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Effects of high-temperature episodes on wheat yields in New South Wales, Australia

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ABSTRACT

High-temperature episodes are known to be damaging to the reproductive mechanisms of crop plants such as wheat. This damage results in a decrease in wheat yields. This study used statistical modeling, three-dimensional (3-D) plots and the Agricultural Production System Simulator (APSIM) to analyze historical wheat yield records in southern New South Wales (NSW), Australia. The aim was to quantify the effects of reproductive stage high-temperature episodes on yields and to compare the predictions of the statistical model with those of APSIM. From the statistical model, it was found that high-degree hours (HDH), a measure of the number of hours that temperatures were above a threshold level during the reproductive stages, always had a negative effect on yields. Furthermore, growing season rainfall, up to approximately 30% above average, had a positive effect. Multi-variable analysis indicated that HDH had the largest negative effect when growing season rainfall was 5–45% below average. In the warmer/drier northwestern shires, there was an average 15% yearly yield reduction due to HDH. Over the whole area, there was an average 5.3% yield reduction for each 1 °C rise in growing season average daily temperature. Averaged across the six shires, high HDH values, which would normally be associated with reproductive system damage, did not affect the accuracy of the APSIM predictions. When the statistical model predictions and the APSIM simulation predictions were tested against a later independent set (1982–2008) of weather data and observed yield records, the predictions of the statistical model (RMSE = 14.6) were more accurate than those of APSIM (RMSE = 18.9). In conclusion, when suitable climate and yield datasets are available, a combination of statistical modeling and 3-D plots is a useful way to separate the effects of high-temperature episodes and rainfall on wheat yields and identify a rainfall range where high-temperature episodes are most damaging to yields.

1. Introduction

High-temperature episodes are known to be detrimental to wheat yields (Farooq et al., 2011; Saini et al., 1983; Ferris et al., 1998; Gibson and Paulsen, 1999; Sikder and Paul, 2010; Ugarte et al., 2007; Wardlaw et al., 1989). Above average temperatures can cause accelerated plant growth development, reduced grain filling period (Sharma et al., 2008), and consequently reduced yields (Anwar et al., 2007). Above average temperatures may also lead to increased maintenance respiration resulting in decreased carbon assimilation and reduced yields (Reynolds et al., 2001; Chauhan et al., 2011). The reproductive stage of most Australian winter grown wheat varieties currently occurs in the August–September time frame. The reproductive stage is considered the weakest link in the susceptibility of wheat to high temperatures (Zinn et al., 2010; Saini and Aspinall, 1982; Porter and Semenov, 2005). High temperatures during the early reproductive stage can damage the reproductive processes, resulting in male and female sterility as well as damage to pollen tube growth and fertilization. This causes subsequent reductions in grain number and grain yield. High temperatures post-anthesis have a more marked effect on grain weight (Saini and Aspinall, 1982; Wardlaw et al., 1989; Prasad et al., 2008; Kaur and Behl, 2010; Talukder et al., 2010; Larcher, 2003). The optimum temperatures for wheat growth during the reproductive stages (terminal spikelet, anthesis, and grain filling) are approximately 12, 23, and 21 °C, respectively (Farooq et al., 2011). Temperatures above these values can significantly reduce yields. Maximum temperatures for the same reproductive stages, above which severe damage may occur, are approximately 22, 32, and 34 °C, respectively (Farooq et al., 2011). Modeling by Teixeira et al. (2013) indicated that some crops at higher latitudes, including spring wheat, were at risk from rising temperatures. For both wheat growers and plant breeders, it would be useful to be able to quantify the effects of high-temperature episodes on Australian wheat

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yields in current and future environments. It is difficult, however, to disentangle the closely correlated effects of temperature and rainfall on yields (Lobell and Burke, 2010). Statistical modeling is one method that can help to elucidate the relationship between historical wheat yields and weather variables (Lobell and Burke, 2010; Lobell et al., 2011; Nicholls, 1997). This approach can be useful when there is a sufficient period of yield and weather data available (Lobell, 2010). For wheat, few studies using time series data have examined the effects of high-temperature stress alone on Australian wheat crops. Nicholls (1997) reported that a decrease in diurnal temperature range (DTR) during the period 1952–1992 contributed to an increase in Australian wheat yields, possibly due to the increase in average minimum temperature and consequently fewer frosts, although Nicholl's use of climatic variables averaged across the continent, rather than just wheat growing areas, has been questioned by Gifford et al. (1998). Godden et al. (1998) also questioned the yield detrending method used by Nicholls and whether it properly accounted for non-climatic factors, such as the location of wheat plantings. In other studies, Lobell (2007) used Food and Agriculture Organization (FAO) of the United Nations yield statistics (1961–2002) for wheat along with gridded climate datasets and found a negative correlation between DTR and wheat yield in both Canada and Australia. There was a positive relationship in France that was attributed to increased solar radiation associated with the increased DTR. It was suggested that temperatures greater than 30 °C caused severe damage to corn, soybean, and cotton crops in the United States (Schlenker and Roberts, 2009; Lobell and Burke, 2010). A remaining difficulty with these and other statistical analyses of crop responses to the weather is identification of effects of individual weather variables on final yield, which arises from the co-variation of weather variables. For example, it may typically be warmest during dry years, obscuring effects of temperature vs. moisture on a crop. Higher than average growing season temperatures may also shorten the growing season as well as change the timing and severity of frosts.

An alternative method for examining the relationship between historical wheat yields and climatic variables is to use ecophysiological modeling. The Agricultural Production System Simulator (APSIM) (Keating et al., 2003) is a cropping simulation program that was developed in Australia. APSIM has been extensively tested in a range of environments (Wang et al., 2009b; Keating et al., 2003; Asseng et al., 2011). For example, there was a good correlation when APSIM predictions were compared with observed wheat yields for a period of over 6 years at a location near Wagga Wagga, NSW (Wang et al., 2009b). Model results were also favorable when compared with data from 17 years of commercial wheat crops from across the Australian wheat belt and with data from on-farm field experiments (Carberry et al., 2009).

Many of the simulation studies using APSIM focused on projections of future wheat crop performance using different climatic change scenarios. Historic climate records have been used as the basis of the simulations and then these are modified to reflect a range of projected temperature increases. Some of these studies focused on increased CO_2 levels in combination with increased temperatures (Luo et al., 2005; Reyenga et al., 1999; Wang et al., 2009a). Few studies have focused on temperature alone. Power et al. (2004) studied the effects of long term increase in minimum winter temperature in conjunction with El Nino Southern Oscillation (ENSO) and its effects on wheat yields at Gunnedah, in NSW. A trend in increased minimum temperatures was associated with increased wheat yield when the effects of other climatic factors were removed. Asseng et al. (2011) used APSIM to quantify the effects of temperature variability on past wheat yields in Australia and to separate the effects of temperature from other factors. They concluded that variations of average growing season temperature of as little as 2 °C could cause yield reductions of up to 50%. Most of this decline was attributed to accelerated leaf senescence at temperatures >34 °C. Another study, by Wang et al. (2009b), used the Queensland Government Specialized Information for Land Owners (SILO) weather station records to simulate Australian wheat yields using +1 °C to +4 °C of simulated warming. In most regions, simulated warming led to predictions of reduced yields.

Heat stress however, is considered to be poorly modeled in ecophysiological models (Fischer, 2011; White and Hoogenboom, 2010). APSIM does not directly model damage to reproductive organs and processes resulting from high-temperature episodes. It models the effects of high-temperature on leaf senescence and stem carbohydrate accumulation and distribution. This raises the question of whether APSIM properly accounts for yield losses resulting from high-temperature episodes during the reproductive stages and the validity of its predictions in seasons where these episodes occur.

A way of cross checking is by fitting a statistical model to a suitable time series of yield and climatic records. The yield predictions of this statistical model can then be evaluated and compared with APSIM simulation predictions while also providing further insight into the relationship between wheat yields, temperature and rainfall.

In this study, therefore, we addressed the following questions in relation to wheat yields in Australia:

- What is the relationship between yield, high-temperature episodes, and growing season rainfall?
- Can the effects of high-temperature episodes and rainfall be separated?
- Can statistical modeling reveal to what extent high-temperature episodes limit yields?
- Are APSIM predictions accurate in seasons when there are high-temperature episodes during the reproductive stages?
- Are APSIM predictions similar to predictions of an empirical statistical model when using the same time period, location, and weather data?

2. Methods

2.1. Overview

A dual approach analyzing (1) historical wheat yield and concurrent weather data along with (2) independent crop process modeling was used (Fig. 1). The first approach built a statistical model, using historical wheat yields and weather station records, and then tested this model against a later independent set of yields and weather records. The second approach simulated past yield for the same areas with the process-based APSIM model, using the same set of weather records. The results of the statistical model and APSIM simulation predictions were then compared.

2.2. Area selection

An initial consideration was the choice of region and spatial extent to include in the study. Too large an area can risk including different climatic zones together, such as areas with more dominant winter or summer rainfall, and within these zones, there may be lighter sandy soils, that drain relatively quickly, and thus, rain may be beneficial, or there may be heavier clay soils where too much rainfall during the growing season leads to water logging. For this reason, and because of the need for the cropped areas in each of the shires over the study period to be reasonably consistent, a relatively small area in the southeastern portion of the NSW wheat cropping zone was chosen for this study.