The spatial response of water-limited wheat yield to historical climate change across Western Australia since 1900

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Abstract
Climate change has affected crop yield potential in major rain-fed crop growing regions in Australia, including Western Australia (WA). Understanding changes in potential crop production due to past climate change can help guide the adaptation of cropping systems to future climate change. However, the spatial response of water-limited yield potential to historical climate change across the wheatbelt of WA is unclear. This research used APSIM (Agricultural Production Systems sIMulator) to simulate and map the spatial-temporal changes in water-limited wheat yield potential on ~5 km × ~5 km climate grids for 117 years (1900-2016) across WA. Observed decreases in rainfall resulted in a shift in the regional pattern of wheat yield potential towards the southwest by 70 km. Future climate change is likely to continue to impact water-limited wheat yield and its spatial pattern in WA. Cropping systems will need to continually evolve to cope with a changing climate, requiring improvements in every aspect of agronomy and genetics.

Key Words
Climate change, wheat, yield, APSIM model

Introduction
Climate change has potentially impacted crop yield potential in many dryland cropping regions, where rainfall is the most important factor determining year-to-year variation in crop production potential (Ludwig et al., 2009). The wheat belt of WA, an important wheat-growing region producing an average of 36% of the total Australian wheat yield, is one of these regions. This region has experienced changes in climate since 1900, with a notable decrease in annual rainfall (from 288 mm to 219 mm) and increase in temperature (from 13.6 ºC to 14.3 ºC) during wheat growing season (May-October) () (Fletcher et al., submitted). These changes lead to the question, what effect this observed climate change has had on water-limited yield potential (Lobell and Field, 2007) and its distribution across the WA wheat belt. The results would provide useful insights for managing future changes in climate.

Crop models, including APSIM, combined with climate data and soil properties, have been widely used in climate change analyses. We used the APSIM wheat module to simulate the impact of climate change on water-limited yield of wheat in a continuous wheat system with a cropping intensity of one crop per year throughout the WA wheatbelt region by combining geographically explicit historic climate data and soil type data. The results were mapped to provide a visual representation of how climate change has affected wheat production potential across WA. The aim was to identify the effect of observed historical climate change on the spatial distribution of water-limited wheat yield in the WA wheatbelt from 1900-2016.

Methods
Climate and soil data
Daily weather data, including maximum and minimum temperatures, rainfall and total solar radiation, were obtained from the SILO data-drill dataset for the period of 1900-2016 (Jeffrey et al., 2001), with a spatial resolution of 0.05° × 0.05° (~5 km × ~5 km). Ten typical soils that represent the wheatbelt of WA were used, with PAWC varying from 76 to 154 mm. The physical and hydrological parameters of these soils required by the APSIM model were obtained from disaggregated soil polygon maps (Holmes et al., 2015), with a spatial resolution of 3" x 3" (~ 90 m × 90 m).

The APSIM model and simulation set-up
The APSIM model (Holzworth et al., 2014; www.apsim.info) version 7.9 was used to simulate water-limited yield potential of wheat with 107-year (1900-2016) historical climate. The APSIM wheat module has been widely validated in the WA wheatbelt (Asseng et al., 1998, 2004), and no further validation was undertaken here.

To simulate water limited wheat yield for each climate grid and each year, a simulation was run using all soils within each climate grid and then the simulated yields were averaged by weighting the simulations based on the fractional area of each soil within the larger climate grid. Parameters for a mid-fast maturity spring wheat cultivar that is typical of the wheat belt of WA were used in all simulations. A crop was sown every year when at least 20 mm of rainfall was received within 5 days between 1 May and 30 June, or when the end of the sowing window was reached. Soil water was reset to the crop lower limit on 1 January every year, assuming maximum water use by previous crop. Soil nitrogen (N) was reset annually to a total of 50 kg N ha^{-1} at sowing. To ensure that weather was the only factor affecting crop growth, soil N was topped up by 50 kg N ha^{-1} whenever it was less than 50 kg N ha^{-1} in the top 60 cm, up to flowering, based on the rule established for determining water-limited crop yield by Hochman et al. (2016).

Analysing the impacts of climate change on the spatial patterns of water-limited wheat yield

To visualise and analyse the spatial changes in water-limited wheat yield as affected by climate change, simulated water-limited wheat yields were firstly averaged for the 117 years for each grid across the wheat belt, and it was used as a benchmark value to develop a yield isoline, using the reclassify function and contour function in ArcGIS 10.2 software. For each grid, the 117 years of simulations were divided into four periods: 1900-1934, 1935-1974, 1975-1999 and 2000-2016, as the large abrupt climate changes occurred during mid-1930s, the mid-1970s and the end of 1990s (IOCI, 2002). The yield isoline for the period of 1900-1934 was used as the baseline, those for the other three periods were compared with the baseline in terms of movement distance and direction to provide a visual representation of how and where wheat yields were impacted by climate through time.

Results

The spatial changes in water-limited wheat yield in Western Australia as affected by climate change

Average water-limited wheat yield from 1900-2016 was 3.2 t ha^{-1} across the wheatbelt of WA, which was used to derive yield isolines to compare and analyse the spatial change of yield. Figure 1 shows the maps of yield isolines for the periods of 1900-1934 (baseline), 1935-1974, 1975-1999 and 2000-2016. There was an initial small southwest shift between 1900-1934 and 1935-1974. Very little movement occurred between 1935-1974 and 1975-1999. And then there was a large movement of yield isohyet to the southwest after about the year 2000. Relative to the baseline, the yield isolines for the periods of 1935-1974, 1975-1999 and 2000-2016 moved towards the southwest of the wheatbelt, with the distances of 27, 23, and 70 km, respectively.

The patterns of the changes in wheat yield isolines corresponded to those in the isohyet (260 mm) of growing season rainfall (obtained from the rainfall during May-October for the period 1900-2016 across the wheatbelt, Figure 2). Declining growing season rainfall across the wheatbelt showed a south-westward shift by about 22, 33 and 67 km for the periods of 1935-1974, 1975-1999 and 2000-2016, respectively, relative to the baseline period (1900-1934). This is attributed to the southward shift of the subtropical ridge and the southern hemisphere polar jet stream (Sudmeyer et al., 2016). There were relatively small changes in growing season mean temperature from the baseline to the other three periods (Table 2). As a result, mean temperature isohyet shifted little.

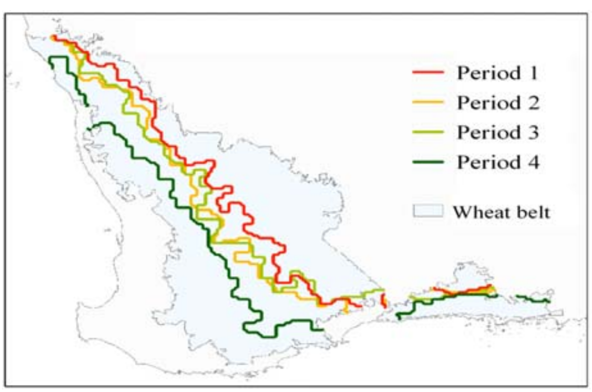

Figure 1. Maps of yield isolines (3. 2 t ha^{-1}, obtained from the average water-limited yield for the period 1900-2016 across the wheatbelt) for the periods of 1935-1974 (Period 2), 1975-1999 (Period 3) and 2000-2016 (Period 4), compared to 1900-1934 (Period 1).

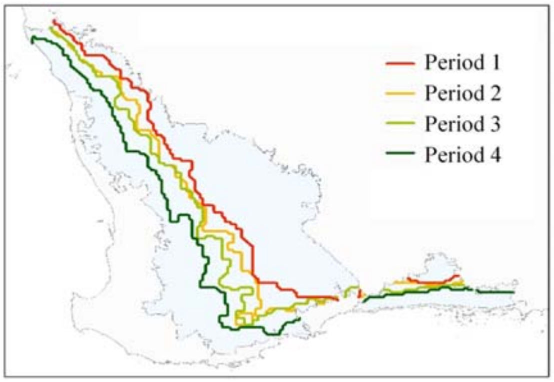

Figure 2. Maps of rainfall isohyet (260 mm, obtained from the average growing season rainfall for the period 1900-2016 across the wheatbelt) for the periods of 1935-1974 (Period 2), 1975-1999 (Period 3) and 2000-2016 (Period 4), compared to 1900-1934 (Period 1).

Table 1. The four time periods (1900-1934, 1935-1974, 1975-1999 and 2000-2016) divided in this study and the corresponding mean temperature (ºC) during wheat growing season. SD: standard deviation.

Time period	Years	Mean temperature (SD)
Period 1	1900-1934	12.9 (0.47)
Period 2	1935-1974	13.0 (0.44)
Period 3	1975-1999	13.3 (0.50)
Period 4	2000-2016	13.6 (0.63)

Actual wheat yield and water-limited yield

Western Australia's actual wheat yields have increased over the last century, with intermittent periods of progress (Figure 3). This was characterized by gradual increase (5.6 kg ha^{-1} yr^{-1}) from 1900 to mid-1970s followed by a more rapid increase (42.0 kg ha^{-1} yr^{-1}) up to the end of 1990s. Then improvement stalled from the early 2000s. Yields from 2000 onward also seemed to become less variable from season-to-season as farmers became more adept at matching inputs to rainfall. In contrast, the water-limited yield averaged across the wheatbelt showed a gradual but consistent decrease since 1900, with a rate of 1% per decade (Figure 3). The decreasing water-limited yield was gradually getting closer to the increasing actual wheat yield. This indicates that crop productivity in WA increased due to tremendous improvements in management practices and varieties against a backdrop of declining water-limited yield potential (Hochman et al., 2017).

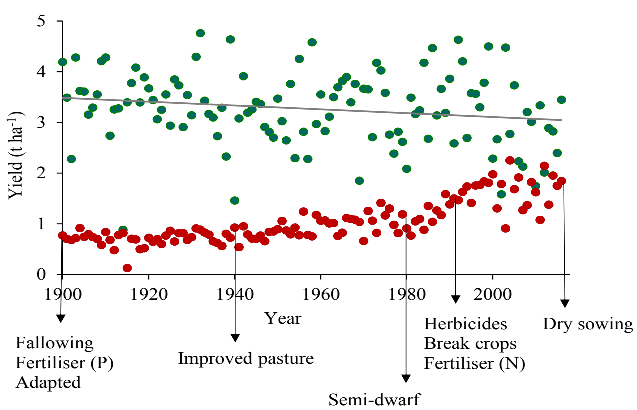

Figure 3. Time series of wheat yield produced in the wheat belt of Western Australia (red dots) and simulated water-limited yield (green dots) from 1900-2016. Approximate timing of adoption of selected management and genetic innovations are shown (modified from Kirkegaard & Hunt (2010)).

Conclusion

The present study is the first attempt to present quantitative evidence on the effect of historical climate change on the spatial patterns of water-limited crop yield in Western Australia. We found that observed decline in rainfall resulted in a shift of water-limited wheat yield by about 70 km towards the southwest of the wheatbelt. This distance was almost equal to that of rainfall, implying that the change in rainfall had the dominant effect on the change in wheat yield in this region. Although observed yields have continued to increase as farmers have implemented technological innovations such as new cultivars, earlier sowing and fertiliser. Nevertheless, observed climate change has reduced the water limited yield potential in Western Australia. The challenge for agricultural research will be to maintain or raise the yield potential of the crop by developing and adopting new varieties and technologies.

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