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ORIGINAL PAPER

Effect of topography on farm-scale spatial variation in extreme temperatures in the Southern Mallee of Victoria, Australia

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Abstract Extreme temperatures around flowering of wheat have the potential to reduce grain yield and at farm scale their impact can be spatially variable depending on topography. Twenty-five data loggers were installed at 0.8-m height across a 164-ha farm in the southern Mallee of Victoria, Australia to spatially record the daily course of temperatures around the average date of flowering of wheat in the region. The experiment was conducted during 2-years period. In 1 year, the farm had no crop cover and in another year the farm had a wheat crop. Multiple linear regression analysis techniques were used to fit models relating daily extreme temperatures to the farm topographic features of elevation, aspect and slope, and the average maximum and minimum temperatures of each day at the farm in order to identify areas of high risk of extreme temperatures around the time of the flowering of wheat. The fitted regression models explained 90% and 97% of the variability in maximum and minimum temperatures, respectively, when the farm had no crop cover and 80% and 94% of the variability in maximum and minimum temperatures, respectively, when the farm had a wheat crop cover. When the farm had no crop, only minimum temperature was partially explained by the topography however, both maximum and minimum temperatures were partially explained by the topography when the farm had a wheat crop. From this study it was concluded that, (1) high temperature variations were found across the farm (2) temperature variations were only partially explained from the developed model presumably due to the flatter topography of the farm and (3) the relationships obtained from this study could be used in a crop model which can explain variation in grain yield based on the topography of a field.

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1 Introduction

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). In a field study in Australia, Banath and Single (1976) estimated that more than 50% of potential yields had been lost as a result of frost. Yield losses in wheat can vary from 5% to 50% in Victoria, Australia due to frost depending on timing and temperature reached (Cawood and McDonald 1996). Both high and low temperatures decrease the rate of dry matter production and, at extremes, 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). Exposure to low temperatures during flowering of wheat can reduce grain yields through the production of infertile florets and frost damage. Temperatures as high as 9.5°C during a few days around flowering can produce infertile florets (Slafer and Slavin 1991; Russell and Wilson 1994). Similarly, brief episodes of hot temperatures above 31°C around flowering have the potential to reduce grain yield by inducing pollen sterility due to water stress, thus reducing grain numbers (Asana and Williams 1965; Wheeler et al. 1996, 2000). 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 grain growers in Australia (Martin 2002).

Apart from spatial variability in soil properties across the field, spatial variability in microclimate, notably extreme temperatures, is the major factor responsible for reduction in grain yield of wheat crop in the southern Mallee of Victoria (Cawood 1996) and in most of Australia (Potgieter et al. 2002). At the farm level, local variation in topography, i.e. elevation, aspect and slope, cause variation in temperature and frost incidence in the landscape (Kelleher et al. 2001; Lookingbill and Urban 2003) even with little variation in topographic relief (Kalma 1984).

Tveito (2002) used elevation and slope as variables in a regression model for deriving mean monthly temperature maps for the Nordic countries. Aspect is also a significant factor in explaining local scale temperature variability (Barringer 1997) and 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 a landscape during frosty nights. Fitzpatrick and Laughlin (1981) reported that in many cases, elevation alone could explain up to 85% of the spatial variation in minimum temperatures in a landscape on a particular day.

The variation in microclimate within a farm can explain variation in grain yield (Cawood 1996; Tveito 2002). Because of the heterogeneity in topography and soil properties across land surfaces, it is important to understand the farm-scale variability to accurately determine the farm-scale model estimates (Bougeault et al. 1991). Variation in local temperatures associated with topography is a significant factor that needs to be accommodated in environmental models and land-use strategies (Barringer 1997). Incorporating frost risk into cropping strategies requires specific on-farm spatial temperature data to obtain generalised relationships between landscape attributes and temperature variation. These relationships offer potential for development of predictive models for improved management of frost risk within cropped landscapes (Kelleher et al. 2001). However, no attempts have been made in the wheat-growing areas of the Victorian southern Mallee, Australia, to obtain relationships explaining the spatial variation in temperatures based on the farm topography. These relationships may be incorporated into a crop model to simulate the effect of varying temperature on grain yield at farm level.

In this study, we develop the multiple linear regression models relating temperature to the topography of a 164-ha farm in the Victorian southern Mallee (from the data collected over 2 years, one with no crop and the other with a wheat crop in the farm) to explain the spatial variation in temperature within the farm. The specific objectives of this study were to (1) demonstrate a simple and economical methodology for data collection of spatial temperature variation within the farm (2) develop simple regression models to predict the spatial variability in extreme temperatures at farm level and (3) test the hypothesis that the spatial variation in extreme temperatures at farm level can be predicted from the elevation, aspect and slope.

2 Materials and methods

2.1 Study area

The study was conducted in a 164-ha farm (35.78°S, 142.98°E), 20 km north of Birchip in the southern Mallee of Victoria, Australia. Wheat is the predominant crop over the region. The farm has approximately 10-m variation in elevation, and regular frost occurrence and frost damage to the crop is reported by the landholder at certain parts of the farm. Previous years of yield maps from this farm showed high spatial variability with areas of consistent high and low yields across the farm (Abuzar et al. 2004; Rab et al. 2006; Fisher et al. 2009). Some of this yield variability was associated with the soil properties of the farm based on apparent electrical conductivity obtained from an electromagnetic induction (EM38) survey (Rampant and Abuzar 2004; Armstrong et al. 2009; Rab et al. 2009). However, in certain parts of the farm, especially in the low-lying areas, the yield was consistently low and the variability was not associated with the variable soil properties and hence could be related to the spatial variation in extreme temperatures. Soils in this farm are Epihypersodic Hypercalic Calcarosols (Isbell 1996). The changes in elevation and orientation resulting in undulating terrain and uneven slopes across the farm can be seen in Fig. 1.

2.2 Experimental setup

Tinytag temperature data loggers (TG-0050, Gemini Data Loggers (UK) Ltd.) 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 casing was 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 facilitate hanging from the setup devised for temperature measurements. They had an internally mounted sensor (Sensor type: 10 k NTC-Thermistor, (Encapsulated)) with measuring range of −30°C to +50°C and a non-volatile memory of

Fig. 1 Experimental setup in the farm

2 k which stored 1,800 data points. The thermistor had an accuracy of ±0.2°C in the temperature range of 0°C to 50°C and a resolution 0.25°C at 0°C. The data was downloaded by means of a cable connected to the computer using Gemini Logger Manager (GLM) software. Kalma et al. (1988) used commercially available, miniature weather-proof, battery-operated infrared temperature transducers specifically developed for continuous monitoring of crop and soil surface temperature. Lindkvist and Lindqvist (1997) used a one channel data logger with built-in thermistor and battery (Tinytalk, logger-sensor unit, Orion Components, Chichester, UK), similar to the ones used in this study for temperature data collection.

The data loggers were encased in PVC pipe of 100-mm diameter, 300 mm in length, and open at both ends with a longitudinal slit of about 30 mm over the length of pipe to facilitate air movement inside the pipe and at the same time to protect data loggers from rain and high wind. These data loggers were suspended inside the pipe using thin, plastic-coated wire from the top of the pipe, as shown in the Fig. 1. This pipe was fastened to a 1-m long wooden peg. The complete setup was erected at the chosen locations (shown in black dots in Fig. 2) over the field 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 more closely in areas of high and low elevations to more effectively capture any topographic effect.

2.3 Calibration

To test the accuracy of the measurement at different temperature ranges, data loggers were calibrated at three different temperature ranges viz., ambient temperature at around 14–18°C, low temperature at around 4–6°C and high temperature at around 36–37°C. All 25 data loggers

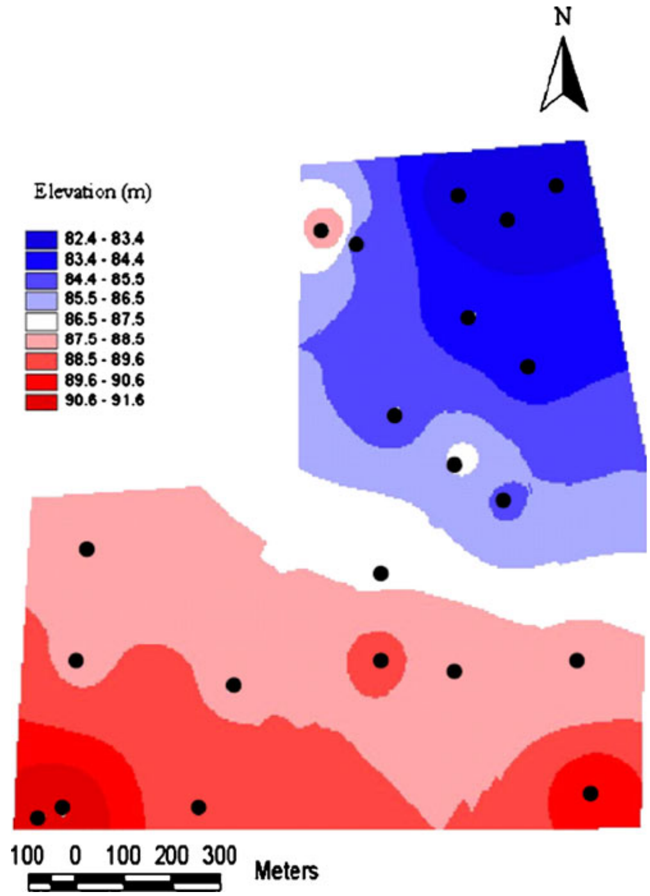

Fig. 2 Variation in elevation in metres across the farm

were kept in an insulated box made of thermocol for 3 days to record temperature at 30-min interval, first at ambient temperature in a room, then in a cool room and then in an incubator. The average temperature recorded by each data logger at the three temperature ranges were calculated and then the difference from average of each data logger to the average of all the data loggers at each temperature range was calculated and then finally percentage error was calculated from this difference. The maximum average percentage error from all the three temperatures ranged from −2.39% to +2.02% which is believed to be negligible and was ignored for this study. There was no bias in the error at the lower or higher temperatures.

2.4 Data collection

In 2003, there was no crop in the farm and the ground was covered with dry thin crop residue as seen in Fig. 1. Twenty-five calibrated data loggers were activated, fixed to the already prepared setup and then erected at different locations in order to capture topographic effects on the daily course of temperature across the farm. Barringer (1997) collected temperature data from 43 sites with elevation range of 600 to 1,800 m (and from 27 sites with elevation range of 800 to 1,400 m as a replicate) over a vast area (144 km^2) in a stratified sample to derive an empirical model relating soil temperature to site characteristics (elevation, aspect and slope). In a similar experiment, Lookingbill and Urban (2003) used temperature data from 45 data loggers over an area of 6,400 ha, with elevation range of 410 to 1,630 m, to develop regression models relating air temperature to site characteristics.

The data loggers were installed in the farm on 12th September 2003 (spring) prior to the commencement of the normal flowering period of wheat in this region. In 2004, wheat growing in this farm commenced flowering on 18th October.

The nearest weather station is the Birchip Post Office (about 20 km south) and one data logger was also installed at Birchip Post Office at 0.8-m height to monitor the difference between temperature in the farm and the temperature recorded at Birchip Post Office. The elevation and coordinates of all the data loggers' locations were recorded using a NavCom Starfire SF-2040G Global Positioning system (GPS; Manufacturer: NavCom Technologies, CA, USA). This instrument had a horizontal and vertical accuracy of 0.5 and 0.7 m, respectively, and uses the Wide Area Augmentation System and the European Geostationary Navigation Overlay System differential correction.

The data loggers were set to record temperature at 15-min intervals; at this interval the data could be stored for 18 days before downloading. After 18 days the data were downloaded to a laptop computer within the experimental farm. A total of 49 days of data were collected between mid September and early November at the farm and 36-days data at Birchip. However, during the course of experiment, four data loggers were found to be either broken or fallen down from their positions. Hence, data from only 21 loggers were taken for further analysis.

In 2004, a wheat (*Triticum aestivum* cv. Yitpi) crop was sown in the farm in the month of May at a sowing rate of 80 kg/ha. The same experimental setups, used in 2003, were erected on 6th October at their original locations. Only 22 data loggers were installed in this year and the temperature was recorded at 30-min intervals. A total of 35 days of data were collected in this year (from 7th October to 10th November 2004).

2.5 Methods

The digital elevation map (DEM; Dixit and Chen 2010) of the farm was developed at 10×10-m resolution by means of interpolation by the inverse distance weighted (IDW) method of ArcView 3.2 with Spatial Analyst (ESRI 1996). This method assumes that data points that are close to one another are more alike than those that are far apart (ESRI 2001). The lowest and highest points in the farm had an elevation of 82.4 and 91.6 m, respectively (Fig. 2). Topographical parameters, e.g. elevation, aspect and slope at each data logger position were derived from the DEM.

Daily average maximum and minimum temperatures in the farm were calculated from all the data loggers. Multiple linear regression models, relating extreme temperatures to the elevation, aspect, slope and average maximum and minimum temperatures at the farm, were developed to predict the maximum and minimum temperature profiles across the farm and to demonstrate the relative change in temperature with respect to change in topography at the farm scale. Barringer (1997) also used multiple linear regressions techniques to build regression models relating elevation, aspect and slope to map soil temperatures at mesoscale.

3 Results and discussion

3.1 Results from 2003 with no crop cover

On 22nd September, which was a warmer day, the maximum and minimum temperatures varied from 30.2°C to 35.2°C and −0.4°C to 2.5°C, respectively, while on 1st October, which was a cooler day, the maximum temperature varied from 12.1°C to 14.2°C and minimum temperature varied from 7.5°C to 8.3°C across the farm. This indicates that intra-daily maximum temperature may vary up to 5°C and minimum temperature up to 3°C within the farm from location to location on a warmer day when the farm had no crop cover. The highest and lowest temperature recorded over the 49 days of observations was 36.1°C and −5.2°C, respectively.

3.2 Model fitting

The regression analysis relating temperature to the topographical parameters was performed using GenStat (version 7.0) statistical software. The elevation, aspect and slope values ranged from 82.4 to 91.6 m, 9.2 to 151 degrees and 0.0004 to 0.11 degrees, respectively. The following model was fitted for both maximum and minimum temperatures.

$$\hat{y} = \alpha_0 + \alpha_1 \text{ elevation} + \alpha_2 \text{ aspect} + \alpha_3 \text{ slope} + \alpha_4 \text{ average farm temperature} + \varepsilon$$

where $\hat{y}$ is the estimated maximum or minimum temperature, α_0 is the constant term, α_1, α_2, α_3 and α_4 are the estimates of elevation, aspect, slope and average maximum or minimum temperature of the farm, respectively, and ε is the error term.

The fitted models explained 90% and 97% of the observed variability in maximum (Fig. 3) and minimum (Fig. 4) temperatures, respectively. The minimum temperature was better estimated by the model compared to the maximum temperature. The reason for this could be the large fluctuations in maximum temperatures during the daytime because of radiation, cloud movement and overcast conditions which might have caused uneven temperature variation that could not be explained by the topography. Marcellos and Single (1975) experienced that the movement of cloud across sky could alter the amount of net outgoing heat and can cause warming and cooling around plant canopy. Cawood (1996) explained that the variations in topography alter the energy balance of the landscape by affecting interception of radiation and modifying the speed and direction of airflow across the surface. High wind due to high pressure gradient in daytime and low vertical mixing of air in the nighttime may also cause large spatial variation in both maximum and minimum temperatures (Kawashima and Ishida 1992). The temperature variation due to these factors could not be accounted for by the models.

The regression estimates (Tables 1 and 2) of the elevation indicate that, over the 10-m elevation range in the farm, increase in minimum temperatures maybe up to 0.3°C. The estimate was significant ($p<0.001$) only in the case of minimum temperature and shows that the lower elevation produced low temperature. The reason for this could be that after the air cools down, it becomes heavier and settles down in low-lying areas where it causes temperature to fall down as reported by Kalma et al. (1986) and Laughlin and Kalma (1987). Tveito (2002) reported that the coldest temperatures are generally associated with the low-lying areas and differences in elevation of only 1 m can allow cold-air drainage down slopes causing the formation of the frost pockets.

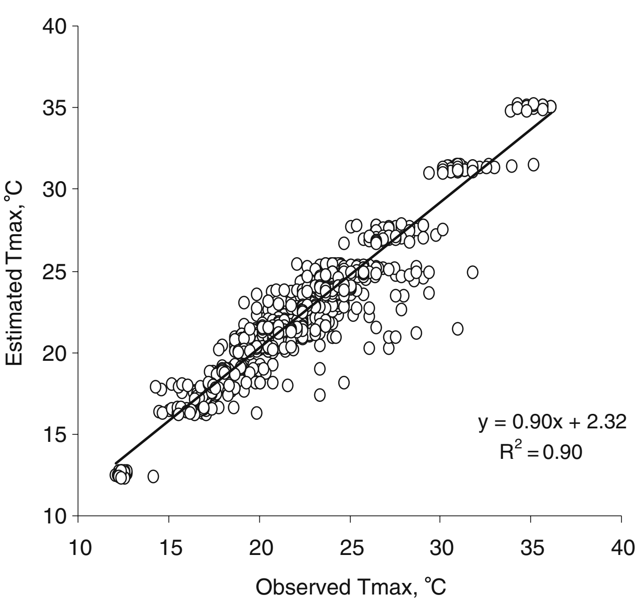

Fig. 3 Observed and estimated maximum temperatures (Tmax) in 2003 with no crop cover

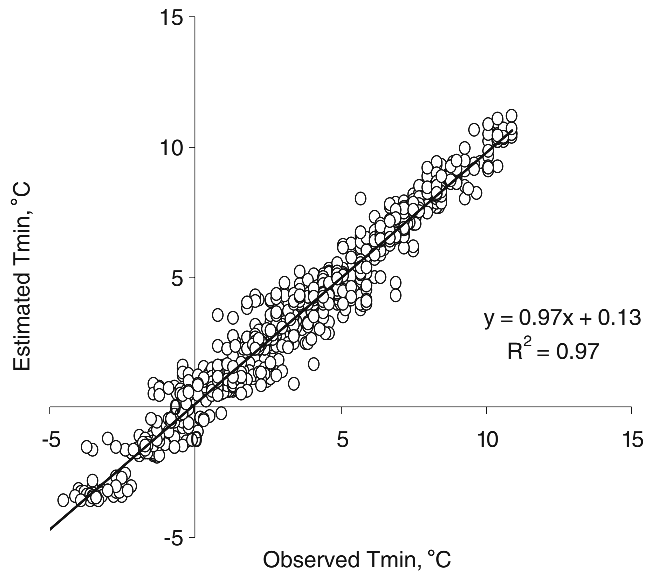

Fig. 4 Observed and estimated minimum temperatures (Tmin) in 2003 with no crop cover

The estimates of slope suggest that a steeper slope caused a higher minimum temperature probably by rapidly draining of cold-air down slope, whereas, a flatter slope caused the opposite. This corroborates the finding in case of elevation as the high elevation points tend to have steeper slope with respect to the lower ground and vice versa. Hence the places of high elevation and steeper slope produced higher minimum temperature at the top similar to the results of Dy and Payette (2007) and places of lower elevation and flatter slopes, e.g. basin type areas, produced lower minimum temperature at the bottom. These results further corroborated the findings of Lindkvist and Lindqvist (1997) who reported that local complex terrain of knob, slope and basin type has a major influence on the establishment of near-surface cold-air within and between slopes and within a landscape as cooling reflects drainage from higher to lower levels along drainage paths determined by the local topography. One degree increase in slope may increase minimum temperature by 6.6°C at the top where slope is measured. However, the slope values indicate relatively flatter topography of the farm and a maximum of 0.7°C increase in minimum temperature can be observed across the farm, which is not large. The estimate of slope was significant only in the case of minimum temperature. Thus slope along with elevation had effect on minimum temperature variation profile across the farm. However, the effect of slope on minimum temperature was more pronounced (6.6°C variation for 1°

Table 1 Estimates of parameters of the regression model describing maximum temperature in 2003 without crop cover (R^2=0.90, n=1029, F probability<0.001)

Parameter	Estimate	SE	t value (df=1,024)	p value
Constant	−3.23	1.33	−2.53	0.015
Elevation	0.037	0.015	2.48	0.014
Aspect	0.000273	0.000283	0.71	0.476
Slope	−2.36	1.37	−1.73	0.084
Average Tmax	1.00	0.01	94.08	<0.001

change in slope) than that of the elevation (0.3°C variation for 10-m change in elevation).

Primary topoclimatic effects result from differences in hill slope angle and aspect (Barry 1992). Lower values of aspect (0–45°, north-eastern exposures) may cause high minimum temperatures during night as they receive more heat during the day. In the southern hemisphere, north-facing slopes experience more radiation than south-facing slopes (Lookingbill and Urban 2003). McCutchan and Fox (1986) showed that aspect differences can be even more important than elevation in controlling temperature. However, the estimates of aspect were not significant for both maximum and minimum temperatures hence their effect cannot be ascertained. Given nonsignificant estimates of elevation, aspect and slope, in the case of maximum temperature, no conclusions cannot be drawn about the effect of these parameters in influencing maximum temperature variation.

The estimated maximum and minimum temperatures showed high residuals and the high value of R^2 is due to the fact that most of the variability was explained by the average maximum or minimum temperatures of the farm. The little difference in the estimated temperature with respect to large difference in observed temperature can be seen in Figs. 3 and 4 in the form of clustered points along horizontal lines. These results show that the minimum temperature profile was partially explained by the elevation and slope whereas maximum temperature profile could not be explained by the topography when the farm had no crop cover. Wind speed, wind direction, soil type and soil wetness also affect temperature variation. While the wind parameters may change air circulation and hence influence temperature near ground, the soil with low surface density and high surface roughness may dry quickly and cause extreme temperatures near ground (Ookouchi et al. 1987; Kawashima and Ishida 1992; Cawood 1996). The nearest wind data available were from Warracknabeal, about 75-km away from the experimental site. Because of the remoteness of the experimental site, wind data could not be included in the analysis. Soil type and wetness also varied greatly across the farm and their effect could not be accounted for.

3.3 Results from 2004 with wheat crop cover

On 17th October (at about anthesis), the highest maximum temperature at the farm was 39°C and a variation of 13.5°C was observed in maximum temperature at a higher and a lower elevation points. On 16th October, the lowest minimum temperature was −1.7°C which was the lowest recorded temperature during the experiment. Up to 5.5°C variation in the minimum temperature across the farm was observed. The highest recorded temperature around the anthesis was 46°C. Comparing the temperature variation across the farm in 2 years, it is evident that the variation was higher for both maximum and minimum temperatures when the farm had a wheat crop cover.

The fitted models explained 80% and 94% of the observed variability in maximum (Fig. 5) and minimum (Fig. 6) temperatures, respectively. In both cases, the models explained less of the variability compared to the 2003 results but the significance of topographical parameters increased for maximum temperature when there was a wheat crop in the farm. This indicates that there was much temperature variation because of the presence of the crop. Some of these crop effects may include the restriction of air movement, variation in soil moisture depletion by the crop, the extent of ground cover depending on the vigour of the crops and crop height (Ghuman and Lal 1983; Gonzalez-Dugo et al. 2009). Further, due to these crop effects, patches of localised temperature were formed during the

Table 2 Estimates of parameters of the regression model describing minimum temperature in 2003 without crop cover (R^2=0.97, n=1029, F probability<0.001)

Parameter	Estimate	SE	t value (df=1,024)	p value
Constant	−2.70	0.649	−4.16	<0.001
Elevation	0.0284	0.0075	3.77	<0.001
Aspect	0.000285	0.00019	1.50	0.133
Slope	6.56	0.68	9.69	<0.001
Average Tmin	1.00	0.006	169.04	<0.001

day, in contrast to the case when the farm was without a crop cover, on which the topography had some bearing. These patches of local temperatures across the farm may have an effect on the crop growth and yield.

The regression estimates (Tables 3 and 4) show that the elevation had significant positive estimate in the case of both maximum and minimum temperatures. This result is in agreement with the results of 2003, with the difference that in 2004, the estimate of elevation was also significant in the case of maximum temperature.

The estimate of aspect, however, was significant in the case of maximum temperature and non significant in the case of minimum temperature, indicating that daytime temperature depended more on aspect rather than temperature during night. The regression estimate of slope was nonsignificant in the case of maximum temperature and significant in the case of minimum temperature, this was just opposite of significance of regression estimates of aspect. For the 10-m elevation range in the farm, increase in maximum and minimum temperatures was 1.5°C and 0.8°C, respectively, much greater than in 2003. One degree increase in slope may reduce maximum temperature by 2.6°C at the top and reduce minimum temperature by 1.3°C at the top where slope is measured, contrary to 2003 result. Looking at the slope values, the maximum reduction in maximum and minimum temperatures can be 0.3 and 0.14°C respectively, which is not large. The reduction in minimum temperature at the top of the areas with higher slope, while there was a crop in the farm, can be due to the flatter topography of the farm. The temperatures at the bottom of these areas were warmer than the top due to the crop cover and moisture as reported by Ghuman

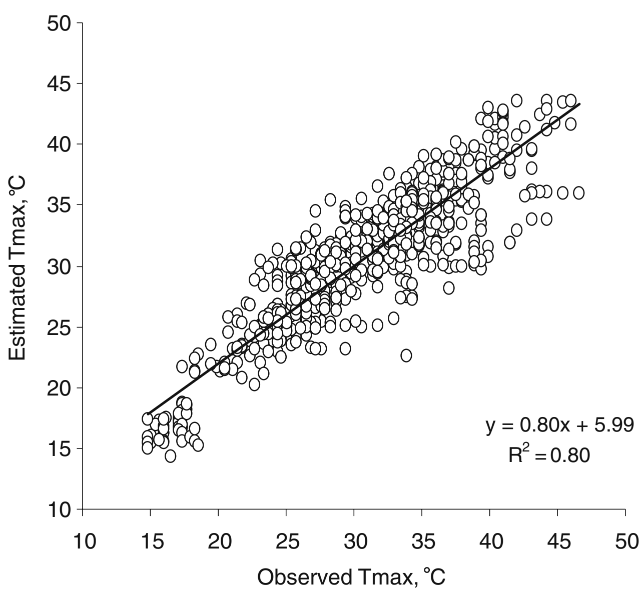

Fig. 5 Observed and estimated maximum temperatures (Tmax) in 2004 with a wheat crop cover

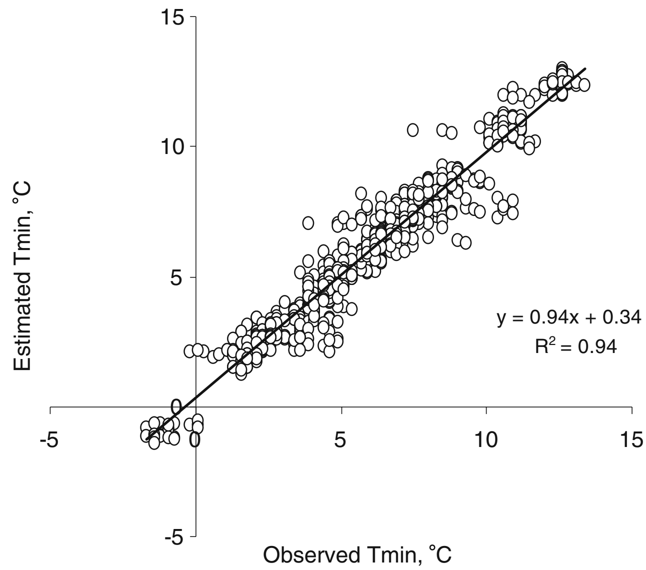

Fig. 6 Observed and estimated minimum temperatures (Tmin) in 2004 with a wheat crop cover

and Lal (1983) and Gonzalez-Dugo et al. (2009). Overall, the extent of variation explained in maximum and minimum temperatures by the topography was low and the models produced more consistent and valuable results when the farm had a cover of wheat crop.

This study showed partially significant relationships of maximum and minimum temperatures with elevation, aspect and slope across the farm during 2 years in compared with the significant results of Lookingbill and Urban (2003) mainly because of the relatively flat topography of the farm and crop effects. Dy and Payette (2007) considered most of frosted depressions to be more than 5-m deep from the top at a particular place whereas; the farm in this study had only 10-m relief across a 164-ha area. However, the study led to development of a simple method of data collection and analysis for studies related to the spatial variability in air temperatures and prediction of spatial variation in temperature based on topography.

A study by Barringer (1997) related soil temperatures to elevation, aspect and slope applying multiple linear regressions techniques within the central South Island high

Table 3 Estimates of parameters of the regression model describing maximum temperature in 2004 with wheat crop cover (R^2=0.80, n=770, F probability<0.001)

Parameter	Estimate	SE	t value (df=765)	p value
Constant	−14.04	3.897	−3.60	<0.001
Elevation	0.15	0.044	3.41	<0.001
Aspect	0.009	0.001	7.79	<0.001
Slope	−2.64	1.074	−2.46	0.014
Average Tmax	1.00	0.018	54.94	<0.001

Table 4 Estimates of parameters of the regression model describing minimum temperature in 2004 with wheat crop cover (R^2=0.94, n= 770, F probability<0.001)

Parameter	Estimate	SE	t value (df=765)	p value
Constant	−7.11	1.002	−7.10	<0.001
Elevation	0.084	0.011	7.30	<0.001
Aspect	0.0002	0.0003	0.53	0.595
Slope	−1.30	0.278	−4.69	<0.001
Average Tmin	1.00	0.009	114.22	<0.001

country of New Zealand. However, it was conducted at meso-scale (144-km^2 area; elevation range, 600–1800 m) to map soil temperature and was not directed to observe the effect of topography on varying temperature in a crop-growing farm in order to find relationships which could explain the effect of varying temperatures on crop yield at farm scale. In turn, we conducted our study at farm scale, in a relatively flatter landscape, applying similar methodology aiming to find potentially useful relationships relating topography to the variation in temperatures across the farm.

Dixit and Chen (2010) identified zones of consistently high and low temperatures in the same farm used in this study from the data collected over 2 years. They argued that those zones can be considered as different units and the different crop management can be practiced to reduce low or high temperature damage to the wheat crop. However, that information could not be extrapolated, in general sense, for other farms or at larger scale. Also, it did not provide any relationships relating the topography to the temperature variation in the farm so that those relationships could be used in a spatial crop model to simulate the effect of varying temperature across a farm on the variability of wheat growth and yield. This work was a way forward in this direction and aimed to identify relationships relating topographic attributes of the farm with the temperature. The results from 2003 when there was no crop and the farm was covered with thin residue of previous crop could be applicable to the crops with a low crop height and sensitive to temperature, e.g. lentil and field pea which are widely grown in the study area.

Wheat-yield data around the data loggers were also collected. However, the yields were very low due to the dry conditions in the farm and varied highly (average 600 kg/ha with maximum 1,900 kg/ha and minimum 0 kg/ha) due to the complex combination of variable soil properties and dryness along with the spatial variation in maximum and minimum temperatures. The temperature does affect the yield as found in literature but its effect on yield could not be separated in this field study owing to the reason that the yield was a result of several varying factors as discussed above. However, the significant relationships relating spatial temperature variation to the topography, found in this study, could be incorporated into spatial crop models which can simulate the variation in grain yield based on the spatial variation in temperature along with the other soil properties at farm or regional level.

3.4 Variations in Birchip and farm temperatures

Before fitting the above models with 49-days data in 2003, the 18-days data collected on the first visit to the farm were used for the model fitting and next 18-days data for validation. The fitted model explained 94% and 95% variability in maximum and minimum temperatures, respectively. When these models were confronted with the next 18-days data for validation, they explained 85% of variability for maximum and 95% for minimum temperature. However, when the 18 days of temperatures at Birchip were used instead of average farm temperature during regression, 69% and 78% variability was explained by the models during validation compared to about 80% and 90% during model fitting in the case of maximum and minimum temperature, respectively (other details and figures not presented). This indicates a large difference between average farm temperature and temperature recorded at Birchip town. Phillips et al. (1992) reported that the weather stations are generally situated at locations that are not representative of the landscape as a whole. Also, the temperatures measured at standard climate stations give only a broad indication of spatial and temporal variations in regional climate but do not explain local farm-scale patterns of climate variation (Barringer 1997).

The models performed better in predicting temperatures when the average farm temperature was taken with elevation, aspect and slope for model fitting rather than temperature at Birchip. However, in both cases, the minimum temperature variation profile was better explained by topographical parameters. These results establish the need to record on-farm temperature data for simulation studies.

4 Conclusions

The study provided a simple method of data collection and analysis for studies related to the spatial variability in air temperatures and prediction of spatial variation in temperature based on topography on two occasions: when the farm had no crop cover and when the farm had a wheat crop cover. From this study it can be concluded that (1) large differences were observed between farm temperature and temperature recorded at Birchip, (2) high temperature variations were found across the farm, (3) minimum temperature variation was better explained from the models which indicates that minimum temperatures depended on topography more than the maximum temperatures, (4) the association of topographical parameters with the maximum and minimum temperatures increased when there was a wheat crop in the farm, (5) both maximum and minimum temperatures were partially explained when there was a wheat crop in the farm whereas, only minimum temperature was partially explained by the topography when the farm had no crop and (6) the models explained temperature variations partially mainly due to the flatter topography of the farm. The results from this study can be used into a crop model to spatially simulate the effect of varying temperature across a farm or region on the variation in grain yield.

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