



Quantifying high temperature risks and their potential effects on sorghum production in Australia



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ABSTRACT

High temperatures across the Australian sorghum belt can reduce sorghum yields, but genotypic differences in heat tolerance could mitigate these yield losses. The objectives of this study were to quantify occurrences of high temperatures around anthesis of sorghum, determine their yield impacts, and assess the potential for management and genetics to minimise any adverse effects. Long term weather records for six locations across the Australian sorghum belt were used to quantify the probability of high temperature occurrence. These records were then used in a simulation study with the APSIM-sorghum model. The model was adapted to capture high temperature effects on grain yield for five hypothetical genotypes that differed in temperature threshold for effects on seed set and in tolerance to temperatures above that threshold. Results showed that the most common incidence of heat stress around anthesis was the occurrence of individual days with maximum temperatures between 36–38 °C. Because these temperatures were near the threshold limiting seed set in tolerant genotypes, an increased temperature threshold generally minimised adverse yield effects. However, 1–5 °C predicted temperature increases in coming decades will justify additional selection for increased tolerance above the threshold. Manipulation of sowing dates did not reduce risks of heat stress around anthesis, unless sowing was extremely late. Hence, genetic improvement provides the best prospect to mitigate heat stress effects on grain yield.

1. Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a major summer grain crop in dryland farming systems in NE Australia, where grain yield is often negatively affected by drought stress (Chapman et al., 2002; Bandaru et al., 2006). Hence, research on environment characterisation has focussed on the identification of prevalent drought patterns at locations throughout the sorghum belt in NE Australia (Chapman et al., 2000). However, drought is often accompanied by high temperatures and in many areas of the sorghum belt, average maximum temperatures are already exceeding 35 °C during the summer months. These maximum temperatures are likely to increase as average temperatures in Australia are predicted to increase by 1–5 °C in 2070 (CSIRO and BoM, 2007) under future climates. As a consequence, the frequency of occurrence of hot days (temperature > 35 °C) could increase by 60–80% by 2030 in eastern Australia (Hennessy et al., 2010). If this increase in frequency of heat stress events coincides with the critical development

phase around anthesis, it can significantly decrease sorghum grain yield (Lobell et al., 2015; Singh et al., 2016). Temperatures above 40 °C around flowering in sorghum growing areas have already caused widespread damage (GRDC, 2014). Lobell et al. (2015) suggested that adverse effects of climate change on grain yield in sorghum crops are likely to be a consequence of increased incidence of heat stress, rather than drought stress. Therefore, more emphasis on heat tolerance is warranted in breeding programs. However, to date, no environment characterisation of the incidence of high temperature stress in the Australian sorghum belt has been conducted, and therefore, the effects of high temperature stress on sorghum grain yield have not been quantified.

In sorghum, the development phase that is most sensitive to increased temperature occurs during a period 10–15 days around anthesis (Prasad et al., 2008; 2015; Singh et al., 2016), when grain number is determined (van Oosterom and Hammer, 2008). Although high temperatures can affect plant height (Nguyen et al., 2013; Prasad et al.,

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2008), leaf growth, and phenology (Hammer et al., 2010; Nguyen et al., 2013), the sensitivity of the period around anthesis to high temperature stress has major consequences on reproductive development, and in particular on pollen germination and seed set (Prasad et al., 2008; Nguyen et al., 2013; Singh et al., 2015, 2016). The effects of heat stress on these two traits are strongly and positively associated, suggesting that effects on pollen attributes, rather than ovule attributes, might be a major reason for reduced seed set under high temperatures (Nguyen et al., 2013; Singh et al., 2015, 2016). In addition to pollen viability, potential mechanisms include a reduction in pollen production per anther and in pollen reception per stigma (Prasad et al., 2006a,b; Nguyen et al., 2013). The critical period for adverse effects of high temperatures on pollen germination and seed set is a period of around 10–15 days immediately around flowering (Prasad et al., 2008, 2015; Singh et al., 2016).

Significant genotypic differences in pollen germination and seed set in response to high temperature stress have been observed for selected sorghum genotypes (Nguyen et al., 2013). These differences occur in both the threshold temperature at which pollen germination and seed set are affected, and in the tolerance to high temperatures above the threshold (Singh et al., 2015). Genotypes differ in the magnitude of the response of pollen germination and seed set to high temperatures during the critical period around flowering, rather than in the duration of this period (Singh et al., 2016). Because the magnitude of the reduction in seed set increases with the duration of exposure to high temperatures during this critical period (Prasad et al., 2008, 2015; Singh et al., 2016), temporal and spatial variations in temperature around anthesis are likely to cause complex genotype \times location interactions for grain yield.

Quantifying the effects of high temperature stress on grain yield of sorghum requires an integration of the spatial and temporal variation in the occurrence of high temperatures with the known genotypic variation in tolerance to high temperature. Crop growth simulation models can provide such integration, provided they have the functionality to capture genotype \times environment \times management (G \times E \times M) interactions of a complex trait like grain yield as an emergent consequence of interactions among the underpinning biological processes (Hammer et al., 2010). The sorghum model that is part of the Agricultural Production Systems sIMulator (APSIM) suite of models has this functionality (Hammer et al., 2010) and incorporation of these effects of high temperature on seed set allows an assessment of the risk of increased frequency of occurrence of high temperatures around anthesis on seed set and grain yield of sorghum in Australia. Hence, the objectives of this study were to quantify (1) the risks of occurrence of high temperature stress in the sorghum production region of NE Australia, (2) the effect of such high temperature stress on sorghum yields, and (3) the potential role of management and genetics in minimising the adverse effects of high temperature stress on grain yield.

2. Materials and methods

The effects on grain yield of the complex interactions between environmental conditions and genotypic differences in high temperature tolerance were captured by using long-term weather data from 1950 to 2008 (59 years) for six locations throughout the sorghum belt of NE Australia as input into the APSIM-sorghum simulation model (version 7.8). Weather data were obtained from the SILO patched point data set (<http://www.longpaddock.qld.gov.au/silo/index.html>). The APSIM-sorghum model was modified to include a routine to capture effects of high temperature stress on reproductive development for the 10–15 day period around anthesis (Singh et al., 2015, 2016).

2.1. APSIM-sorghum model description

The APSIM modelling platform has been specifically designed as a farming systems simulation model that can provide accurate long-term

yield estimates of crops in response to the effects of management decisions, genetic differences, crop rotations, and soil and weather conditions (Hammer et al., 1993, 2010; Holzworth et al., 2014). APSIM has a modular structure that allows easy plug-in and pull-out of modules to enable setting up simulation runs that can be tailor-made to address specific research questions. To simulate grain yield of a single crop, a simulation run requires at a minimum the inclusion of a crop module, modules to simulate soil water and soil nitrogen dynamics, a weather input file that includes details of the location, and a manager file to specify crop management decisions, such as the date, density, and depth of sowing, genotype used, and details on fertiliser application, such as the amount, type, and date of application.

The APSIM-sorghum module is based on a generic cereal template (Wang et al., 2002) and has been described in detail by Hammer et al. (2010). It can be downloaded from www.apsim.info. The model contains processes that simulate phenology, canopy development, crop growth, and nitrogen dynamics. Many of the processes have the biological functionality to allow the simulation of genotypic differences or G \times E \times M interactions for specific traits as emergent consequences of the model dynamics (Hammer et al., 2010).

Phenology is simulated through a number of development stages, using thermal time targets for each stage (Muchow and Carberry, 1990; Muchow et al., 1994). During vegetative stages, the base, optimum, and maximum temperatures are 11, 30 and 42° C, respectively (Hammer et al., 1993). The timing of panicle initiation, which signals the moment the apical meristem stops initiating new leaves and commences initiation of the panicle, is a function of day length. The total number of leaves produced is thus a function of the duration of this period and the leaf initiation rate (Muchow and Carberry, 1990). The total number of leaves produced, multiplied by the leaf appearance rate, determines the timing of the flag leaf stage. All subsequent stages use thermal time targets, although cardinal temperatures during reproductive development differ from those during vegetative phases, with a base temperature of 5.7° C, an optimum temperature of 23.5° C, and no maximum temperature (Hammer and Muchow, 1994). Canopy development is simulated on a per plant basis as the sum of the area of all fully expanded leaves on the main shoot and each tiller. The leaf area index (LAI) of the crop is subsequently calculated as the product of plant density and individual plant leaf area (Hammer et al., 2010). The LAI is used to calculate the fraction of intercepted radiation using a canopy light extinction coefficient (Lafarge and Hammer, 2002). Under optimum growing conditions, dry mass accumulation is radiation limited and is calculated as the product of incoming radiation, the fraction of intercepted radiation, and the radiation use efficiency (RUE) (Hammer et al., 2010). For triple dwarf sorghum grown in Australia, the RUE is around 1.24 g MJ⁻¹ (Lafarge and Hammer, 2002). The daily accumulated dry mass is subsequently allocated across organs in ratios that depend upon the growth stage of the crop (Hammer et al., 2010). The crop growth rate between panicle initiation and the start of grain filling determines grain number, and grain yield is calculated as the product of grain number and individual grain mass.

Under drought stress, dry mass accumulation is water limited and is the product of transpiration (water used) and the transpiration efficiency (TE) (Hammer et al., 2010). The TE is inversely related to the ambient vapour pressure deficit (VPD) (Tanner and Sinclair, 1983). Hence, if high temperatures occur during drought stress, then it is likely to have a negative effect on biomass accumulation, as increased VPD will reduce TE (Lobell et al., 2013). Effects of water limitation on individual processes are simulated through a plant water status indicator, the water supply/demand ratio, where drought stress affects the particular process if the water supply/demand ratio drops below a threshold (Hammer et al., 2001). Simulation of nitrogen dynamics in the crop is based on the crop physiological understanding that nitrogen content per unit leaf area (SLN, specific leaf nitrogen) is highly correlated to photosynthetic capacity (Sinclair and Horie, 1989). It uses a nitrogen supply/demand framework that allocates nitrogen amongst

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