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# Modelling wheat yield change under $CO_2$ increase, heat and water stress in relation to plant available water capacity in eastern Australia

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ABSTRACT

Increasing heat and water stress are important threats to wheat growth in rain-fed conditions. Using climate scenario-based projections from the Coupled Model Intercomparison Project phase 5 (CMIP5), we analysed changes in the probability of heat stress around wheat flowering and relative yield loss due to water stress at six locations in eastern Australia. As a consequence of warmer average temperatures, wheat flowering occurred earlier, but the probability of heat stress around flowering still increased by about 3.8%–6.2%. Simulated potential yield across six sites increased on average by about 2.5% regardless of the emission scenario. However, simulated water-limited yield tended to decline at wet and cool locations under future climate while increased at warm and dry locations. Soils with higher plant available water capacity (PAWC) showed a lower response of water-limited yield to rainfall changes except at very dry sites, which means soils with high PAWC were less affected by rainfall changes compared with soils with low PAWC. Our results also indicated that a drought stress index decreased with increasing PAWC and then stagnated at high PAWC. Under high emission scenario RCP8.5, drought stress was expected to decline or stay about the same due to elevated $CO_2$ compensation effect. Therefore, to maintain or increase yield potential in response to the projected climate change, increasing cultivar tolerance to heat stress and improving crop management to reduce impacts of water stress on lower plant available water holding soils should be a priority for the genetic improvement of wheat in eastern Australia.

## 1. Introduction

Global Climate Models (GCMs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset point to a significant increase in mean temperature and marked shifts in the distribution of rainfall patterns (IPCC, 2013). In a warmer future climate, most GCMs also predict a substantial increase in the frequency and severity of extreme weather events (Alexander and Arblaster, 2009; Kharin et al., 2013). Changes in climate and extreme weather events are likely to affect agricultural crops (Barlow et al., 2015; Gornall et al., 2010; Moriondo et al., 2011; Porter and Semenov, 2005).

The occurrence of extreme high temperature during sensitive stages of crop development, such as the period around anthesis, could reduce grain yield due to its direct effect on grain number and grain weight (Stone and Nicolas, 1994; Talukder et al., 2014; Wollenweber et al., 2003). The individual grain mass and the grain set can be substantially reduced if a cultivar, sensitive to heat stress, is exposed to even a short period of high temperature around flowering (Talukder et al., 2010). For example, in a field experiment on the combine effects of $CO_2$ and temperature on the grain yield Nuttall et al. (2013) showed that a temperature of 36–38 °C around flowering (6 days after anthesis) could result in a high number of sterile grains (grain number reduced by 12%) and therefore 13% grain yield loss. A modelling study for the main wheat growing regions in Australia showed that variations in average growing-season temperature of 2 °C caused reductions in grain production of up to 50% (Asseng et al., 2011). Therefore, mitigating the impacts of heat stress on crop yield is one of crucial tasks for securing food under a future and variable climate.

Numerous simulation studies, linking projected climate data from climate models to crop models, have assessed the effects of heat and drought stress in combination or isolation on crop yield under future climate change in rainfed cropping systems (Deryng et al., 2014; Gourdji et al., 2013; Lobell et al., 2015; Semenov and Shewry, 2011). Using climate projections from the CMIP3 multi-model ensemble with

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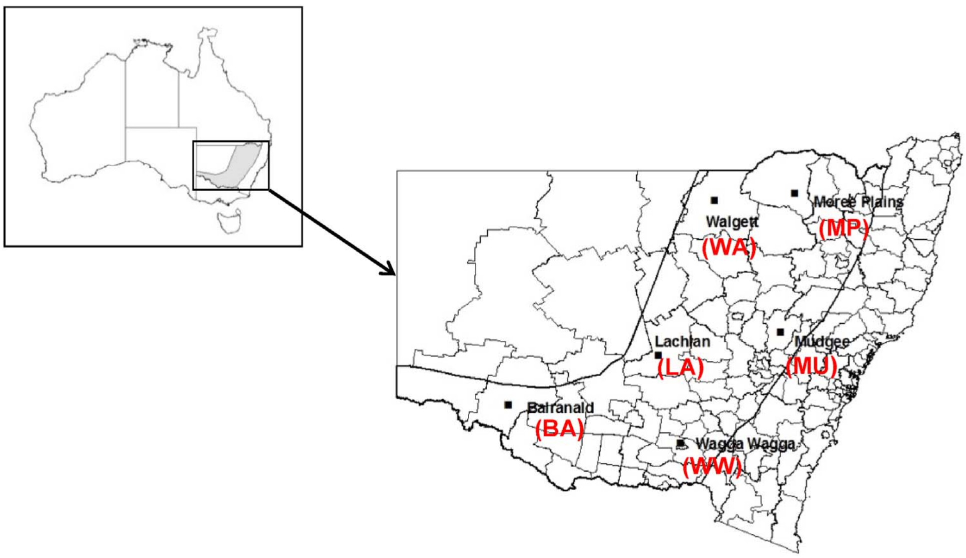


**Fig. 1.** The six selected sites (Walgett, Moree Plains, Lachlan, Mudgee, Balranald and Wagga Wagga) used in this study.

LARS-WG weather generator, Semenov and Shewry (2011) demonstrated that droughts would not increase vulnerability of wheat in Europe. It is noteworthy that relative yield losses from water stress were likely to decrease due to earlier maturity avoiding terminal drought stress. As drought could be associated with high temperature, crop experience heat and drought stress often simultaneously (Chung et al., 2014; Rezaei et al., 2015). However, Lobell et al. (2015) found that the significant direct damage to wheat crops from heat stress was increasing and estimated that aggregate yield impacts of heat stress might equal drought impacts for wheat by the mid-21st century in northeast Australia. The combination of increasing $CO_2$ and associated climate changes was likely to gradually reduce the drought impact in northeast Australia. However, previous analyses modelling the effect of water stress on wheat have been limited to using single soil types at specific sites. Furthermore, there are many uncertainties in these projections due to uncertainty in future greenhouse gas emissions. Finally, linking crop simulation models to projected climate data for the future from climate models at specific locations is not straightforward. Indeed, the spatio-temporal scale mismatches between GCMs and crop simulation models must be bridged through downscaling methods.

It is well-know that under the same climatic conditions, soil characteristics are the key to sustaining agricultural production. Soil can provide a buffer to store water and supply to the crop and therefore minimize the effects of severe drought. However, the soil's ability to support crop growth is largely dependent upon its water-holding and supply capacity. Soils with larger plant available water holding capacity (PAWC) are generally higher yielding as high PAWC can lead to more water use and reduce water leakage below the crop root zone, resulting in increased rainfall use efficiency and decreased offsite impacts (Morgan et al., 2003; Wang et al., 2009a; Wong and Asseng, 2006, 2007). Wong and Asseng (2006) showed a linear increased of measured wheat yield with soil PAWC of the top 100 cm of the soil profile in West Australia, which was consistent with crop model simulated results from Wang et al. (2009a). However, soil PAWC does not change the crop water use efficiency, but change the availability of water to crops (Wang et al., 2009a). Although efforts have been made to evaluate the impact of PAWC on crop yields, little evidence is available to prove how water stress responds to soil PAWC as a result of climate change.

The New South Wales (NSW) wheat belt contains 29.3% of the Australian wheat planted area and accounts for 28.7% of Australia's wheat production (averaged by 2003–2014) (http://www.abs.gov.au). It is among the most vulnerable regions in Australia due to its great reliance on climate. Extreme events in the NSW wheat belt have been predicted to increase in frequency, length and intensity by the end of the century (Alexander and Arblaster, 2009; Lewis and Karoly, 2013; Wang et al., 2016). However, it is not yet clear what the extent of yield losses resulting from water stress or heat stress will be under future climate change in this particular region. In addition, the lack of daily temperature and rainfall data for future climate has been a major obstacle to demonstrate the site-specific impact assessment of climate change on crop production. This study accounted for uncertainties in future climate conditions by considering two scenarios for future atmospheric greenhouse gas concentrations. We used a statistical downscaling method to downscale GCM projections from the CMIP5 ensemble to a local scale. The use of statistical downscaling in climate change studies allows exploration of the effect of changes in mean climate as well as changes in climatic variability and extreme events (Ahmed et al., 2013; Wang et al., 2016). A wheat simulation model was used to simulate impacts of climate change on wheat yield based on different soil types across a range of wheat cropping regions in eastern Australia.

The objectives of this study are to (1) quantify change in the probability of heat stress around flowering; (2) quantify the relative yield loss due to water stress across different soils. We focus on the analyses of two 30-year simulations: the first examines the time period 1961–1990 (referred to as 'present'), which was selected because a number of climate change indices were calculated using 1961–1990 as the base period (http://etccdi.pacificclimate.org/list_27_indices.shtml); the second the period 2061–2090 (referred to as 'future'), based on the latest greenhouse gas emissions and GCM projections. We here present a study in heat stress and water stress impacts on wheat involving 12 soil types for a great degree of soil variability and six represented sites across the NSW wheat growing area.

## 2. Materials and methods

### 2.1. Study sites, climate and soil data

The NSW wheat belt is located between the arid interior of Australia and the Great Dividing Range to the east. The topography is characterized by plains in the west and slopes in the east. The climate is Mediterranean (with winter-dominant rainfall) characterized by large inter-annual variations in rainfall. Six sites, representing different agro-climatic zones within the wheat belt, were selected for this study (Fig. 1). The principal characteristics of these sites are summarized in Table 1. The two northern sites (WA, MP) are relatively warm and the three western sites (WA, LA and BA) are relatively dry. Sites to the south and east are cooler and wetter, respectively.