How heat tolerant are our wheats?

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Take home message

Many Australian wheat cultivars are heat tolerant. However, new materials developed from extensive diversity using field-based phenotyping and genomic selection show that the heat tolerance of Australian wheat can be significantly improved.

Aim

The work was conducted to improve the heat tolerance of Australian wheat. The research aimed to develop heat tolerant wheat germplasm, protocols for high-throughput field-based screening and molecular tools to assist commercial wheat breeders.

Introduction

Periods of extreme high-temperature, particularly short periods of heat shock, are a major threat to wheat yield and grain quality throughout much of the Australian wheat belt. Current projections of Australian climate change indicate that heat waves and temperature variability will become more frequent and more intense in the coming decades (CSIRO 2011, Climate Change in Australia. http://climatechangeinaustralia.com.au). It is vital that new wheat germplasm with improved high-temperature tolerance and molecular tags linked to this tolerance are developed and introduced into commercial breeding programs.

Genomic selection is a breeding method that requires a reference population of wheat lines that are phenotyped for the trait of interest and genotyped using many DNA markers distributed across the whole genome. Statistical methods are then used to estimate the effect of each DNA marker on the phenotype; the collection of all these DNA marker effects provides a prediction of genomic breeding value. This information can then be used to predict new plants that are only genotyped and do not have a phenotype. This allows early selection of plants/lines without phenotyping which decreases the breeding cycle leading to increased genetic gain.

What did we do?

A highly diverse set of agronomically adapted materials were assembled for phenotyping. These included thousands of new lines developed by the University of Sydney, including crosses with synthetic wheat, emmer wheat collected in warm areas, landraces, adapted germplasm with putative tolerance identified in hot wheat growing areas globally and Australian wheat cultivars and other sources of heat tolerance developed by others.

These materials were phenotyped for various traits including yield using a three-tiered strategy. Firstly, thousands of lines were evaluated in the field in replicated yield plots at Narrabri in northwestern NSW at different time of sowing. Later sown materials were exposed to greater heat stress. Subsets of materials, based on performance in the previous year and estimated genetic values, were sown at sites in Western Australia (Merredin and Cadoux) and Victoria (Horsham) at 2-3 times of sowing to assess the transferability of traits. Each year, high performing lines were retained from the previous year, intolerant materials removed, and new materials added. Materials identified as heat tolerant in times of sowing experiments were subsequently evaluated in the field using heat chambers set at 4˚C above the ambient temperature to induce heat shock during reproductive development and grain filling to confirm heat tolerance. Finally, those lines that maintained heat tolerance in the heat chambers were screened in temperature-controlled greenhouses to assess pollen viability under heat stress. Materials surviving all three stages of testing were considered highly heat tolerant.

All materials (>6,000 lines) phenotyped in time of sowing experiments were genotyped using a 90K SNP platform and these formed the reference population for genomic selection from which all DNA marker effects were estimated. A prediction equation was developed and used to calculate genomic estimated breeding values (GEBVs) on selection candidates which were genotyped but not phenotyped. A genomic selection model that incorporated environmental covariates (e.g. temperature, radiation, rainfall) directly was developed and improved. This allowed the prediction of line performance under high temperature conditions. Environmental covariates were defined for each plot and growth development phase (vegetative, flowering, and grain fill). An in-field validation of GEBV selected lines was then conducted by correlating GEBVs with field trial phenotypes. Various cycles of crosses were made among diverse lines with high GEBVs and progeny subsequently selected for high GEBV. These formed the basis of our new elite heat tolerant materials.

What did we find?

Extensive field-based phenotyping over a 6-year period identified lines with superior adaptation to terminal heat stress. Many of the superior materials had high yield under heat stress, low percentage screenings and high kernel weights. However, stay-green was not an advantage and only an intermediate level of glaucousness was linked to higher yield under stress (Tables 1 and 2). (Glaucous leaves are covered with a grey/blue or whiteish waxy coating that is easily rubbed off). Materials with a wide range of GEBVs were identified and recombined in crosses to produce new heat tolerant lines with higher heat tolerance than current cultivars (Figure 1). The prediction accuracy of genomic selection using models trained at Narrabri was assessed in other environments around Australia (Table 3). The predictions were moderate indicating that phenotyping in Narrabri was relevant nationally.

Table 1. Influence of stay-green on yield in early and late sowing (576 genotypes) at Narrabri

Time of sowing	**Non-stay green**	**Stay-green**	**Probability**	
Main season	5.585 a	5.501 b	P<0.01	
Late	4.808 a	4.657 b	P<0.001	
Numbers of lines	429	149		

Means in rows followed by different letters are significantly different at the probability indicated

Table 2. Impact of Glaucousness on yield at early and late sowing (576 genotypes) at Narrabri

	Glaucousness		
Time of sowing	Low	Medium	High
Main season	5.683 a	5.556 b	5.560 b
Late	4.756 b	4.804 a	4.694 b
Numbers of lines	71	431	74

Means in rows followed by different letters are significantly different at P<0.05

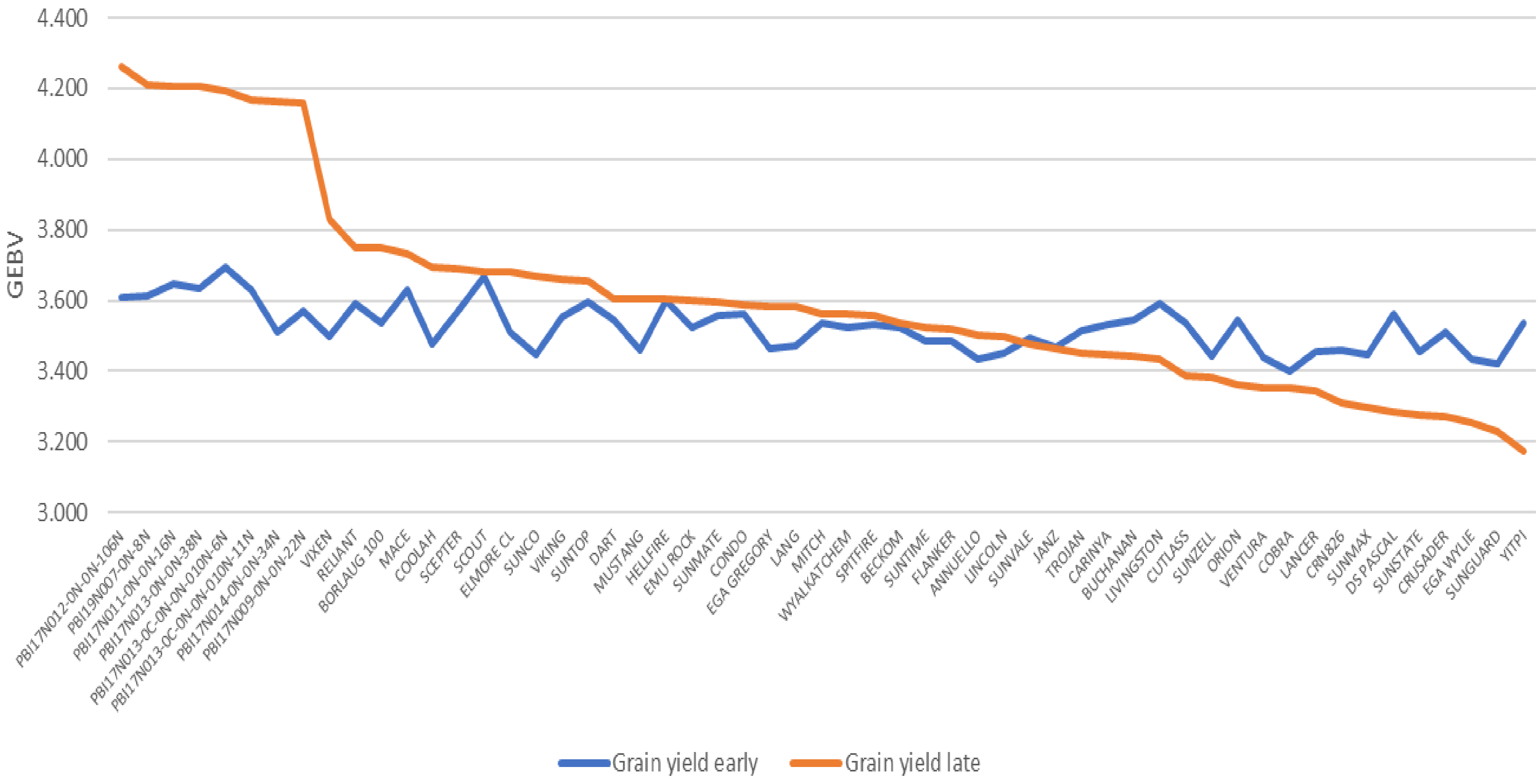

Figure 1. Genomic estimated breeding values (GEBVs) for yield of a subset of the most heat tolerant breeding lines and Australian cultivars (approx. 7,000 genotypes). Main season and late sowing (For PBR status of varieties in graph please refer to Table 5)

The heat tolerance of lines selected from time of sowing experiments in the field was subsequently confirmed using field-based heat chambers. Both night and daytime temperatures were observed to reduce yield, increase screenings and reduce kernel weights (Table 4).

Table 3. Prediction accuracy of materials trained in Narrabri (2017 – 2020) and validated at Cadoux (WA), Horsham (VIC) and Merredin (WA) for grain yield

Environment	Early sowing	Late sowing
Cadoux 2017	0.31	0.17
Horsham 2017	0.47	0.59
Horsham 2018	0.40	0.38
Horsham 2019	0.22	0.14
Merredin 2018	0.50	0.26
Merredin 2019	0.36	0.13
Merredin 2020	0.38	0.20

Note: accuracy determined as the correlation between GEBV and yield (environmental covariates not included)

Table 4. Impact of day/night temperature (heat chambers; 20 genotypes)

	Yield (kg/ha)	% Screenings	1000 grain weight (g)
Heat chamber (day, anthesis)	2925 a	3.423 b	38.74 a
No chamber (day, anthesis)	3363 b	2.369 c	41.75 b
Heat chamber (night, grain fill)	2894 a	4.134 a	39.21 a
No chamber (night, grain fill)	3275 b	3.034 b	41.28 b

Means in columns followed by different letters are significantly different

Lines that performed well in field-based heat chambers were then tested in the greenhouse and those lines with poorer pollen viability under high-temperature (35˚C/22˚C, day/night) and elevated CO_2 (800 ppm) tended to have reduced seed set and lower yield (Figure 2). Control conditions were maintained at 22˚C/15˚C and 400 ppm CO_2.

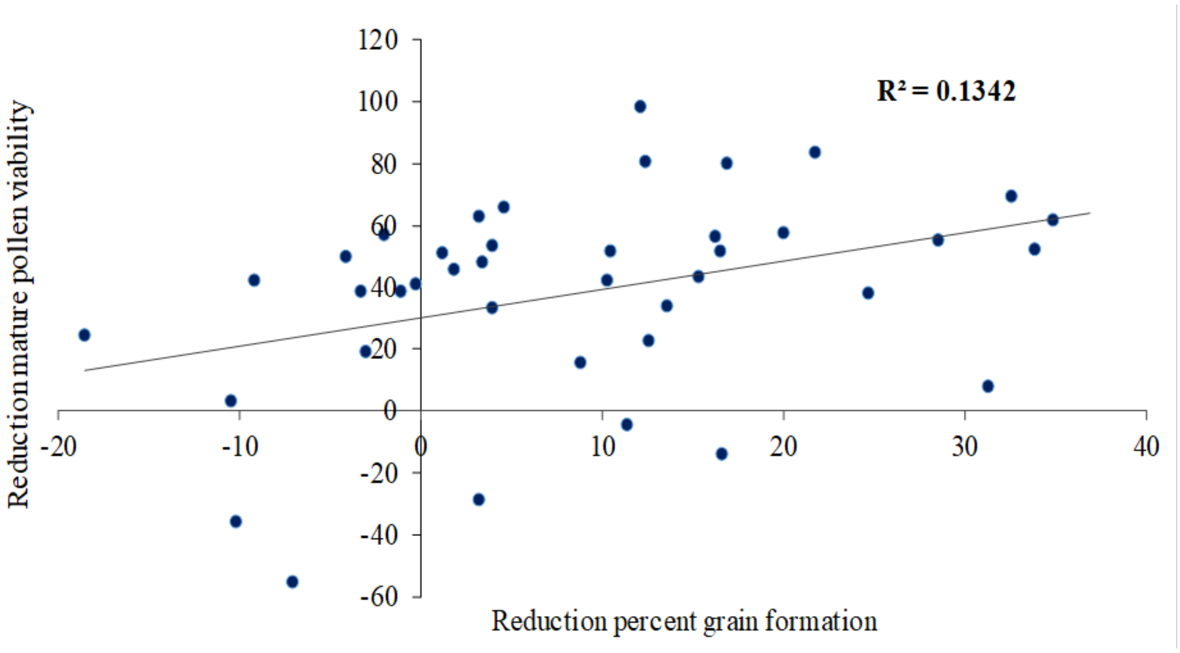

Figure 2. Relationship between pollen viability and grain yield at high CO_2

Based on extensive testing in time of sowing experiments, using field-based heat chambers and under controlled glasshouse conditions, the Australian cultivars evaluated between 2016-2020 were rated for heat tolerance (Table 5). Different varieties arrive at heat tolerance in different ways, with some yielding well in the field but more susceptible to high temperature during pollen formation. The rating in Table 4 is indicative only and based on a number of different observations.

The varieties for which we have detailed knowledge of both their genetics (genotype) and behaviour in a range of environments (phenotype) have enabled us to link the field impact and plant behaviour with parts of the genome that code for specific traits. The process used to do this is called genome wide association analysis. This process has been used to identify a number of meta quantitative trait loci (meta-QTL's) or locations on the genome that express as traits with varying levels of expression in different environments. This knowledge will assist wheat breeders to recombine this new diversity into new cultivars for all regions of Australia.

Table 5. Heat tolerance rating of Australian cultivars

Name	Field yield	Chamber yield	Thousand grain weight	Screenings	Pollen viability	Heat tolerance rating
MACEɸ	HIGH	HIGH	HIGH	MODERATE	MODERATE	T
MUSTANGɸ	HIGH	HIGH	MODERATE	LOW	MODERATE	T
DARTɸ	HIGH	MODERATE	MODERATE	LOW	MODERATE	T
SCOUTɸ	HIGH	MODERATE	HIGH	MODERATE	HIGH	T
SUNCHASERɸ	HIGH	HIGH	LOW	LOW	MODERATE	T
BORLAUG 100ɸ	HIGH		HIGH	MODERATE		MT
SCEPTERɸ	HIGH	LOW	HIGH	MODERATE	MODERATE	MT
VIXENɸ	HIGH	LOW	HIGH	HIGH	HIGH	MT
CONDOɸ	MODERATE	MODERATE	HIGH	LOW	HIGH	MT
FLANKERɸ	MODERATE	MODERATE	MODERATE	MODERATE	HIGH	MT
LANCERɸ	LOW	MODERATE	MODERATE	LOW	MODERATE	MT*
HELLFIREɸ	HIGH		HIGH	HIGH		M
RELIANTɸ	HIGH		HIGH	MODERATE		M
EMU ROCK ɸ	HIGH	LOW	HIGH	MODERATE	LOW	M
SUNTOPɸ	HIGH	LOW	MODERATE	MODERATE	MODERATE	M
COOLAHɸ	HIGH	MODERATE	LOW	MODERATE	LOW	M
SUNTIMEɸ	MODERATE	MODERATE	HIGH	MODERATE	MODERATE	M
CUTLASSɸ	MODERATE	LOW	MODERATE	LOW	HIGH	M
EGA GREGORYɸ	MODERATE		HIGH	MODERATE		M
LIVINGSTONɸ	MODERATE		MODERATE	LOW		M
MITCHɸ	MODERATE		HIGH	MODERATE		M
SPITFIREɸ	MODERATE		MODERATE	MODERATE		M
SUNMATEɸ	MODERATE		MODERATE	LOW		M
SUNVALE	MODERATE		LOW	LOW		M
BECKOMɸ	MODERATE		LOW	LOW		M
WYALKATCHEMɸ	MODERATE		MODERATE	MODERATE		M
PHANTOMɸ	MODERATE	HIGH	LOW	HIGH	MODERATE	M
VIKINGɸ	HIGH	LOW	LOW	LOW	MODERATE	MS
SUNPRIMEɸ	MODERATE	LOW	MODERATE	MODERATE	LOW	MS
SUNMAXɸ	LOW	LOW	MODERATE	MODERATE	HIGH	MS*
BUCHANANɸ	MODERATE		LOW	HIGH		S
LINCOLNɸ	MODERATE		HIGH	HIGH		S
SUNZELL	MODERATE		LOW	HIGH		S
TROJANɸ	MODERATE	MODERATE	MODERATE	HIGH	LOW	S
COBRAɸ	LOW	HIGH	HIGH	HIGH	LOW	S
ZANZIBARɸ	LOW	HIGHI	LOW	HIGH	HIGH	S
DEVILɸ	LOW	HIGH	LOW	HIGH	MODERATE	S
CRUSADERɸ	LOW		MODERATE	LOW	LOW	S
ORIONɸ	LOW		LOW	HIGH		S
SUNGUARDɸ	LOW		LOW	LOW		S
VENTURAɸ	LOW		MODERATE	MODERATE		S
YITPIɸ	LOW		MODERATE	HIGH		S

*Late maturity confounded field-testing

Hear tolerance rating scale: T=Tolerant; M=Moderate; S=Susceptible

Conclusion

Some recent Australian cultivars combine both high yield and heat tolerance. However, new pre-breeding materials developed using genomic selection offer commercial wheat breeders' new sources of diversity for both yield and heat tolerance that can be used to mitigate the effects of a warming environment. GEBVs and QTL linked to key traits will allow wheat breeders to integrate this new diversity into their existing genomic selection pipelines.

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