An Assessment of the Variability of Soil Temperature at the Catchment Scale

Martinez, C.[1], G.R. Hancock[1], T. Wells[1], and J.D. Kalma[2]

[1]School of Environmental and Life Sciences, The University of Newcastle, Australia

[2]School of Engineering, The University of Newcastle, Australia

Email cristina.martinez@studentmail.newcastle.edu.au

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EXTENDED ABSTRACT

Soil temperature is a controlling factor in many biogeochemical processes. For many plants, soil temperature controls germination, inhibits or enhances root growth as well as acting as a buffer to the extremes of air temperature. Many crop simulation models require soil temperature information to reliably predict plant growth and productivity. Similarly, soil temperature influences biological soil activity (e.g. rates of decomposition and soil respiration), and CO_2 efflux from soils (Kang *et al*., 2000). The heating and cooling of soil and resultant change in soil temperature has been studied for many years and is a well known process. What is less well known is how soil temperature varies at the hillslope and catchment scale with most studies focusing on a single point.

The measurement of soil temperature is relatively straightforward, however it is not regularly available and measurements are essentially point-based. An important point to consider is how representative such biophysical measurements are at larger scales, particularly the catchment scale, which is the fundamental hydrological and geomorphological unit. To address this lack of spatial and temporal data many researchers have developed models to estimate soil temperature (Kang *et al.*, 2000; Plauborg, 2002). Additionally, researchers have suggested relationships between air and soil temperature be investigated, due to the fact that air temperature is measured at more locations throughout the world than soil temperature (Watson, 1980).

This paper reports on an assessment of the spatial variability of soil temperature in a series of catchments at a number of scales. We are particularly interested in whether point and hillslope scale measurements of soil temperature can provide accurate catchment scale measurements. While soil temperature is routinely monitored at many sites throughout the world, this appears to be the first reported assessment of soil temperature at the hillslope, sub-catchment and larger catchment scale. The relationship between air and soil temperature at the catchment scale is also investigated.

The results of this study demonstrate that soil temperature does not vary widely within the catchments examined. Strong and significant relationships were found between point scale soil temperature measurements and catchment average data. This suggests that for understanding soil temperature on the catchment scale, or inputting data into catchment scale models, a single site is sufficient to provide catchment wide information.

Air and soil temperatures were not as highly correlated in this study as soil temperature alone. The strongest relationships were found when comparing data within the same catchment and further strengthened when average air temperatures over the previous 7 days were employed. These findings suggest soil temperature can be predicted from air temperature measurements with some confidence if longer-term air temperature averaging is utilised. This is particularly advantageous, since air temperature measurements are often much more readily available. The importance of representative monitoring sites is also highlighted.

The results of this study have many implications for future work in these study catchments. In particular, the ability to accurately capture soil temperature dynamics, both spatially and temporally at the catchment scale, will help to improve our understanding of vegetation and soil organic matter dynamics, in particular the terrestrial carbon cycle, across landscapes (Kang *et al*., 2000). This is important given growing concerns within the climate change research community regarding future global warming effects. More specifically, how soil temperature dynamics will be affected, and how these changes will affect the future dynamics of primary productivity and the concentration and distribution of soil organic carbon will become increasingly important (Kang *et al*., 2000).

1. INTRODUCTION

It is well recognised that soil temperature is a major driver in vegetation growth and soil biological activity, and is a controlling factor in many biogeochemical processes (Kang *et al*., 2000; Storrier, 1965). The heating and cooling of soil and resultant change in soil temperature have been studied for many years and are well known processes. What is less well known is how soil temperature varies at the hillslope and catchment scale with most studies focusing on a single point. There appears to be no reported data on soil temperature at the point, sub-catchment, and catchment scale. Our ability to quantify the spatial and temporal variability of soil temperature is a critical factor in improving our understanding of soil processes. Improved models that better incorporate all soil processes will allow us to better assess the effects of environmental change.

Soil temperature exerts significant control over the spatial distribution of vegetation and the decomposition of organic matter by microbial activity, and is therefore an important variable influencing the spatial and temporal distribution of soil carbon within the landscape. This study, which complements other work by the authors on the spatial and temporal dynamics of soil carbon at the hillslope and catchment scale, examines the spatial variability of soil temperature in a series of nested catchments. The aim of the study is to determine if point scale measurements of soil temperature can accurately represent catchment scale averages.

2. STUDY SITES

This study examines soil temperature for two nested catchments located in the Upper Hunter Valley, New South Wales, the Krui River catchment and a smaller 150ha sub-catchment (Stanley). Point scale soil temperature data recorded at the Scone Soil Conservation Service (SCS) research centre is also included in this study.

2.1 Krui and Stanley Catchments

The 562km^2 Krui River catchment (150°07'00"E and 32°05'32"S) is located in the Upper Hunter Valley of New South Wales, Australia (Figure 1). The catchment has six permanent monitoring stations (K1 – K6), which cover a range of land use, topography, soil and vegetation types (Figure 1 and Table 1). The 150ha Stanley catchment, a tributary of the Krui catchment, has seven permanent monitoring stations installed (S1 – S7) (Figure 1). Soil temperature is continuously recorded at each site (20-minute intervals) at a depth of 150mm. Two automated weather stations (AWS), one located on the Stanley catchment (S2), in the lower half of the Krui catchment, and a second in high terrain to the north of the catchment (K6), provide additional data on air temperature, measured at a height of 2m (Figure 1).

The study area is bounded to the north by the Liverpool Ranges, where topography is rugged, while the landscape to the south, around Merriwa and Cassilis, is hilly to undulating (Story *et al*., 1963). The catchments are underlain with Tertiary basalt of the Liverpool Range beds and forms part of the Merriwa Plateau (Story *et al*., 1963).

The site is located in the temperate zone of eastern Australia. Climate in the region is dominated by a continental influence, although topography, elevation and proximity to the ocean are also considered important (Kovac and Lawrie, 1991). Monthly rainfall figures for the region are 50 – 60mm in summer and 30 – 40mm in winter, where winter rainfall is least variable, and rainfall in late summer-autumn is most variable (Kovac and Lawrie, 1991). Annual average rainfall is highest in the north near the Liverpool Ranges (approximately 1000mm), and decreases gradually upon moving southwards to the Merriwa Plateau (approximately 500mm). The monthly mean minimum and maximum air temperatures are 3°C (winter) and 16°C (summer), and 17°C (winter) and 30°C (summer) respectively (Australian Bureau of Meteorology, 1988).

Much of the original vegetation in the region has been cleared, the extent of which has largely been influenced by topography. In the north (i.e. Liverpool Ranges), the terrain is rugged and accessibility restricted, hence the area remains highly vegetated. To the south (i.e. Merriwa Plateau), clearing has been more extensive as the rolling to hilly terrain ensures greater accessibility. Grazing (sheep and beef cattle) and cropping activities dominate cleared areas, due to the high fertility of basaltic soils. Kovac and Lawrie (1991) classify the region's vegetation as eucalypt tree savannah, with sparse tree cover.

2.2 Scone Soil Conservation Service (SCS)

The Scone SCS research centre site (150^{o}56'38"E and 32^{o}04'48"S) is located within the Upper Hunter Valley region of New South Wales, approximately 80km east of the Krui and Stanley catchments (Figure 1). The elevation at the site is 216m. The site is classified as belonging to the Euchrozem soil group and the dominant plant cover is native grass (Watson, 1980).

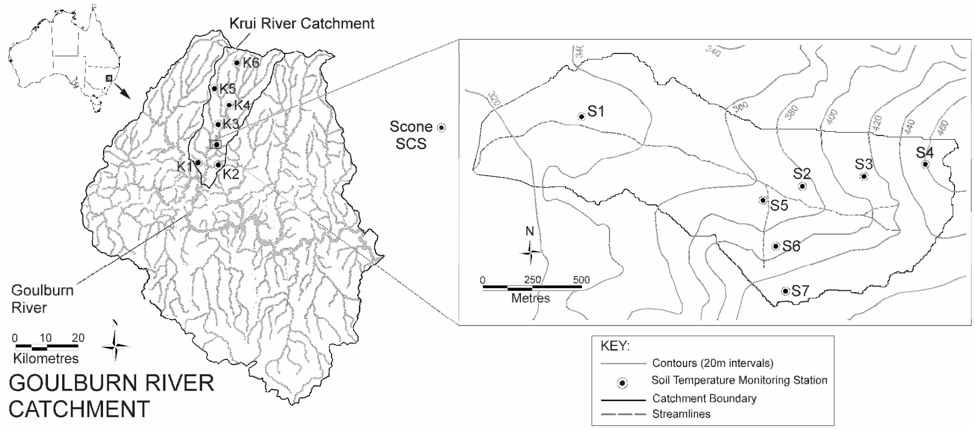

Figure 1. Location map showing the Krui and 150ha Stanley catchments (including location of monitoring stations), and location of Scone Soil Conservation Station (SCS) site.

3. MONITORING DATA

Field data collection commenced in late 2002 and is ongoing. Results presented here were recorded from early 2003 to late 2006. Soil temperature data recorded at sites K1 – K6 and S1 – S7 were measured at a depth of 150mm using Campbell Scientific T107 temperature sensors (20-minute intervals). At some sites, soil temperature was recorded at greater depths, with the limiting factor being soil depth to bedrock. In this paper, only results from the 150mm deep sensors are reported as this is the depth above which most soils are biologically active. Soil temperature data obtained from the Bureau of Meteorology (BoM) for Scone for the same period, was recorded daily at 9am, at a depth of 100mm. Daily average soil temperature at the K and S sites was calculated by averaging the 20-minute data and compared with the Scone data recorded at 9am.

Air temperature is routinely recorded at the AWS within the Stanley catchment (S2) and in the headwaters of the Krui at K6 (Figure 1).

4. RESULTS

Soil temperature data were assessed on the catchment basis only during periods when data were simultaneously available at all sites within each catchment. This ensures that data obtained for each site within a catchment can be reliably compared with other sites within the catchment. This resulted in 598 days of data.

To check the data for consistency, cumulative temperature for one site was compared to cumulative temperature for the other sites (i.e. a double mass curve). No major differences were found in the data for either the Krui or Stanley catchments (Figure 2).

4.1 Temporal Trends

Soil and air temperature trends for S2 and K6 are shown in Figure 3. The data shows a large temperature range experienced by air and soil from maxima of *c.* 25°C in the summer months to minima of *c.* 5°C in winter (Figure 3). Figure 3 also suggests that air and soil temperatures at the two sites are well correlated, with the strongest correlation observed for the S2 data (r^2 = 0.82). There also appears to be a lag in the response of soil temperature to changes in air temperature at both sites such that soil temperatures remain warmer than air temperature in cooler conditions, and vice versa. This is particularly evident for S2 as temperatures fall between January and July.

4.2 Spatial Variability at Regional Scales (Krui Catchment)

Daily average soil temperatures were determined for the Krui catchment sites K1 – K6 over the 598 day period (Table 1). A soil temperature gradient was observed, with mean soil temperature increasing upon moving southwards within the catchment as elevation decreased. K2, located in the lower reaches of the catchment experienced the highest average temperature (18.9°C), while K6, located at the highest elevation had the lowest average (15.5°C). K4 had the lowest minimum (6.9°C), which is believed to be due to the fact that, unlike the other K sites which are located in relatively open and exposed areas, K4 lies within a depression, in the shadow of a number of adjacent hillslopes. Conversely, K2 had the highest maximum (32.3°C). The sandy nature of the soil at K2 is thought to contribute to the higher soil temperature values found here, as sandy soils have a reportedly higher thermal conductivity than clay soils (Abu-Hamdeh and Reeder, 2000).

Table 1. Krui and Stanley monitoring sites summary data.

	K1	K2	K3	K4	K5	K6	S1	S2	S3	S4	S5	S6	S7
Elevation	400m	424m	408m	376m	475m	739m	329m	376m	412m	454m	373m	397m	439m
Slope	1°	5°	1°	0°	4°	10°	2°	5°	5°	8°	4°	9°	0°
Aspect^	0°	250°	274°	70°	121°	90°	0°	244°	218°	245°	284°	330°	346°
Soil Depth	>90cm	>90cm	>90cm	>90cm	>90cm	>90cm	>90cm	60-90cm	30-60cm	>90cm	60-90cm	30-60cm	<60cm
Soil Type	Silt Loam	Loamy Sand	Clay	Clay	Clay	Clay Loam	Clay	Clay Loam	Clay Loam	Clay Loam	Silty Clay	Clay	Silt Loam
Land Cover	Crop/ fallow	Native pasture	Crop/ fallow	Native pasture	Native pasture	Improve pasture	Improve pasture	Native pasture	Native pasture	Native pasture	Native pasture	Native pasture	Native pasture
Land Use	Crop	Grazing	Crop	Grazing	Grazing	Grazing	Grazing	Grazing	Grazing	Grazing	Grazing	Grazing	Grazing
Mean ST	18.1	18.9	17.5	17.0	17.1	15.5	18.0	18.0	17.7	17.4	18.4	19.7	18.1
St. Dev. ST	6.1	6.0	5.5	6.0	5.5	4.1	6.0	5.9	5.9	5.7	5.7	5.9	5.6
Min. ST	8.3	9.4	8.6	6.9	8.1	8.2	7.7	8.5	8.1	8.2	8.6	10.0	9.2
Max. ST	30.7	32.3	29.0	30.1	30.2	23.0	30.9	31.4	29.7	28.9	30.3	32.6	30.5

Source: Rüdiger *et al*. (2007) * ST = soil temperature (150mm); ^ aspect: 0/360° = N; 90° = E; 180° = S; 270° = W

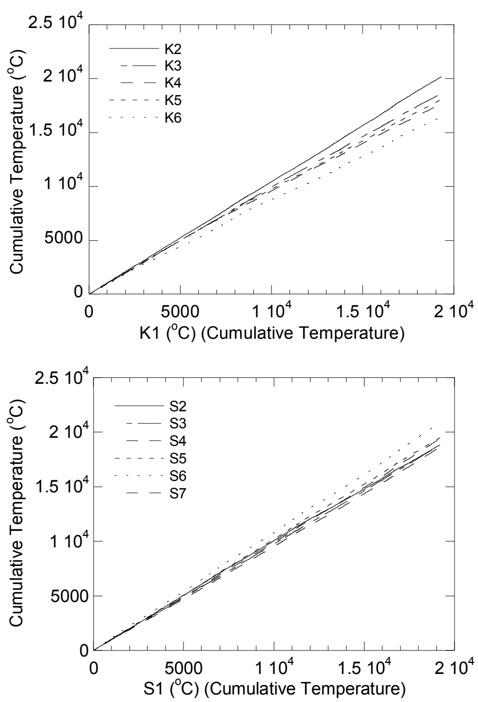

Figure 2. Cumulative soil temperature (150mm) double mass curves for K1 to K6 (top) and S1 to S7 (bottom).

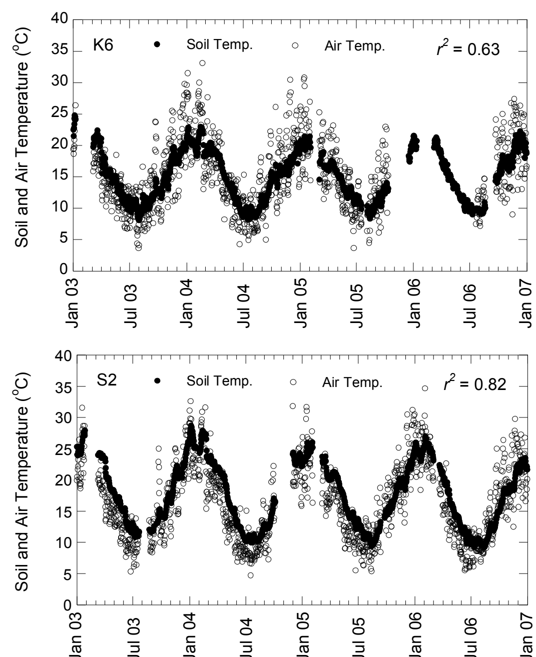

Figure 3. Daily average soil temperature (150mm) and air temperature determined from the 20-mintue data for K6 (top) and S2 (bottom).

4.3 Spatial Variability at Local Scales (Stanley Catchment)

Daily average soil temperature determined over the 598 day period at each of the Stanley sub-catchment sites S1 – S7 reveal little difference in average soil temperature (Table 1). S4 had the lowest average (17.4°C), while S6 had the highest average (19.7°C). S1, located on the creek flat, had the lowest minimum (7.7°C), while S6, located on the midslope, with a north facing aspect, had the highest maximum (32.6°C) (Figure 1).

In this study, aspect, and therefore exposure to incoming solar radiation, appears to be the dominant factor controlling soil temperature spatial patterns within the Stanley catchment. Sites S2 – S4, located along the south facing half of the catchment, are among the sites with the lowest mean soil temperature for the recorded period, while sites S5 – S7, located along a north facing hillslope are among the highest. In a previous study, aspect was also found to be the main factor influencing the spatial and temporal distribution of near-surface (0-50mm) soil moisture (Martinez *et al*., 2007), and could therefore be contributing to the differences in soil temperature observed in this study. In particular, the low soil temperature recorded at S1, previously reported to be amongst the wettest sites with respect to root zone (0-300mm) soil moisture (Martinez *et al*., 2007), seems to support this suggestion.

4.4 Point Scale vs Catchment Scale Soil Temperature Variability

The relationship between point scale soil temperature and catchment average soil temperature was investigated by comparing soil temperatures recorded at the individual K and S sites and Scone SCS with catchment average soil temperatures for the Krui and Stanley catchments.

Point scale soil temperature recorded at K1 – K6 and S1 – S7 were highly correlated with catchment average soil temperature for the Krui and Stanley catchments respectively ($r^2 \geq 0.96$, e.g. Figure 4). While the data from most sites is positioned on or near the 1:1 line, K6, despite having a high r^2 of 0.96, clearly underestimates the catchment average soil temperature (Figure 4). K6 represents soil temperature for the upper reaches of the Krui catchment, at a much higher elevation than any other site (Table 1), and is therefore subject to cooler conditions. The high correlations observed suggests that catchment average soil temperatures within the Krui and Stanley catchment can be reliably predicted from soil temperature data recorded at individual sites however caution is needed when applying this to sites which are not representative of average conditions (e.g. K6).

The correlation between point scale soil temperatures and respective catchment averages were also found to be subtle cyclical functions of the time of year (Figure 5). Accounting for this effect by incorporating sine functions of the Julian date further improved the correlation between point and catchment scale soil temperatures.

Point scale soil temperature data recorded at the Scone SCS were compared with catchment average soil temperature data for the Krui and Stanley catchments (Table 2 and Figure 6). Table 2 indicates that the average soil temperature recorded at Scone and the Krui and Stanley catchments was not significantly different, falling in a 1°C range. Furthermore, strong and significant correlations were found between the Scone soil temperature and the Krui (r^2 = 0.98) and Stanley (r^2 = 0.97) catchment average soil temperatures (Figure 6).

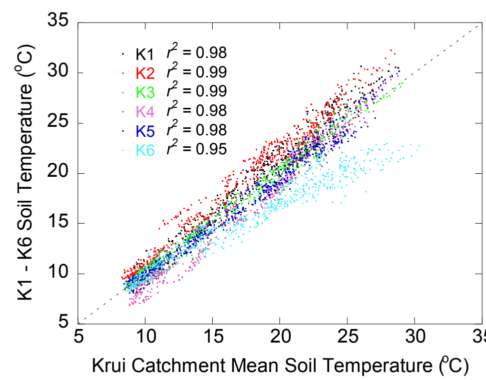

Figure 4. Krui catchment daily mean soil temperature (°C) versus average soil temperature at K1 – K6. Catchment average values do not include individual sites being correlated against.

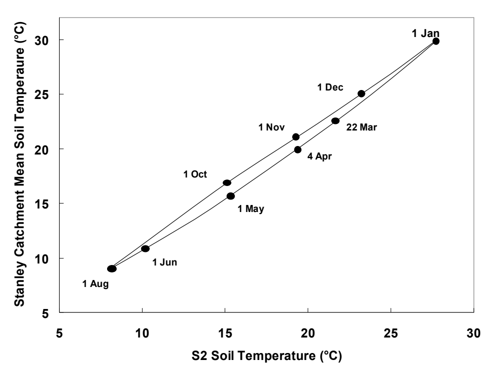

Figure 5. Stanley catchment daily mean soil temperature (°C) versus S2 soil temperature throughout the year 2006.

Table 2. Daily soil temperature summary data for Scone and the Krui and Stanley catchments.

	SCONE	KRUI	STANLEY
Mean	17.8	17.3	18.2
Minimum	8.0	8.5	8.6
Maximum	29.0	29.1	30.6
Std. Deviation	5.5	5.5	5.8
Std. Error	0.23	0.23	0.24

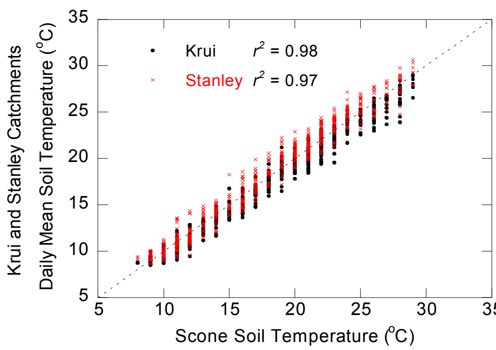

Figure 6. Daily soil temperature at Scone (0-100mm) versus mean daily soil temperature for the Krui and Stanley catchments.

4.5 Soil Temperature vs Air Temperature

A comparison of mean daily air temperature with mean daily soil temperature recorded at Scone, and for the Krui and Stanley catchments reveals weaker relationships than that observed between point scale and catchment average soil temperatures. Mean daily air temperatures recorded at K6 and S2 were correlated against daily average soil temperature across all three sites. The strongest relationship was observed between the various catchment averages and S2 air temperature (r^2 =0.85 – 0.87, e.g. Figure 7). The relationship between catchment average soil temperatures and K6 air temperature was considerably weaker across all three sites (r^2 = 0.68 – 0.71). This once again suggests that conditions at S2 are more representative of the catchment average and hence data from this site are more suitable for the prediction of catchment average soil temperatures. Selecting a suitable site in the absence of such an extensive data set requires choosing a site which is representative of average topographic conditions, open and accessible, while also considering lapse rates (i.e. air temperature increases approximately 0.6 [wet] and 1.0 [dry] degrees per 100m increase in altitude).

The correlation between soil and air temperatures improves significantly when longer-term air temperature histories are utilised. In this study the

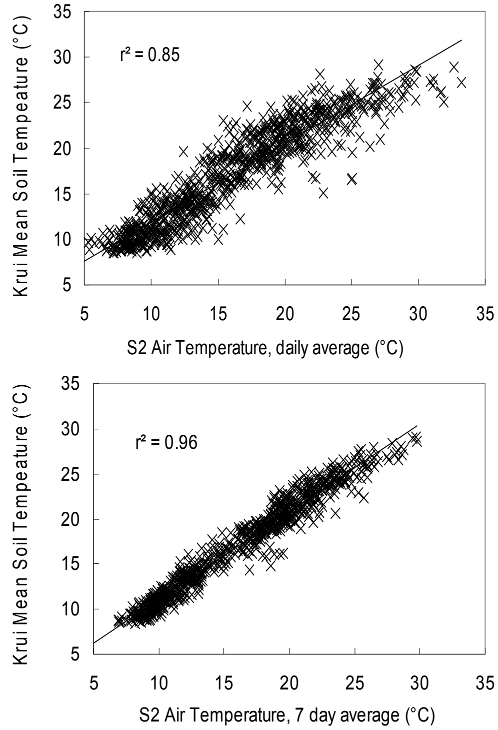

Figure 7. Daily soil temperature for the Krui catchment (150mm) versus daily (top) and the 7 day averaged (bottom) S2 air temperature.

strongest correlations were obtained when soil temperatures were related to air temperatures averaged over the previous 7 days. The correlation between Krui catchment average soil temperatures and S2 air temperature data was improved from r^2 = 0.85 to r^2 = 0.96 using this approach (Figure 7).

5. DISCUSSION AND CONCLUSIONS

While soil temperature is monitored routinely at many sites throughout the world, this appears to be the first reported assessment of soil temperature at the catchment scale. The results demonstrate that daily average soil temperatures do not vary widely within the Stanley and Krui study catchments, nor at the Scone SCS station. This suggests a single site is sufficient to provide catchment scale information for the purpose of understanding soil temperature on the catchment scale.

Although soil temperatures were similar across the study area, scale dependent differences were observed. At the larger scale of the Krui catchment, large-scale topography (i.e. elevation) was the primary factor influencing the spatial patterns of soil temperature. A temperature gradient was observed among the Krui sites K1 – K6, whereby mean soil temperatures decreased as elevation increased (Table 1). At the smaller scale of the Stanley sub-catchment, small-scale micro-topographical differences were more important. Differences in soil temperature for sites S1 – S7 were attributed to variations in aspect (i.e. exposure to radiant energy) and soil moisture within the Stanley catchment. The nature of the variability in soil temperature among sites therefore appears to be dependent on the scale at which the observations are being made.

Despite these differences, significant relationships were found between soil temperature recorded at K1 – K6 and S1 – S7 and catchment average soil temperature for the Krui and Stanley catchments respectively. In addition, Scone SCS point scale soil temperatures were strongly correlated with the Krui and Stanley catchment average soil temperatures. The results suggest catchment average soil temperature dynamics can be reliably predicted from soil temperature data recorded at representative points within the landscape.

Less significant statistical relationships were found between catchment average soil temperature and air temperature data recorded at S2 and K6. The strongest relationships were found when comparing air temperature data recorded at S2, which suggests S2 is a better representation of average catchment temperature conditions and therefore has the potential to be used as a means of predicting soil temperature within the study region. A significant time lag between soil and air temperatures, particularly at S2, was observed. Vegetation cover and the depth at which soil temperature measurements were taken are suspected to be contributing factors to the lag response. Incorporating more historical air temperature data (such as 7 day averages) into the analysis to account for the buffering action of vegetation and soil improved the correlation between soil and air temperatures significantly to the point where the correlations were almost as significant as those observed when using point scale soil temperature data.

The current study provides a catchment-wide assessment of spatial and temporal soil temperature dynamics. The importance of soil temperature to many ecological processes, in particular vegetation growth and soil biological activity, and therefore the soil carbon cycle, highlights the significance of this research.

6. ACKNOWLEDGMENTS

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