Estimating the real cost of frost: A field-based frost control treatment using a diesel heater to stop freezing damage

Brenton Leske[1,2] and Ben Biddulph[2]
[1] University of Western Australia, 35 Stirling Highway, Crawley, WA, 6009, brenton.leske@research.uwa.edu.au
[2] Department of Primary Industries and Regional Development, 3 Baron-Hay Court, South Perth, WA 6151 ben.biddulph@dpird.wa.edu.au

Abstract
The effectiveness of a diesel heater to protect a field plot of wheat (*Triticum aestivum* L.) from frost damage was tested by changes in canopy and ambient air temperatures and yield components at a frost-prone field site. Despite several frost events when canopy air temperatures falling below zero degrees Celsius, the plot heater was able to maintain the canopy air temperature above freezing (0 °C) for the duration of the frost. These results demonstrate that plot heaters are a useful tool to study freezing damage in cereal crops due to frost, by way of preventing freezing damage in non-frosted field plots for direct comparison to frosted plots.
Keywords
Triticum aestivum L., floret sterility, phenotyping, diesel heater, frost control

Introduction
Spring frosts that occur at the reproductive stage of cereal crops cause significant yield loss to growers in Australia (Woodruff and Tonks 1983). To understand the effect of frost on cereal crops, controlled environments have been preferred as it is much easier to have a non-frosted control (Marcellos and Single 1984), however they are limited in replicating field conditions. Non-frosted controls in field studies have proven difficult to implement successfully (Fredericks *et al.* 2012). Field evaluation of frost damage to crops could be aided by a new method to have an unfrosted control for plot-scale research using a diesel heater (Stutsel *et al.* 2019). This previous research demonstrated the effectiveness of the heaters to raise plot canopy temperatures during cold nights and validated that the heater did not impact plant growth or grain yield in the absence of frost. However, due to only mild frosts being present for this study in 2017, the impact of frost on yield and yield components compared to the non-frosted control could not be made. The aim of this study was to quantify frost damage in wheat of heated and non-heated plots.

Methods
Field experiments were conducted at the DPIRD research site at Dale, Western Australia over the 2018 and 2019 seasons (32°12'24.48" S, 116°45'31.32" E). The field plots (1.6 x 3 m) of wheat (*cv.* Wyalkatchem) consisting of six rows, 250 mm apart, with heated (H+) and non-heated (ambient) treatments (H-). Plots were arranged in a randomised block design with three replicates. The plot heaters were developed and described in Stutsel *et al.* (2019) (named prototype three); from here on these will be referred to as plot heaters.

Plot heaters
Briefly, a 1.7 m by 2 m area of a plot including the 4 inside rows had canopy temperature maintained above 0°C throughout the frost susceptible window (Z50-Z69) through the use of a 2 kW diesel space heater. Hot air produced by the heater was distributed through a PVC manifold at ground level to heat the plants. The plot heater was switched on when the air temperature at 600 mm AGL (canopy height) fell to 2 °C, via a relay on the data logger. Air temperature was measured every minute by thermocouples spaced every 200 mm, at 200, 400, 600, 800 and 1000 mm above ground level (AGL) (T-Type, Temperature Controls Pty, Sydney, NSW, Australia) and data recorded by a DT50 data logger paired with a calibrated Campbell Scientific CR5000 . Relative humidity sensors were installed in 2019 in addition to the thermocouples.

Plot heaters were installed prior to when the wheat plants reached Zadoks growth stage Z39 (Zadoks *et al.* 1974). The aim was for the heaters to be installed before young microspore stage, although the exact determination of this stage by dissection was not carried out but based on growth stage instead. Weekly Zadok scores were recorded of plots for (Z39 to Z70). There were no crop development differences between the H+ and the H- treatments caused by the heating during the night or warming of the manifold by the sun during the day. Anthesis cuts were not taken in 2018 Heater+ plots as the removal of biomass would influence the canopy air movement in the plot and the amount of radiation entering the plot and soil surface during the day. In 2018 the three plot heaters and their weather stations were later removed (16/08/2018) at Z71 in time of sowing (ToS) block one (sown 12/04/2018) and moved to three new replicated plots in ToS block five (sown 10/05/2018) so that more data could be collected on additional field plots. The plot heaters remained at their second location until Z87 when harvest index cuts were taken. Harvest index cuts, spike samples for sterility measurement and harvest cuts were taken as described by (Leske *et al.* 2017). In 2019 three additional plot heaters were built, so in total six heaters were deployed at the same developmental stages as 2018. Three were deployed in ToS block two (sown 17/04/2019) and three in ToS block six (sown 17/05/2019). This provided testing over two seasons x two different blocks or environments.

Yield and yield components were analysed using a linear mixed model in Genstat 19th Edition (Genstat - VSN-International Ltd. 2018). Significance tests were made using Fisher's protected LSD test ($p < 0.05$) with each ToS compared separately when comparing treatments across measured traits as noted in the tables, with replicate as the grouping factor.

Results and Discussion

Frost events

The frosts provided opportunities to test the plot heater to provide non-frosted control plots when adjacent plots were at sub-zero degree temperatures on multiple occasions, using three different heaters in two environments per season. Frost events were frequent in 2018 and 2019 at Dale, with a number occurring throughout the flowering window of Wyalkatchem (Figure 1). 2019 was characterised by more events with lower minimums and longer cold duration compared to 2018. There were 9 frost events from 30/7/2019 during Z55 to Z69 for Wyalkatchem sown on 17/04/2019 and only one for the same window in 2018 (Figure 1). Figure 2 Shows the difference in canopy temperature and RH relative of the heated relative to the un-heated during a frost event on the 7th of Sept 2019.

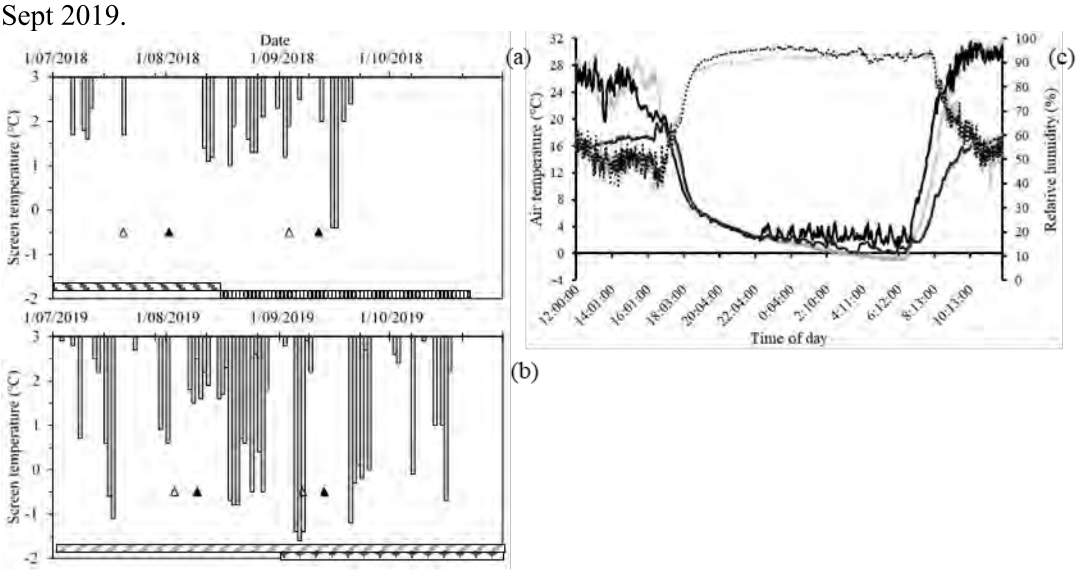

Figure 1. Heading (Z55 – shaded triangles) and flowering dates (Z65 – black triangles) with frost events (screen temp< 3°C) at Dale from July to October 2018 (a) and 2019 (b). The dashed bars show the period the plots heaters installed. Sowing dates for the corresponding heading and flowering dates are: 12/04/2018 and 10/05/18 (a), 17/04/19 and 17/05/19 (b). Typical diurnal canopy, screen temperature and relative humidity (dashed lines) at 600 mm above ground level, with (black lines) and without (grey lines) heaters during heading of TOS 6 (Z55) on the 7th Sept 2019 (c).

Plot heater performance

The plot heaters were able to maintain temperatures above 0°C during frost events that occurred in 2018 and 2019, demonstrating their ability to act as non-frost controls and prevent freezing damage to plants. Canopy air temperatures were warmest nearest to the soil surface which is where the freezing process is initiated from (Livingston *et al.* 2018). The plot heaters were successful in heating an enlarged area of field plot without the heat escaping into neighbouring plots. Thermal images confirmed that heat was not being lost to neighbouring plots and confirmed what was reported in Stutsel *et al.* (2019). Air temperatures at the top of the canopy during September frosts in 2019 reached 0°C, which would result in chilling damage, but not freezing damage to plants. In future designs, the heater output and heated area could be increased by using a 5 kW heater and increasing the diameter of the PVC manifold. Fans could be included to draw air through the manifold away from the heater. In conclusion, the plot heaters were able to maintain canopy air temperatures above 0°C when the ambient air temperature was at or below 0°C. They are useful tools in moderating the effects of frost on wheat plants to enable the further study of the effect of frost yield and yield components, as considered in the next section.

Floret sterility

Floret sterility confirmed the plot heaters were successful in reducing the severity of the frost and the resulting frost damage. Though significantly lower levels of floret sterility were observed on both ToS blocks for the plots with heaters installed, some damage (21.4% ToS 1, 8.5% ToS 5 and 32.6% ToS 2, 28.5% ToS 6) was still present at significant levels in heated plots in both 2018 and 2019 (Table 1). We expect that the resultant damage is from chilling damage that occurs prior to heater installation (before Z39) or at <5°C canopy air temperature at the post heading stage. Prevention of this type of damage could potentially be achieved by installing heaters earlier and setting higher activation temperature for more severe frost events when great heat output is required to maintain the minimum temperature threshold to prevent freeze damage and lessen chilling damage. The results presented demonstrate the impact of freezing damage at the post heading stage in wheat. Some of the sterility present in ToS 1 2018 heated plots was due to frost damage during grain set that occurred after the heaters were shifted to ToS 5 on August 16th.This was confirmed in grain samples from the harvest index cuts. Non-heated plots also had grain frost damage in 2018, resulting in lower grain weight and grain number. In 2019 grain set and grain filling frost damage was prevented by heaters being able to be left in their plots until plants at harvest maturity. The 20-30% of FS could be due to young microspore damage prior to the heaters being installed or just the impact of cold temperatures during flowering.

Yield and yield components

Plot heaters significantly prevented reductions in grain yield, harvest index, grain number and grains per spike in April sown (ToS 1 and 2) wheat in 2018 and 2019 by reducing frost damage in comparison with plots in ambient conditions. For the Dale 2018 data, grain yield and harvest index were 1.4 times greater in heated versus non-heated plots (Table 2). Likewise, in 2019 data grain yield was three-fold and harvest index by 3.7 times greater in heated versus non-heated plots. Grain yield loss due to frost was 1.0 and 1.6 t/ha in 2018 and 2019 for April sown wheat. Grain number was reduced in the non-heated plots by 1.3 and 4.1 times compared to the heated plots in April sown wheat for both seasons. This was particularly evident in the spike, with three times less grain being present in spikes from non-heated comparted to heated plots in 2019. Thousand grain weights were reduced by 3 mg in non-heated plots in both seasons, although later was not a significant difference between the treatments (p>0.05). May sown wheat (ToS 6) did not experience significant amount of frost damage (Table 1). Hence there were no significant differences in grain yield, harvest index, grain number, thousand grain weight or grain number per spike (Table 2). Anthesis biomass increased with the later sowing. Productive tillers numbers did not vary between the treatments for both ToS in 2019 (Table 2). The significant differences in yield components demonstrate that plot heaters can be used to estimate the real cost of freezing frost damage and be used to target frost damage at different growth stages in cereal crops, by changing minimum temperature and duration of natural frost events at a plot level. As discussed by Barlow et al. (2015) the diesel heater approach can help determine the yield impact of frost at different crop stages in combinations with freezing and chilling damage through a dose response experiment to develop frost damage functions for crop modelling.

Conclusion

The plot heaters were able to prevent freezing damage in the wheat by maintaining plot canopy air temperatures above 0°C during frost events and demonstrating the ability to use heated plots as “frost controls”. Our “frost control” design has several advantages: it is modular, enabling easy transport from one field plot to another when running sequential experiments; the design fits within standard field trial designs (making replication of control plots straightforward) and can be easily modified to heat more or less crop rows within a plot; the smaller scale of the heated area reduces the chance of frost gradients occurring across the trial site; and finally, there are no known artifacts caused by the heater we are aware of (no radiation, shading or light interception effects). This is a significant milestone for frost research in Australia as this result enables us to quantify frost damage effects across different cultivars with tissue sampling and various analyses to increase our understanding of physiological and biochemical changes in plants under field conditions.

Table 2. Grain yield, floret sterility and yield components of Wyalkatchem in heated and non-heated plots for the 2018 and 2019 seasons at Dale, WA. Letters indicate a significant difference ($p < 0.001$) between the means as determined by Fisher’s protected LSD test ($p < 0.05$) with ToS compared separately.

Treatment	Sowing date	ToS	Grain yield (g/m2)	Harvest index (%)	Anthesis biomass (g/m^2)	Floret sterility (%)	Grains spike^{-1}	Grains m^{-2} (000s)	1000 grain weight (mg)	Spikes m^{-2}
Heater +	17/04/2019	2	234^a	0.22^a	-	21.4^a	25^a	5.8^a	48.3^a	232^a
Heater -	17/04/2019	2	77^b	0.06^b	724	36.4^b	8^b	1.4^b	45.3^a	209^a
Heater +	17/05/2019	6	502^a	0.40^a	-	8.5^a	41^a	11.3^a	44.3^a	278^a
Heater -	17/05/2019	6	452^a	0.40^a	910	11.2^b	40^a	11.7^a	43.2^a	299^a
Heater +	12/04/2018	1	344^a	0.23^a	-	32.6^a	-	9.5^a	36.4^a	-
Heater -	12/04/2018	1	241^b	0.17^b	709	43.7^b	14	7.3^b	33.0^b	522
Heater +	10/05/2018	5	492^{ns}	-	-	28.5^a	-	9.9^{ns}	49.4^a	-
Heater -	10/05/2018	5	436^{ns}	-	992	58.7^b	18	8.5^{ns}	51.7^b	463

Acknowledgements

We thank Professor Tim Colmer for his comments on the paper, Associate Professor Nik Callow and Dr. Bonny Stutsel for their assistance with the plot heaters and Mr. Peter Hanson for maintaining the weather station network at Dale. Brenton Leske was supported by GRDC (GRDC Research Scholarship), DPIRD (Grains R&D Postgraduate Scholarships and Development Program).

References

Barlow KM, Christy BP, O’Leary GJ, Riffkin PA, Nuttall JG (2015) Simulating the impact of extreme heat and frost events on wheat crop production: A review. Field Crops Research 171:109-119. (doi:http://dx.doi.org/10.1016/j.fcr.2014.11.010)

Fredericks TM, Christopher JT, Harvey GL, Sutherland MW, Borrell AK (2012) Current and emerging screening methods to identify post-head-emergence frost adaptation in wheat and barley. Journal of Experimental Botany 63, (15):5405-5416. (doi:10.1093/jxb/ers215)

GenStat for Windows 19th Edition (2018) VSN-International Ltd. .

Leske B, Nicol D, Biddulph B Optimising sowing time in frost prone environments is key to unlocking yield potential of wheat. In: The Proceedings of the 18th Australian Society of Agronomy Conference, Ballarat, Victoria, 24 – 28 September 2017.

Livingston DP, Tuong TD, Murphy JP, Gusta LV, Willick I, Wisniewski ME (2018) High-definition infrared thermography of ice nucleation and propagation in wheat under natural frost conditions and controlled freezing. Planta 247, (4):791-806. (doi:10.1007/s00425-017-2823-4)

Marcellos H, Single W (1984) Frost Injury in Wheat Ears After Ear Emergence. Functional Plant Biology 11, (2):7-15. (doi:http://dx.doi.org/10.1071/PP9840007)

Stutsel BM, Callow JN, Flower K, Biddulph TB, Cohen B, Leske B (2019) An Automated Plot Heater for Field Frost Research in Cereals. Agronomy 9 (2):96

Woodruff D, Tonks J (1983) Relationship between time of anthesis and grain yield of wheat genotypes with differing developmental pattern. Australian Journal of Agricultural Research 34, (1):1-11. (doi:http://dx.doi.org/10.1071/AR9830001)

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Research 14, (6):415-421. (doi:10.1111/j.1365-3180.1974.tb01084.x)