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Farm-scale zoning of extreme temperatures in Southern Mallee, Victoria, Australia

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Extreme temperatures around the flowering of wheat have the potential to reduce grain yield and at farm scale their impact can be spatially variable. In this study, the zoning of extreme temperatures, using data collected over two years, was carried out for a 164 ha farm in the Southern Mallee, Victoria, Australia in order to identify areas at high risk of extreme temperatures around the time of the flowering of wheat. Twenty-five data loggers were installed at 0.8 m height across the farm to spatially record the daily course of temperatures around the average date of flowering for the region. After applying the zoning algorithms, the maps of different temperature zones were produced by spatial interpolation in ArcView 3.2. It was found that in 2003, about 58% of the farm area was prone to exposure to higher temperatures and about 73% to the lower temperatures whereas in 2004 about 46% of the farm area was prone to exposure to higher temperatures and about 39% to the lower temperatures.

1. Introduction

Farm-scale spatial variability in microclimate, notably extreme temperatures, is the major factor responsible for reduction in grain yield of wheat crop in Southern Mallee, Victoria, Australia (Cawood, 1996) and in most of Australia (Potgieter *et al.*, 2002). Extreme temperatures can have severe consequences for crops and significantly reduce yields (Porter and Gawith, 1999). Each year considerable yield losses in wheat occur globally due to untimely frosts at flowering time (Maes *et al.*, 2001). Yield losses in Victoria due to frost can vary from 5% to 50% depending on timing and temperature reached (Cawood and McDonald, 1996). Both high and low temperatures decrease the rate of dry matter production and, in the extreme, can cause production to cease (Grace, 1988).

The time of flowering of wheat (Single, 1961) and many crop plants (Wheeler *et al.*, 2000) is sensitive to extremes of temperature and for maximum yield, flowering should occur after the last damaging frost (Fischer, 1979). Planting of crops at a time when the risk of frost during flowering has diminished to an acceptable level is the best approach for the growers in Australia (Martin, 2002). Exposure to low temperatures during flowering of wheat can reduce grain yields through the production of infertile florets and frost damage. Reproductive tissues of the developing wheat ear are extremely susceptible to damage by freezing (Single and Marcellos, 1974) and damage from severe frosts during the critical flowering and grain filling stages causes severe economic loss to winter crop producers (Kelleher *et al.*, 2001). Temperatures as high as 9.5 °C, for a few days around flowering, can produce infertile florets (Slafer and Slavin, 1991; Russell and Wilson, 1994). Similarly, temperatures above 31 °C immediately before flowering have the potential to reduce grain yield by inducing pollen sterility, thereby reducing grain

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Nomenclature

°C	degree Celsius
%	percent
σ	standard deviation
θa_1 and θa_2	threshold value for $avgMx_i$ and $avgMn_i$ (°C)
θb_1 and θb_2	threshold value for $cvMx_i$ and $cvMn_i$
$avgMx_i$	average maximum temperature at i data logger (°C)
$avgMn_i$	average minimum temperature at i data logger (°C)
cv	coefficient of variation
ha	hectare
i	data logger point
k	kilo
km	kilometre
Mn	daily minimum temperature (°C)
Mx	daily maximum temperature (°C)
n	number of days
sd_{diff}	difference from threshold values for standard deviation (°C)
$sdMn_i$	standard deviation of minimum temperature at i data logger (°C)
$sdMx_i$	standard deviation of maximum temperature at i data logger (°C)
t	day of measurement
T_{diff}	difference from threshold values for temperature (°C)
$Tmax$	maximum temperature (°C)
$Tmin$	minimum temperature (°C)
x_i	temperature at logger location i (°C)

numbers (Wheeler *et al.*, 1996). Brief episodes of hot temperatures at the time of flowering can reduce the potential number of seeds or grains that subsequently contribute to the crop yield (Wheeler *et al.*, 2000). Wheat is vulnerable to high temperature during its most reproductive stages (Nicolas *et al.*, 1984; Wardlaw *et al.*, 1989; Tashiro and Wardlaw, 1990a,b), and kernel number, kernel weight, or both can be diminished (Gibson and Paulsen, 1999).

At farm scale, the combination of local variations in elevation, aspect and slope cause variations in temperature and frost incidence in the landscape (Kelleher *et al.*, 2001) even with little variation in topographic relief (Kalma, 1984). Differences in elevation of only 1 m can allow cold-air drainage down slopes and the formation of the frost pockets. The coldest temperatures are generally associated with the low-lying areas and studies show that temperature variations have a distinct relation to the atmospheric circulation (Tveito, 2002). Aspect is associated with differences in relative radiation load, while relative slope position is associated with airflow effects such as cold-air drainage (Lookingbill and Urban, 2003). Hocevar and Martsolf (1971) related the occurrence of minimum temperatures to elevation in the landscape during frosty nights. They reported that the minimum temperatures in complex terrain are influenced by the temperature of the well mixed air stream, measured on an exposed hilltop, and effects controlled by the terrain such as katabatic flows and stagnation of cold air. In many cases elevation alone can explain up to 85% of the spatial variation in minimum temperatures in the landscape on a particular day (Fitzpatrick and Laughlin, 1981). Air temperature close to the ground is a factor in plant growth (Hudson and Wackernagel, 1994) and is extremely variable in space and time, depending on numerous environmental factors such as solar radiation, elevation, aspect, distance from the sea, shape of the valley and presence of water bodies (Petkov *et al.*, 1996).

Thus, the variation in microclimate within the farm can explain variation in grain yield (Cawood, 1996; Tveito, 2002). This study aims to identify different zones of extreme temperatures within the farm which may be treated as separate units to practice different management in order to minimise losses due to crop exposure to extreme temperatures around the time of flowering.

2. Materials and methods

2.1. *Study area*

The study was conducted in a 164 ha farm (35.78°S, 142.98°E), 25 km north of Birchip in Southern Mallee, Victoria, Australia. The farm has approximately 10 m variation in elevation. Soils are Epihypersodic Hypercalic Calcarosols (Isbell, 1996). A digital elevation map (Fig. 1) of the farm was developed at 10 m × 10 m resolution using ArcView 3.2 with Spatial Analyst (ESRI, 1996) and shows the variation in elevation across the farm.

2.2. *Experimental setup*

Tinytag temperature data loggers (TG-0050, Gemini Data Loggers (UK) Ltd., Chichester, UK) were used to record temperatures across the farm. These data loggers offer flexibility of recording time and data management as the data can be easily downloaded to a laptop computer in the farm. The Tinytag was contained in a flat snap canister (diameter: 60.2 mm, thickness: 15.3 mm and weight: 26 g) with a hanging tab of 12 mm and a mounting hole of 6 mm diameter to enable it to be mounted on a stand for temperature measurements. The loggers had an internally mounted sensor [Sensor type: 10 k negative temperature coefficient (NTC)-Thermistor (Encapsulated)] with measuring range of −30 °C to +50 °C and a non-volatile memory of 2 k which stored 1800 data points. The thermistor had an accuracy of ±0.2 °C in the temperature range of 0–50 °C and a resolution 0.25 °C at 0 °C. The data was downloaded by means of a cable connected to a computer using the manufacturer's Gemini Logger Manager (GLM) software.

The data loggers were mounted within a radiation screen that consisted of a Polyvinyl chloride (PVC) pipe of 100 mm diameter, 300 mm in length, and open at both ends with a longitudinal slit of about 30 mm to facilitate air movement and fastened to a 1 m long wooden peg as shown in Fig. 2. The screened loggers were erected at the chosen locations (shown by the black dots in Fig. 1) throughout the farm at a height of 0.8 m to represent crop head height. The locations of the data loggers were chosen according to the elevation across the farm and not in a regular grid. Data loggers were grouped

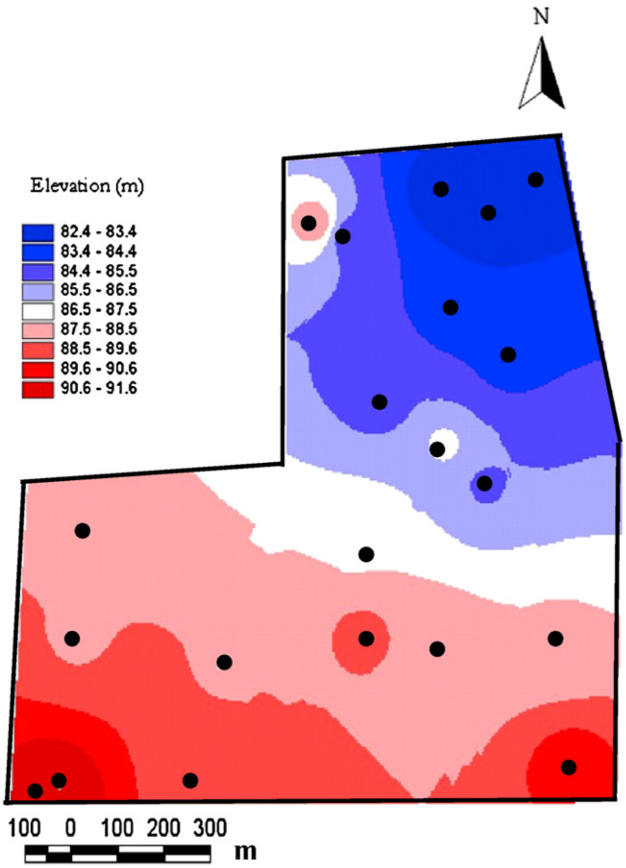

Fig. 1 – Variation in elevation (m) across the farm.

more closely in areas of high and low elevations to more effectively capture any topographic effect.

2.3. *Experiment*

Twenty-five data loggers were activated, fixed to the already prepared screens and then erected at different locations in order to record daily course of temperature across the farm during September 2003 and October 2004. No crop was grown in 2003, because the farm was kept fallow to conserve moisture, but in 2004 a wheat crop was planted which flowered around October, 18. The location of data loggers, in terms of latitude and longitude, were obtained by a NavCom Starfire SF-2040G Global Positioning system (Manufacturer: NavCom Technologies, Torrance, CA, USA) with an accuracy of 0.7 m and the same data loggers were used at each position in both years.

Fig. 2 – Experimental setup in the farm.

Temperatures were recorded for a total of 49 days at 15-min interval in 2003 and for 35 days at 30-min interval in 2004. During the course of experiment, four data loggers were found to be either broken or displaced from their original positions. Hence, data from only 21 loggers were taken for further analysis.

2.4. *Methods*

Blackmore (2000), Larscheid and Blackmore (1996) and Blackmore *et al.* (2003) conducted research on zoning of a field on the basis of yield map and biomass and described zoning methodology and algorithms in detail. Similar methods were followed in this exercise. Forty nine days maximum and minimum temperature data from 2003 and 35 days data from 2004 were analysed to produce zones of consistently high, variable high, consistently low and variable low temperature zones for maximum and minimum temperatures in both the years. These data were treated separately as one year the farm had crop and the other it did not.

Average maximum and minimum temperatures, standard deviation from mean and coefficient of variation were calculated at each location for both years by applying the following algorithms.

The temporal average of maximum and minimum temperatures at any point within the farm ($avgMx_i$, $avgMn_i$) was calculated as

$$avgMxi = \frac{\sum_{t=1}^{n} Mxit}{n} \quad \text{and} \quad avgMni = \frac{\sum_{t=1}^{n} Mnit}{n}$$

where Mx, Mn are the daily maximum and minimum temperatures. i is a data logger, t is the day of measurement and n is the number of days considered.

The following equation was used for calculating the standard deviation (σ).

$$\sigma = \frac{1}{n}\sqrt{n\left(\sum_{i}^{n} x_i^2\right) - \left(\sum_{i}^{n} x_i\right)^2}$$

where x_i is the temperature at logger location i and n is the total number of days.

Coefficient of variation (cv) at a point was calculated as

$$cvMx_i = sdMx_i/avgMx_i \quad \text{and} \quad cvMn_i = sdMn_i/avgMn_i$$

where $sdMx_i$ and $sdMn_i$ are the standard deviations of maximum and minimum temperatures at a point over the period considered.

After calculating these parameters for each location, and applying the variability status criteria (Table 1), final maps for each year were produced in ArcView 3.2 by means of interpolation by the inverse distance weighting (IDW) method (ESRI, 2001) with a pixel size of 7 m × 7 m, giving consistently high, variable high, consistently low and variable low

Table 1 – Variability status criteria

Variability status	Condition 1	Condition 2
Consistent high temperature	$avgMx_i, avgMn_i \geq \theta a_1, \theta a_2$	$cvMx_i, cvMn_i \leq \theta b_1, \theta b_2$
Consistent low temperature	$avgMx_i, avgMn_i < \theta a_1, \theta a_2$	$cvMx_i, cvMn_i \leq \theta b_1, \theta b_2$
Variable high temperature	$avgMx_i, avgMn_i \geq \theta a_1, \theta a_2$	$cvMx_i, cvMn_i > \theta b_1, \theta b_2$
Variable low temperature	$avgMx_i, avgMn_i < \theta a_1, \theta a_2$	$cvMx_i, cvMn_i > \theta b_1, \theta b_2$

θa_1, θa_2 are the thresholds for $avgMx_i$, $avgMn_i$ and θb_1, θb_2 are the thresholds for $cvMx_i$, $cvMn_i$.

temperature zones across the farm. The IDW method assumes that data points that are close to one another are more alike than those that are far apart.

The threshold values were taken as the overall average of a particular parameter taking all the data loggers over the number of days considered. For example θa_1 is the 49-day average of maximum temperature of all the data loggers. The values of θa_1 and θa_2 were 22.42 and 3.79 °C in 2003 and 30.12 and 6.15 °C in 2004 and the values of θb_1 and θb_2 were 0.18 and 0.94 in 2003 and 0.20 and 0.52 in 2004, respectively.

3. Results and discussion

The difference between threshold values and the average maximum and minimum temperatures and standard deviation were calculated by subtracting the average value in each zone (based on the number of data loggers in that zone) from the threshold value for that zone for both maximum and minimum temperatures and the standard deviation (Table 2). In 2003, no values were obtained for the variable high temperature zone in the case of minimum temperature; hence there is little of this zone in Fig. 4a. Likewise, in 2004, no values were obtained for variable high and consistently low temperature zones in the case of minimum temperature; hence there is little of this zone in Fig. 4b.

The percentage area in each zone was calculated from the ratio of number of pixels lying in that zone to the total pixels in the entire farm. In 2003, about 33.6% of the farm area had consistently high, 24.6% variable high, 22.2% consistently low and 19.5% of the farm area had variable low temperature, respectively (Fig. 3a). This indicates that about 58% of the farm was in zones of consistently high and variable high temperature when the farm was bare. However, in 2004 with the wheat crop in the farm about 19.1% of the farm area had consistently high, 27.2% variable high, 38.4% consistently low and 15.3% of the farm area had variable low maximum temperature, respectively (Fig. 3b) indicating that about 46% of the farm area encountered the higher temperature. The crop in 2004 may have altered the circulation and mixing of air across the farm and hence a difference between the different zones was observed over the two years.

For the minimum temperature, in the case of no cropping on the farm (in 2003), about 25% of the farm area had consistently high, 2% variable high, 4% consistently low and 69% of the farm area had variable low minimum temperature, respectively (Fig. 4a) suggesting that about 73% of the farm area could have suffered low temperature or frost damage of crop during the season. However, with wheat crop growing on the farm (in 2004) about 60.4% of the farm area had consistently high, 0.8% variable high, 1.2% consistently low and 37.6% of the farm area had variable low minimum temperature, respectively (Fig. 4b). This indicates that about 39% of the farm could have suffered from frost or low temperature damage during the crop season, contributing to the reduction in grain yield.

When comparing the two years, zones of maximum and minimum temperatures were found to be different, when there was no crop and when there was wheat crop growing on the farm. The north-east corner of the farm had lowest elevation (Fig. 1) and this corresponded to the low temperature area in both years for both maximum and minimum temperatures. Likewise, the south-west corner of the farm had the highest elevation and it corresponded to the high temperature area in both years for both maximum and minimum temperatures. However, it is important that the experiment with the wheat crop on the farm is extended for a longer period in order to establish consistent zones of extreme temperatures across the farm over a number of years. Maling (2002) reported that if an area gives consistently low or consistently high yield and biomass over five or six years, it is

Table 2 – Difference between threshold values and the average maximum and minimum temperature and standard deviation in each zone

Zone	*Tmax* (°C)				*Tmin* (°C)			
	T_{diff}		sd_{diff}		T_{diff}		sd_{diff}	
	2003	2004	2003	2004	2003	2004	2003	2004
Consistent high temperature	0.32	1.38	−0.08	0.08	0.34	0.26	−0.11	−0.08
Consistent low temperature	−0.58	−1.20	−0.24	−0.57	−0.09	–	−0.06	–
Variable high temperature	0.45	2.69	0.17	1.11	–	–	–	–
Variable low temperature	−0.30	−2.04	0.07	−0.26	−0.22	−0.37	0.08	0.13

Tmax is the maximum temperature, *Tmin* is the minimum temperature, T_{diff} and sd_{diff} are the differences from threshold values for temperature and standard deviation.

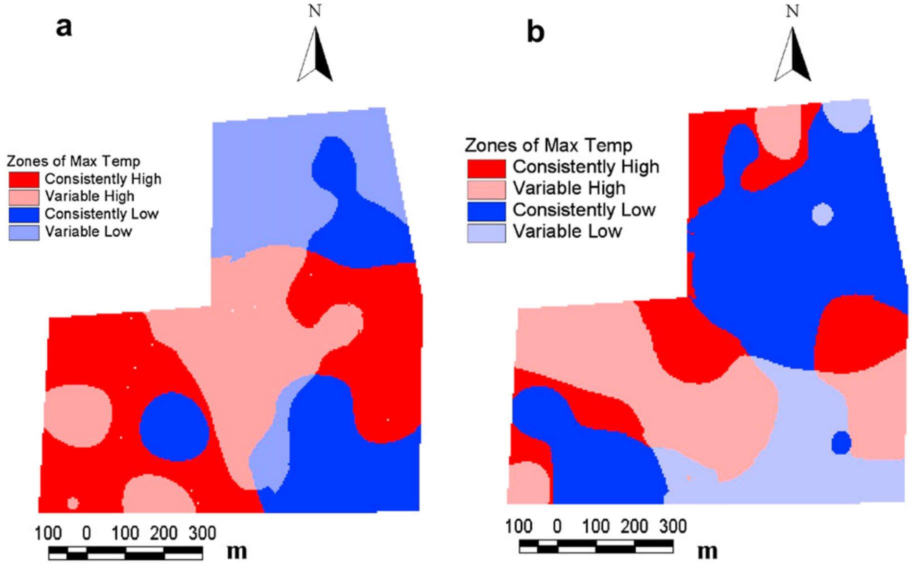

Fig. 3 – Zones of maximum temperatures in the farm in 2003 (a) and 2004 (b).

fairly safe to assume that the pattern will be duplicated in the next season. This finding may be extended to the studies related to identifying temperature zones and the consistent zones of extreme temperature found over the five years may be treated as separate management units.

The results from 2003 may be applied to the crops which are sensitive to extreme temperatures and have low canopy height e.g., lentil. This study may enable farmers to consider extreme temperature damage of crop and incorporate it in their management practices for better yield achievement and to reduce financial losses. The potential remedies could be the choice of sowing date and variety to minimise the risk of crop exposure to extreme temperatures at the critical crop stage around flowering (Liu *et al.*, 2003). Less fertiliser application can also be recommended in areas likely to have extreme temperatures in order to avoid crop damage and financial loss. High nitrogen levels make wheat plants prone to low temperature damage (Forbes and Watson, 1992). The risk of low temperature damage increases with high plant-N status, which can result from a long pasture phase or large nitrogen application at sowing (Heenan and Lewin, 1982). Wheat that has had good growing conditions and high nitrogen is more sensitive to frost injury because of its lush growth and high moisture content (Warrick and Miller, 1999). It has been suggested (Anonymous, 2006) that the farmers should not encourage crops by using high nitrogen rates on high frost-risk paddocks. Crops with access to high nitrogen tend to sustain more frost damage than crops with a lower nitrogen supply. Weber *et al.* (2001) and Melaj *et al.* (2003) recommended application of low nitrogen rates in the areas experiencing

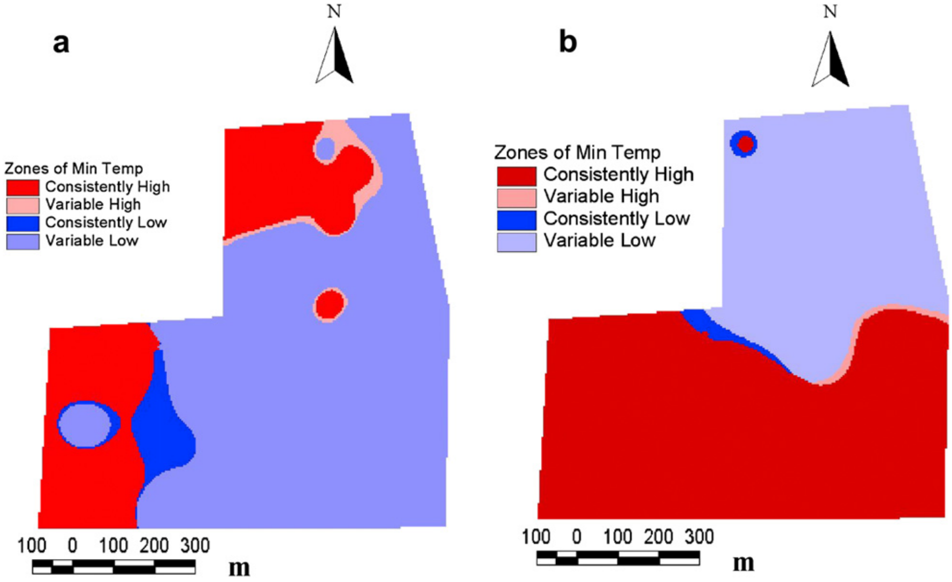

Fig. 4 – Zones of minimum temperatures in the farm in 2003 (a) and 2004 (b).

high temperatures because the risk of NH_3 losses is significantly higher in the high temperature conditions due to low moisture in the soil.

4. Conclusions

Maps of zones of consistently high and low temperatures, such as found in this study, may be used in precision agriculture to create management zones according to their risk of frost and heat stress. The zoning exercise proposed a simple and efficient way to identify different zones of extreme temperatures across the farm by observing the consistency of temperature variation over the time and space. Although the temperatures during the period of observation were not extreme, the information is of value for more extreme conditions to when farmers may seek to minimise crop exposure to extreme temperatures and reduce financial losses by altering management practices. Simulation studies and incorporating zones of extreme temperature into crop models to simulate zonal crop yield may be of more value in this environment and may help to explain spatial variations in grain yield.

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