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Crop residue incorporation can mitigate negative climate change impacts on crop yield and improve water use efficiency in a semiarid environment

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ABSTRACT

Mitigation of the deleterious impacts of climate change on agriculture is a crucial strategy for securing food resources to meet the future demand of the world with a steadily increasing population. We used a pre-validated Agricultural Production Systems sIMulator (APSIM) to explore the implementation of crop residue incorporation (RI) to mitigate the impacts of climate change on water use and crop yield for four winter crops at six sites in eastern Australia. Various residue management practices were simulated under current climate data and statistically downscaled climate data from 28 GCM simulations of RCP4.5 and RCP8.5 for the period 1900–2100. The results showed that increasing future temperature shortened crop growth duration ranged from 7.4 ± 0.9 days $^{\circ}C^{-1}$ for barley to 3.9 ± 1.9 days $^{\circ}C^{-1}$ for canola. Under projected increases in the CO_2 concentration and associated climate change, the overall average crop yield for 2021–2100 in eastern Australia without RI could change by $-28 \pm 5\%$ for wheat, $-22 \pm 6\%$ for barley, $-6 \pm 6\%$ for canola and $+7 \pm 17\%$ for chickpea relative to 1951–2000 yields. With RI, crop yields could be changed by $+16 \pm 14\%$ for wheat, $11 \pm 12\%$ for barley and $7 \pm 8\%$ for canola and $+9 \pm 17\%$ for chickpea. Further analysis showed that greater crop transpiration was the major advantage of RI. WUE in wheat and barley also increased significantly under RI due to reduced soil evaporation and surface runoff. This effect increased under future climate changes, but the effectiveness of RI varied by location. In general, the positive effects of RI on water balance and crop yield were higher at dry sites than at wet sites. Therefore, RI can be an effective adaptation option for mitigating the impacts of climate change on winter crops by improving WUE, but is more effective in narrow-leaf cropping systems in hot and dry environments.

1. Introduction

With a steadily increasing world population projected to reach 9.7 billion by the year 2050 (UN, 2015), humanity faces the challenge of securing food resources to meet future demand. The negative impacts of climate change on agriculture will enhance such challenges. Therefore, it is crucial to both mitigate climatic change impacts and explore new technologies for increasing world food production (Rosenzweig and Parry, 1994).

Grain production in Australia provides a substantial fraction of Australia's food and feed exports (Australian Bureau of Statistics, http://www.abs.gov.au/). Eastern Australia has a large region of dryland farming, that accounts for approximately 27.5% of the nation's total cultivated land area (ABS, 2015). The yields of rain-fed winter crops vary greatly from year to year, mainly because of large inter-annual variability in rainfall and extreme temperature events (Lobell et al., 2015; Wang et al., 2015). Water shortages and uneven distribution of water resources often lead to poor crop yield and low crop water use efficiency (WUE), as in dryland cropping areas else-

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where in the world (Valipour, 2014, 2015a,b; Valipour et al., 2017, 2015; Wang et al., 2009; Yang et al., 2016, 2014a). Climatic effects are exacerbated by the poor native fertility of many soils in this zone (Freebairn et al., 1993). Therefore, the exploration of farming management, such as water management (Valipour, 2015b,c, 2016b; Valipour et al., 2015), for future climate conditions is important in this region.

In Australia, until the mid-1970s, the common approach to fallow management was to remove all crop residues by burning (Freebairn et al., 1993). The agronomic advantages of burning crop residues include the following: rapid removal of residue with less labor and costs; destruction or facilitation of the germination of weed seeds; potential reduction of insect populations and the incidence of certain leaf diseases and release of minerals from residues (Hemmat and Taki, 2001). However, the negative effects of residue removal include decreased crop yield, increased soil erosion, and decreased soil organic carbon (SOC) levels and soil fertility (Lemke et al., 2010; Whitbread et al., 2000; Wilhelm et al., 1986). Additionally, the burning of crop residues can cause environmental pollution (Sharma et al., 2010).

As an alternative to burning, residue incorporation (RI) which is defined as the use of tillage implements to bury remnant plant residues into soil has traditionally been used to return organic matter to the soil and protect against erosion. Lower fuel and labor costs, as well as improved soil conservation and moisture retention, are the most commonly stated reasons for the adoption of conservation agriculture by Australian farmers (Kirkegaard et al., 2014). Because crop residues are rich in organic material and soil nutrients, crop residues returned to the soil can increase or maintain soil quality and productivity through favorable effects on soil properties (Lal and Stewart, 1995; Mulumba and Lal, 2008). Wan et al. (2011) and Hunt et al. (2013) reported that crop straw application had a positive effect on crop yield, which was attributed mainly to improved soil quality. Residue mulch at the soil surface shades the soil, serves as a vapor barrier against moisture losses from the soil, reduces surface runoff and increases infiltration rates (Foley and Silburn, 2002; Freebairn et al., 1993; Whitbread et al., 2000). Mulumba and Lal (2008) found that the addition of crop residue to cultivated soils increased the total porosity, available water content, soil aggregation and moisture content at field capacity. Zhang et al. (2014) demonstrated that WUE and crop yields were higher with straw incorporation than with conventional tillage.

Future climate change (including increasing atmospheric carbon dioxide (CO_2) concentrations, warming and changes in rainfall amounts and variability) in combination with conservation agriculture practices can significantly affect crop biomass production, SOC, soil water dynamics and other water-related ecosystem processes (Fuhrer, 2003; Luo et al., 2010). Rockström and Barron (2007) suggested that the mitigation of seasonal dry spells through crop residue management is key to improving water productivity for rain-fed agriculture. However, the effect of RI on crop production under a changing climate was not assessed.

Modelling approaches have been widely used to simulate the effects of agricultural management and climate change on soil carbon dynamics and to assess the potential capacity of carbon sequestration under conservation agriculture practices (Grace et al., 2006; Qiu et al., 2009; Rosenzweig et al., 2013; Wan et al., 2011; Zhao et al., 2013a). In Australia, several models (Chilcott et al., 2007; Liu et al., 2014, 2009) have been used to model continuous cultivation and cereal cropping systems. These models can satisfactorily predict the impact of long-term cultivation and cereal cropping on total organic carbon as well as other related attributes. Models have also been used to assess soil carbon dynamics under future climate change. For example, Liu et al. (2014) used the Agricultural Production Systems sIMulator (APSIM) model to investigate changes in SOC in southeastern Australia under simulated climate changes over the 21st century. They found that crop RI can increase SOC under both current and future climate conditions. However, the interactions between the effects of climate change and RI on crop productivity and WUE were not examined.

This study uses a modelling approach to assess the effect of the interaction of RI and future climate change on crop production, soil water balance and WUE. Ultimately, we will investigate whether RI can be an adaptation strategy for mitigating future climate change impacts on water use and crop yield in semiarid areas of eastern Australia. This study focuses on the yields of four broadacre crops, i.e., wheat (*Triticum aestivum* L), barley (*Hordeum vulgare* L), canola (*Brassica napus* L) and chickpea (*Cicer arietinum* L) at six semiarid locations in the northern to central cropping region of New South Wales (NSW), Australia (Fig. 1). Contemporary Global Climate Models (GCMs) project a warming climate for this region over the 21st century (Ekström et al., 2015). Some GCMs project an increase in annual rainfall over the century, whereas others project a decrease. In this study, we applied statistically downscaled projections from a set of 28 GCMs that reflect this warming and uncertainty in the direction of annual rainfall change. The projections also include two different scenarios for the future magnitude of the greenhouse effect on the climate system; we consider two Representative Concentration Pathways (Van Vuuren et al., 2011).

2. Materials and methods

2.1. Study sites

The six sites selected for this study were distributed across the northern to central NSW cropping region (Fig. 1). The northernmost site, Moree, has a typical subtropical climate and is characterized by a hot, wet summer and a dry winter, with an average annual rainfall of 585 mm, of which 40% occurs in May-October (Table 1). The proportion of May-October rainfall gradually increases from northern to southern sites and reaches 48% at the southernmost site, Condobolin. Among the six sites, Quirindi is the coolest (annual average of 16.7 °C) and highest rainfall (679 mm) site. In contrast, Walgett is the warmest site with relatively low average annual rainfall of 473 mm and an average annual temperature of 19.7 °C. Condobolin has the lowest average annual rainfall of 435 mm, of which only 209 mm occurs in May-October. Soil types are typically Grey Vertosol at northern sites and sandy clay over light to medium clay at southern sites (Table 1).

2.2. Climate data

Climate observations were required to drive APSIM and to correct biases in GCM output as a part of the statistical downscaling procedure (Liu and Zuo, 2012). The observed daily climate data (solar radiation, rainfall, maximum and minimum temperature) for the period 1900–2014 for each of the six study sites were downloaded from the SILO-patched point dataset (PPD) (Jeffrey et al., 2001).

More than 60 GCMs have contributed simulations to the World Climate Research Programme's (WCRP') Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset (see http://cmip-pcmdi.llnl.gov/cmip5/availability.html). Among these simulations are four different scenarios for the amount of energy added to the climate system by increasing atmospheric greenhouse gas concentrations (i.e., greenhouse forcing). These are known as Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011). However, data are not available for all GCMs for all four RCPs. In this study we used 28 GCMs with simulation data available for both RCP4.5 and RCP8.5 (Table S1). RCP 4.5 features annual greenhouse gas emissions peaking in around 2040 and then declin-