Heat stress effects on grain sorghum productivity-biology and modelling

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Abstract
Heat stress can cause sterility in sorghum and the anticipated increased frequency of high temperature events implies increasing risk to sorghum productivity in Australia. Here we summarise our research on specific varietal attributes associated with heat stress tolerance in sorghum and evaluate how they might affect yield outcomes in production environments by a crop simulation analysis. We have recently conducted a range of controlled environment and field experiments to study the physiology and genetics of high temperature effects on growth and development of sorghum. Sorghum seed set was reduced by high temperature effects (>36-38^{o}C) on pollen germination around flowering, but genotypes differed in their tolerance to high temperature stress. Effects were quantified in a manner that enabled their incorporation into the APSIM sorghum crop model. Simulation analysis indicated that risk of high temperature damage and yield loss depended on sowing date, and variety. While climate trends will exacerbate high temperature effects, avoidance by crop management and genetic tolerance seems possible.

Key words
Climate change, sorghum, pollen germination, seed set

Introduction
Sorghum (*Sorghum bicolor* L. Moench) is a major summer crop in dryland farming system in NE Australia, where grain yield can be negatively affected by high temperature stress. The maximum temperature in sorghum growing areas will exceed 32^{o}C in summer months (Muchow et al. 1994) under future climate change scenarios (IPCC 2007). As a consequence, the frequency of high temperature occurrences is likely to increase. However, to date no environment characterisation of the incidence of high temperature stress in the Australian sorghum belt has been conducted and therefore effects of high temperature stress on sorghum grain yield have not been quantified.

Sorghum is most sensitive to high temperature stress around the reproductive development stage (Prasad et al. 2008; Nguyen et al. 2013; Singh et al. 2015;), although high temperatures can also affect plant height (Prasad et al. 2008; Nguyen et al. 2013), leaf growth, and phenology (Hammer et al. 2010). Importantly, significant genotypic variation in seed set response to high temperature has been observed for sorghum, both in the threshold temperature and in the tolerance to high temperatures above the threshold (Singh et al. 2015). These differences in threshold temperature around anthesis are likely to cause complex genotype by location interactions for grain yield.

The superiority of specific genotype and management combinations can vary from year to year depending on prevalent environmental conditions. Therefore, quantification of the effects of high temperature on grain yield of sorghum requires an integration of genotypic variation in tolerance to high temperatures with spatial and temporal variation in the incidence of high temperature occurrence. Crop growth simulation modelling can provide such integration. The APSIM suite of models provides a suitable platform to incorporate novel scientific knowledge on the physiology of crop growth and development (Hammer et al. 2010) into crop models, which can be combined with historical climate records to simulate the effects on crop productivity under high temperatures of changes in genetics (G), environment (E), and management (M) – the G*E*M landscape. Hence, the aims of this research were to (1) quantify genotypic differences in the response of seed set to high temperature stress, and (2) assess effects of these differences on production risks of sorghum, using long-term simulations for grain yield at Moree in the sorghum belt of Eastern Australia as an example.

Experiments

Genetic material

A diverse set of 20 sorghum genotypes, provided by the DAF/UQ sorghum breeding program, was used in the experiments. The material included parents of mapping populations, and elite lines that are parents of hybrids used in the sorghum breeding program.

Growing conditions

To quantify the physiology and genetics of high temperature effects on sorghum, experiments were conducted in controlled growth chambers at St Lucia, and in the field at Gatton, Queensland. In the first controlled environment experiment, 20 diverse sorghum genotypes were grown through to maturity at four day/night temperature ranging from 30/22°C (optimum temp - OT) to 38/22°C (high temperature - HT) without water limitation. In the second controlled environment experiment, that aimed to identify the development stage that is most sensitive to high temperature stress, plants of tolerant and susceptible genotypes were grown either at OT or HT, and then transferred between chambers at 5 day intervals starting just after flag leaf emergence. The field experiment was conducted on contrasting lines, selected from the controlled environment experiments, to validate in the field the effects observed in the controlled environments. Plants were grown either with or without specifically designed covers that raised daytime maximum temperature by about 6°C.

Observations

Pollen germination was measured using an *in vitro* pollen germination method (Nguyen et al. 2013). Panicles were harvested at physiological maturity and seed set percentage was measured (Nguyen et al. 2013).

Results

Reproductive development stage most sensitive to increased temperature

The 20 sorghum genotypes differed in the threshold at which temperature can affect seed set percentage (34-36˚C) and in the tolerance (low-high) to high temperature stress above that threshold. Temperature effects on seed set percentage were consistent between the field and control environment facility (Singh et al. 2015).
In the transfer experiment, a transfer of five days from OT to HT or from HT to OT had no effect on seed set percentage if the transfer occurred at 18 leaf stage, at flag leaf stage, or at 20 days after flag leaf stage (Fig. 1). However, the effect of transfer was greatest if the transfer occurred at 10 days after the flag leaf stage, suggesting that the 10-15 day period just before and around anthesis is the period most sensitive to high temperature stress.

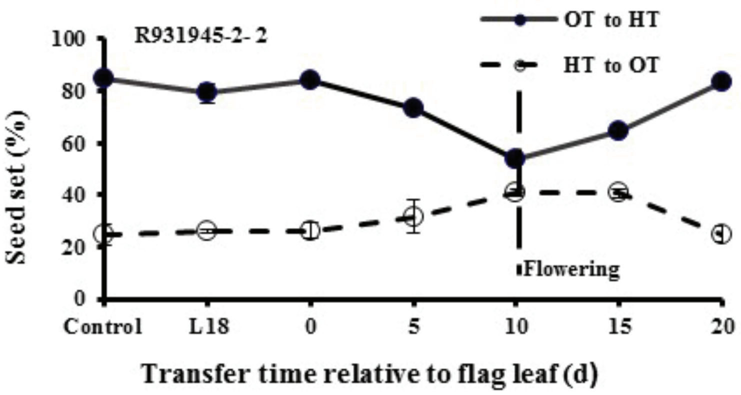

Fig. 1. Effect on seed set percentage of transferring plants of genotype R931945-2-2 from 31/21°C (OT) to 38/21°C (HT) (●___●) and from HT to OT (o----o) for five days at leaf 18, flag leaf (0), 5 days after flag leaf (DAFL), 10 DAFL, 15 DAFL, and 20 DAFL. The control plants were grown continuously in either OT or HT. Error bars indicate the standard error of the mean for each transfer. Vertical dotted line indicates approximate time of anthesis.

Simulating production risks associated with high temperature effects on grain yield

In order to quantify production risks, long term simulations were conducted using 59 years of weather data for Moree (NSW). Implementation of the effect of high temperature stress on seed set percentage, and hence grain yield, was based on the results of the controlled environment experiments. Five hypothetical genotypes were used in the simulations, where the first genotype was completely tolerant to high temperature and the other four represented a factorial design with two thresholds and two levels of tolerance (Fig. 2).

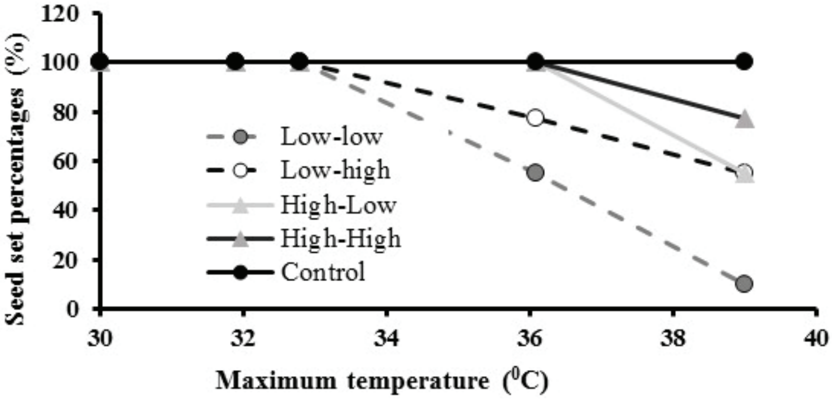

Fig. 2. Seed set percentage versus maximum temperature for five hypothetical genotypes that differ in either the threshold (high vs Low) and tolerance (high vs low) of seed set response to high temperature.

The effects of high temperature on simulated grain yield for each year at Moree are shown in Fig.3. A sowing date of 1 October was used every year, as this resulted in a high probability of occurrence of high temperature stress around flowering. Yield of two genotypes with either low or high threshold and tolerance is expressed relative to that of a control genotype that is not affected by high temperatures. The simulated yield reduction varied considerably across years for the heat sensitive genotype (L-L) and in many years the yield reduction exceeded 10%. In contrast, grain yield of the heat tolerant genotype (H-H) was rarely affected by high temperature stress (Fig. 3).

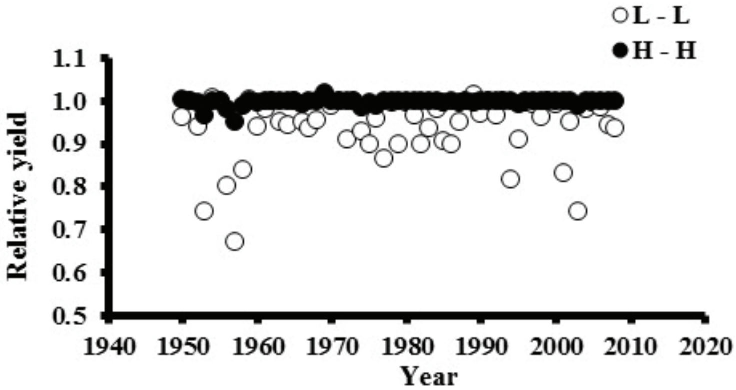

Fig. 3. Simulated grain yield of sorghum genotypes with either high threshold and high tolerance for high temperature stress (H-H) or low threshold and low tolerance (L-L), relative to yield of a control genotype that is not affected by high temperature stress at Moree for a period of 59 years following sowing in October.

Consistent with the large year effect on relative grain yield for the sensitive genotype (Fig. 3), the effect of variation in sowing date on grain yield was also greatest for the sensitive genotype (L-L, Fig. 4). The average yield loss associated with high temperature effects for genotype (L-L) was greatest for sowings from October to December, whereas sowing in early September or late December had lower risks of excessive yield reductions. In contrast, genotype (H-H) never experienced yield reductions greater than 10%. The results thus suggest that while it is plausible to reduce high temperature risks through changing sowing dates, the introduction of genetic tolerance would be a more effective strategy.

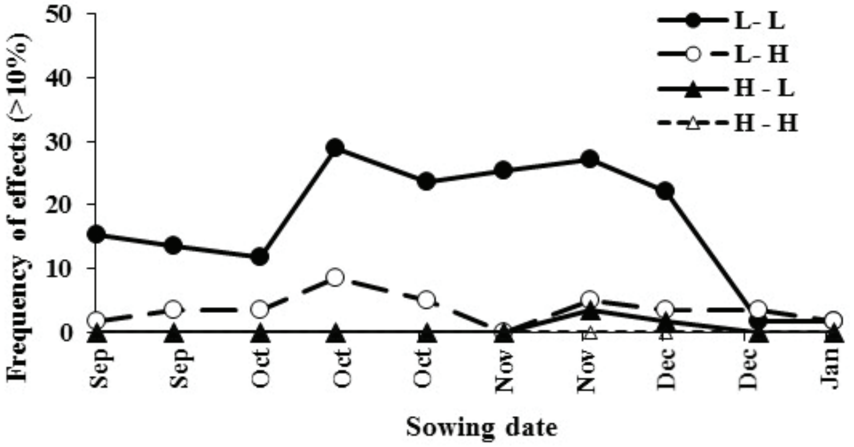

Fig. 4. Probability of yield loss exceeding 10% compared to the control genotypes for four hypothetical genotypes for a range of sowing dates at Moree. Genotypes differed in the threshold or tolerance to high temperature above the threshold: L-L low threshold, low tolerance; L-H low threshold, high tolerance; H-L high threshold, low tolerance; H-H high threshold, high tolerance.

Conclusion

The frequency and severity of high temperature events are predicted to increase over the next decade (IPCC 2007) and this will likely exacerbate the adverse effects of high temperature stress on crop yields. It is clear that risks of yield reduction of sorghum due to high temperature effects will increase. Recent research suggests that there is genotypic variation for tolerance among sorghum genotypes and that a period of 10-15 days around flowering is the period most sensitive to high temperature stress. Simulation studies suggest that management of sowing date can somewhat reduce the adverse effects of high temperature on grain yield, but this is less effective in moderating high temperature risks than genetic improvement. The presence of potential sources of genetic tolerance to high temperature effects make genetic improvement a suitable avenue to mitigate long-term effects of climate change on sorghum productivity in eastern Australia.

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