Designing a Mobile Free-Air Temperature Extreme (FATE) System to Impose Heat Shocks on Crops in the Field

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Abstract
Extreme heat events often coincide with the reproductive phase in crops in SE Australia, negatively impacting crop production and farm profitability. Because the incidence of hot days is continuing to increase, understanding heat wave impacts on crops is critical for assessing climate risks to production. Research into heat wave impacts to crops under controlled experimental conditions is challenging. To address this, we present the development of an Australian-first Free Air Temperature Extreme (FATE) facility and the world's first mobile FATE trolley system, equipped with infrared heaters, controllers, dataloggers, sensors and software control, which will enable increasing crop temperatures up to 10°C above ambient to mimic heat waves. Design criteria such as power calculations, heating uniformity, mobility, and heater height adjustment are discussed. The FATE facility will improve understanding of extreme heat impacts on crops by quantifying heat damage functions for computer simulation models and facilitate validation of heat tolerant lines of crops under open-field conditions.

Keywords
Heat shocks, heat damage, wheat, lentils, canola, Australia, global warming, climate change

Introduction
Sensitivity to heat stress events, which typically coincides with the reproductive phase in crops, is a significant problem for the cereal industries in Australia and overseas (Nuttall et al. 2012; Bergkamp et al. 2018). The 2009 south-eastern Australia's prolonged heat wave commenced in November and caused a 70% yield reduction in lentil crops, equating to $1000/ha loss (Delahunty et al. 2016). The real-world assessment of heat tolerant lines under heat wave/shock in realistic field conditions is critical for delivering crops adapted to changing climate. Although chambers and heat tents are deployed in fields (Nuttall et al. 2012; Bergkamp et al. 2018; Thistlewaite et al. 2020), they create artefacts by enclosing the crops. Kimball et al. (2008) describe a method using free-air infrared heaters to study the impact of elevated temperatures on wheat by increasing the crop canopy temperature by a few degrees throughout a cropping season thereby simulating future warming.

Although temperatures are expected to rise in Australia by a few degrees in the coming decades, one of the major concerns is the increasing frequency of short-lived but intense heat waves (Steffen et al. 2014). The free-air heaters described by Kimball et al. (2008) can be adapted to impose short term (e.g., 3-5 days) heat waves at critical phenological stages. Our FATE system is designed to permit canopy temperature increases up to 10°C above ambient to mimic heat shock/wave events. In addition to accommodating multiple crops and experiments, the heaters with controllers and loggers will be mounted on mobile trolleys, thereby allowing movement to multiple research plots successively.

Data from this facility is expected to improve our understanding of heat extreme impacts on crops, allow testing of new genetic lines for resilience to heat, and provide data to improve heat damage functions in crop simulation and genetic models. In this paper, we describe the FATE project development and design, including the mobile FATE research trolleys.

Methods

Designing the Field Facility

Paired heated and non-heated (control) plots will be separated by a buffer (Figure 1). A range of crops can be sown (cereals, oilseed, pulses) and different traits tested at different phenological stages. These will be sown in 2.4 m wide x 6 m long plots in a north-south direction within the 10.8 m wide and 100 m long strips (Figure 1a), allowing for multiple experiments, including irrigation, if needed. Trolleys carrying heaters (red rectangle, Figure 1b), process control, datalogger and sensors will be powered from the in-field generator (Figure 1a). Although heat can be applied at any time during the growing season, it is anticipated that the time of anthesis (October/November) will be the principal period of application, coinciding with flowering for winter-sown crops in Horsham Victoria. There will be at least 3 replications with a 4th anticipated in the future.

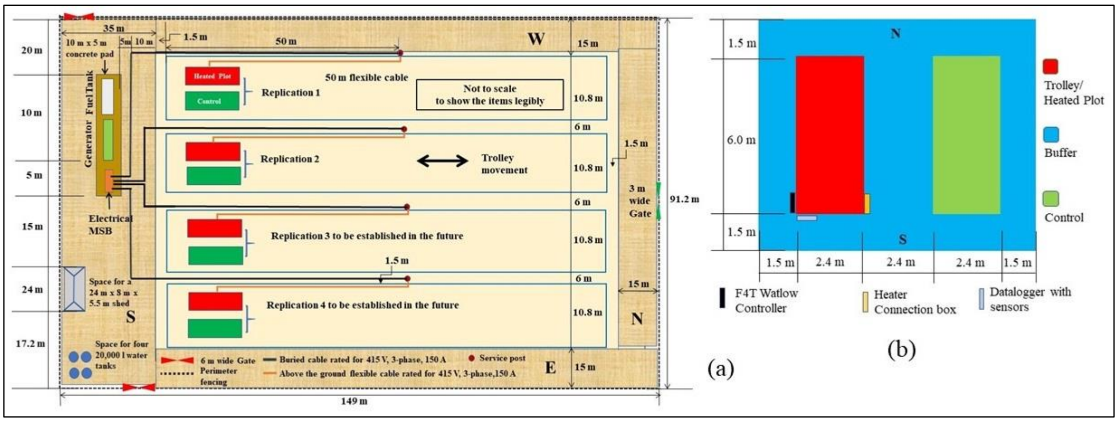

Figure 1. (a) Schematic of FATE site and electrical layout, (b) Plot orientation with the position of FATE trolley.

FATE System Components

For each trolley, 12 three-phase 415 V, 12 Amp and 8.64 kW rated liquid tight infrared ceramic panel heaters (Heat & Sensor Technologies LLC, 627 Norgal Drive, Lebanon, OH, USA) will be mounted as shown in Figure 3b. In each trolley, there will be one process controller for the heaters (F4T Controller, Watlow®, Watlow West, CA, USA), one SDM-CV04 current/voltage output module, one CR1000X datalogger, two IR radiometers (IRT), two soil temperature probes, one mineral insulated thermocouple to measure heater temperature, one air temperature and humidity sensor, and one wind speed and direction sensor (Campbell Scientific Australia Pty Ltd, 411 Bayswater Road, Garbutt, Queensland, Australia) to build the heating system with software feedback control (Figure 2).

How the FATE System Works

For system control, the 'Watlow Composer' software for the F4T heater controller and 'Loggernet' software for the CR1000X data logger (also holds the control software modified from Kimball et al. (2008) to allow set absolute temperatures) are used. A single infrared thermometer (IRT) directed at the canopy will provide a voltage signal to the F4T controller via the SDM-CV04 to operate the heaters to maintain a set canopy temperature (e.g., 37°C). A solid-state-relay is used to modulate the heater temperature, thereby enabling a better and tighter temperature control. Wind speed measurement is used to estimate the efficiency of the heaters and an insulated thermocouple attached to one of the heaters allows for correction for radiation from the heaters that is reflected from the vegetation canopy and sensed by the IRTs. Data from the wind speed, humidity, air, soil, and canopy temperature sensors will be logged at predetermined intervals.

Design and Construction of Research Trolleys

The light-weight aluminium trolleys have wheels allowing movement along the experimental tracks to accommodate successive plots to be heated. These will be moved manually through the field along the replications and positioned over each experimental plot (Figure 1).

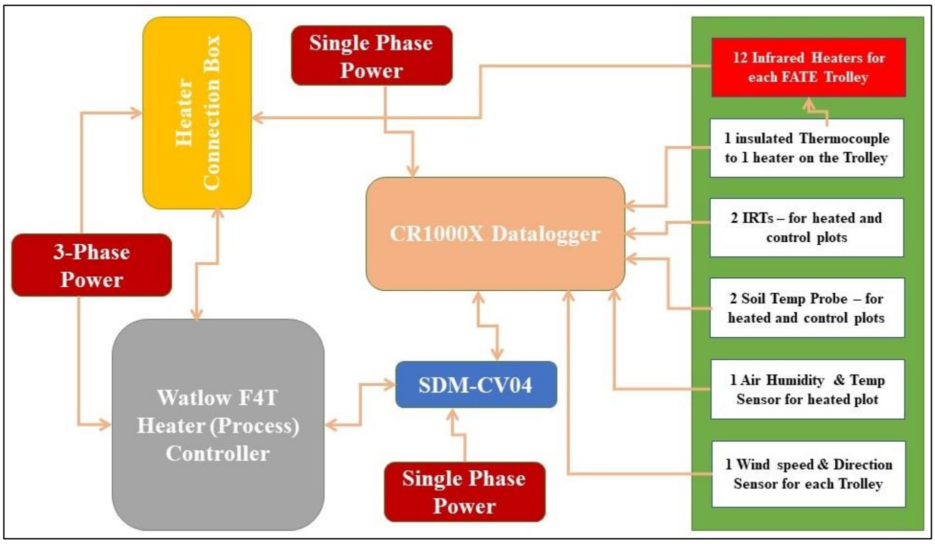

Figure 2. Schematic of FATE system assembly.

Discussion

Heater Numbers and Orientation on Each Trolley

Following Kimball et al. (2012), radiation distribution from the heaters was modelled on a 2.5 m × 5.0 m area, representing each trolley to inform the 3-dimensional positioning of the 12 heaters (Figure 3a). To achieve a uniform distribution of heat, heaters are positioned at various angles, tilts, and azimuth angles (Figure 3b) but are divided into four symmetric groups, (i.e., heaters 1, 5, 7 & 11; 2, 4, 8 & 10; 3 & 9; and 6 & 12) (Figure 3b).

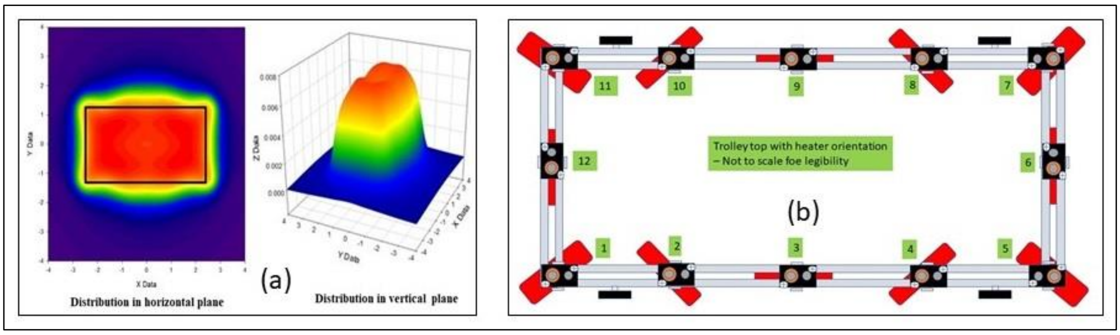

Figure 3. (a) Computer simulation of radiation distribution and (b) Schematic of FATE trolley top with heater orientation determined following Kimball et al. (2012).

Generator and External Fuel Tank

For the 4 replications, 48 heaters will be deployed across four trolleys requiring 415kW power (48 × 8.64 kW). Generator power rating (size) is expressed as kVA (apparent power) which is related to kW as: Actual Power (kW) = Apparent Power (kVA) × Power Factor (pf). For diesel generators, a pf value of 0.8 is commonly used. A 550 kVA generator (415 kW / 0.8) will be required to deliver the required power to the experiment. This 550 kVA generator produces a line current of ~722 Amp (calculated using 3-phase electrical formula) which is more than sufficient to supply 4 replications under full load (12 × 48 = 576 Amp).

Heat waves will likely be imposed for periods of 3 – 5 days during daylight hours for up to 14 h/day but following a diurnal curve to simulate actual heat waves, thus the power and fuel loads will neither be constant, nor at 100%. At 100% load, fuel consumption from a 550 kVA diesel generator is expected to be around 120 L/h. A 3-day (42 h) run for a single experiment would require ~5,000 L of diesel at maximum load, which will be contained in a 6,300 L bunded fuel tank and be positioned adjacent to the generator to supply at least one experimental run without refuelling.

FATE Research Trolley

Each trolley (Ian Antonoff Engineering Pty Ltd, 44 Hamilton Street, Horsham) has an external frame (6.1 m long × 4.6 m wide × 4.5 m high) and an internal platform on which the heaters are attached. The internal platform is raised and lowered by an electrical winch motor to adjust heater height. This allows accommodation of the 12 pre-configured heaters above the height of the crop canopy, which can be adjusted depending on crop species and/or phenological stage.

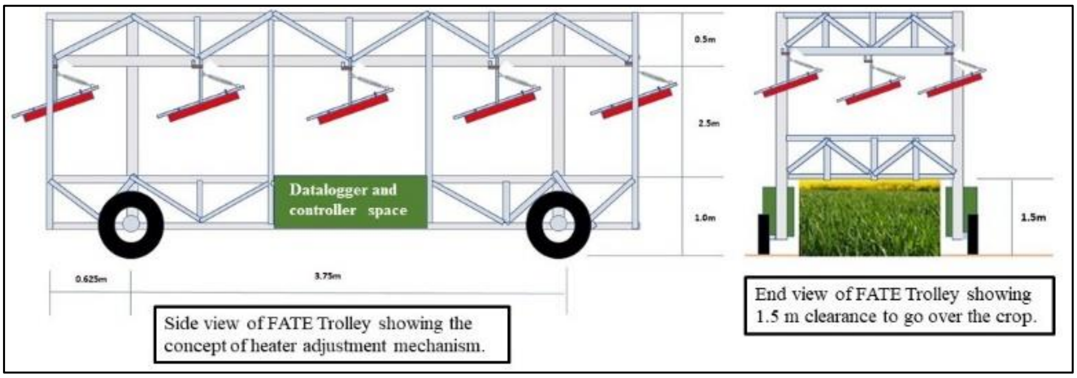

Figure 4. Schematic drawings of a FATE trolley.

Conclusion

Australia's first novel Free Air Temperature Extreme (FATE) Facility on a mobile instrumented trolley is expected to undergo a pilot phase in late 2021. At completion, simulated heat waves imposed by the FATE system are expected to improve our understanding of heat extreme impacts on crops. The FATE Facility will facilitate testing of new genetic lines for resilience to heat and provide input to crop simulation and genetic models.

Acknowledgement:

The research is funded by the Victorian Government through SmartSkills from SmartFarms project.

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