Effects of high temperature stress on grain crops on current and future climates: observations and simulations

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Abstract

The yield of grain crops is highly sensitive to brief episodes of high temperature that coincide with the time of flowering. Such stress temperatures occur in some locations in the current climate, and are projected to become more frequent with human-induced climate change. We have quantified the effects of the magnitude, timing and duration of high temperature, and their interaction with crop genotype, in more than 10 years of controlled environment experiments with wheat, rice and groundnut. The threshold temperature at flowering for reducing grain-set was between 31 and 36°C, depending on crop and crop genotype. Above this, final grain number, and hence yield was reduced. These effects of high temperature at flowering were simulated, added to an existing crop simulation model and used to examine the change in risk to crop yield from high temperature stress in future climates.

Media Summary
Adaptation of crops to high temperatures that can dramatically reduce crop yields is required for crop production under climate change.

Keywords
Temperature stress, grain-set, climate change, abiotic stress

Introduction
Most annual crops are sensitive to brief episodes of high temperature when they coincide with the time of flowering (Wheeler et al., 2000). Maximum temperature above about 31-36°C, depending on crop and crop genotype, for only a single day or more at this time reduced grain-set and hence final crop yield (Prasad et al. 2001, Jagadish et al., 2007). Such stress events occur at some locations in current climates as part of the natural variability of climate. High temperature stress is also expected to become more frequent in the future due to human-induced climate change because of a warmer mean climate and an increase in the variability of climate (IPCC, 2007). It is therefore necessary to understand the crop response to high temperature stress, identify sources of tolerance in current crop germplasm, and to model the response in order to study crop vulnerability under climate variability and change.

Methods

Genotypic variation for high temperature tolerance in rice
The effect of high temperature at anthesis on spikelet fertility was measured in 7 rice mapping population parents with cv. N22 as a check for two consecutive years. Plants were exposed to 30, 35 and 38°C on the second day of anthesis for 2 h (10.00 to 12.00h) during the first screen to coincide the heat exposure with peak anthesis and increased to 6 h (09.00 to 15.00h) for the second screen to overcome the potential confounding effect of escape under short durations. Exposure to 6 h encompassed >97% spikelets opening on the flowering day and ensured that all opened spikelets received at least one hour of high temperature, sufficient to test the spikelet for its tolerance (Yoshida et al., 1981). Spikelets that opened under high temperature exposure were marked with acrylic paint. Similarly, spikelets opening under ambient conditions (30°C) in a temperature controlled glasshouse were marked as controls. The plants were returned to ambient temperatures for the rest of the period and seed-set was recorded 15 days after anthesis from the marked spikelets from plants exposed to high temperatures and control.

Response to high temperature of rice grown at elevated CO_2

The interaction of high temperature and CO_2 was studied in a mega variety of rice (IR64), a heat tolerant variety (N22) and a hybrid (IRH). Plants were grown in growth cabinets at either ambient or elevated CO_2 (380 and 760 ppm, respectively) until the time of first anthesis. Cohorts were then transferred to one of the following treatments for 5 days:

1) Ambient temperature and CO_2 concentration (29°C and 380ppm)
2) Ambient temperature and elevated CO_2 concentration (29°C and 760ppm)
3) High temperature and ambient CO_2 concentration (35 or 38°C from 0900 to 1500 and 380ppm)
4) High temperature and elevated CO_2 (35 or 38°C and 700ppm).

Plants returned to their original environments and subsequent grain-set and grain yield was measured. Spikelet tissue temperatures during the stress treatments were measured using copper constantan thermocouples and a reduction of 0.5, 2.0 and 3.4 at 30, 35 and 38°C, respectively was found.

Modelling the effects of high temperature stress

Our modelling objective was to assess the effects of high temperature stress on crops over large areas – states, countries and regions. Therefore, we need a comparatively low level of complexity of the high temperature sub-model. We linked the high temperature routines to the General Large Area Model for annual crops (GLAM) of Challinor et al. (2003). The components of the simulation of the effects of high temperature stress were:

- Parameterisation of diurnal temperature variation
- Detailed description of the time-course of flowering
- The effects of temperature threshold exceedence on grain-set
- The effect of on harvest index, and yield, when grain number falls below a critical value

Full details are in Challinor et al. (2005). Here, we present a simulation using regional climate model output (the PRECIS RCM from the UK Hadley Centre) to project the number of years that two varietal types of groundnut are affected by high temperature stress under a A2 SRES scenario for 2071-2100. Full detains of these simulations can be found in Challinor et al. (2007).

Results

Genotypic variation for high temperature tolerance in rice

None of the mapping population parents were as heat tolerant as N22 both at 2h and 6h of high temperature exposure. During the first screen, parents with highest spikelet fertility at 35 and 38°C along with N22 were Bala and IR64 while the most susceptible genotypes were Azucena and Moroberekan, both of which had <10% spikelet fertility at 38°C compared with 86% in N22. However, during the second screen none of the genotypes performed on a par with the check cv. N22. Azucena and Moroberekan, with <10% spikelet fertility at 38°C were still the most susceptible genotypes. Therefore, 6h of high temperature for a day was ideal for screening rice genotypes for true tolerance to high temperatures at anthesis.

Response to high temperature of rice grown at elevated CO_2

N22 previously documented as heat tolerant (Yoshida et al., 1981; Prasad et al., 2006 and Jagadish et al., 2008) maintained its ability to tolerate heat during anthesis even under high CO_2 concentration (Table 1). At 38°C and 380ppm 59 and 72% lower seed set was recorded in IR64 and IRH compared to N22 while at 38°C and 700ppm the seed-set decline was >70% in both genotypes compared to N22. These results show that elevated CO_2 concentration has little or no influence on the degree of heat tolerance, or that it cannot off-set the effect of increasing temperatures, in rice. Although hybrid vigour did not influence heat tolerance, IRH did produce many more spikelets than IR64 or N22, and at least at 35°C had similar seed numbers.

CO2	Variety	29°C	35°C	38°C
380	IR64	81.1	46.1	22.8
	IRH	77.7	46.1	15.6
	N22	85.2	68.0	55.4

760	IR64	84.3	43.0	15.6
	IRH	75.9	43.1	13.3
	N22	85.6	66.0	54.7
	Mean	81.6	52.0	29.6
	SED		0.53	

The effects of var x T x CO_2, T x CO_2, T, CO_2, var were significant at P<0.001

Table 1. Spikelet fertility (%) in three rice varieties exposed to high temperature stress for 5 days at the time of anthesis at ambient or elevated CO_2 concentration

Modelling the effects of high temperature stress

The effects of high temperature stress on pod-setting of groundnut across India under one scenario of climate change for 2071-2100 varied spatially and were affected by simulated crop tolerance to high temperature (Figure 1). Crop production in the north and south-east was vulnerable to high temperature stress. Vulnerability was reduced considerably when a more tolerant genotype was simulated by changing the threshold temperature, and other parameters, within the simulation (Figure 1).

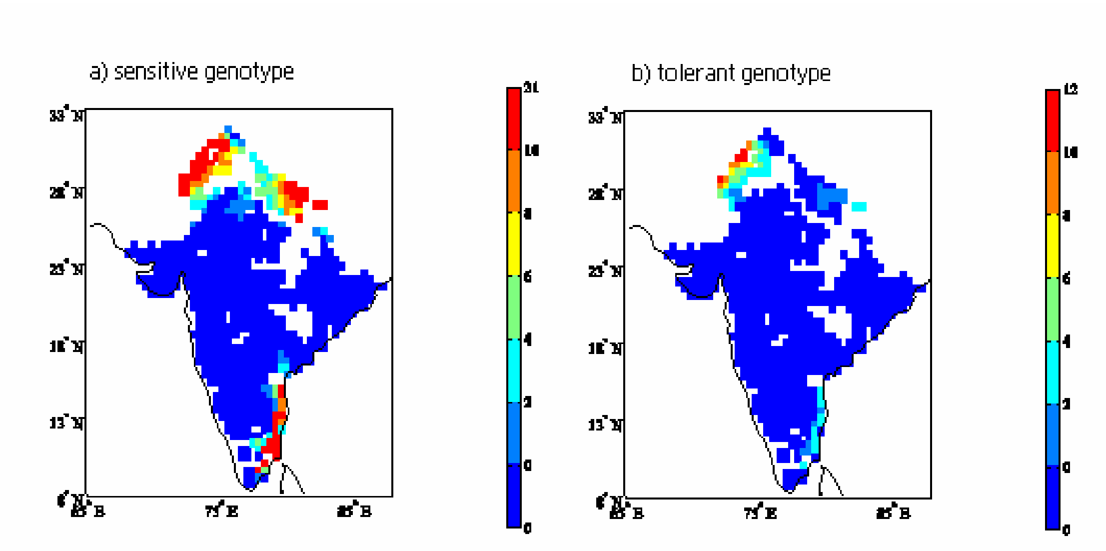

Figure 1. Number of years (out of 30) when the fraction of pod-setting of groundnut is reduced to <50% due to high temperature stress across India for 2071-2100. Figure taken from Challinor et al. (2006)

Conclusion

Episodes of high temperature that coincide with the time of flowering in annual crops can impair seed-set and potentially reduce grain yields considerably. The quantitative response to high temperature varies between different crops, and crop genotypes. Simulation of the effects of one scenario of climate change for a sensitive and tolerant genotype of the groundnut crop in India shows that crop adaptation to climate variability and change can partly be achieved through crop improvement to high temperature.

References

Challinor AJ, Wheeler TR, Craufurd PQ, Slingo JM,Grimes DIF. 2004. Design and optimisation of a large-area process-based model for annual crops. Ag For Met 124: 99-120.

Challinor AJ, Wheeler TR, Craufurd PQ, Slingo JM. 2005. Simulation of the impact of high temperature stress on annual crop yields. Ag For Met 135: 180-189.

Challinor, A. J., T. R. Wheeler, T. M. Osborne and J. M. Slingo. 2006. Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Avoiding Dangerous Climate Change. Schellnhuber, J., W. Cramer, N. Nakicenovic, G. Yohe and T. M. L. Wigley (Eds). Cambridge University Press. Pgs 187-194.

Challinor, A. J., T. R. Wheeler, P. Q. Craufurd, C. A. T. Ferro and D. B. Stephenson. 2007. Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agriculture, Ecosystems and Environment, 119 (1-2) 190-204.
IPCC 2007: Summary for Policymakers, In: Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (Eds)] Cambridge University Press, Cambridge, UK.
Jagadish SVK, Craufurd PQ, Wheeler TR. 2007. High temperature stress and spikelet fertility in rice (*Oryza sativa* L.). J.Exp. Bot. 58: 1627-1635.
Jagadish SVK, Craufurd PQ, Wheeler TR. 2008. Phenotyping parents of mapping populations of rice (*oryza sativa* l.) For heat tolerance during anthesis Crop Sci. in press.
Vara Prasad PV, Craufurd PQ, Kakani VG, Wheeler TR and Boote KJ. 2001. Influence of temperature during pre- and post-anthesis stages of floral development on fruit-set and pollen germination in groundnut (*Arachis hypogaea* L.). Aust J Plant Physiol 28: 233-240.
Prasad PVV, Boote KJ, Allen Jr LH, Sheehy JE, Thomas JMG. 2006. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Res. 95: 398–411.
Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Vara Prasad PV. 2000. Temperature variability and the yield of annual crops. Ag Eco Env 82: 159-167.
Yoshida S, Satake T, Mackill DS. 1981. High temperature stress in rice. IRRI Research Paper Series. 67.