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Climate adaptation in early Australian wheat
farming (1860-1960)

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Climate adaptation in early Australian wheat farming (1860-1960)*

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Abstract

The “European” agricultural model introduced during the first British settlement in 1788 proved unsuitable for the very different Australian environment, forcing farmers to adapt creatively. This study examines how climate shaped such adaptive behavior in wheat farming in Australia from the mid-19th century until just before the green revolution. Climate adaptation is modeled using a methodology that allows one to disentangle long-term from short-term responses of farmers to climate without explicit data on adaptation. We apply this approach to digitalized historical records on sub-national wheat yields and gridded climate reanalysis data for the period 1860 to 1960. There is evidence of significant adaptation to precipitation but no adaptation to temperature for wheat yields in the long run. The results broadly coincide with how adaptations are known to have developed differently across time and regions in Australia.

JEL Codes: N00, N57, Q10, Q54

Keywords: Wheat, Climate adaptation, Colonial Australia, Agri-cliometrics

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1 Introduction

Since agriculture’s emergence about 12,000 years ago, farming practices and biological and technological innovations have continuously evolved to enable farmers to better contend with climate variations and change. For instance, archaeological evidence suggests that the Harappan civilization at Bhirrana, which thrived during the Bronze Age from approximately 3300 to 1300 BCE in the Indus Valley, adapted to declining monsoons by transitioning to more drought-resistant crops and developing water storage systems, such as reservoirs, and wells (Upreti et al., 2019). Other notable early examples include Mesopotamia (Brooke, 2014), ancient China (He, 2023), ancient Egypt (Kees, 1961), the Mayans (Haug et al., 2003), and pre-Incan farmers (Denevan, 2002), to name just a few. In terms of more recent historical contexts, during the Little Ice Age, European farmers are known to have introduced crop rotation to reduce fallow periods (Fagan, 2019), while Tello et al. (2017) argue that significant temperature decreases at the start of the English Agricultural Revolution led farmers to increase the use of organic matter and manure.¹ However, while there is little disagreement as to the importance of such adaptations to climate in the historical evolution of agriculture, a lack of relevant data for most of the past has generally prevented researchers from being able to go much beyond narrative descriptions or broad data trends to demonstrate their actual role. The aim of this study is to fill this gap by explicitly quantifying the impact of climate and adaptation to it in early Australian wheat farming, a period that witnessed the gradual shift from unsuitable English agricultural practices to farming techniques more adapted to Australia’s climate.

The wheat industry in Australia has a long history dating back to the first British settlement in 1788, with early evidence indicating that climate had an influence on the sector. As noted by Gergis et al. (2010), the settlers faced a steep learning curve due to the unfamiliar climate, requiring numerous adaptations: *“the novelty and challenges of the climate, like those of the broader environment, required adaptations and adjustments from the settlers - it was a steep learning curve. [p. 487]”*. Droughts and floods linked to El Niño and La Niña events highlighted agriculture’s vulnerability to climate changes (Gergis et al., 2010). As a matter of fact, while Australian wheat cultivation saw a large

¹Relatedly, Martínez-González (2024) show that a substantial portion of the variation in yields during the English agricultural revolution can be explained by climatic factors.

expansion of farmed land until the 1890s, this growth was accompanied by low and declining wheat yields (Davidson, 1981). By the late 19th century, Australian agriculture underwent numerous structural transformations. Advancements in farming techniques and biological innovations (Olmstead and Rhode, 2008), such as the rust-resistant wheat variety developed by William Farrer, were instrumental in tackling climatic issues (Henzell, 2007).² Arguably, these innovations, alongside the contribution of agricultural research institutions, contributed to reversing the declining wheat yields observed up to the 1890s, eventually restoring productivity levels by 1920.

Unlike the United States, where agricultural innovation was defined by a combination of biological advancements and mechanization, Australia’s innovations were driven by limits posed by its peculiar climate and poor soil quality (Lennon, 2015). As Lennon (2015) pointed out, Australian farming faced significant environmental challenges, which led to innovative solutions. To remain competitive, farmers had to quickly adopt irrigation, drainage methods, and storage systems due to barriers like limited access to fresh water and the *tyranny of distance*.³ Adaptation strategies differed by location in response to varying climatic conditions. For instance, Tasmanian farmers adapted to cold and wet conditions with small-scale farming, while Queenslanders implemented multiple planting times to cope with tropical climates. Instead, regions like Western Australia, which is characterized by low precipitation, adopted dryland farming practices.

There is a large body of literature documenting the aforementioned structural changes in Australia, as well as highlighting the role of climate in influencing these changes and its specific impact on wheat farming.⁴ For example, Stephens and Lyons (1998) emphasized that wheat yields in Australia were predominantly influenced by rainfall during the growing season. Similarly, Dunsdorfs (1957), when analyzing the “Australian wheat growing industry 1788-1948”, identified precipitation as the key driver of yield changes, whereas temperature appeared to have a less important impact. According to DoA (1922), temperature was a less important factor in explaining wheat distribution. In terms of cli-

²Similar to developments in the United States, research schools and institutions in Australia were crucial in fostering agriculture practices (Henzell, 2007; Olmstead and Rhode, 2008).

³Blainey (2001) describes how distance and isolation have been central to Australia’s history and development and coins this as the *Tyranny of Distance*.

⁴Sources including Banerjee and Shanahan (2016), Dunsdorfs (1957), Henzell (2007), Wadham (1967), and Williams (1967) documented agricultural transformations and the impact of climate in posing challenges to farmers. Dunsdorfs (1957) and Henzell (2007), for instance, argued about the role of climate in influencing these changes.

matic variability, Cornish (1950) showed that rainfall from April to October accounted for roughly 65% of yield variance in South Australia between 1896 and 1941. Dunsdorfs (1957) conducted regression analyses in all former colonies, revealing geographical differences in the relationship between precipitation and yield. Between 1884 and 1913, Copland and Hilgendorf (1920) found a strong positive correlation between wheat yield and composite precipitation in Victoria. More recently, Wang et al. (2015) found that while precipitation positively influenced wheat yield in New South Wales between 1922 and 2000, the maximum temperature had a negative impact.

Despite the well-documented historical sensitivity of early Australian wheat farming to climate, no quantitative estimate currently exists on the role of adaptive agricultural practices in mitigating these challenges, which arguably contributed to Australia’s emergence as a global player in the wheat market. Thus, the purpose of this article is to quantify farmers’ adaptive behaviors over a century (1860-1960) in early Australian wheat farming. To do so, we combine digitized administrative unit-level data on wheat area and production with local climate measures constructed from climate reanalysis data. Given the absence of historical comprehensive data on agricultural practices across space and time, we adopt the approach introduced by Mérel and Gammans (2021), which allows us to disentangle local long-term adaptations to climate from short-term responses to weather fluctuations, even without explicit information on adaptive behavior.⁵ Our findings evidence that while precipitation consistently had a positive impact on wheat yields up to a specific threshold, adaptation to rainfall became increasingly effective throughout the 20th century. This aligns with the structural transformations that occurred around the turn of the century, including technological and biological advancements alongside shifts in agricultural practices. In contrast, there is no evidence of adaptation to temperature.

The remainder of this paper is organized as follows. Section 2 describes the Australian environment and its historical context before and during the Federation era. Section 3 covers data sources and dataset compilation, whereas Section 4 highlights trends and statistics of our data. Section 5 details the methodology used to identify the climate adaptation, and presents the results of the analysis. Finally, Section 6 concludes.

⁵This method has been shown to be useful in identifying climate adaptations in a number of modern contexts, such as Cui et al. (2019), Da et al. (2024), Fileccia (2024), Kumar and Khanna (2023), Mérel and Gammans (2018, 2021), and Olper et al. (2021)

2 Background

2.1 Australia’s Environment

Australia is the sixth-largest country in the world, covering over 7.7 million square kilometers. Located in the southern hemisphere, between the Indian and Pacific Oceans, the country is well-known for its diverse landscape and climate (Cresswell et al., 2021). Its geography may be divided into three regions: the Western Plateau, the Great Plains or Central Lowlands, and the Eastern Highlands (Gentilli et al., 1951). The Western Plateau, covering nearly half of the country’s surface, is an ancient landmass shaped by erosional processes, which result in arid deserts and relatively flat sandy soils. The Central Lowlands include the Great Artesian Basin and major river systems such as the Murray-Darling Basin. This area is predominantly flat, with occasional elevated land, such as the Flinders Ranges. Although the area receives the heaviest rainfall amount, precipitation patterns are irregular, often leaving water sources dry for much of the year. The Eastern Highlands is dominated by the Great Dividing Range, recognized as the longest mountain range in Australia (Year Book, 1908) and extending from northern Queensland (QLD) through New South Wales (NSW), and Victoria (VIC). It plays a crucial role in regulating major river systems vital for agriculture and water supply and creates unique environmental conditions on its eastern and western sides (Year Book, 1908). On the east side, it causes an orographic lift, in which moist air from the ocean rises, cools, and condenses, resulting in more rainfall and green landscapes. The western side has a rain shadow effect, in which descending air warms and dries out, resulting in much lower precipitation amounts. This leads to substantially drier conditions in the interior regions, contributing to the arid and semi-arid climates in the country’s center and west.

Figure 1, adapted from Beck et al. (2018), illustrates the spatial variation in climate across Australia according to the Köppen-Geiger Climate Classification (KCC) categories. In general, Australia encompasses five primary groups and 10 out of fifteen climate types according to the KCC.⁶ The interior of the country is predominantly characterized by a desert climate, while temperate and tropical climates are more relevant along the outer

⁶Detailed landform mapping has identified 23 physiographic provinces and 220 sub-regions within these broad divisions (Pain et al., 2011). Each state features a variety of physiographic regions, highlighting the country’s diverse topography.

regions. Except for Tasmania (TAS), which has mostly an oceanic climate (although King Island has a Mediterranean climate), the other states in Australia exhibit at least three distinct climates. Western Australia (WA) and Northern QLD have tropical climates along their coasts, from monsoonal to wet and dry before changing to semi-desert further inland. The Western Plateau and Interior Lowlands have either desert or semi-desert climates. South Australia (SA) and southwest WA experience a Mediterranean climate, whilst southeast regions such as VIC and NSW range from temperate oceanic to subtropical along their coasts, gradually becoming drier or very dry further inland.

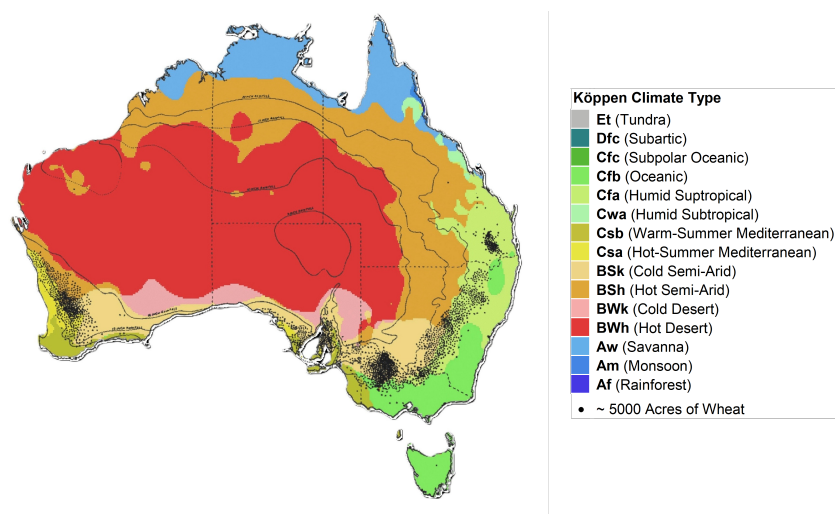


Figure 1: Köppen Climate Classification & wheat acreage distribution in 1954. Note: KCC has 5 main groups: A (tropical), B (dry), C (temperate), D (continental), and E (polar). Overlapped map of wheat acreage: 1 black dot = 5000 acres obtained from Year Book (1957).

2.2 Early Wheat Farming in Australia: From Colonization to Self-Sustenance (1788-1850)

Wheat was introduced to Australia with the arrival of the First Fleet in 1788, but the first harvest near the Parramatta River was less than successful, producing only 200 bushels.⁷ Other staple crops, such as barley, oats, and corn, also struggled to provide food for the population (Dunsdorfs, 1957). Over the following six decades, British colonists attempted to expand wheat cultivation across NSW, TAS, and later VIC, relying on the standard British agricultural model designed for the temperate climate of the British

⁷According to the Statistical Registers, 1 bushel contained around 60 pounds (lbs) of wheat, equivalent to 27 kilograms (kg) or 0.027 metric tons. on this note, 200 bushels corresponded to roughly 5,400 kg.

Isles. However, they faced considerable obstacles, including low soil fertility and dense hardwood forests. Australia’s unfamiliar climate—ranging from the hot and dry outback to the more temperate coastal areas— further posed challenges, as settlers frequently contended with droughts and unpredictable rainfall patterns. Moreover, coastal areas proved largely unsuitable for wheat growing, and the continuous reliance on traditional European methods contributed to soil degradation and inconsistent yields.

Everything was exacerbated by a government policy that granted land concessions primarily to senior officials and emancipated convicts, many of whom lacked agricultural expertise (Henzell, 2007).⁸ As a result, wheat cultivation in the early colonial period was largely intended to provide self-sustenance as an occupation for a limited group of settlers. In contrast, pastoral activities, particularly wool production, quickly gained importance. High transportation costs to the interior and the unsuitability of coastal areas for wheat farming encouraged sheep grazing and made wool a more reliable source of revenue. The government further supported sheep farming by giving newcomers enormous land grants and pastoral leases. By the 1820s, the wool industry expanded outside the hilly area, and by the 1850s, despite regional disparities, Australia provided approximately 55% of British wool imports (Clarkson, 1971).

2.3 Pre-Federation⁹ Expansion: Challenges and Innovations in Wheat Farming (1850-1890s)

The 1850s gold discovery in NSW and VIC had profound economic effects. The rush initially shifted the attention away from agriculture, as many farmers turned to gold diggers or related trades (Dunsdorfs, 1957). At the time, the mining industry, particularly copper, tin, coal, and iron ore, expanded and fostered infrastructural development and economic diversification. The gold rush caused rapid population growth, with the number of residents doubling in a decade, and increasing sixfold by 1890, boosting food consumption (Attard, 2008). Significant investments were made in railways which drastically reduced

⁸From 1788 to 1823, NSW was a penal colony with approximately 850 convicts, Marine guards, and officers, led by Governor Arthur Phillip. From 1810 to 1821, however, Governor Macquarie transformed the colony into a haven where redeemed prisoners could thrive. In 1819, 857 liberated settlers cultivated an average of 46 acres (Williams, 1967).

⁹Aside from the foundation of the Commonwealth of Australia in 1901, the term “Federation” here refers to the events that occurred from the 1890s onward: e.g. “Federation” wheat variety developed by William Farrer.

transportation costs from inland farms to ports. Additionally, the construction of silos and flour mills for storage and processing improved the efficiency of export and distribution (Banerjee and Shanahan, 2016). These factors and favorable climatic conditions resulted in an expansion of wheat areas and production.

Between 1860 and 1890, wheat cultivation expanded by 5% annually, mainly in VIC, NSW, and SA. The total area under wheat grew from 644 thousand to more than 3.4 million acres (Dunsdorfs, 1957). After slowing briefly in 1880, growth resumed until 1895. This rapid expansion, however, did not come without costs. The use of inappropriate agricultural practices led to soil depletion and erosion, ultimately reducing long-term land productivity. Farmers were driven by the belief that virgin soil would offer greater returns (Dunsdorfs, 1957), and by a period of “unusually” favorable rainfall (Banerjee and Shanahan, 2016). As a result, wheat farming expanded inland from coastal areas in NSW and VIC, often onto less fertile soils. When farmers moved to less fertile lands, they significantly underestimated the climatic challenges. Practices like intensive clearing of woodlands and the use of vulnerable wheat varieties hindered wheat yield progress, which was exacerbated by the spread of black stem rust. These factors collectively contributed to significant declines in wheat yield, which fell from an average of 15.9 bushels per acre (bsh/ac) in 1860 to 8.4 bsh/ac in 1890 (Dunsdorfs, 1957).¹⁰ The effect was most severe in SA and VIC, where yields were halved.

2.4 Post-Federation Progress: Dominance and Adaptation in Wheat Farming (1900s-1960)

The wheat sector lost £2-3 million due to the 1890s economic slump and the prolonged “Federation drought” (1895–1903) (Davidson, 1981). Wheat area grew at a 17% annual rate between 1890 and 1895, but slowed to 8.4% from 1895 to 1900. The drought’s impact became more severe in the early 1900s, causing a nearly 10% decline in wheat area between 1900 and 1901. The most affected colonies were VIC and TAS, with cultivated land shrinking by 13-14%. By 1902, the drought had also severely affected QLD, where wheat cultivation shrank to barely 1,880 acres, a drastic annual decline from the previous year (Year Book, 1908). This period, however, also marked a turning point for the

¹⁰Wheat output decreased by around 135 kg per acre at the time.

Australian wheat sector, as farmers and policymakers began to recognize the need for innovation and adaptation to the local environment. Government assistance to farmers increased, with subsidies becoming more widespread (Year Book, 1908). States promoted agricultural colleges and experimental farms to provide farmers with the most up-to-date crop management information, technology, and methods: the School of Agriculture (SA, 1879), Hawkesbury Agricultural College (NSW, 1891), Dookie Agricultural College (Victoria, 1886). To address environmental constraints, a wide range of wheat varieties were imported and distributed through these experimental farms (Spennemann, 2001), attempting to improve wheat resilience.

Except for the period 1900-1902, wheat production began to accelerate, especially after 1903 when the “Federation” wheat variety was introduced. This new strain was specifically bred to thrive in Australia’s diverse and often harsh climatic conditions, offering greater resistance to drought and disease and providing higher yields (Dunsdorfs, 1957). The post-Federation era saw a wave of other agricultural innovations that transformed wheat farming. More efficient plows, seed drills, threshing machines, and tractors enabled farmers to cultivate larger areas and increase productivity. New farming strategies, such as crop rotation with cereal and annual pasture legumes, helped maintain soil fertility, while dryland farming methods, including stubble retention and contour plowing, allowed farmers to conserve moisture and optimize productivity in arid and semi-arid regions. In some regions, land reclamation projects converted previously abandoned or unusable land into productive farmland. To address water scarcity, after the establishment of the “Water Conservation and Distribution Act” in 1881 and the “Irrigation Act” in 1886, new investments were made in irrigation systems and infrastructure. Key projects that took place along the Murray Rivers in VIC, NSW, and SA were the Goulburn Weir in 1891 (GMW, 2025), the Renmark Irrigation Trust in 1893 (Tripney, 1993), and the Hume Weir opened in 1936 (MDBA, 2024). These facilitated the expansion of agriculture in areas previously constrained by limited access to water.

The share of wheat in total cropland increased rapidly until World War I. In 1895, wheat accounted for 54% of the total cultivated area, rising to over 67% by 1915 and peaking at 70% in 1930. Wheat yield, which ranged between 10 and 11 bsh/ac, rose to 13-14 bsh/ac by 1915 and 14-15 bsh/ac by 1930. The war triggered a wheat boom, with exports rising from 5-6% to 20% of global trade (Grogan, 1948). However, workforce

shortages due to conscription made it difficult to keep output levels consistent. The postwar period saw further technological improvements such as the widespread adoption of tractors, plows with more 3 to 5 furrows, pneumatic tyres, and efficient machines that combined harvesters and mechanized seeders. Scientific research, especially in soil sciences and pasture management, also contributed to substantial increases in production and efficiency (Pratley and Rowell, 2003). However, price instability exacerbated by a severe dry spell from 1918 to 1919 severely impacted productivity.¹¹ Despite these problems, the wheat industry recovered quickly in 1920, although it faced another downturn during the Great Depression, which lasted until World War II. The postwar recovery once again ushered in innovations in farming, including the increased use of fertilizers, pest control, and biological innovation, all of which increased yields. By 1960, Australia had firmly established itself as a major player in the global wheat market, thanks to the resilience and adaptability of its agricultural sector.

2.4.1 Regional transformations

The growing awareness of the country's diverse climate and regional variations was instrumental in customizing wheat farming practices to suit different environments, leading to more effective agricultural methods. As a result, the wheat belt expanded westward. SA and WA became the major wheat-growing regions, while VIC, NSW, and QLD cultivated areas continued to extend because of technological progress and environmental adaptation. In WA, for example, farmers began implementing mixed farming strategies tailored to local climate conditions. While in southwestern areas with high temperatures, deep plowing was used to manage the soil's poor fertility, in the arid eastern WA, dryland practices were adopted, including sowing drought-resistant wheat varieties. These approaches improved WA's yields to an average of 13 bsh/ac by the mid-20th century (Dunsdorfs, 1957). In SA, particularly the Eyre Peninsula and the Flinders Ranges, farmers relied on minimal tillage and stubble retention techniques to preserve soil moisture in dry conditions. SA's average yields improved from 5.6 bsh/ac in the late 1890s to 11 bsh/ac in the late 1930s, mostly caused by higher productivity of land. The increased use of both natural manure

¹¹This drought was notably documented: *"While admitting that 1915-16 was a record year, and yields per acre for 1918-19 and 1919-20 were generally below the average as the result of protracted droughts in the wheat growing States,[...].* (Year Book, 1908, p. 356)

and artificial fertilizers had a significant role in these developments. Superphosphate and other fertilizers improved soil fertility and nutrient contents, increasing water retention and making wheat more resistant to drought or excessive rains (Donald, 1965). Furthermore, bare fallowing at first and legume-based pasture rotation later became essential for maintaining soil health (Henzell, 2007).

The introduction of the stump-jump plow and the “mullenising” method facilitated the cultivation of northwestern districts of VIC, as well as some border areas in SA and NSW, together known as the Mallee region (Wadham, 1967). Cultivated lands in this region grew rapidly, increasing more than tenfold in the early 1900s, from 50,000 acres in 1890 to 2.4 million acres in 1930. Eastern regions in NSW and VIC, characterized by temperate climates, saw farmers using modern machinery, such as the stripper-harvester, to increase efficiency during wheat harvesting. In regions with irrigation, such as the Murray-Darling Basin, farmers were able to cultivate wheat year-round by utilizing extensive irrigation systems that ensured continuous cropping and an abundant harvest. Similarly, in QLD, the tropical climate, combined with the availability of irrigation in areas like the Darling Downs, allowed for multiple planting and harvesting times for specific varieties. The irrigation systems reduced dependence on seasonal rainfall, enabling farmers to manage water supply effectively and ensure adequate moisture for crops even during dry periods (Henzell, 2007). Finally, TAS, with a colder and wetter climate, allowed for a wider range of wheat varieties and growing seasons. However, farmers mostly focused on small-scale farming without crop rotation.

3 Data

3.1 Climate Data & Crop Suitability Index

This study used climate data from the Twentieth Century Reanalysis Version 3 (20CRv3) Project (Slivinski et al., 2019).¹² The 20CRv3 provides annual time series of 3-hourly analysis fields performed with a model resolution of $\sim 0.75^\circ$, which offers a globally consistent, long-term dataset suited for examining historical climate trends and variability.

¹²This project is developed by NOAA’s Physical Sciences Laboratory in collaboration with CIRES at the University of Colorado.

However, this is especially beneficial in areas where historical weather station data is few or limited (e.g. rural farming districts in Australia).¹³

Data on maximum and minimum temperatures and total precipitation were retrieved for the period 1836-2015, covering the geographical coordinates 10-44° S and 113-155° E. The extracted data were used to create both meteorological and climate variables specific to the wheat growing season (GS). The definition of the wheat GS was informed by historical sources, including *Statistical Registers* or *Year Books* of each former colony,¹⁴ as well as studies by Dunsdorfs (1957), and Cornish (1950). More recent sources, such as the International Production Assessment Division of the USDA’s Foreign Agricultural Service (IPAD, 2023), were also consulted.

As a result, variables were calculated from general sowing (April) to maturity (October), excluding the harvesting and dormancy phases. Although wheat GS varies by location,¹⁵ the exact definition of a GS for each region over time is hardly feasible. As Dunsdorfs (1957) noted, GS in Australia varies between and within states, influenced by environmental factors and evolving farmer preferences for different wheat varieties. Davidson (1981) further observed that wheat was initially in regions with a GS exceeding nine months. However, after railway expansion and the opening of inland areas, by the late 1890s, wheat was increasingly grown in regions with a GS between 5 and 9 months. While variations exist, the adoption of a fixed GS ensures consistency across the long-time series analyzed and provides a practical and coherent framework for the analysis given that the wheat statistics were available only as annual aggregates.

The total daily precipitation was accumulated over the wheat GS, and growing degree days (GDD) were computed using the formula from Method I provided by FAO (2016, (p. 3-19)) and then summed over the GS. Specifically, the mean temperature is determined

¹³Since these variables are derived from model equations rather than directly assimilated, some general concerns about accuracy might arise (Auffhammer et al., 2013). However, the 20CRv3 dataset ensures consistency in climate variables by relying on physical laws and circulation patterns (e.g., ENSO), which strongly influence Australia’s climate. Weather station data might reduce some modeling biases, although they can be largely sparse, near urban areas, and subject to changes over the long term and data gaps, which in turn determines high measurement errors. Reanalysis data mitigates these limitations by integrating historical observations with model predictions.

¹⁴For example, the *Official Year Book of South Australia 1913* states: “The cereal crops are sown at the commencement of the winter (April to May, according to district), and they make most growth before the summer. The warm weather of early summer (October-November) brings the crop to maturity, and usually secures the production of a bright, heavy grain [...]”

¹⁵Wheat is mostly farmed as a winter crop in Australia. It is sown between April and June when cooler temperatures favor growth. During spring and early summer, the crop goes through germination, vegetative development, and reproductive growth, generating tillers, leaves, and grain-filled wheat heads. Harvest typically begins in late spring and might last from November to January, depending on regional circumstances.

using the minimum and maximum temperatures for each grid cell. Thus, the degree days are calculated using 5°C as the base temperature and 27°C as the upper threshold, according to the ECOCROP database guidelines (FAO, 2022), and then accumulated over the GS.¹⁶ Additionally, when the mean temperature exceeded the upper threshold or fell below the base temperature, heating degree days (HDD) and cooling degree days (CDD) were respectively calculated.¹⁷

To preserve as much cross-sectional variation as possible, climate variables were spatially aggregated using a weighted transformation matrix based on the crop suitability index (CSI) from the Global Agro-Ecological Zone (GAEZ-FAO) database (IIASA/FAO, 2021), following the approach of Ortiz-Bobea (2021).¹⁸ Specifically, CSI data were collected from the “Suitability and Attainable Yield theme” for wheat between 1961 and 1990, selecting “low input level” and “no CO₂ fertilization” conditions, which likely reflect pre-Green Revolution agricultural practices. The CSI raster was resampled to match the climatic data resolution, and weights were used to average weather records within the historical geographic units described in the next section.

3.2 Agricultural Data

Wheat acreage and production data were collected at the county and district levels for six former colonies—NSW, QLD, SA, TAS, VIC, and WA—covering the period from 1860 to 1960. These data were digitalized from the annual official *Colonial Statistical Blue Books* (BB), *Statistical Register* (SR), and *Year Books* (YB). We focus exclusively on wheat for grain, as the quantity cultivated for hay was relatively small and not consistently documented. Wheat yield, expressed in bushels per acre, was calculated using area and production data, which accounts for land use efficiency and the efficacy of agricultural

¹⁶The base temperature represents the absolute minimum temperature required for wheat germination, while the upper threshold is the maximum absolute temperature for growth

¹⁷The Max Planck Institute’s Climate Data Operators (CDO) and the NetCDF Operators (NCO) library were used to manipulate NetCDF files and compute daily weather data. ArcGIS Pro and R were used to develop and analyze variables and data sets.

¹⁸This data set has been used in a number of historical (and contemporary) studies, including Andersson and Berger (2019), Berger (2019), Chan (2022), Fiszbein (2022), and Travieso and Westland (2024). While its primary use has been to provide weights to average climatic variables, concerns have been raised regarding the extent to which the CSI accurately captures historical wheat suitability in the nineteenth century. Nonetheless, as illustrated in Figure A.1 (Appendix A) the spatial distribution of wheat suitability in the CSI aligns closely with historical patterns of wheat cultivation, as documented by Year Book (1957).

operations.¹⁹ Yield data were further transformed to logarithms to mitigate the potential impacts of differing unit sizes and to reduce the influence of outliers that might distort actual yields. We considered yield value as missing when either area or bushel figures were not recorded (about 1%).

Our empirical analysis covers the period 1860 to 1960. The starting year of 1860 was selected to account for two factors: i) the independence of VIC and QLD from NSW in 1851 and 1859, respectively; and ii) the availability of more extensive and accurate statistical data following the 1850s (Butlin et al., 2014). The choice of the ending year 1960 was in order to exclude the onset of the Green Revolution, thereby avoiding the confounding effects of rising CO_2 , associated fertilization impacts and the shift in global mean temperature that could otherwise affect the estimated effect.

3.2.1 Historical-Geographical Units

While administrative divisions of agricultural statistics recorded in the BBs and SRs of some states remained relatively stable over time, others—such as those in NSW and WA—underwent variations in their recorded classifications. For example, the SRs of NSW provide statistics for counties and districts prior to 1879, electorates from 1880 to 1891, counties and districts from 1892 to 1921, and shires and municipalities beginning in 1922. In WA, agricultural data were reported for statistical districts, including references for the specific lots. But after 1930, these references were discontinued complicating the reallocation of newly established or restructured districts. In QLD, data were reported by petty session districts until 1948, when local authority districts replaced them. In contrast, TAS, VIC, and SA reported more consistent statistical classifications, with only minor changes in SA district boundaries over time (Marsden, 2012). However, SA statistics often included “hundreds” as a reference lot, making them easier to reconstruct.

To homogenize these data,²⁰ a *reference year* was selected for each former colony, cross-referencing historical maps (DoL and SGO, 1935; DoLS and SGO, 1906; SGO, 1935; Stanford, 1904; YB, 1906).²¹ In the case of NSW, three maps illustrating the

¹⁹Using “production” alone does not consider the varying sizes of cultivated areas while using “area” alone may overlook the effectiveness of farming practices and the implementation of fallowing/crop rotation in specific portions of the lands.

²⁰The structure of SRs varies across colony and period, with changes in recorded units, names, and the creation, division, or reorganization of districts.

²¹The chosen reference year typically corresponds to local government acts and the availability of historical maps.

administrative units were used: counties in 1906, electorates in 1892, and shires and municipalities in 1923. These maps were *georeferenced*, *digitized*, and overlaid to align with the statistical units recorded in the BBs and SRs. Counties and districts served as primary aggregation units, as they were consistently documented throughout the sample period. When a shire was divided between two counties with non-overlapping borders, these counties were merged into a single unit, termed *geographic or agricultural unit*. This approach was applied to other states as well, with results cross-verified against secondary sources, such as Marsden (2012) for SA and Dunsdorfs (1957) for WA.

3.2.2 Sample

To ensure the analysis captured both weather realizations and climate patterns (Schlenker et al., 2006), the sample was restricted to geographical units with records available for at least half of the maximum observed years (47 years). The final sample consists of an unbalanced panel of 205 agricultural units, each observed for a period ranging from 47 to 93 years, resulting in a total of 17,999 observations, representing approximately 85% of the unrestricted data set. Figure 2a illustrates the spatial distribution of wheat yield observations calculated over the period 1860-1960. A comparison of the geographical coverage of our sample to the historical wheat distribution retrieved from the Australian Year Book (1957) (see Figure 2b), confirms that the major agricultural regions within the wheat belt are well represented.

Maps were georeferenced in ArcGIS Pro using a second polynomial transformation.

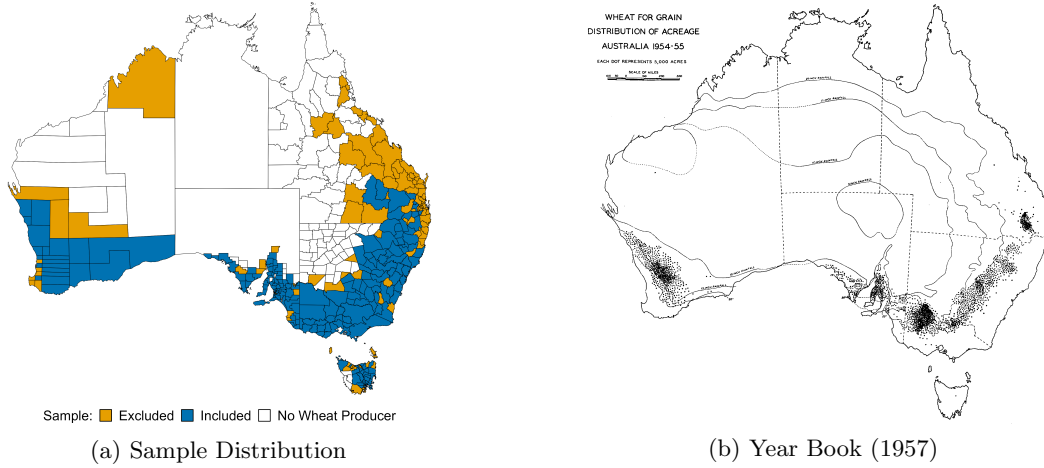


Figure 2: Wheat sample & historical distribution. Note: Fig. (a) shows districts included in the sample based on having wheat yield data for at least 50% of the observed years between 1860 and 1960. Fig. (b) shows wheat acreage in 1954, with each dot representing 5000 acres (Year Book, 1957)

4 Climate & Wheat Farming 1860-1960

4.1 Trends

Figure 3 shows the evolution of wheat planted area and total cropland, and the normalized national average wheat yield before and after the Federation in our sample data. As shown in Figure 3a, total cropland and wheat agricultural areas consistently rose from 1860 to the early twentieth century. Wheat acreage doubled within the first decade, rising from approximately 637,000 to 1.07 million acres. By 1890, it exceeded 3 million acres, accounting for nearly 60% of total cropland. This expansion was driven by economic factors such as the gold rush and infrastructure investments, and by favorable climatic conditions, where no major droughts occurred. In the post-Federation phase (Figure 3b), total cropland and planted wheat areas continued to increase until 1930, with an average annual growth rate of 6%. However, after 1930, growth slowed, and the wheat-planted area began to decline at an annual rate of approximately 1%. Wheat's share of total cropland decreased from 72% in 1930 to around 40% by the mid-20th century. This reduction may be attributed to economic challenges like the Great Depression and adverse climatic events, including the WWII drought of 1937-1945 (Gergis, 2018). Despite these challenges, the total area of wheat cultivation continued to expand, eventually surpassing

10 million acres. In contrast, the national average wheat yield declined until the late 1890s, when it reversed direction and began to increase throughout the twentieth century.

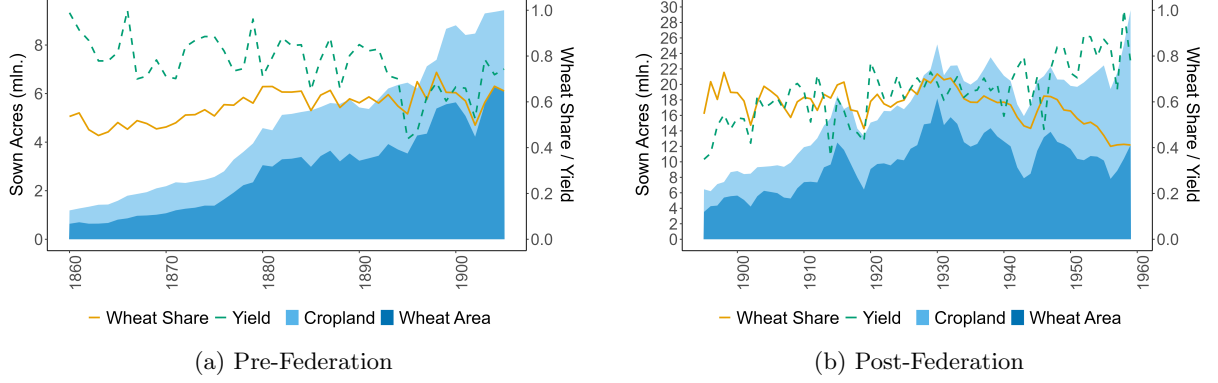


Figure 3: Wheat trends and total cropland. Note: For better understanding, state-level aggregate statistics from Dunsdorfs (1957) were used to fill gaps in administrative data. Specifically: 1860-1895 for WA; 1885-1888 & 1893-1895 for SA; 1940-1943 for NSW and QLD; and 1955-1959 for Victoria. The yellow line refers to the share of area wheat over total cropland, while the green line refers to wheat yield normalized $[0,1]$.

Wheat yield (bsh/ac) trends over the sample period, however, varied among the former colonies. Similarly to the national average, Figure 4 shows a U-shaped trend in all colonies, except for TAS and WA (owing to data limitations). This pattern is consistent with prior findings (Banerjee and Shanahan, 2016; Dunsdorfs, 1957; Henzell, 2007), as noted in Section 2. Yields in NSW varied greatly, averaging approximately 10 bsh/ac in the late 1890s and rising to over 20 bsh/ac by the 1950s. QLD followed a similar trend but with more variation, particularly during severe dry spells like those in 1895, 1902, 1917-18, and 1937. SA saw a notable reduction by the end of the 1890s, followed by a steady climb: yields increased from roughly 10 bsh/ac to nearly 22 bsh/ac on average by the mid-20th century. TAS remained relatively stable, averaging around 20 bsh/ac with minor variations. VIC experienced more dramatic oscillations: yields ranged between 10 and 20 bsh/ac until the mid-20th century, when a notable upward trend drove yields beyond 20 bsh/ac. A decline can be observed between 1895 and 1902, corresponding with the “Federation drought”. Meanwhile, WA showed an upward pattern, reaching up to 15 bsh/ac by the 1950s. Overall the yield trends across different states highlight the diverse agricultural conditions and responses to both climatic and economic factors influencing wheat farming in Australia, as discussed in Section 2.

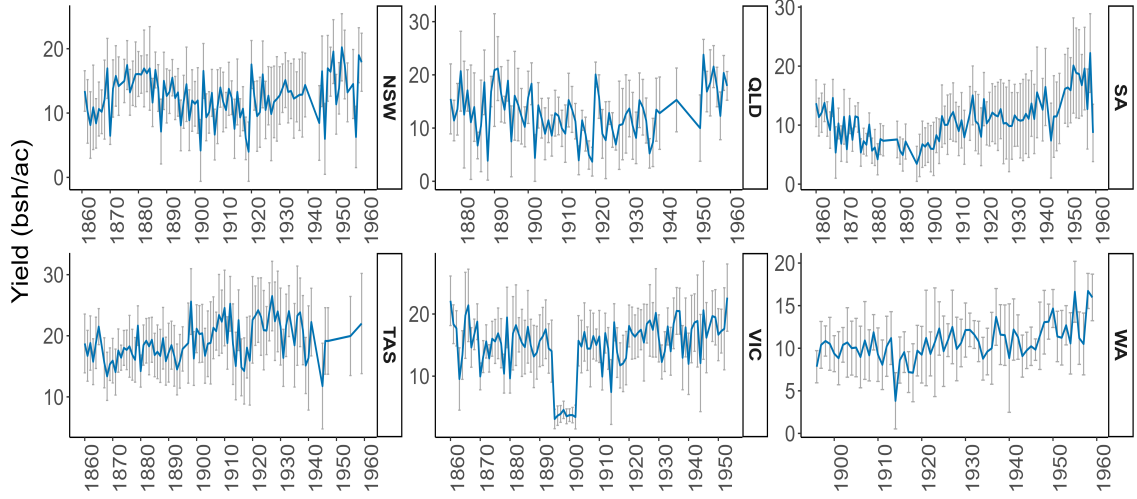


Figure 4: Wheat yield trends by former colony. Note: The gray error bars represent the standard deviation, indicating considerable variability in yields depending on the geographical units of reference within each state, while the blue lines refer to the average yield for each colony.

Regional differences can also be observed in the climatic variables in the sample. Figure 5 shows that all states have significant year-to-year fluctuation in GS precipitation, with some experiencing severe highs and lows. Most wheat-growing regions received around 250-300 mm of precipitation, except for TAS and VIC, where averages exceeded 500 mm. In NSW, precipitation varied widely, ranging from 250 mm to 750 mm, with peaks around 500-600 mm. In contrast, SA and WA recorded lower and less variable GS precipitation, typically between 200 and 400 mm. QLD saw several upper peaks exceeding 500 mm, particularly in the early and mid-20th century, alongside lower peaks below 200 mm, corresponding with well-documented Australian prolonged droughts. Notably, historical records from sources like the *Statistical Registers* indicate that only a few locations in QLD were identified as wheat-producing areas (Figure 2a). From a long-term perspective, climate precipitation trends downward after 1900 in most states apart from TAS and WA.

Unlike precipitation, GS temperature trends remained relatively stable over the observed period, exhibiting minimal year-to-year fluctuations and long-term variation across each wheat-growing region (Figure 6). TAS and VIC were the coolest regions, with typical mean GS temperature around 8-10°C, though TAS exhibited higher spatial variability. Similarly, NSW and WA experienced moderate spatial variability but higher average temperatures, with wheat-growing districts in NSW averaging 11-12°C during the GS. WA, along with SA and QLD, recorded higher GS temperatures, i.e. 12-14°C.

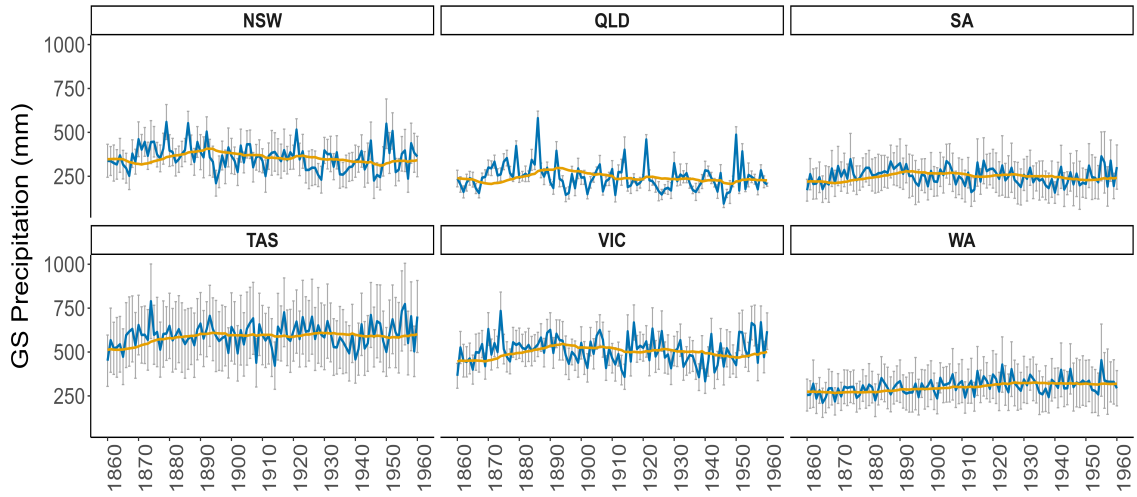


Figure 5: GS precipitation trends by colony. Note: Average across wheat-growing geographical units for each state over the wheat GS (April to October). Yearly GS precipitation is shown in blue, with gray error bars indicating its spatial variability, and a yellow line representing the 25-year moving average.

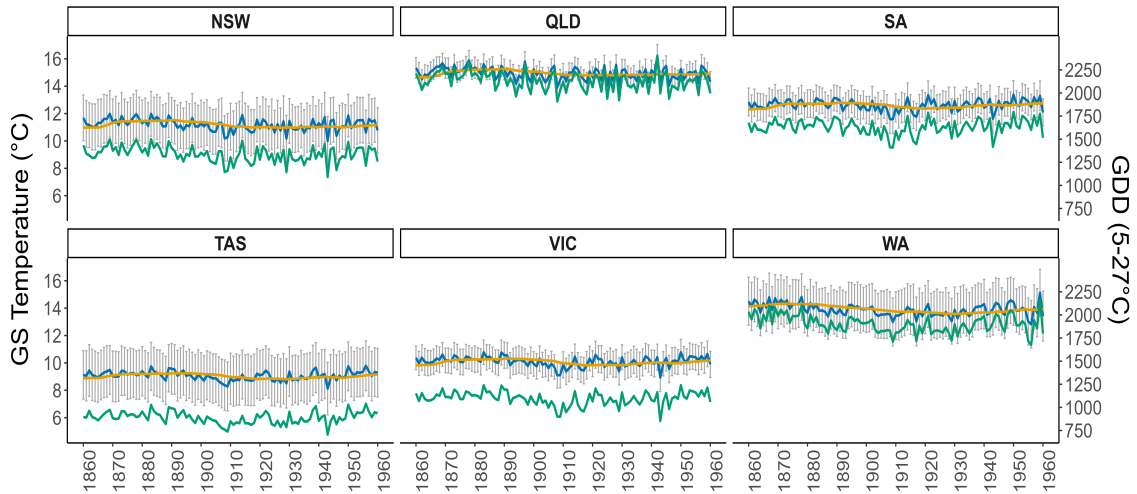


Figure 6: GS temperature and GDD trends by colony. Note: Average across wheat-growing geographical units for each state over the wheat GS (April to October). Yearly GS mean temperature is in blue, 25-year moving average is in yellow, and GDD (5-27°C) is in green.

Figure 7a illustrates the total precipitation during the GS in Australia's wheat-growing regions from 1836 to 2015. The data reveal dynamic fluctuations and a pronounced declining trend in precipitation over time, while temperature remains steady until the end of the study period. While there was not enough consistent data before 1860, historical records indicate that the wheat industry saw modest expansion prior to that period (Donald, 1965). Indeed, wheat cultivation covered less than 94,000 acres in 1836. It had only begun in VIC, while QLD and SA had yet to establish its production. Over the

following 15 years, wheat farming expanded slowly, with more significant growth occurring after 1855 as wheat became a staple crop. Precipitation patterns in Figure 7a do not indicate favorable conditions throughout this period when compared to the average sample period, aligning with findings from Gergis (2018). At the end of the 1830s, precipitation was higher than the average sample period (~ 360 mm in 1860–1960). It then decreased dramatically for about two decades, falling below Australia’s long-term average of less than 250 mm of rain per year. This tendency reversed only in the 1870s when precipitation levels returned to more beneficial levels. As discussed in Section 2, this “favorable” rainfall likely encouraged farmers to clear and cultivate in more semi-arid areas. Since 1900, alternating dry and wet periods became more pronounced, with drier years intensifying after the 1970s. GS temperature records from the pre-sample period, on the other hand, suggest relatively low averages compared to the overall mean of the sample. From 1860 onward, temperatures stabilized around the long-term average ($\sim 11.7^\circ\text{C}$), remaining consistent through the end of the observed period.

Wheat production experienced a significant and rapid increase in the years after the study period, even though the expansion in cultivated areas was comparatively moderate: by 1980, wheat acreage had doubled from 1960, totaling nearly 27 million acres. Afterward, it fluctuated between 27 and 34 million acres. In comparison, wheat production surged to 591 million bushels in 1980 and exceeded 735 million bushels by 2015, marking a fourfold increase compared to 1960—alongside an average yield of 20–21 bus/ac (Statistics, 2024). GS precipitation began to decline after 1950, with severe droughts occurring in 1967, 1976–1977, and the early 1980s, when levels dropped below 200 mm. After the late 1990s, the country witnessed persistent negative anomalies relative to the sample average (1860–1960), with average levels below 200–230 mm and a minimum of less than 50 mm (Figure 7a). This corresponds to the “Millennium Drought 1997–2009”, which led to an estimated 40% reduction in wheat production (Statistics, 2024). Regarding temperature trends, the sample period (1860–1960) exhibited relatively stable GS mean temperatures, albeit with a slight U-shaped pattern, reflecting cooler conditions in the earlier years and followed by gradual warming. However, a more pronounced increase in temperature became evident around 1950, approximately a decade before the end of the sample period.

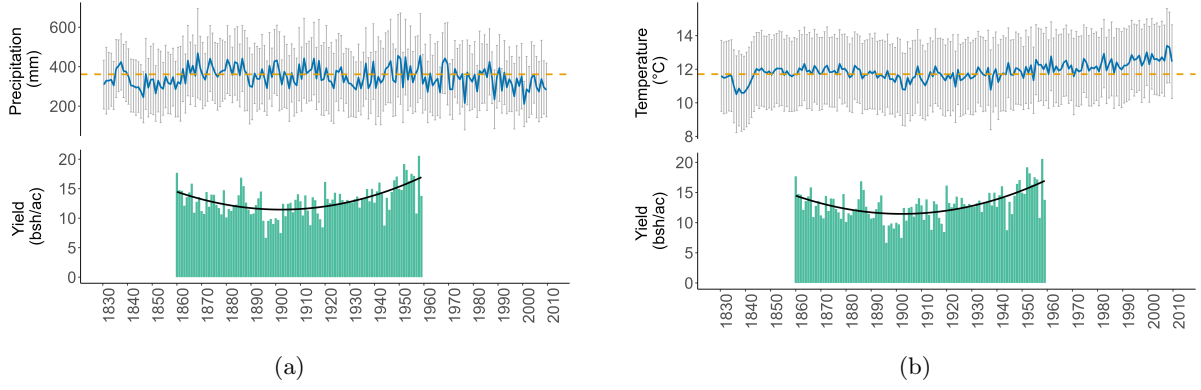


Figure 7: Weather and wheat trends during GS. Note: To simplify, mean temperature trends are displayed instead of GDD. Top graphs: gray error bars refer to std. deviation from the national mean. Bottom graphs: the black line is a polynomial regression (degree 2) that shows a U-shaped pattern in wheat yield, while the yellow dashed line is the average precipitation or temperature from 1860 to 1960.

4.2 Summary Statistics

Table 1 provides summary statistics for wheat yield, weather, and climate data used in the regression analysis from 1860 to 1960. The average wheat yield (log) is 2.36 bsh/ac, which corresponds to approximately 12.8 bsh/ac in level terms. However, with a standard deviation of 0.7, the data exhibit substantial variability across the sample. Given that a bushel of wheat weighs around 27 kilograms (60 pounds), the average yield corresponds to nearly 345 kilograms of wheat per acre. The average cultivated area is some 35,000 acres, with values ranging from less than 500 acres to a maximum of 2.35 million acres. This large variability reflects the rapid expansion of wheat cultivation over the study period, as discussed in Section 2. The average GDD for weather conditions is approximately 1428, with a range from 149 to 2965. GDD for climate follows a similar distribution, averaging approximately 1426, which aligns with historical temperature trends over the studied time. The number of HDD, representing days with temperatures exceeding 27°C during the growing season, is relatively low, suggesting that extreme heat events were infrequent within the sample period. On the other hand, precipitation (R) for weather averages 347 mm, with a maximum of 1320 mm. The distribution is positively skewed, suggesting occasional instances of exceptionally high rainfall. Similarly, climatic precipitation averages 344 mm, indicating some variation in long-term precipitation trends.

Table 1: Summary Statistics of the Sample

Variable	Unit	Mean	Min	Max	St.Dev
<i>Area(Planted)</i>	<i>000ac</i>	35.30	0.00	2357.29	103.98
<i>Yield</i>	<i>bsh/ac</i>	12.81	0.00	46.96	6.58
<i>Log(Yield)</i>	<i>bsh/ac</i>	2.36	-5.36	3.85	0.73
<i>GDD</i>	<i>5 – 27°C; (weather)</i>	1428.23	149.94	2965.05	420.69
<i>GDD</i>	<i>5 – 27°C; (climate)</i>	1426.01	186.85	2715.28	413.40
<i>HDD</i>	<i>> 27°C; weather</i>	0.03	0.00	12.17	0.27
<i>CDD</i>	<i>< 5°C; weather</i>	7.11	0.00	223.36	21.53
<i>R</i>	<i>mm; (weather)</i>	347.34	77.94	1320.20	174.51
<i>R</i>	<i>mm; (climate)</i>	344.00	125.81	1037.66	160.15

5 Climate Adaptation

5.1 Methodology

This study applies the framework developed by Mérel and Gammans (2021) to investigate the extent of climate adaptation in early Australian wheat farming. A key advantage of this approach is its ability to estimate the long-term impact of climate on an agricultural outcome through farmers’ adaptive behaviors, without using explicit adaptation data. This rests on the premise that historical observational data inherently reflect some past behaviors, including adaptation. The fundamental idea is that farmers make both short- and long-term adjustments in response to weather and climate. While some inputs, such as fertilizers, are modified in response to both weather and climate, others, like irrigation systems, are more likely to be adjusted in response to shifts in climate.

To capture climate adaptation Mérel and Gammans (2021) propose a quadratic-in-weather panel model with fixed effects augmented by climate penalty functions. The quadratic-in-weather specification captures nonlinear effects of weather on outcomes, consistent with the climate impact literature.²² Intuitively, this non-linearity acknowledges that crops typically exhibit optimal ranges for factors like precipitation or temperature, with deviations leading to diminishing returns or significant yield losses. Meanwhile, the climate penalty term, defined as the quadratic difference between current weather and the long-term climate average, indicates the extent to which outcomes deteriorate when

²²Indeed, the complex relationship between weather variables and agricultural yields has been widely debated, with linear models often criticized for their inefficiency in distinguishing the impacts of extreme weather events from those of moderate variations (Schlenker and Roberts, 2009).

current weather deviates from the climate to which agents are adapted. This penalty term thus reflects a behavioral component of farmers’ decision-making, as it reflects their adjustments in response to expected climate to maximize outcomes or when the difference between weather and climate conditions is minimized.

Importantly, Mérel and Gammans (2021)’s approach enables disentangling the long-run (LR) adaptations to climate from the short-run (SR) responses to weather variations, with the difference between the two capturing the extent of adaptation. Mérel and Gammans (2021) provide evidence that the climate penalty model is nested within a global quadratic model, where weather realizations align closely with the local climate and adaptation minimizes the deviation in the long run. As a result, if locations with historically fluctuating climates exhibit different sensitivities to weather, this suggests that these areas have adapted to their local climate. For instance, regions with persistently low precipitation may have developed drought-resistant crops, which the model can detect through greater sensitivity to precipitation compared to non-adapted regions. The model thus analyzes cross-sectional variations in climate across different geographical units by examining historical data and tracking how the relationship between weather and wheat yields evolves. By exploiting this variation and comparing the weather-outcome relationship across different regions and periods, the model identifies empirical patterns indicative of adaptation, even without explicitly relying on adaptation data.

Based on this framework, we specify our data-generating process. We assumed a non-stationary climate defined as a 25-year moving average. Intuitively, the penalty terms can be interpreted as farmers adjusting their expectations and adapting, at any point in time, based on the weather conditions experienced in previous years 25 years. The regression specification is as follows:

$$\ln(y_{it}) = \beta_1 \mathbf{x}_{it} + \beta_2 \mathbf{x}_{it}^2 + \beta_3 (\mathbf{x}_{it} - \boldsymbol{\mu}_{it})^2 + \beta_4 \mathbf{Z}_{it} + \alpha_i + \gamma_t + \epsilon_{it} \quad (1)$$

where subscripts i and t denote geographical and year units, respectively. The dependent variable $\ln(y_{it})$ is the logarithmic wheat yield. \mathbf{x}_{it} is a vector of climate variables expressed in both linear and quadratic terms, including GDD and GS precipitation R . $(\mathbf{x}_{it} - \boldsymbol{\mu}_{it})^2$ represents the climate penalty term for each variable described, where \mathbf{x}_{it} is the weather realization for a given location in a specific year, and $\boldsymbol{\mu}_{it}$ is the 25-year

moving average climate. A negative sign of its coefficients would indicate potential yield losses caused by the deviations of weather from the historical expected climate, which has been minimized by long-term adaptation.

Vector \mathbf{Z}_{it} includes control variables to account for temperature thresholds beyond GDD, such as the square root of HDD and CDD. Although this approach may complicate the interpretation of the individual effect of GDD on wheat yield, it reduces confounding effects and ensures that the estimated effect is not biased by temperature variations outside the GDD range. Controlling for these extremes also captures seasonal variations and accounts for the nonlinear nature of temperature effects. \mathbf{Z}_{it} also includes a linear trend for each geographical unit i to allow for common increasing or decreasing factors in wheat yields and climate (Cui et al., 2019).

The term α_i represents geographic-specific fixed effects, accounting for unobserved and time-invariant factors, whereas γ_t denotes year-specific fixed effects, capturing external shocks affecting all locations uniformly, such as the two world wars or fluctuations in international prices. Finally, ϵ_{it} is the error term, corrected for cross-sectional dependence and serial correlation using the Conley (1999) approach, with spatial weights based on geographical distance and the temporal lag cutoff.

We also experiment with including colony-specific quadratic time trends in an alternate specification to control for technological advancements and broader secular changes within specific locations. Additionally, given the ongoing debate regarding the suitability of GDD as a predictor of a potential nonlinear relationship with crop yield (Blanc and Schlenker, 2017), we conducted robustness tests using minimum and maximum temperatures in separate and joint alternative regressions (See A).

5.2 Results

Table 2 provides the results for our model in Equation 1, which parametrizes climate adaptation by considering deviations of weather realizations from a 25-year average climate. Column (1) shows estimates over the entire sample period from 1860 to 1960. The positive and highly significant linear coefficient for R suggests a beneficial effect of increased precipitation on wheat yields. However, the negative quadratic term indicates diminishing returns at higher levels, implying that while additional rainfall generally sup-

ports wheat growth by providing necessary water, excessive rainfall might be detrimental. The estimated maximum precipitation is approximately 583 millimeters (mm). Notably, around 90% of the geographical units in our sample received less than 583 mm, suggesting that most regions were within a range where increasing rains would have been beneficial to wheat yield. This finding is consistent with the historical literature (Dunsdorfs, 1957; Stephens and Lyons, 1998), which emphasizes the critical role of rainfall patterns in Australian agriculture. The negative and significant β_3^R coefficient on the penalty term further indicates that there was an adaptation to typical precipitation, and significant deviations (either higher or lower) from the long-term norm could affect wheat yield. For instance, a 100-mm deviation from the long-term average reduced yield by 2.6%, while a 200-mm deviation led to a 10% reduction.

The coefficient estimates on GDD, i.e., the temperature-related component, exhibit a U-shaped relationship that is not statistically significant, suggesting that it might not have played a role. The point at which the negative impact of increasing GDD on yield is minimized is estimated at 1626. Over 70% of the sample locations were below this minimum point, indicating that many regions might have experienced sub-optimal temperature conditions for optimal wheat growth. Additionally, the positive β_3^{GDD} coefficient contrasts with the expected negative sign from Mérel and Gammans (2021), which would typically indicate adaptation. This discrepancy might suggest a lack of adaptation, or even maladaptation, where deviations from the average GDD could be beneficial rather than harmful, perhaps because the climate norm is suboptimal. Alternatively, the absence of potential interactions with other factors, such as soil fertility, could also play a role; in regions with naturally poor soils or degraded, crops might be more vulnerable to temperature stress, exacerbating the negative impacts of temperature extremes and making it challenging for farmers to achieve consistent yields.

Columns (2) and (3) of Table 2 show the results for the pre-(1860-1902) and post-(1903-1960) Federation sub-samples. As can be seen, the relationship between R and wheat yield remains qualitatively consistent with the full-period results. During the pre-Federation period, the estimated optimal R beyond which additional rainfall could be damaging was around 660 mm. However, in the post-Federation period, this threshold is estimated to be around 590 mm. The higher pre-1903 maximum point in R might imply that wheat farming required more water to maximize yields during this period,

potentially due to less efficient farming practices or wheat varieties with lower drought resistance, as corroborated by the historical literature. After 1903, the lower threshold could be attributed to increased agricultural efficiency as a result of the adoption of more drought-resistant wheat varieties like Farrer’s Federation wheat, better soil management, or more effective farming techniques that allowed farmers to achieve optimal yields using less water. As for the entire period, the coefficients β_3^{GDD} capturing adaptation are not statistically significant, indicating no or limited adaptation to temperature. However, in the post-Federation (Column 3), the sign turns negative. One possible explanation is the relatively small cross-sectional variation in temperature across the studied areas, which may have resulted in minimal observable differences in adaptation.

Since the choice of a breakpoint in 1903 is arguably somewhat arbitrary, as the discussed agricultural changes took place gradually beginning in the late 1880s. We thus also tested an alternative breakpoint by defining the pre-federation period up to 1897, thus excluding the Federation drought from it (see Table A.1). Findings remain mostly unchanged, although the optimal R threshold declined to 223 mm, indicating that locations were more sensitive to too much rainfall. Nonetheless, over two-thirds of the sample units already exceeded this threshold, placing them in a range where additional rainfall likely reduced yields, possibly due to inefficient adaptive practices. This finding is consistent with historical challenges faced by farmers, where poor soil management, extensive land clearance, and reliance on traditional European farming led to soil degradation (Davidson, 1981, p.182-183). As a consequence, degraded soils may have failed to efficiently absorb and utilize additional rainfall, resulting in water-logging or erosion, thereby contributing to inconsistent and often reduced wheat yields. The coefficients β_3^R remain consistently negative. However, during the pre-Federation period, the coefficient is no longer statistically significant, whereas in the post-Federation period, it became more significant compared to the results reported in Table 2. This shift can potentially be explained by the inclusion of the Federation drought in the post-Federation period, which likely captures structural changes in farming, including the introduction of the Federation wheat variety, better irrigation practices, and other technological advancements, improved adaptation to precipitation, making yields more resilient to deviations from the expected precipitation levels.

It is also important to acknowledge that the choice of 25 years to define climate

inherently assumes a specific “long memory” of farmers. A shorter threshold, such as 10 years, would suggest more rapid adjustments in expectations (Mérel and Gammans, 2018). Determining the appropriate time horizon on which farmers base their decisions can be particularly challenging, particularly in the historical context of an unfamiliar environment. To account for this uncertainty, we conducted robustness tests under different climate definitions, considering time windows from 5 to 25 years (See Figure A.3). This did not change our results noticeably.

Overall, the results suggest that general weather conditions had a substantial impact on wheat yield. At the same time sensitivity to deviations from long-term climate norms, indicative of climate adaptation, played a significant role, particularly in the later period. The evidence suggests that adaptation to precipitation became more effective post-Federation, likely due to technological advancements and/or improved farming practices. More specifically, Australian farmers gradually developed methods to manage climatic variability (Banerjee and Shanahan, 2016; Donald, 1965, p. 204, p. 133), including the cultivation of drought-resistant crop varieties and, later, the adoption of practices such as irrigation or crop rotation to optimize soil moisture retention and better cope with variable precipitation levels. Over time, these strategies became more effective and consistent. However, adaptation to temperature was not apparent, suggesting that this climatic factor might not have had an impact over the observed period. The results remain largely the same when controlling for secular changes or substituting GDD with minimum and maximum temperature as explanatory variables. Precipitation remains statistically significant across all other specifications (See Tables A.2 and A.3), while the coefficients for minimum and maximum temperature adaptation change depending on the model specification. Generally, the findings suggest that higher minimum temperatures benefited yield, while higher maximum temperatures were detrimental.

Table 2: Regression results of wheat yield

	(1)	(2)	(3)
$\beta_3^R * 10^4$	-0.02669* (0.01212)	-0.05054* (0.02088)	-0.03582** (0.01161)
$R * 100$	0.31840*** (0.04091)	0.16020* (0.07336)	0.38350*** (0.04526)
$(R * 100)^2$	-0.02727*** (0.00354)	-0.01219 (0.00649)	-0.03206*** (0.00392)
$\beta_3^{GDD} * 10^4$	0.02324 (0.01289)	0.11460** (0.02876)	-0.00327 (0.01335)
$GDD * 100$	-0.02181 (0.04501)	-0.13430 (0.08922)	-0.09296 (0.04930)
$(GDD * 100)^2$	0.00067 (0.00124)	0.00304 (0.00261)	0.00114 (0.00131)
R^2	0.4446	0.5302	0.4742
$N.Obs.$	17,999	6,004	11,995
Time Period	1860-1959	1860-1902	1903-1959

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Note: a) Log(Yield) is the dependent variable (bushel per acre);
b) All specifications include the geographical unit and time-fixed effects; c) Errors in () are corrected for cross-sectional dependence ($cutoff = 250km$) and for serial correlation ($lag = 2$) (Conley, 1999).

5.3 Rolling-Window Analysis

To more thoroughly explore how the degree of adaptation may have changed over our sample period, we use rolling sub-windows of 50-year samples starting from 1860-1909 until 1909-1959 for the specification in Column (2) in Table 2. The resulting estimates are shown in Figures 8b and 8a, where the blue line represents the evolution of the climate penalty coefficient for growing degree days (GDD) and precipitation (R) and the gray error bars are their 95% confidence intervals.

As shown in Figure 8a, a clear downward trend can be seen in the context of temperature adaptation. Until the 1897 to 1946 sub-period, the coefficients were positive and, with a few exceptions, always statistically significant. The initial positive GDD penalty coefficient indicates that deviations from expected GDD substantially impacted agricultural outcomes, reflecting either a lack of adaptation to changing climatic conditions or ineffective adaptation strategies during this period. This may not have been consistently

helpful in the long term. Rather, there may have been short-term responses to weather fluctuations that resulted in a favorable outcome instantly but had negative long-term implications (Aragón et al., 2021; Chandio et al., 2020). The gradual decline in the coefficients suggests an increasing resilience or adaptation to variations in GDD over time. By the late 19th and early 20th centuries, the penalty term decreased, indicating that farmers adapted to the average climate, consistent with the historical improvements in agricultural practices and technological innovations; and a deviation from the expected climate might have led to decreasing yield.

Similarly to temperature adaptation patterns, the adaptation potential to precipitation varies throughout time. Figure 8b shows an initial increasing trend, which later declines. The initial coefficients suggest that there might have been a weak or inconsistent adaptation to precipitation, which persisted until the end of the century. Over time, however, there was a stronger and more successful adaptation, particularly during the 1897-1946 period, where the coefficients become and remain negative and statistically significant. This could reflect the adoption of better and sustained adaptive measures as described in Section 2, such as irrigation practices or drought-resistant varieties and better soil management techniques.

The patterns observed in both the GDD and R penalty coefficients suggest that there was initially little evidence of effective adaptation. However, the coefficients became more negative over time, implying increasingly effective adaptation strategies. Both figures show a considerable shift in structure in response to climate across the 1897 to 1946 sub-period. This is consistent with the historical literature that describes the period between the two centuries as crucial, where adaptation measures, such as improved agricultural practices or technological innovations, were particularly effective in increasing wheat yield and mitigating climate conditions (Banerjee and Shanahan, 2016, p. 134).

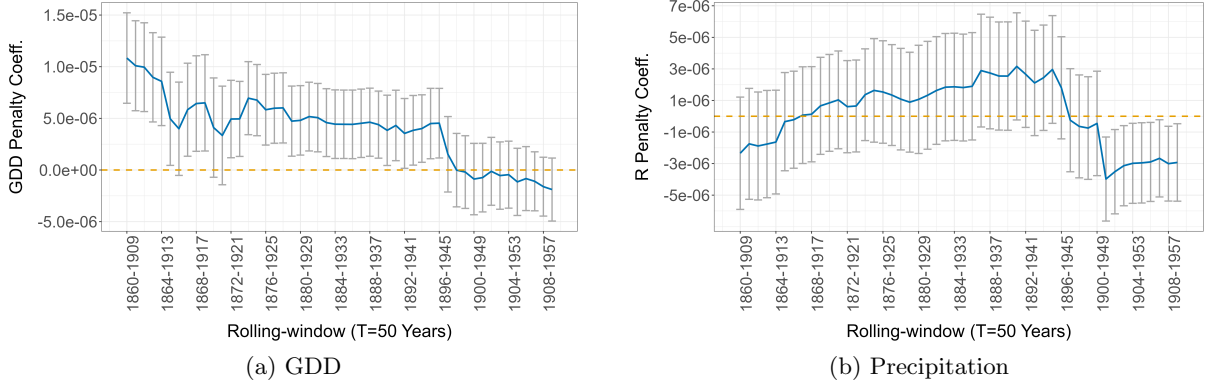


Figure 8: Climate adaptation in multiple sub-periods of 50 years

6 Conclusions

This paper investigated the extent of climate adaptation in early (1860-1960) Australian wheat farming. Our results show that precipitation was a robust and significant climatic factor in influencing wheat yields, and that adaptation to precipitation occurred over the century studied, aligning with historical narratives (Dunsdorfs, 1957; Nicholls, 1997). Notably, a pivotal structural change in climate adaptation strategies occurred at the turn of the 20th century, i.e., during the Federation Drought, marking an increased emphasis on and commitment to adaptation efforts. In contrast, we found no evidence that temperature influenced adaption, which is also consistent with historical reports (DoA, 1922; Dunsdorfs, 1957).

It is important to emphasize that while the approach we used here allowed us to measure the degree of adaptation without having direct measures of it, one can only conjecture how important the various adjustments highlighted in the historical narratives of early Australian wheat farming actually were relative to each other. Acquiring relevant data to do so, if they can be constructed, would also allow one to relax some of the assumptions we needed to make with regard to how farmers adapt to weather and climate, and thus provide more insight into historical adaptive behavior.

More generally, the history of Australian wheat shows that climate adaptation may be a slow process. Part of the reason, at least in the Australian case, was likely that it took time for the colonial settlers to become familiar with the local terrain and climate, in particular since with wheat they were introducing a non-indigenous crop. Moreover,

most of the adaptation seems to have occurred after a drought of rare severity with extensive repercussions. Environmental catastrophes serving as trigger events in inducing adaptation have often been observed historically, such as after the 1755 Lisbon earthquake (Pereira, 2009), or the 1930s Dust Bowl (Orlove, 2005), to name a few. Moreover, like in Australia, extreme environmental events have been shown to spark greater innovation to deal with such events in the past, as was demonstrated in the case of hurricanes in the United States (Noy and Strobl, 2023).

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A Appendix

A.1 Wheat suitability index & wheat distribution in 1954

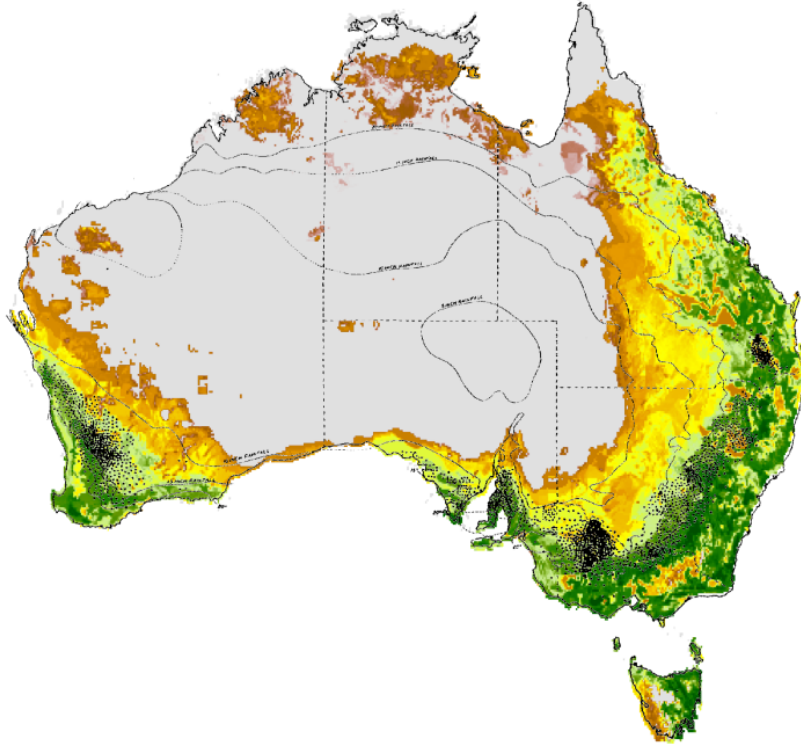


Figure A.1: Wheat suitability index in Australia from 0 to 10000 (gray to dark green) by Berger, 2019 overlapped with wheat for grain distribution of acreage in 1954 by Year Book, 1957.

A.2 Climate Trends

To identify possible climate trends in wheat-growing regions over the past century, we conducted a regression analysis of climate variables, such as precipitation and temperature, using 25-year moving averages to isolate the linear trends for each geographical unit. Figure A.2 illustrates the geographical distribution of trends in precipitation and GDD during the growing season on a per-decade basis. To simplify the interpretation of GDD trends, the figure also shows the geographical distribution of temperature trends.

Notably, regions in eastern Australia, excluding coastal areas, saw a significant reduction in precipitation over the period 1860-1960, with some areas experiencing nearly a 1% decline per decade. In contrast, western regions in WA, especially those with Mediterranean climates near the coast, experienced a notable increase in precipitation (Figure

A.2a), with some areas registering a 3% rise. Additionally, certain regions in SA and Tasmania also saw an increase in climate precipitation. Similarly, regions in southern QLD and Tasmania experienced a temperature rise (0.02-0.04 degrees per decade), while in SA, the increase was even higher, ranging from 0.05 to 0.075 degrees per decade, leading to an increase in GDD. Conversely, more inland areas in NSW became progressively colder over the decades. Most of WA experienced a temperature reduction of approximately -0.02 to -0.06 degrees per decade as shown in Figure A.2b.

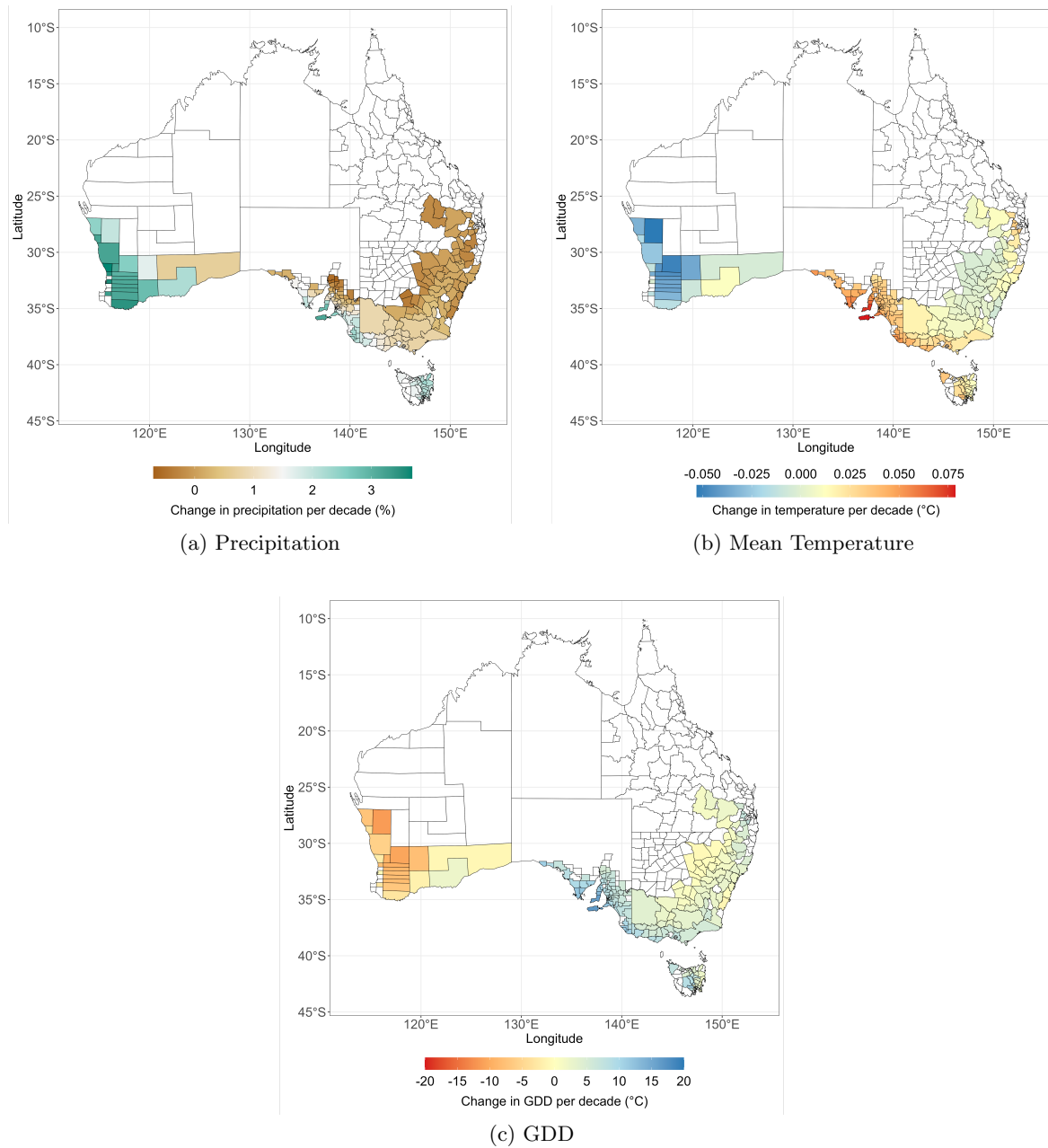


Figure A.2: Climate trends in wheat-producing areas per decade, 1860-1960

A.3 Robustness Tests

Table A.1: Regression results of wheat yield. Breakpoint: 1897 (based on Rolling Windows analysis)

	(1)	(2)	(3)
$\beta_3^R * 10^4$	-0.02669* (0.01212)	-0.03487 (0.02394)	-0.04379*** (0.01194)
$R * 100$	0.3184*** (0.04091)	0.1772 (0.07838)	0.3996*** (0.04480)
$(R * 100)^2$	-0.02727*** (0.00354)	-0.00039 (0.00594)	-0.03373*** (0.00399)
$\beta_3^{GDD} * 10^4$	0.02324 (0.01289)	0.08991** (0.03040)	-0.00112 (0.01353)
$GDD * 100$	-0.02181 (0.04501)	-0.1240 (0.09454)	-0.0579 (0.05108)
$(GDD * 100)^2$	0.00067 (0.00124)	0.00219 (0.0028)	0.00132 (0.00135)
R^2	0.4446	0.5529	0.4742
$N.Obs.$	17,999	4,661	13,338
Time Period	1860-1959	1860-1896	1897-1959

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Note: a) Log(Yield) is the dependent variable (bushel per acre);
b) All specifications include the geographical unit and time-fixed effects;
c) Errors in () are corrected for cross-sectional dependence ($cutoff = 250km$) and for serial correlation ($lag = 2$) (Conley, 1999).

Table A.2: Regression results of wheat yield, State-specific quadratic time trends

	(1)	(2)	(3)
$\beta_3^R * 10^4$	-0.04461*** (0.006577)	-0.04850** (0.01990)	-0.04160*** (0.007912)
$R * 100$	0.4179*** (0.02526)	0.4606*** (0.06125)	0.4094*** (0.03499)
$(R * 100)^2$	-0.02878*** (0.002557)	-0.03157*** (0.006391)	-0.03076*** (0.003210)
$\beta_3^{GDD} * 10^4$	0.02732*** (0.005659)	0.13190*** (0.01657)	-0.000736 (0.007533)
$GDD * 100$	-0.07719** (0.02619)	-0.09457 (0.05076)	-0.04929 (0.04108)
$(GDD * 100)^2$	-0.000163 (0.000814)	0.00176 (0.00168)	-0.000247 (0.00117)
R^2	0.3817	0.5475	0.3936
$N.Obs.$	17,999	6,004	11,995

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Note: a) Log(Yield) is the dependent variable (bushel per acre);
b) All specifications include the geographical unit and time-fixed effects;
c) Errors in () are corrected for cross-sectional dependence ($cutoff = 250km$) and for serial correlation ($lag = 2$) (Conley, 1999).

Table A.3: Regression results of wheat yield - Min & Max Temperature

	Min	Max	Min-Max
Pen_{Prec}	-2.79e-06* (1.20e-06)	-2.64e-06* (1.18e-06)	-3.23e-06** (1.20e-06)
$Prec$	3.10e-03*** (4.08e-04)	3.18e-03*** (4.06e-04)	1.73e-04 (5.31e-04)
$(Prec)^2$	-2.67e-06*** (3.52e-07)	-2.69e-06*** (3.49e-07)	-8.26e-07* (3.80e-07)
Pen_{Tmin}	8.48e-02 (6.13e-02)		-4.51e-02 (1.46e-01)
$Tmin$	5.52e-02 (1.12e-01)		6.51e-01* (3.19e-01)
$(Tmin)^2$	-7.39e-04 (4.48e-03)		2.56e-02* (1.28e-02)
Pen_{Tmax}		1.05e-01* (5.35e-02)	1.75e-01 (1.37e-01)
$Tmax$		-5.04e-03 (1.31e-01)	-5.00e-01 (3.74e-01)
$(Tmax)^2$		-6.29e-04 (4.61e-03)	-2.60e-02 (1.33e-02)
R^2	0.444	0.444	0.450
$N.Obs.$	17999	17999	17999

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Note: a) Log(Yield) is the dependent variable (bushel per acre); b) All specifications include geographical unit fixed effects; c) Errors in () are corrected for cross-sectional dependence ($cutoff = 250km$) and for serial correlation ($lag = 2$) (Conley, 1999).

A.4 Alternative Climate Expectations

As discussed in Section 5.1, we assumed a non-stationary climate defined as a 25-year moving average, which can be intuitively rephrased as the adjustment period over which farmers align their expectations and adaptation strategies based on the weather conditions they experienced in the past 25 years. Considering the learning process of farmers in understanding the Australian environment, and given the historical evolution in the understanding of climate and the practice of adapting to climate change, we explored whether using different time spans to define climate, meaning shorter adjustment periods over which farmers align their expectations, would influence the sign and significance of the adaptation coefficient during the study period. Specifically, we tested alternative values for the averaging period T , ranging from 5 to 24 years, to determine if farmers might have based their expectations on shorter time frames for both precipitation (R) and growing degree days (GDD).

For precipitation, the results remained robust to all climate definitions longer than five years. As shown in Figure A.3 (top), the climate penalty coefficients for precipitation consistently fall between -0.02 and -0.04 for a (squared) deviation of 100 millimeters, regardless of the specific frame used to define climate. This stability may suggest that farmers' adaptive practices were relatively consistent with respect to precipitation, and they likely relied on longer-term climate trends when adjusting their strategies. In contrast, the results for GDD exhibit a downward trend when the climate is defined based on different time frames (Figure A.3 (bottom)). However, independently of the definition of climate, the coefficient for climate adaptation remains statically insignificant. This suggests that farmers did not base their decisions on long-term temperature averages; that is to say, there was likely no adaptation to GDD in the sample period.

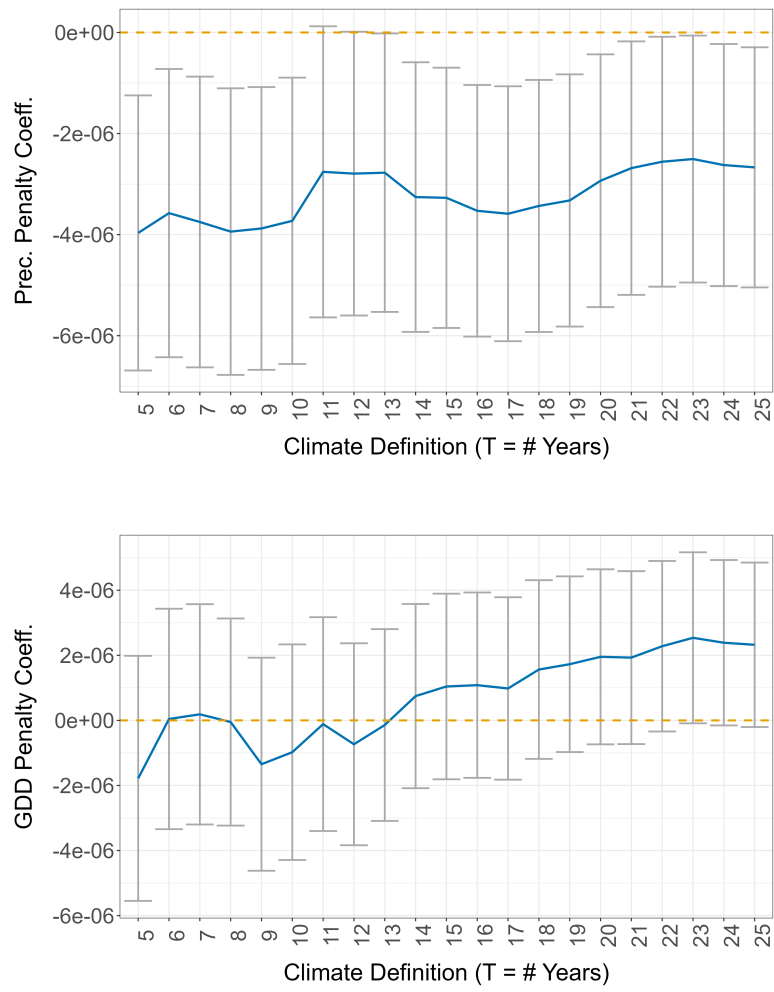


Figure A.3: Climate adaptation in multiple sub-periods of 50 years

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