KIT 1.1

Minimise the impact of high temperature at flowering and grain fill on grain yield and stability

Impact	**Growers manage their farm businesses to minimise the impact of flowering heat stress on yield.**
Summary	• Growers understand how much the impact of heat stress on yield is costing their businesses. • Growers understand their options to manage heat stress. • Varieties with increased tolerance to heat stress.

OVERVIEW

Heat stress is an important annual production constraint across the grain producing environments of Australia. Heat stress reduces yields of all grain crops with the magnitude of the yield reduction dependent upon the timing and severity of the heat stress relative to the developmental stage of the crop as well as the heat sensitivity of different crops. Elevated temperatures can affect grain crops in five ways:

1. By incurring metabolic changes within plant that can in turn reduce photosynthetic activity and increase respiratory rates.
2. By speeding the rate of plant development. This can reduce the time available for development of sufficient floral structures necessary to achieve maximum yield potential and bring flowering forward earlier than optimal in a given environment thereby increasing the risk of frost damage.
3. By inducing partial sterility when elevated temperatures occur during floral development and at flowering.
4. By shortening the grain filling period, thereby reducing grain size.
5. By significantly increasing the rate and extent of leaf area senescence.

Periods of extreme high temperature, particularly short periods of heat shock (above 30°C), at flowering and grain filling plant development stages are very damaging to most grain crops. High temperatures during pollen formation reduce pollen viability resulting in reduced final grain number and lower yields[1]. Most grain crops have a narrow optimum temperature range for fertilisation. High temperatures at anthesis typically result in grain abortion and significantly reduced grain number[2]. High temperatures also impact the duration and rate of grain filling resulting in reduced grain size and higher levels of screenings[3].

Whilst much R&D has focussed upon the response of grain crops to extreme 'heat shock' events, elevated maximum temperatures in what would be considered to be the non-stressful range, have also been shown to significantly impact yields. Higher daily minimum temperatures, particularly temperatures during the night, have been reported as having a larger negative impact on wheat grain yields than daily maximum temperatures[4,5].

Within Australia, a study employing five years of National Variety Trial data reported that generally there was an association between higher temperatures and lower yields in wheat, barley, canola, chickpea and field pea trials[2]. Higher temperatures within the optimal range were strongly associated with lower yielding wheat, barley and canola trials from early development phases through to post-flowering in the Southern cropping region but only post-flowering in the Western region. By contrast, higher temperatures were largely unrelated to low yielding trials in the East and only weakly associated with low yield post-flowering in the Northern cropping region. Similarly, a sowing date experiment with four chickpea breeding lines found that half of the variation in yield was associated with developmental, non-stressful thermal effect[6]. Warmer temperatures impact yield by accelerating crop development resulting in reduced resource capture for establishment of grain number and for grain filling[7,8].

There is variation in sensitivity of different grain crops to heat stress. Wheat yields are reduced by 3-5 per cent for every one degree Celsius increase in average temperature above 15°C at critical stages of crop development[9]. A canola study reported

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yield declines of 11-15 per cent for every 1°C increase above 12°C in post-anthesis temperatures[10] whilst for chickpea yield loss has been calculated at 10–15 per cent for every 1°C increase beyond the optimum temperature[11]. Analysis of a range of grain crops has demonstrated that for temperatures above 30°C wheat is most impacted, followed by canola, chickpea and barley[2]. In canola, in addition to negatively impacting yield, heat also significantly reduces seed oil content[12]. Unlike many other grain crops, the stigma (female part) of the canola flower is more sensitive to heat stress than the pollen[13].

High temperature during grain filling also negatively affects quality in many grain crops which in turn can reduce grower profitability through downgrading of delivered grain[14-17]. In addition, as heat can affect grain functionality characteristics, there is potential for heat-driven variability in grain functionality to have a negative impact on the perception of Australian wheat quality by end users. The impact of environmental stresses on grain quality and functionality is not the focus of this key investment target strategy and is considered under KIT 2.2.

Elevated temperatures also have the potential to impact crop establishment. Increases in early season air temperatures result in increased soil temperatures which can in turn impact crop emergence, particularly where growers are employing deeper sowing, moisture-seeking approaches. Mean coleoptile length of commercial Australian wheat varieties has been demonstrated to be significantly reduced with increased soil temperature[18].

Photosynthesis and respiration are sensitive to temperatures above plant developmental optimums and heat also impacts crop carbon capture. Photosynthetic rate reduces substantially under high temperature[19]. In contrast, respiration increases in response to elevated temperatures and has been shown to double for every 10°C increase in temperature above thermal optimum[20]. However, plants are also able to acclimatise photosynthesis and respiration to increased temperatures and become more efficient at fixing CO_2[21].

The economic impacts of heat stress on grain production in Australia are significant. GRDC commissioned a study of the yield losses and economic impacts associated with temperatures 32°C and above during flowering through to grain/pod filling. This study determined the average annual economic losses in wheat, barley and canola to be $1.1 billion, $350 million and $136 million, respectively[22]. In the case of wheat, heat at flowering and grain filling was estimated to result in potential lost production of a total of 4 million tonnes per annum across Australia or an average of 330kg/ha in affected regions. These estimates reflect direct economic losses of heat shock but not the indirect effects of elevated temperature including accelerated crop development pre-flowering.

The KIT 1.1 strategy is aligned to the grower decision-making process as it relates to heat stress. The strategy focusses upon investing in the generation of new knowledge and the development of tools and technologies which support growers in heat affected cropping regions:

A. Improve pre-season planning for heat stress.
B. Make informed in-season management decisions.
C. Implement effective post-heat event responses.

FUTURE RD&E FOCUS

SCOPE – Improved pre-season planning for heat stress

Growers make optimal crop choice and sowing decisions in heat affected cropping regions.

In planning their cropping operation to maximise yield in heat affected cropping regions, grain growers are seeking accurate information about:

a. what crops and varieties to sow given knowledge of their yield stability in heat-affected environments; and
b. when to sow crops and varieties in order to maximise water use and minimise exposure to heat and frost stress events.

Current State

Despite the well-recognised detrimental impact of heat on crop yields in Australia, data detailing the relationship between temperature and yield loss at different crop developmental stages for many grain crops either does not exist or is incomplete. In part, this reflects the complexity of generating such data given the interaction between temperature, water and nitrogen supply[23]. Heat damage functions have been described for wheat, canola and sorghum at specific sensitive growth stages. The absence of accurate heat damage functions in other crops limits industry capacity to calculate the yield and economic impacts of heat events and determine the value proposition of different heat R&D approaches in many grain crops.

Genetic variation in heat tolerance has been described for Australia's major grain crops[24-29]. Heat reduces both grain number and grain size in affected crops, however, grain number has been shown to explain most of the yield response to temperature stress even in environments where significant heat stress during grain filling is common[30,31].

Reproductive heat tolerance is a complex quantitative trait which is difficult to phenotype. Controlled environment and in-field heat phenotyping methods have been established and used to identify genetic variation in heat tolerance of a number of grain crops[25-28]. These established methods, however, are currently only able to account for a proportion of the variance in crop yield responses to heat.

Incorporating environmental data into varietal performance prediction models presents opportunities to improve understanding of the contribution of temperature to yield variability across Australia's grain production areas. An example of this is the recently negotiated partnership between GRDC and the multinational research initiative INnovations in plant VarIety Testing in Europe (INVITE) program.

Grain growers are seeking information on the frequency and severity of heat events across different production regions and the impact these events have on yield in different crops. This in turn would inform variety selection and sowing decisions to minimise risk of heat and frost exposure and hedge input costs. Selecting an appropriate crop phenology for a particular sowing time and production environment is currently an important management option in limiting damage from heat stress. GRDC and co-investment partners have and continue to invest in a range of projects to improve understanding of the genetic control of phenology in major crops and to develop tools which improve prediction of plant development and flowering[32,33]. There is a further need for the Australian grains industry to have access to accurate phenology prediction tools for grain crops.

With grain growers increasingly seeking to exploit early sowing opportunities to maximise seasonal water use, the impact of elevated temperatures on crop establishment is predicted to increase in importance. The observation that increased soil temperature negatively impacts wheat coleoptile length has potential implications for crop establishment where growers are pursuing very early sowing opportunities and particularly when combined with deep-sowing practices to access sub-surface moisture[18]. Australian breeders have been provided novel sources of genetic variation for increased coleoptile length, however the breeding and agronomic value of this germplasm in different target production environments is not yet fully understood.

Pre-season agronomic practices for conservation of soil moisture, such as summer weed control, no-tillage and stubble retention have an important bearing on the capacity of plants to withstand heat stress in many cropping environments. GRDC and research partners have invested in RD&E to assist growers maximise seasonal water use and this will continue. The optimisation of crop moisture management by growers to reduce the gap between economically attainable yield and water-limited yield potential is the focus of KIT 1.5.

Heat stress significantly disrupts plant carbon fixation and release dynamics. Improving the photosynthetic and respiratory heat tolerance of grain crops has been identified by the international research community as a mechanism for raising the yield of grain crops in environments where heat is a major production constraint. Heat affects photosynthesis by inhibiting Rubisco activation[34] and through damage to photosystem II in the chloroplast electron transfer chain[35]. Respiration is more impacted by short-term temperature change than photosynthesis, however, the biochemical basis of this process is not well understood. Similarly, little is known about the genetic variation for photosynthetic and respiratory thermal acclimation to high temperatures in major grain crops. Genetic variation for capacity of wheat to acclimate respiration to temperature has been reported[36], however, the relationship between this variation and yield under high temperature stress has yet to be elucidated.

Future Focus

GRDC will continue to invest in the development of tools which support breeding of crop varieties with increased heat tolerance. GRDC will also invest in the generation of new knowledge and tools that assist grain growers optimise crop/variety selection and sowing to manage heat risk. Future RD&E in this area will target the following outcomes:

Investment Outcome 1.1.1 – Growers have access to varieties with improved yield under heat stress.

Germplasm with enhanced flowering heat tolerance or developmental patterns which minimise heat exposure has been identified for many grain crops. Accelerating breeder use and deployment of such germplasm in major grain crops will be an investment priority. Improved heat tolerance phenotyping tools, advanced genomic prediction methods and novel mathematical and statistical approaches will likely be required to improve the accuracy and intensity of selection for improved heat tolerance by plant breeders.

Investment Outcome 1.1.2 – Growers use accurate information on the pattern and severity of heat stress in their region to guide variety selection and sowing decisions.

Accurate information about the frequency and severity of heat stress, coupled with accurate heat damage functions, would support growers to make better informed crop choice and time of sowing decisions. This may require digital agriculture software providers to develop and deliver accurate temperature spatial measurement tools (KIT 3.2). Industry will also require ongoing access to advanced crop phenology models and tools to guide variety selection and sowing time decisions.

Investment Outcome 1.1.3 – The grains industry has access to accurate information about the relationship between the severity and timing of heat stress and final yield of major grain crops.

The development of accurate heat damage functions for major grain crops will underpin tools which support on-farm decision making, economic modelling and research prioritisation. Initial crop focus for development or refinement of damage functions will be wheat, barley, sorghum, canola, chickpeas and lentils.

Investment Outcome 1.1.4 – Plant breeders have tools to effectively improve the heat tolerance of major grain crops.

Heat impacts both grain number and grain size, however, grain number is the primary determinant of yield in grain crops[6,37-39] and as such will be the primary focus for future heat genetic improvement investments. Plant breeders and researchers will require greater knowledge of how elevated temperatures influence establishment and maintenance of grain number. Elucidating the genetic and biochemical basis of floral/spike development and mortality under elevated temperatures will be an investment priority. Accelerating breeder access to, and deployment of, genetic variation for maintenance of grain number under heat stress will also be an investment priority. Expansion of high value crops such as canola into some production environments is constrained by the impact of heat. Addressing heat-related genetic barriers to the expansion of crop area will support the objectives of KIT 2.1 and will be a focus of future investment under KIT 1.1.

SCOPE – Informed in-season management decisions

Growers optimize canopy management and type and timing of crop inputs to minimize the impact of heat stress.

Growers making in-season heat management decisions are seeking information on:

a. Approaches to managing crop inputs and water-use which can be employed to improve the capacity of a crop to respond to heat events and improve overall yield stability.
b. Forecasting tools which can accurately predict heat shock events early enough to inform management responses.
c. Products which can be applied to crops in advance of a heat-shock event to minimise crop damage.

Current State

Fertiliser (particularly N), represents a significant input cost in most Australian grain cropping enterprises. There is a strong relationship between crop nitrogen and water use pattern and the capacity of a crop to withstand high temperature stress[40]. The capacity of crops to maintain yield under heat stress events is strongly influenced by the timing, intensity and duration of the heat event and crop water supply at the time of heat stress. Water uptake is in turn significantly influenced by nitrogen supply[23]. Improved knowledge of the interaction between crop nitrogen supply, water uptake and the crop response to high temperature events during spring has the potential to assist growers better manage nitrogen use in heat-affected cropping regions to maximise crop yields. Beyond manipulating nitrogen rate and timing, there is increasing grower interest in the potential for growth regulators to be used to actively manage crop canopies. However, there is limited experimental data available on the impact of PGR-mediated canopy management and crop yield responses to heat.

High temperatures can impact the efficacy of many crop protection products including fungicides, herbicides and insecticides[41,42], depending upon humidity. Growers currently use temperature and humidity information to calculate ΔT which is employed as an indicator of suitable spraying conditions. Consequently, improved forecasting of heat events has the potential to assist grain growers better plan timing of crop protection product applications to maximise value derived from such inputs in heat-affected cropping environments. Similarly, the potential for extreme spring temperature events (frost and heat) can lead to the use of conservative nitrogen rates as growers concerned with such events reduce inputs to lower their financial exposure. In such cases, improved heat event forecasting could assist growers make more informed in-season nitrogen management decisions.

The capacity of grain growers to manage the impact of heat through in-season management activities is constrained by the limitations of current weather forecasting tools where accurate temperature predictions are limited to 7-10 days. This gap is currently being addressed by the GRDC-supported *Rural R&D For Profit* project, *Forewarned is Forearmed*, which aims to develop and deliver forecasts on the likelihood of climate extremes on multi-week and seasonal timescales[43].

There is considerable grain grower interest in the identification of products which can be applied to crops to reduce yield losses under heat stress. To date, GRDC investment in the targeted evaluation of different chemistries and biologicals which may be deployed by Australian grain growers to improve yield under flowering heat stress has been limited. However, internationally there is a body of research and commercial activity related to investigation of chemical compounds and biologicals with the potential to reduce the yield impact of different biotic and abiotic stresses. These international efforts could be leveraged for the benefit of Australian grain growers[44-46]. As with frost, opportunities exist to explore a greater diversity of compounds through targeted partnerships with companies that own extensive chemical and biological libraries, and which have proven product development and commercialisation expertise.

Future Focus

GRDC will continue to invest in the development of new knowledge and tools that assist grain growers optimise the type and timing of crop inputs in heat affected cropping regions to manage risk. Future RD&E in this area will target the following outcomes:

Investment Outcome 1.1.5 – The grains industry has improved in-season forecasting tools to better predict heat stress and guide risk management decisions.

Opportunities for heat stress R&D to value-add to weather forecasting tools being developed by the Bureau of Meteorology and other parties will be explored.

Investment Outcome 1.1.6 – Growers have improved knowledge of how different crop input and canopy management practices influence yield under heat stress.

Accurate data regarding the relationship between crop inputs, water supply and temperature will be required. Development of tools which integrate each of these elements to guide management decisions or parameterisation of existing models/tools may be necessary. Improved knowledge of interaction between crop nitrogen supply, water uptake and yield responses to high temperature events will also support KIT 1.5 and KIT 3.5.

Investment Outcome 1.1.7 – Growers have access to novel and innovative in-season heat mitigation products.

There is potential to leverage an increasing body of international research and commercial activity in the development of new products with the potential to mitigate heat stress risk. The aim would be to examine the value proposition of using new products in different Australian grains cropping environments and under a range of cropping systems. Priority will be given to interaction with companies that have proven chemical and biological research, freedom-to-operate and path to market expertise.

SCOPE – Effective post-heat event responses

Growers make informed decisions regarding extracting value from heat affected crops.

Following a significant heat stress event, grain growers are commonly considering the following:

a. How bad was the heat stress and how much damage was caused?
b. What is the likely capacity of the crop to recover?
c. If the crop is badly damaged with little potential for recovery what can I do with it to maximise returns or minimise losses?

Current State

The ability to rapidly and accurately predict the impact of heat stress events on crop yields is critical to growers making well informed decisions about how they should respond following a heat stress event. Internationally, there is considerable research activity seeking to develop improved methods for identifying and quantifying crop responses to a range of stresses, and to scale such methods to the field via remote sensing technologies[47,48]. However, the development of improved methods to quantify heat damage is hampered by incomplete fundamental knowledge regarding the relationship between heat severity and duration at different crop developmental stages and the subsequent impact on yield (damage function) for many grain crops.

The biochemical and physiological basis of heat tolerance and recovery from heat stress has been studied in numerous crop species. However, in many cases these studies have been conducted under controlled environment conditions and a limited number of findings have been validated in the field. Scaling lab studies to the field will be necessary for the development of tools which assist industry to accurately predict the recovery potential of grain crops.

Currently, there is a lack of information about options to extract maximum value from severely heat impacted crops. This includes data on timing of management options such as cutting for hay and the impact on quality of the grain or hay produced.

Future Focus

GRDC will continue to invest in the development of new knowledge and tools that assist grain growers make better-informed decisions regarding extracting value from heat stress affected crops. Future RD&E will target the following outcomes:

Investment Outcome 1.1.8 – Growers have access to tools to predict, monitor and quantify yield loss associated with heat stress.

Sensing and measurement tools which enable growers and their advisors to rapidly, and accurately quantify heat yield loss in winter cereal, oilseed and pulse crops will be required (overlap with KIT 3.2). To support grower decisions, such tools will need to be cost-effective and deliver accurate data in short timeframes. In addition, grain growers and their advisors may require tools to integrate heat severity data, crop development, soil moisture and other environmental data to estimate the recovery potential of heat-stressed crops. Sound experimental data describing how the timing and severity of heat impacts the recovery potential of different crops, in the context of available soil moisture, will be required.

Investment Outcome 1.1.9 – Growers have knowledge of the economic value of different salvage options which can be applied to heat-affected crops.

Accurate economic data for different salvage options including hay production, grazing and manuring in different cropping regions will be required.

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