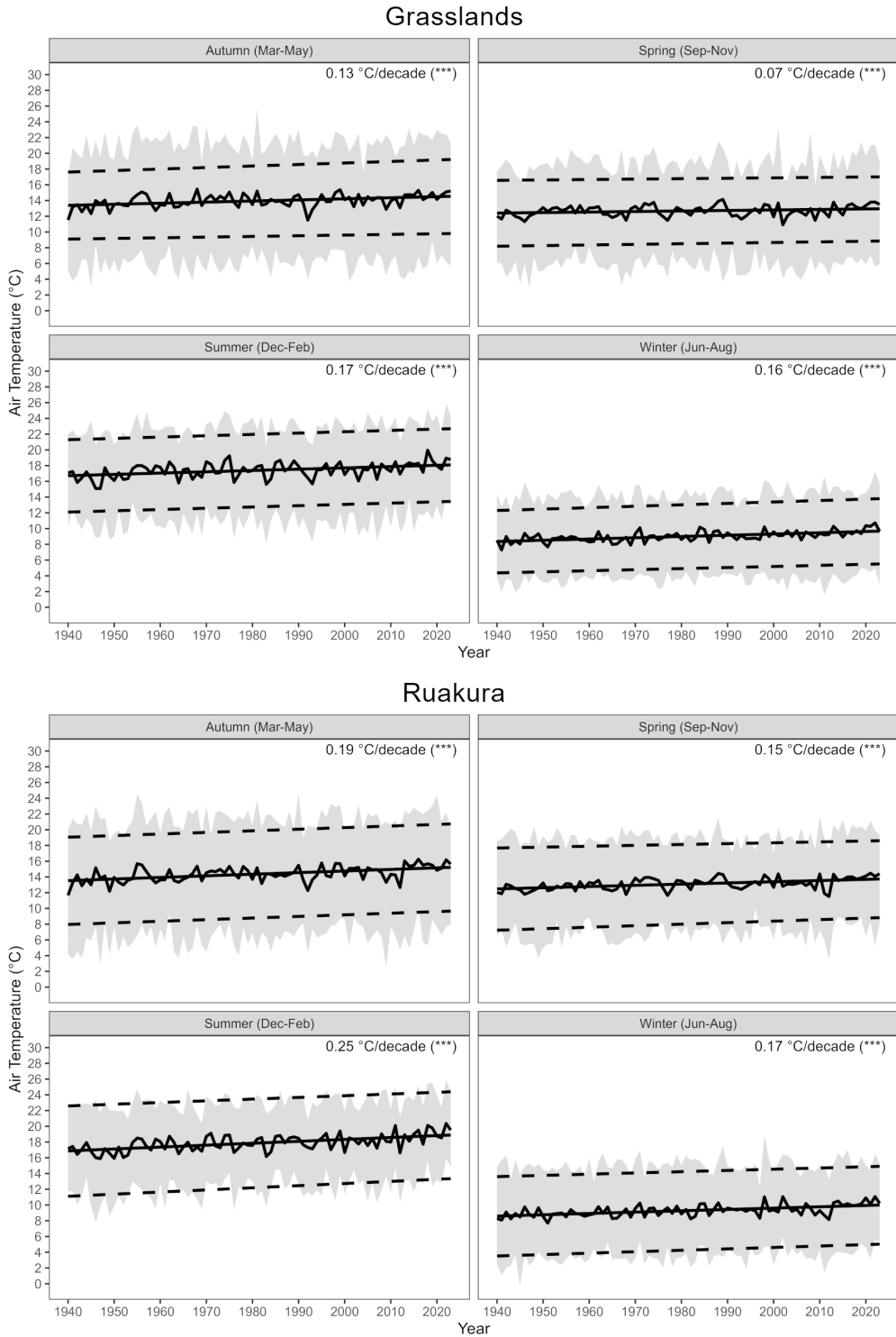
up to a factor of two (data not shown).

### Growing Season

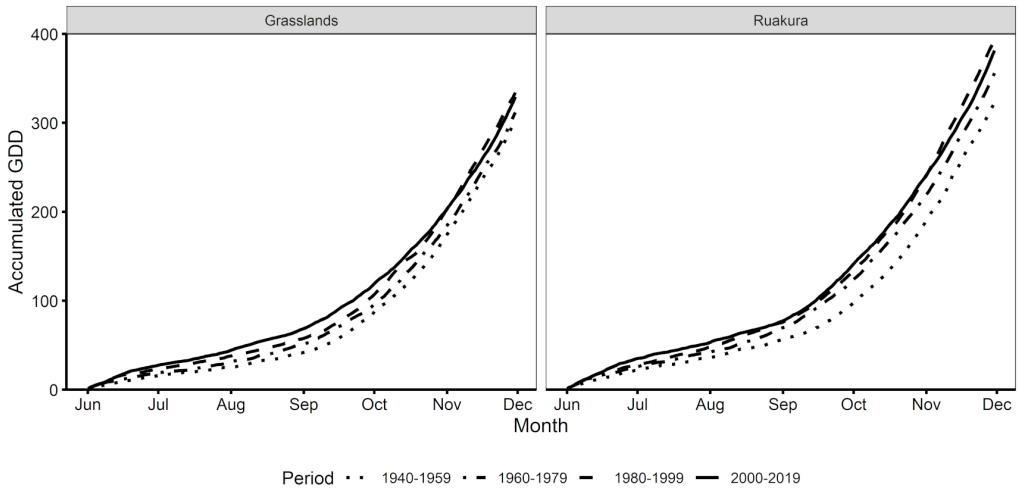
Both sites were characterised by long thermal growing seasons, commonly defined as the number of days where daily average air temperature exceeds 5°C (Ergon 2017). This is typical of a temperate climate and limits the scope for the growing season to extend via warming, however from the 1970s onward both sites averaged fewer than seven non-growing days per year, with the number of non-growing days each year declining by 0.7 days per decade and 0.8 days per decade at Grasslands and Ruakura, respectively, from 1940 to 2024. High temperatures sufficient to subject perennial ryegrass (*Lolium perenne* L.) or white clover (*Trifolium repens* L.) to thermal stress irrespective of moisture availability (Hannaway et al. 1999; Qi et al. 2021) were observed sporadically from 1980 onward but were not a regular feature of the local climates at either site. The Grasslands site was variable in the number of frost days per year or decade and observed fewer frost days overall compared to Ruakura, which declined significantly ( $p < 0.001$ ) at a rate of 1.9 days per decade, effectively halving by the decade from 2010 to 2019.

In general, winter daily mean temperatures were not low enough to inhibit the growth of cool season grasses (Hutchinson et al. 2000), however, the growth of cool season grasses does decline rapidly below 10°C (Moser and Hoveland 1996). Therefore, we have used 10°C as a base temperature from which to examine accumulation of thermal time as it relates to the transition from winter to spring productivity levels of temperature pastures.

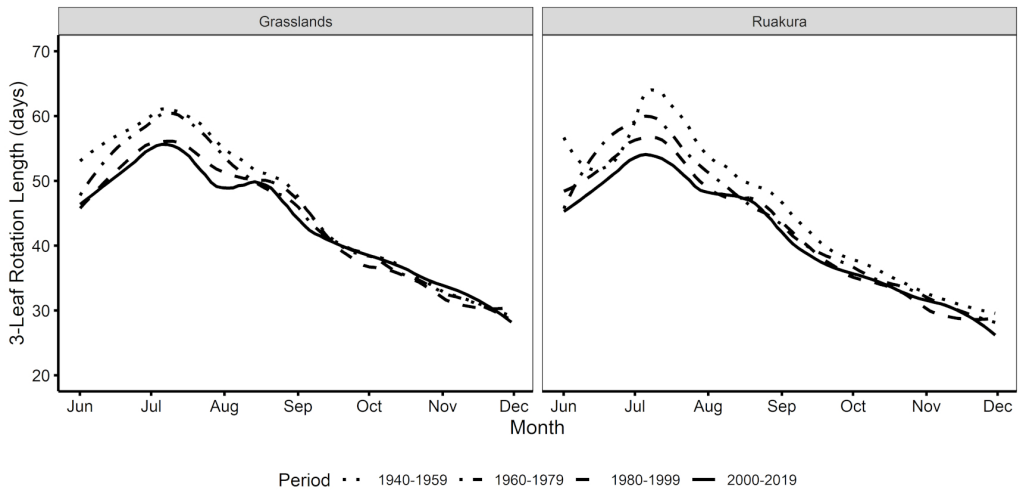
Dividing the temperature record into 20-year sections revealed important differences in the early season thermal time dynamics at both Grasslands and Ruakura sites (Figure 2). On average, equivalent heat units accumulated at least two weeks earlier from July through October between the initial and final period, creating the conditions for a more rapid onset of spring growth rates. Annual total thermal time increased by more than 300 GDD<sub>10</sub> per year from 1940 and 2019, with Grasslands and Ruakura sites accumulating



**Figure 1** Seasonal temperature trends at Grasslands and Ruakura (1940-2024). Solid line is trend in average daily temperature (°C) for given season (\*\*\*) =  $p < 0.001$ ). Upper and lower dashed lines are trends in daily maximum and minimum temperature, respectively. Ribbons are the extreme daily observations for each season each year.



**Figure 2** Accumulation of growing degree days (GDD; base 10°C) through winter and spring at Grasslands and Ruakura.

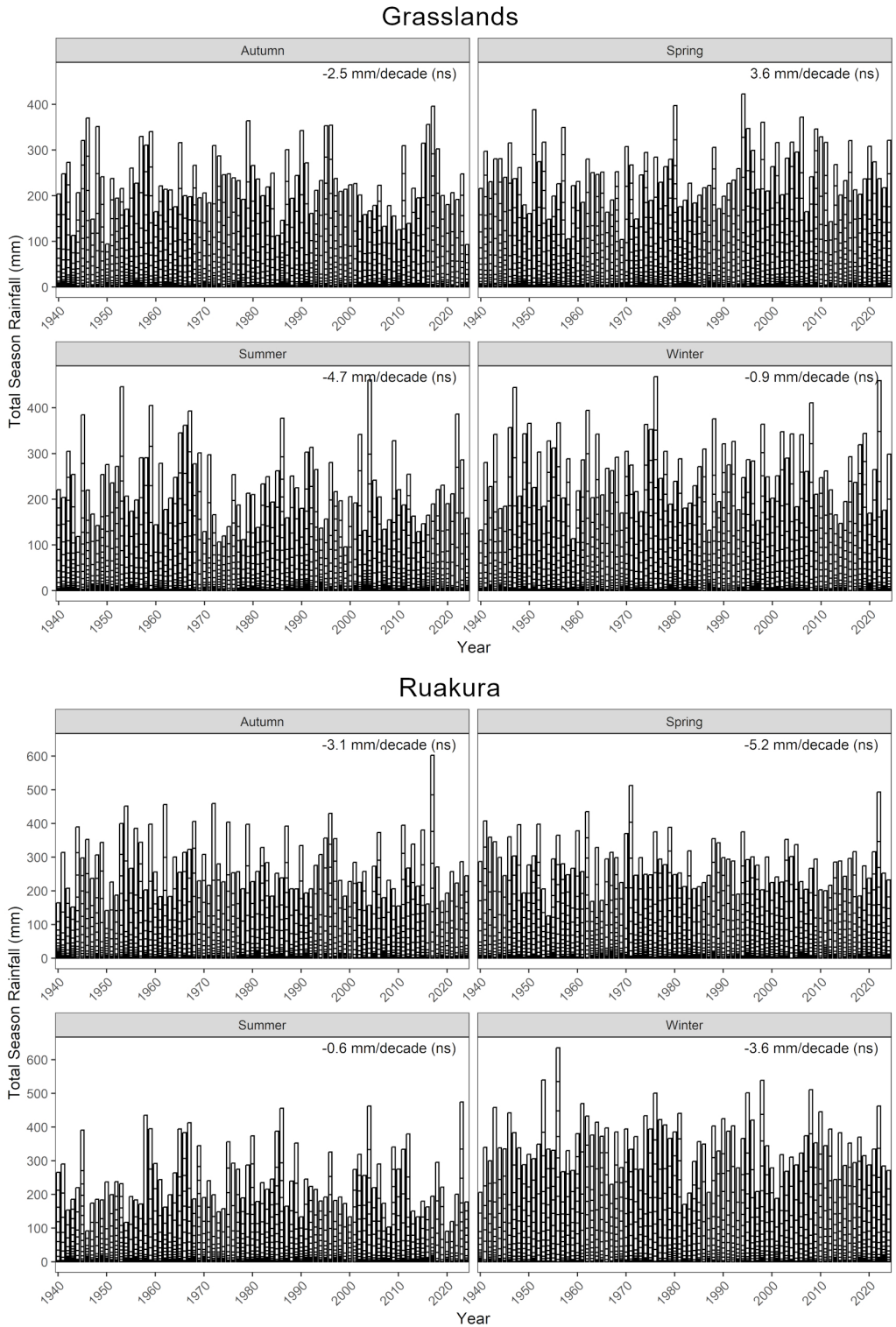


**Figure 3** Estimated grazing rotation length to achieve 3-leaf stage in perennial ryegrass (*Lolium perenne* L.) at Grasslands and Ruakura.

averages of 1467  $GDD_{10}$  per year and 1680  $GDD_{10}$  per year, respectively, between 2010 and 2019.

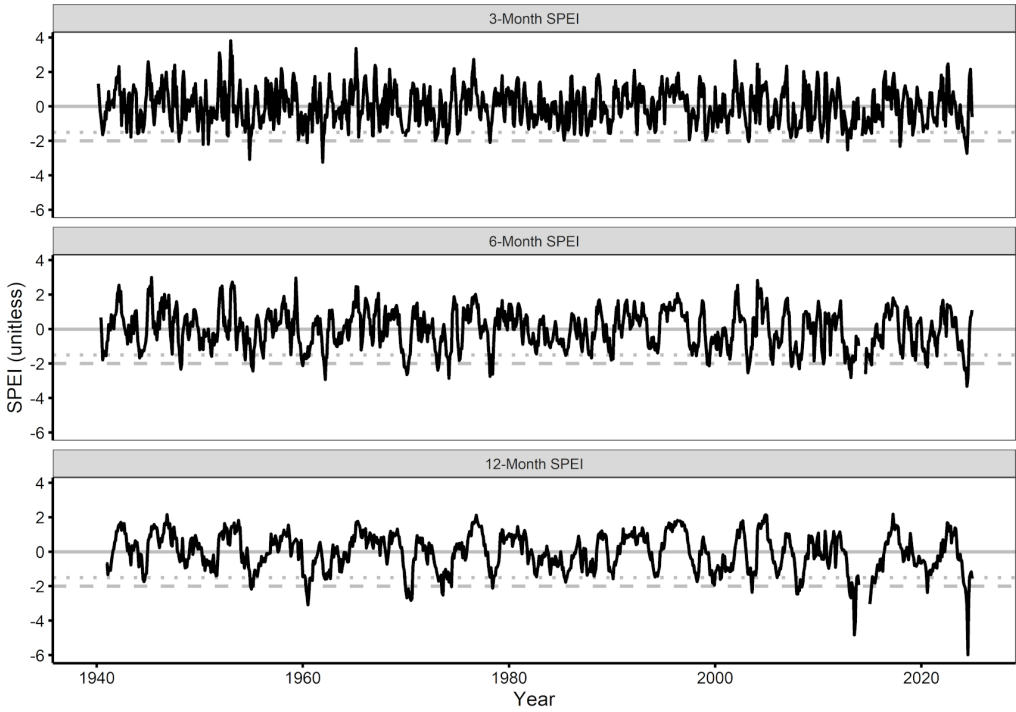
To further contextualise changes in winter temperature within A-NZ pastoral grasslands, the number of days required for perennial ryegrass to develop three fully expanded leaves was estimated using the model from the Tasmanian Institute of Agriculture (n.d.) for the average of years within each two-decade period (Figure 3). If we assume that moisture (either deficit or excess) was not a limiting factor for the rate of leaf appearance between June and November, it appears that duration of winter rotation length necessary to provide optimal recovery time from grazing for a perennial ryegrass

pasture (Fulkerson and Donaghy 2001) declined markedly, while optimal spring rotation lengths remained similar. We suggest, that for our locations winter grazing intervals could be shortened, reducing the negative effects of shading on root development and sward density of perennial ryegrass/white clover pastures, thereby improving pasture resilience and recovery from summer dry conditions, while still maintaining optimal conditions for spring regrowth (Devkota et al.; Black et al. 2009).

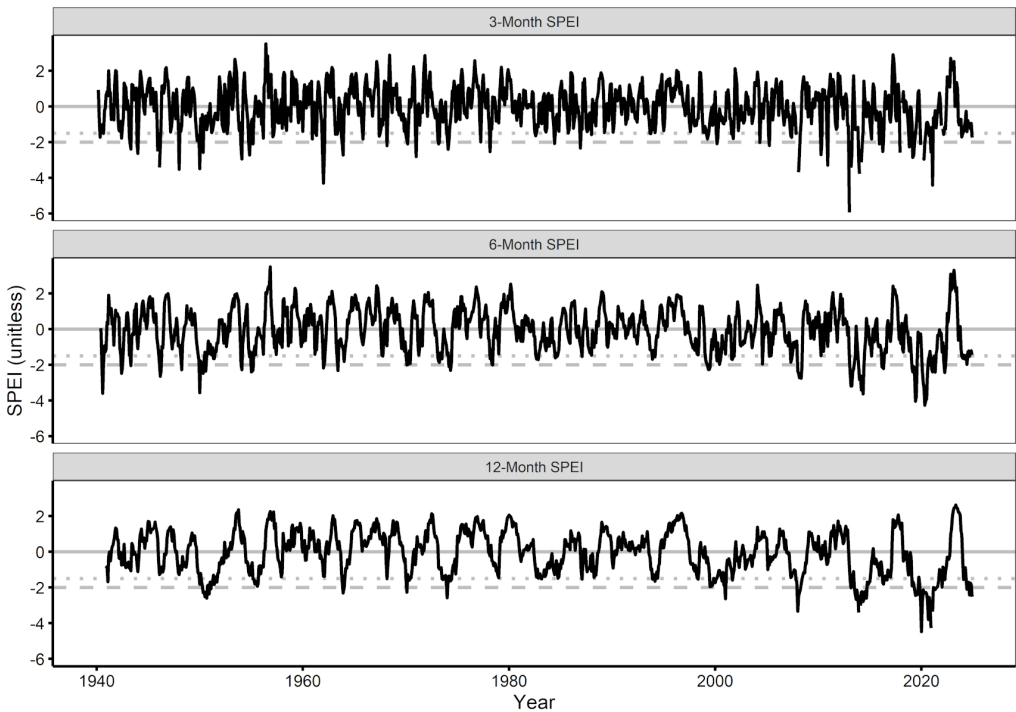


**Figure 4** Total season rainfall (mm) at Grasslands and Ruakura (1940-2024). Each bar segment represents an individual rainfall event within the corresponding season and year.

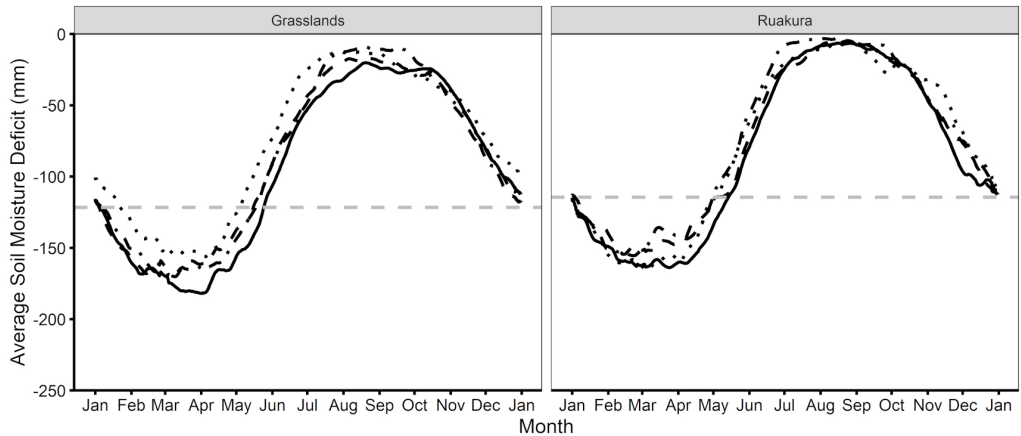
### Grasslands



### Ruakura



**Figure 5** Standardised Precipitation Evapotranspiration Index (SPEI; unitless) at Grasslands and Ruakura (1940-2024). The dotted and dashed lines are the thresholds indicating severe- and extreme- dry conditions, respectively. The solid line is at zero for baseline reference.



**Figure 6** Modelled soil moisture balance at Grasslands and Ruakura. Dashed line represents the drought threshold of 50% available water holding capacity (AWHC; mm).

### Rainfall

Rainfall events were highly variable at both sites and few significant changes were observed (Figure 4), this may reflect the limited data and could be sensitive to the start and end dates of the climate records. However, average annual rainfall declined at a rate of 5.5 mm/decade and 13.7 mm/decade at Grasslands and Ruakura, respectively, which warrants consideration within the context of agricultural risk. Monthly total rainfall declined significantly by 4.8 mm/decade ( $p < 0.01$ ) for January at Grasslands and by 4.7 mm/decade ( $p < 0.05$ ) for October at Ruakura. Average intensity of rainfall increased significantly in May and September at Grasslands, which has the potential to impact pasture productivity through increased waterlogging.

The variability and inconsistent direction of the trends aligns with those previously identified across the North Island although it is important to note that there is evidence for a systematic shift in rainfall in the South Island, where rainfall has decreased on the eastern side and increased on the western side of the island (Caloiero 2015). Overall, the available data do not suggest the occurrence of a wholesale change in seasonal rainfall patterns but affirms the complexity and variability of the A-NZ climate (Hopkins et al. 2015).

### Drought

#### *Meteorological*

The Standardised Precipitation Evapotranspiration Index (SPEI) is a development of the Standardised Precipitation Index commonly used to detect and characterise meteorological drought conditions, and accounts for the increased evapotranspiration demand associated with warming climate (Svoboda 2016). Window periods of 3-, 6-, and 12-months are used to infer the presence of meteorological, agricultural, and hydrological drought, respectively (Stats NZ

2023), however the progression of drought from atmospheric conditions through to soil moisture and hydrological flow are not derived from meteorological conditions alone, and specific metrics should be used to characterise different conceptualisations of drought where data are available (Wanders et al. 2010; Wang et al. 2016).

Following the classifications adopted by Spinoni et al (2016), drought is considered to commence at any given time window once SPEI falls below -1 and ends when it returns to zero, within thresholds of -1.5 and -2 representing onset of severe dry and extreme dry, respectively. No statistically significant trends in drought duration or severity, as characterised by SPEI, were detected at the Grasslands site (Figure 5), while both indicators increased significantly at the long-term (12 month) window at Ruakura. There are visual indications that the severity of drought may have trended higher since the year 2000, and the most extreme dry observations occurred mostly after this point, however there are only weak trends to suggest that the meteorological water balance has shifted.

#### *Agricultural/Agronomic*

A continuous soil moisture model (Woodward et al. 2001) was run from 1940 to 2024 to synthesise the interaction between trends and variation of temperature and rainfall at each site. While the severity and duration of the soil moisture deficit remained highly variable throughout the entire period, taking the average soil moisture profile across 20-year windows revealed a general tendency toward more severe soil moisture deficits which persisted further into autumn (Figure 6). From 2010-2019 the soil moisture deficit in the average year extended until 25 May at Grasslands and 13 May at Ruakura, respectively.

## Discussion

Acknowledging that they provide a limited representation of climate change throughout A-NZ, records from Grasslands and Ruakura weather stations do present an opportunity to contextualise a 'lifetime' of change as it occurred at two research sites where substantial contributions were made to our present understanding of A-NZ grassland productivity and management.

Much of the foundational research underpinning contemporary pasture-based dairy systems in A-NZ was conducted at the Number 2 Dairy unit at Ruakura, where in the 1960's it was recognised that annual and seasonal variations in climate were the primary driver of differences in pasture productivity (Macdonald and Roche 2024). Parallel research into fundamental pasture plant morphology, management, and breeding was also underway at Grasslands Palmerston North, Aorangi, and Ballantrae research farm during the same period (Brougham 1970; Brock 1974; Chapman 1983; Cosgrove and Brougham 1985, Hay and Hunt 1989; Harris 1996). Taking the logic that testing research treatments under a wide range of environmental conditions is key for their utility for farmers across the country, it follows that ongoing change in underlying climate warrants a re-examination of previously established practices to ensure that they remain fit for purpose.

Another key limitation to address is the retrospective nature of examining climate trends, to a greater or lesser degree the A-NZ pastoral sector has necessarily evolved along with its climate in order to "cope" with the changes in growing conditions (Griffin et al. 2023). The value of a retrospective examination is in how it can help us to contextualise the additional changes forecasted through the 21<sup>st</sup> Century and encourage reflection on whether our current farm systems will remain productive and resilient should the changes experienced in the preceding decades be compounded, amplified, or accelerated. A lesson is well taken from Northland, where climate conditions have already exceeded the growing conditions of perennial ryegrass-based pastures (McCahon et al. 2021) and have necessitated shifts in agronomic practice and impacted the socioeconomics of the region (Marmont et al. 2024).

The trends in rainfall and temperature observed at the Grasslands and Ruakura sites broadly conform to the projections and observations of the North Island climate that have been discussed in the literature over the last several decades and are gradual, however, gains in pasture productivity that were anticipated from increased temperatures and atmospheric carbon dioxide under similar rainfall (Baars et al. 1990; Butler et al. 1990) have not occurred. Instead, there has been a tendency toward static or declining pasture production

through the 21<sup>st</sup> century in A-NZ with gains since the 1990s largely explained by increased use of nitrogen fertiliser (Chapman et al. 2024), a strategy which has come under increasing regulatory pressure (Ministry for the Environment 2021). Against this backdrop of stalled pasture productivity, a tendency toward regular severe droughts and more frequent extreme weather events has emerged since 2009, with medium-scale adverse events declared yearly in some parts of the country to trigger government drought relief, except in 2012 and 2023 (New Zealand Government 2009-2024). With growing seasons becoming regularly punctuated by summer-dry conditions, the question arises as to whether the increase in drought impact experienced by farmers and rural communities diverges from the changes in climatic conditions, which are modest over the span of the last 20-30 years.

Drought, as previously introduced, is a somewhat nebulous term and is a natural hazard that cannot be defined in isolation from its socioeconomic context, yet the measures and thresholds for characterising and declaring drought, including those used in this paper, attempt to do just that, often overlooking what would be considered normal or sufficient rainfall to meet the livelihood needs of farmers (Glantz and Katz 1977; Wilhite 2000; Meze-Hausken 2004).

The sheep and beef sector have reduced stocking rates since the 1980s, with many hill country farmers focusing on lambing percentage and spring feed conversion efficiency to optimise for liveweight production per hectare at weaning before summer dry conditions set in (Gobilik et al. 2021). In contrast, dairy farm stocking rates have increased by 33% between 1981 and 2023 (Livestock Improvement Corporation 1999, 2024). Farm debt across the agricultural sector has also increased significantly in recent decades, 188% from 1999 to 2009 and 28% from 2009 to 2019 (Ministry for Primary Industries 2019). NZ is now one of the most agriculturally indebted countries in the world, ranked 9<sup>th</sup> for the decade to 2022 for overall sector debt, including forestry and aquaculture (FAO 2023), and ranking 37<sup>th</sup> in the world for gross value of agricultural production over the same period (FAO 2024). While higher debt levels may reflect a greater access to capital provided by low interest rates and high commodity prices, the need to service debt can increase the financial challenges faced by farmers under climate stress, such as drought (Kamal and Noy 2023; Lees 2014; Lu 2023).

For the dairy sector, which carries the majority of the national agricultural debt (Lees 2014), the net effect of both environmental and system changes may explain part of why many farms are experiencing difficulty under prevailing climate conditions, where summer dry conditions were previously reported as being

manageable (Gray 1996). Thus, adapting management strategies and system configuration to maximise the productive use of pasture before the onset of summer dry conditions has become increasingly important, as changes in growing conditions over successive decades compound upon farm structural and operational shifts in the resilience of A-NZ pastoral farming systems.

### Practical Implications

While severe summer dry conditions have become one of the key features of the A-NZ pastoral landscape, they are countered by increased (warmer) winter temperatures translating into increased pasture growth if management is optimised.

Farmers in A-NZ are among the most indebted in the world, which may reduce farm system flexibility and resilience to climate change. Changes in climatic and socioeconomic conditions in recent decades suggest that it is timely to reassess whether contemporary grazing management tools and practices are still the most effective implementation of the principles established through research over the last half century.

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