Agriculture, Ecosystems and Environment 246 (2017) 343–353

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Interactive effects of elevated CO_2, temperature and extreme weather events on soil nitrogen and cotton productivity indicate increased variability of cotton production under future climate regimes

Yui Osanai[a,⁎,1], David T. Tissue[a], Michael P. Bange[b], Michael V. Braunack[b], Ian C. Anderson[a], Brajesh K. Singh[a,c,⁎]

[a] Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, New South Wales 2751, Australia
[b] CSIRO Agriculture and Food, Australian Cotton Research Institute, Locked Bag 59, Narrabri, New South Wales 2390, Australia
[c] Global Centre for Land Based Innovation, Western Sydney University, Locked Bag 1797, Penrith, New South Wales 2751, Australia

ARTICLE INFO

Keywords:
Flooding
Drought
Elevated CO_2
Elevated temperature
Cotton (*Gossypium hirsutum* L.)
Soil nitrogen

ABSTRACT

Increased atmospheric concentration of CO_2 (C_E) and temperature (T_E), and extreme weather events, are predicted to affect future agricultural production. However, our knowledge regarding interactions between these factors is limited, thus potentially underestimating the impact of future climates on agricultural productivity. Using a large glasshouse experiment, we examined how flooding and drought events affected cotton productivity and soil nitrogen availability when grown in the current and future CO_2 and temperature regimes, and whether these responses differed between different soils. In the absence of extreme weather events, season-long T_E, and C_E to a lesser extent, significantly increased cotton yield. Flooding induced immediate physiological responses in cotton and soil nitrogen losses, leading to reduced vegetative growth and a significant yield loss under all climate regimes but particularly at T_E. Drought greatly reduced physiological processes, growth and yield under all climate regimes and resulted in a large amount of residual nitrogen in the soil, particularly at T_E. There were also small but significant differences between the two soils in some responses to flooding and drought under the current and future climate regimes. Our results demonstrated that T_E greatly increased yield in the absence of extreme weather events, however, it generated greater yield reduction following flooding and drought events, indicating that inter-annual variability in yield is likely to increase under more extreme future climates. Contrasting consequences for soil nitrogen also suggest that adaptive nutrient management will become increasingly important to secure the resilience of agricultural production under future climates.

1. Introduction

Rising atmospheric carbon dioxide (CO_2) and temperature, and associated increased frequency of extreme climate events (drought and flood), are predicted to occur in the coming decades (IPCC, 2014), and in combination may have catastrophic impacts on agricultural production. While elevated CO_2 (C_E) has the potential to increase crop productivity (Tubiello et al., 2007), the effect of elevated temperature (T_E) depends on the temperature optimum of crop species, and therefore may have either negative or positive consequences (Challinor et al., 2014; Hatfield et al., 2011). The interactive effects of C_E and T_E are not necessarily additive (Dieleman et al., 2012), making prediction of their impacts more challenging. Furthermore, water and nutrient availability strongly determines the magnitude of C_E and T_E impacts on crop productivity (Bloom et al., 2014; Li et al., 2003; Rogers et al., 1996) such that projected increases in the frequency and intensity of flooding and drought events may significantly impact crop productivity under future CO_2 and temperature regimes (Fuhrer, 2003; Porter and Semenov, 2005; Tubiello et al., 2007). Surprisingly, few studies have investigated the impact of these extreme weather events on crop productivity under future climatic conditions (Robredo et al., 2007, 2011; Shimono et al., 2012), and rarely have impacts of extreme climate been studied in conjunction with the main and interactive effects of C_E and T_E on crop productivity.

Drought and flooding may have a direct impact on crop physiology and growth by generating dry soil and waterlogged conditions. Crops under these conditions often exhibit immediate physiological responses such as reduced stomatal conductance, photosynthetic rate, water and

⁎ Corresponding authors.
E-mail addresses: yosanai@une.edu.au (Y. Osanai), b.singh@westernsydney.edu.au (B.K. Singh).
[1] Present address: School of Environmental and Rural Science, University of New England, Armidale, New South Wales 2351, Australia.

http://dx.doi.org/10.1016/j.agee.2017.06.004
Received 27 February 2017; Received in revised form 30 May 2017; Accepted 4 June 2017
0167-8809/

nutrient uptake, which can reduce the yield of many crop species (Bange et al., 2004; Farooq et al., 2009; Milroy and Bange, 2013). The magnitude of these extreme events on yield depends on the timing (Bange et al., 2004; Cannell and Belford, 1980; Shao et al., 2013; Wright et al., 1991) and duration of the event (Glaz and Lingle, 2012; Hodgson, 1982; Wright et al., 1991; Yaduvanshi et al., 2012), as well as management strategies to assist recovery (Hodgson, 1982; Huang et al., 1994; Singh et al., 2002; Sugimoto et al., 1989; Swarup and Sharma, 1993). In cotton, Bange et al. (2004) found that a waterlogging event at an early developmental stage, but not at a later developmental stage, caused a significant reduction in yield due to reduced fruit production. Waterlogging may have a direct impact on crop growth, but it may also alter soil nutrient availability to further contribute to loss of crop productivity. Indeed, nutrient addition following the flooding (waterlogging) event has been shown to alleviate the adverse impact on the yield of cotton (Hodgson, 1982), sorghum (Singh et al., 2002) and wheat (Swarup and Sharma, 1993), because flooding impairs nutrient uptake by roots and reduces soil nitrogen (N) availability through increased leaching, run-off and denitrification (Cameron and Haynes, 1986; Patil et al., 2010). Thus, the impact of flooding on soil nutrients is likely to hinder crop recovery, adding to the adverse impact of flooding on crop productivity. The impact of moderate drought on crop productivity may be reduced by adding soil nutrients (Gimeno et al., 2014; Saneoka et al., 2004), although, it is unclear whether adding soil nutrients may play a significant role in reducing crop loss under severe water limitation.

The effect of extreme weather events on crop productivity in future CO_2 and temperature regimes remains relatively unknown. In our previous study on cotton in well-watered conditions, C_E and T_E increased seed cotton yield (Osanai et al., 2017). C_E increased photosynthetic rate by 109% at ambient temperature (T_A) and by 46% at T_E, contributing to higher growth rates and greater seed cotton yield. T_E strongly accelerated the rate of vegetative growth, which resulted in greater light capturing capacity to support higher cotton yield. T_E significantly increased stomatal conductance and reduced instantaneous water use efficiency, reflecting a greater evapotranspiration demand at T_E. These changes in crop physiology at C_E and T_E may affect cotton response to flooding and drought events. For instance, T_E is likely to accelerate the onset and/or magnitude of drought stress on crops through increased evapotranspiration and soil drying, while C_E may reduce the impact of drought and flooding on crop growth by allowing crops to maintain photosynthesis and carbohydrate supply to support cellular functions under reduced stomatal conductance. Understanding the potential interactions between extreme weather events (drought and flooding) and climate change drivers (C_E and T_E) on crop physiology may provide valuable insights into the mechanisms affecting crop productivity under future climatic conditions. Such knowledge will be essential for predicting the vulnerability of crop production in future climates.

Differences in soil N availability may affect the impact of extreme weather events, particularly flooding, on crop productivity, as a function of the effect of C_E and T_E on soil N cycling and availability (Bai et al., 2013; de Graaff et al., 2006; Hovenden et al., 2008). Greater soil N availability may buffer crops from flooding-induced loss of soil N, and enhanced mineralisation may also assist crop recovery by increasing plant available N in the soil. The effect of C_E and T_E on crop productivity may differ in different soils, particularly when applied nutrients become limiting (Osanai et al., 2017), reflecting differences in their inherent capacity to supply nutrients and water. Differences in water infiltration rates, drainage and water holding capacity of soil may determine the severity and duration of soil waterlogging conditions and the magnitude of N loss during flooding events (Aulakh et al., 1991; Sogbedji et al., 2000), as well as the rate of recovery which can determine final yield (Hodgson, 1982; Malik et al., 2001). Similarly, differences in water-holding capacity of soil are likely to influence the rate of soil drying and the onset of drought stress in crops. Crop production occurs across a range of soils that differ in physical, chemical and microbial properties that can influence nutrient and water availability, yet the possible role of soils in mediating crop response to these extreme weather events are rarely explored. This lack of understanding could limit our ability to predict yield loss associated with extreme weather events, and hamper development of adequate management strategies to minimise the impact on productivity under projected future climate regimes.

Here, we set up a large glasshouse experiment to investigate the impact of flooding and severe drought events on cotton productivity in two different soils, under current (ambient CO_2 and ambient temperature; C_AT_A) and future CO_2 and temperature regimes (C_AT_E, C_ET_A and C_ET_E) in a factorial design to examine how flooding and drought may interact with the main and interactive effects of C_E and T_E. We proposed the following hypotheses:

- The flooding event will saturate the soil and have an immediate impact on cotton growth and physiology. C_E will ameliorate the impact of flooding on cotton growth by maintaining photosynthetic rate at reduced stomatal conductance, while T_E will exacerbate the impact by reduced evaporative cooling at reduced stomatal conductance. Flooding effects on yield will depend on the impact on soil N status and recovery under each climatic condition.
- Impacts of drought will be greater under T_E due to increased evapotranspiration and reduced access to soil water, leading to a greater reduction in yield. C_E will reduce the impact of the drought on yield by maintaining photosynthesis for longer periods of time under limiting water conditions. Soil N availability will play little role in mediating cotton response to severe drought.
- Given the importance of soil properties in mediating water and nutrient movements, the impact of extreme weather events on cotton productivity will differ between soils due to differences in soil characteristics.

2. Materials and methods

2.1. Soil and plant materials and climate conditions in the glasshouse

A large glasshouse experiment was set up in 2013 using two soils (grey and black vertosols) collected from two adjacent cotton growing regions in New South Wales, Australia. The majority of irrigated cotton production in Australia occurs on heavy clay soils (Cattle and Field, 2013). The grey vertosol (USDA Soil Taxonomy: Typic Haplustert) was collected at the Australia Cotton Research Institute in Narrabri (30°10′S, 149°40′E) and black vertosol (Ustic Pellustert) was collected from a farm in Spring Ridge (31°21′S, 150°12′E). Top-soil (0–20 cm) and sub-soil (20–40 cm) were collected separately at each of the two field sites, and were re-assembled into large pots (24 L; 26 × 26 × 40 cm deep). These soils differed in physical and chemical properties (Table S1). The pots were watered to field-capacity and allowed to drain for two weeks prior to planting cotton seeds.

Cotton seeds (*Gossypium hirsutum* L. Cv, 71BRF [Bollgard II® Roundup Ready Flex®], CSIRO Australia, Stiller, 2008) were sown into pots filled with grey or black vertosol, and maintained under [CO_2] and temperature treatments for *ca.* six months. Pots were fertilised with Multigro® fertiliser (8 g, 10.1% N, 3.5% P, 5.5% K, 16.3% S, 7.8% Ca, Incitec Pivot Ltd, Melbourne) and 500 mL of Aquasol® (1.6 g/L, 23.0% N, 40% P, 18.0% K, 0.05% Zn, 0.06% Cu, 0.0013% Mo, 0.15% Mn, 0.06% Fe, 0.011% B, Hortico, Vic) to achieve a N fertiliser rate of 180 kg N ha^{-1}, which is commonly applied to irrigated cotton in the field (Braunack, 2013) in addition to the pre-existing soil inorganic N. The pre-existing inorganic N for grey and black vertosols were 74 kg N ha^{-1} and 100 kg N ha^{-1}, respectively for the whole soil (i.e. combined top-soil and sub-soil). Fertiliser was applied once before cotton seeds were sown.

Four adjacent naturally lit glasshouse compartments