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Growing-season temperature and soil moisture along a 10 km transect across a forested landscape

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ABSTRACT: This study characterizes a set of growing-season microclimate variables at the landscape level and examines the relationships between these variables and landscape structure along a transect in the SE Missouri Ozarks. Temperature and soil moisture and their spatial variations at the landscape level were also compared with those at the stand level, a 200 m segment of the transect. We measured air temperature (T_a; at a height of 1 m), soil temperature (T_s; 5 cm in depth), soil-surface temperature (T_{sf}), and soil moisture (0 to 10 cm in depth) every 10 m along a 10 050 m transect using mobile and permanent weather stations during the growing season, June to September, 1996. Topographic features, overstory and understory coverage, and landscape patch types were also recorded at each point. Elevation at each point was measured using a submeter-resolution GPS (global positioning system) in November 1996. We describe the spatial variation of microclimate with standard deviation. We found that the spatial variations of T_a, T_s and T_{sf} and soil moisture were large along the transect, ranging from 19.6 to 22.7°C for seasonal mean T_a and from 3.5 to 28.6% for gravimetric soil moisture. We found that seasonal means at the landscape level were not significantly different from those at the stand level. However, the spatial variations at the landscape level were significantly different from the variation at the stand level. In addition, the diurnal patterns of the spatial variation at the 2 scales were also different, with high spatial variation observed during the daytime and low variation during the nighttime. The spatial variations of T_s and T_{sf} had typical 'bell-shaped' diurnal patterns, while the diurnal pattern of the spatial variation of T_a was relatively 'flat'. In general, the peaks of spatial variation at the stand level occurred earlier in the day than those at the landscape level, most noticeably for T_s. No apparent seasonal trend was identified for the spatial variations of the microclimatic variables examined. Based on the data collected, topography (such as aspect, slope position, and elevation), patch type, and overstory canopy coverage explain 22 to 52% of the variation in the microclimatic variables examined.

KEY WORDS: Microclimate · Landscape structure · Transect · Scale · Spatial variation · Topography

1. INTRODUCTION

Microclimate, especially temperature and soil moisture, has been extensively studied because it is critical to individual organisms for germination, growth, and reproduction; and ecological processes, such as photosynthesis, respiration, evapotranspiration, decomposition, nutrient cycling, microbial activity, and carbon sequestration (Sutton 1953, Geiger 1965, Wilson 1970, Zobel et al. 1976, Sorensen 1983, Kuhns et al. 1985, Bonan & Van Cleve 1992, Kochy & Wilson 1997, Kozlowski & Pallardy 1997, Xu et al. 1997a). However, most studies on microclimate focused on stand and even smaller scales because traditional resource management was practiced mainly on these scales (Beckett & Webster 1971, McCaughey 1982, Hungerford & Bab-

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bit 1987, Chen et al. 1993, 1995, Breshears et al. 1997, Xu et al. 1997a, Young et al. 1997). The interactions between climate and vegetation have also been studied at regional and even larger scales (Major 1977, Stephenson 1990, Prentice et al. 1993, Sanderson & Ustin 1998). Few studies have examined microclimate and its relationship with vegetation, ecological processes, and landscape structure at the landscape level (but see Saunders et al. 1998).

Recent ecosystem management theories and practices have required us to manage natural resources at landscape levels (Christensen et al. 1996, Haeuber & Franklin 1996, Thomas 1996, Franklin 1997). Therefore, characterizing microclimate at the landscape level and studying the relationships between microclimate and vegetation and landscape structure will improve our ability to manage natural resources at ecosystem and landscape levels. For example, Menning (2001) found that microclimate could change landscape structure and vegetation configuration through its effects on plant development, regeneration and fire. Chen et al. (1999) concluded that microclimate directly influences ecological processes and ecosystem functions, further driving the changes in landscape structure. Saunders et al. (1998) also found that the relationship between landscape structure and temperature is hierarchical in a managed forested landscape in Wisconsin. On the other hand, changes in landscape structure may modify microclimate by changing the energy and water balance of the vegetation canopy and ground surface (Hungerford & Babbitt 1987, Chen et al. 1993, 1995). Therefore, monitoring microclimate at the landscape level may facilitate evaluation and comparison of different management regimes on forested landscapes.

Landscape management may help resource managers to conserve biodiversity and enhance carbon sequestration of an ecosystem more efficiently at the landscape level than at small scales. Microclimate could be considered the 'pulse' of an ecosystem because of the direct and indirect effects of microclimate on most ecological processes, and vice versa. Species richness is well correlated with climatic variables at global and continental scales, as revealed by the 'species-energy' theory, the proposition that increased available energy supports more species (Pianka 1966, Currie & Paquin 1987, Currie 1991, Leathwick et al. 1998), and the 'habitat heterogeneity' theory, which posits that more diverse physical environments support more species (MacArthur & Wilson 1967, Probst & Crow 1991, Bowman 1996). If these theories hold at the landscape level, we may be able to manage biodiversity at the landscape level through the influence on microclimate, because microclimate (especially temperature and soil moisture) is a good indicator of the effective energy within an ecosystem. Numerous studies have pointed out that soil carbon sequestration/emission is strongly dependent on soil temperature and moisture (Bowden et al. 1998, Davidson et al. 1998, Xu & Qi 2000a). Therefore, by examining the spatial and temporal variation of temperature and soil moisture, we can estimate the spatial and temporal patterns of soil carbon emissions and evaluate the efficiency of soil/ecosystem carbon management at the landscape level.

Temperature and soil moisture are 2 of the more important microclimatic variables affecting ecosystem processes and functions. These 2 variables are also easy to measure, especially at a large spatial scale. The objectives of this study are (1) to characterize temperature and soil moisture and their spatial variation at the landscape level; (2) to compare the spatial variation of temperature and soil moisture at the landscape level with that at the stand level; and (3) to examine the relationship between landscape structure and temperature and soil moisture across a forested landscape in the SE Missouri Ozarks.

2. METHODS

2.1. Study area

This study was conducted on research sites of the Missouri Ozark Forest Ecosystem Project (MOFEP). Initiated by the Missouri Department of Conservation in 1990, the MOFEP is a pilot project studying the effects of different forest management practices on main landscape patterns and processes. The 9 MOFEP sites range in areal size from 260 to 527 ha. They are located in Carter, Reynolds, and Shannon counties in the SE Missouri Ozarks (91° 01′ to 91° 13′ W and 37° 00′ to 37° 12′ N). These counties are 84 % forested, with large contiguous forested areas separated only by roads and streams (Brookshire & Hauser 1993). Agricultural activities are limited to bottomland corridors along primary streams. The study area consists of mature upland oak-hickory and oak-pine forest communities. Predominant overstory species include white oak *Quercus alba* L., black oak *Q. velutina* L., post oak *Q. stellata* Wang., scarlet oak *Q. coccinea* Muenchh., blackjack oak *Q. marilandica* Muenchh., chinkapin oak *Q. muehlenbergii* Engelm, shortleaf pine *Pinus echinata* Mill., maple *Acer* spp. and hickory *Carya* spp.. Understory species include dogwood *Cornus* spp., sassafras *Sassafras albidum* and blackgum *Nyssa sylvatica*.

Geologically, this region is underlain mainly by Ordovician dolomite with areas of Cambrian dolomite. Precambrian igneous rocks are also present (Missouri

Geological Survey 1979). Weathering of the Ordovician and Cambrian dolomites has resulted in a deep mantle of leached, very cherty residuum on the MOFEP study sites (Gott 1975). Soils on this area were formed mostly in residuum. The common series are Viburnum, Midco, Gepp, Bardley, Viraton, Poynor and Clarksville (Gott 1975). 99% of the study area has a slope <40%, and 92% of the area has an elevation <300 m. Road and stream densities, on average, are 1.4 and 1.7 km km^{-2}, respectively (Xu et al. 1997b). Mean annual temperature is 13.3°C, and annual precipitation is 1120 mm.

The MOFEP is currently composed of 10 subprojects that focus on vegetation dynamics, biodiversity, hydrology, nutrient cycling, and microclimate and landscape management. The microclimate subproject serves multiple purposes. First, the MOFEP project provides data to other projects that require climate data inputs from plot to landscape levels. Second, it examines the long-term effects of different forest management practices on local climate. Therefore, our microclimate measurements along a 10 km transect provide the pretreatment climate reference, because the transect covers an area that includes essentially all the planned treatment scenarios. Third, the transect microclimate measurements plus measurements from 21 mobile weather stations located within different patch types provide the ground truth for calibrating satellite data (Landsat TM thermal band). Ultimately, we want to use the satellite data to monitor microclimate, especially temperature, continuously in the MOFEP study areas. Finally, the transect data are also used to examine the relationship between microclimate and biodiversity, decomposition, and landscape structure.

2.2. Experimental design and instrumentation

Field experiments were conducted from June to September 1996. We sampled a set of microclimatic variables, landscape elements, vegetation, and topography along a 10.05 km transect. The transect was oriented in the south-north direction, with its starting point located randomly in MOFEP Site 1 (see Xu et al. 1997b for locations). At a location every 10 m along the transect, we sampled air temperature at 1 m above ground (T_a), soil temperature at 5 cm depth (T_s) and soil-surface temperature (T_{sf}) using custom-built thermocouple sensors and dataloggers. We used T-type thermocouples to measure T_s and T_{sf}, and E-type thermocouples to measure T_a. Where a litter layer was present on the forest floor, T_{sf} was measured just under the litter layer at the soil surface. The temperatures were measured under natural conditions by minimizing the disturbance to the ground vegetation. Six mobile weather stations were used to measure temperatures along the transect. Each station, equipped with 1 datalogger (21X or CR10; Campbell Scientific) and 1 multiplexer (AM416; Campbell Scientific) housed in a cooler, could sample 150 m along the transect (15 points with 3 temperature measurements at each point, extending 70 m north and south of the cooler). As a result, we simultaneously sampled 900 m with the 6 mobile stations along the transect. We added 4 more mobile stations similarly equipped in August 1996. Therefore, simultaneous measurements were obtained over a 1500 m transect during the second half of the growing season. Dataloggers were programmed to sample data every 10 s and to record average values every 20 min. Data were collected at each 900 (or 1500) m segment for about 2 wk before all the stations were moved to the next 900 (or 1500) m segment along the transect.

For the data beyond the 2 wk data-collection period, we relied on 2 permanent weather stations in the study area, one in a forest opening and the other in the closed canopy. The 2 wk of data collected with the 6 mobile stations were first used to establish a correlation with the permanent weather stations through multiple regression analysis (see 'Data analysis'); then, these data were extrapolated to the entire growing season for each 900 (or 1500) m section based on the statistical relationships established. Microclimatic variables measured at the permanent stations included solar radiation, wind speed, wind direction, relative humidity, precipitation, soil heat flux, soil moisture, soil temperatures at 0, 5, 10, 15, and 20 cm depths, and air temperatures at 0, 0.5, 1.0, 1.5, and 2.0 m above the ground surface.

Overstory canopy coverage (above 1.5 m) was measured at each point where we measured microclimate (every 10 m along the transect) using GRS densitometer (Forestry Suppliers). Understory coverage, including herbs, shrubs, and seedlings to a height of 1 m above the ground surface, was recorded by species using 1 m × 1 m quadrats along 4260 m, starting at the south end of the transect. The percentage cover of each species was estimated by observation and the quadrats were centered on the point where we would measure temperature and soil moisture. We also recorded aspect (degrees), slope (degrees), and slope position, based on the average situation over 10 m (5 m on each side of the point where microclimate was sampled) along the transect. Soil samples were taken at 10 cm depth in each plot to determine soil moisture. We collected soil samples once a month and finished the whole transect in 1 d to minimize the temporal impacts on soil moisture. Soil samples were oven-dried for 24 h at 105°C to calculate gravimetric soil water content (%). Elevation at each sampling point along the transect was measured using a submeter-resolution GPS (globla positioning system; Trimble Navigation) in November 1996, when most leaves were absent, in order to improve GPS measurement accuracy.

2.3. Data analysis

We used multiple regression analysis to fill the data gaps in time with statistical software (SAS, SAS Institute). T_a, T_s, and T_{sf} at the 2 permanent stations were independent variables, and the temperature along the transect was a dependent variable. Sample sizes were 1008 for most parts of the transect and 504 for some points due to instrumental failure. When T_s and T_{sf} were among the independent variables to regress with T_a, or vice versa, time lags (20 min to 2 h) between them were applied to improve the fitting results of the regression equations. Generally, models used to fill data gaps had an $r^2 > 0.90$. Extreme weather events did not occur during the measurement period.

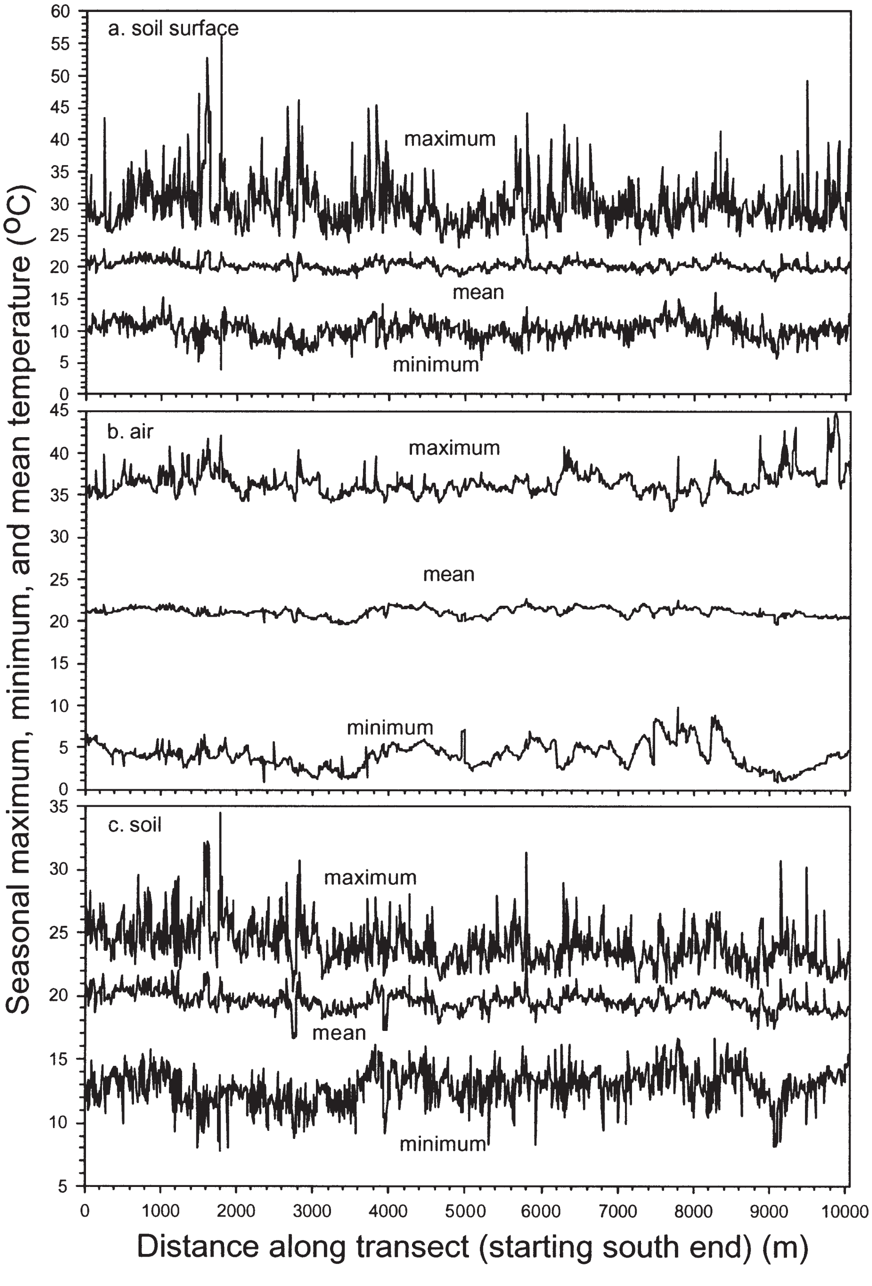

Fig. 1. Seasonal maximum, minimum, and mean (a) soil-surface (T_{sf}), (b) air (T_a) and (c) soil (T_s) temperatures along the transect (from south to north)

Standard deviation (SD) was used to characterize the spatial variations of temperatures and soil moisture at both landscape and stand levels. The effects of aspect, slope position, and patch type on temperature and soil moisture were examined through general linear models followed by Duncan's multiple range tests. Regression analyses were also used to obtain the correlation between temperature and soil moisture and continuous landscape structure variables, such as slope, elevation, and overstory canopy coverage. We used general linear models to characterize the effects of landscape structure variables on temperature and soil moisture. We used SAS to perform all the statistical analyses. GPS data were differentially corrected according to a base station (about 200 km from the study area) using Trimble's GPS Pathfinder TM Pro XR (Trimble Navigation).

3. RESULTS

3.1. Temperature and soil moisture across the landscape

Although there were no significant spatial trends in the minimum, mean, and maximum T_a, T_s and T_{sf} along the transect, irregular fluctuations existed along the entire transect for all the temperatures examined (Fig. 1). Seasonal mean T_a, T_s and T_{sf} averaged over all points along the transect were quite close (20.29, 21.13, and 19.61°C, respectively). However, the results for seasonal minimum and maximum T_a, T_s and T_{sf} were quite different. The seasonal maximum T_a was higher than that for T_{sf}, which was higher than that for T_s. The seasonal minimum temperatures had the opposite pattern. According to the univariate regression analyses, seasonal mean T_a only explained 37 % ($r^2 = 0.37$, $n = 1006$, $p < 0.01$) of the total variation in seasonal mean T_{sf} and 31 % ($r^2 = 0.31$, $n = 1006$, $p < 0.01$) of the total variation in seasonal mean T_s. But the correlation between T_s and T_{sf} was very strong ($r^2 = 0.76$, $n = 1006$, $p < 0.01$).

Seasonal temperature range, the difference between seasonal maximum and minimum temperatures, was different for air, soil, and soil surface. T_a had the largest seasonal range, followed by T_{sf} and T_s (Fig. 1). Diurnal temperature range (DTR), daily maximum minus daily minimum, averaged over the measurement period had the same order as seasonal temperature range between air, soil, and soil surface, with T_a having the largest DTR, followed by T_{sf} and then T_s (Fig. 2a). Unlike temperature, soil moisture showed a spatial trend along the transect though it had high oscillations. Soil moisture, in general, decreased from south (the starting end) to north along the transect (Fig. 2b). The overall soil gravimetric water content was about 13 % during the growing season, but its spatial variation was remarkably high, ranging from 3.5 to 28.6 %.

T_a and T_{sf} showed similar diurnal patterns. Daily minimum T_a and T_{sf} occurred around 06:00 h in the morning, and daily maximum around 14:00 h in the afternoon (Fig. 3a,b). T_s lagged behind T_a and T_{sf} by about 1 h. Daily minimum and maximum T_s occurred around 07:00 and 15:00 h, respectively (Fig. 3c). The rate of temperature increase from early morning to

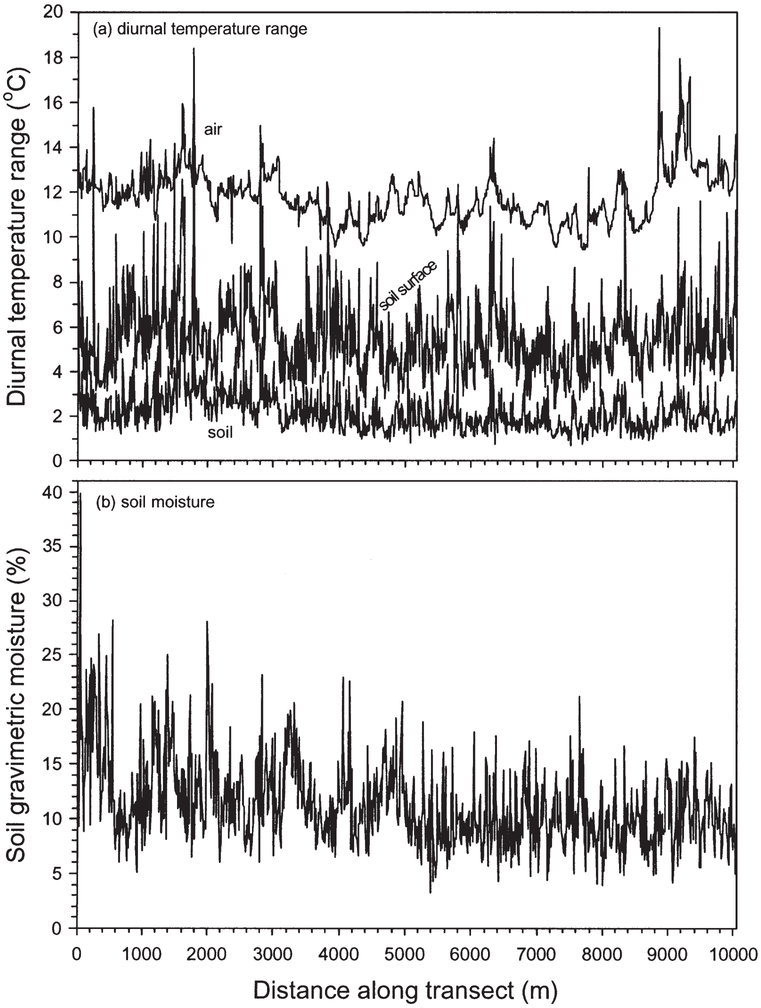

Fig. 2. Seasonal mean (a) diurnal temperature range (DTR) and (b) soil moisture (gravimetric percentage) averaged over the measurement period for each point along the transect (starting at the south end of the transect)

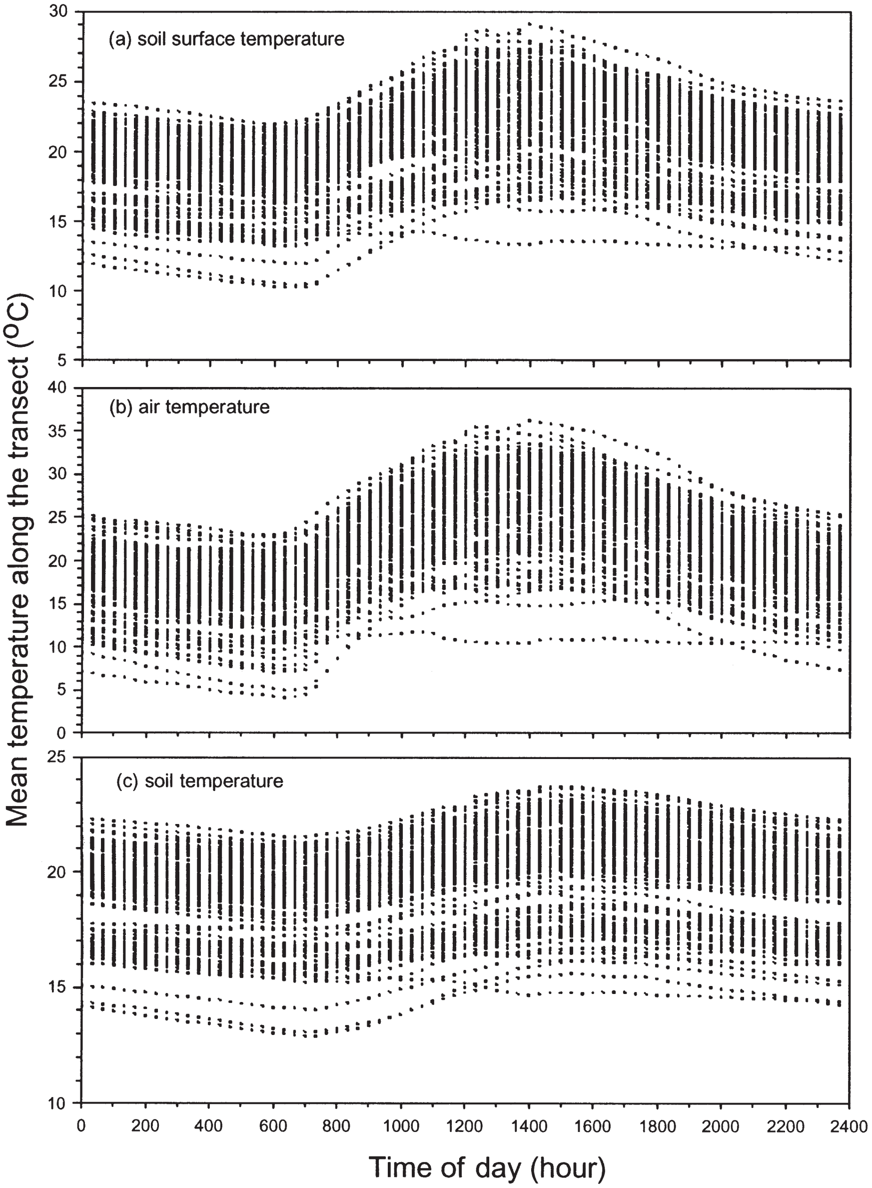

Fig. 3. Diurnal patterns of the mean (a) T_{sf}, (b) T_a and (c) T_s along the transect

early afternoon was higher than its rate of decrease from late afternoon to early next morning. Therefore, the diurnal temperature patterns were asymmetric (Fig. 3).

Temperature also showed seasonal trends (Fig. 4). Fig. 4 can be divided into 5 periods along the time axis. Period 1 was in early June (Days 153 to 163), characterized by moderate temperatures. Period 2, from Day 164 to 203, was hot, with temperatures jumping from 3 to 5°C compared with Period 1. Period 3, the end of July to early August, was characterized by a 'cool' mid-summer, with the temperature dropping under 20°C. Period 4, from Day 215 to 250, was another period with high temperatures. Period 5, from Day 250 to 274, was identified as the late growing season, with gradually declining temperatures. We also noticed that temperature oscillations existed within each period. However, the 3 temperatures showed very similar seasonal patterns along the transect (Fig. 4). In general, the differences among T_a, T_{sf} and T_s increased as the 3 temperatures increased, and the differences decreased as the temperatures decreased during the growing season. The periods of small differences between T_a, T_{sf} and T_s were well correlated with rainy days, except in the early and late growing season (Fig. 4).

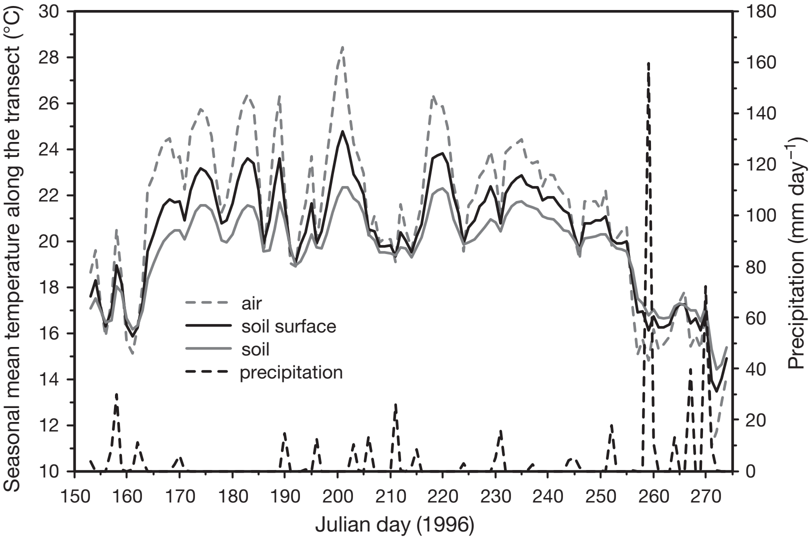

Fig. 4. Seasonal trend of the seasonal mean temperature along the transect and daily precipitation at a permanent weather station (forest opening site) (June to September 1996)

3.2. Spatial variations of temperature and soil moisture at the landscape level

3.2.1. Diurnal pattern of the spatial variation of temperature

The spatial variation, as measured by the standard deviation (SD), of T_{sf} was relatively small and stable during the nighttime, but it started increasing at about 08:00 h in the morning and reached its highest value around 13:00 h. It gradually declined back to the nighttime level around 20:00 h (Fig. 5a). The spatial variation of T_a did not show a clear diurnal pattern. The daytime peak was not as obvious as those of T_{sf} and T_s, with an indistinct 'peak' appearing around noon (Fig. 5b). The diurnal pattern of spatial variation in T_s was similar to that of T_{sf}, except that its peak occurred at about 16:00 h instead of 13:00 h (Fig. 5c), and its peak values were smaller than those of T_{sf}. Soil surface, air, and soil had different mechanisms to partition the total spatial variations of temperatures throughout the day.

3.2.2. Seasonal patterns of the spatial variation of temperature

The seasonal patterns of spatial variation of temperatures were irregular, with oscillations observed throughout the entire growing season (Fig. 6a–c). Based on seasonal average, the SD of T_{sf}, T_a and T_s was 1.07, 0.90, and 0.94°C, respectively. The SD of T_{sf} ranged from 0.55 to 3.40°C during the whole growing season (Fig. 6a). The spatial variation of T_{sf} showed a similar seasonal pattern as that of T_s (Fig. 6c). The SD of T_a generally decreased from early June to early August (mid-summer) and then increased to the end of the growing season (Fig. 6b). Two periods with noticeable low SD, especially for T_{sf} and T_s, existed during the growing season. The first period was in June (around Day 163), and the second occurred during a rainy period from the end of July to early August (around Day 213) (Fig. 6). The spatial variation of temperature was significantly affected by the mean temperature values, but their relationships were nonlinear. The relationship between spatial variation and mean temperature along the transect can be quantified by nonlinear regression equations:

$$\mathrm{SD_{sf}} = 8.26 - 0.815T_{sf} + 0.022T_{sf}^2 \quad (r^2 = 0.58,\ n = 8784,\ p < 0.01) \tag{1}$$

$$\mathrm{SD_{a}} = 2.27 - 0.133T_{a} + 0.003T_{a}^2 \quad (r^2 = 0.18,\ n = 8784,\ p < 0.01) \tag{2}$$

$$\mathrm{SD_{s}} = 11.36 - 1.154T_{s} + 0.031T_{s}^2 \quad (r^2 = 0.61,\ n = 8784,\ p < 0.01) \tag{3}$$

where $\mathrm{SD_{sf}}$, $\mathrm{SD_a}$, and $\mathrm{SD_s}$ are the standard deviations of T_{sf}, T_a, and T_s, respectively.

3.3. Effects of topography on temperature and soil moisture

The effects of aspect on temperatures and soil moisture were statistically significant ($\alpha = 0.05$, $p < 0.01$). Based on mean seasonal T_s and T_{sf}, west-facing slopes had the highest temperatures and east-facing slopes had the lowest (Table 1). According to Duncan's multiple range tests, all aspects were significantly different for T_s and T_{sf}, except for the south-facing slope versus neutral (flat) and the north-facing slope versus the east-facing slope. Based on mean seasonal T_a, the ordering of temperature based on aspect was west > north > south > east > neutral (Table 1). All the aspects were significantly different ($p < 0.05$) based on seasonal mean T_a, except that there was no significant difference between west-, north-, and south-facing slopes. Flat areas (neutral) had the highest DTR for air, soil, and soil surface. North-facing slopes had the lowest DTR for T_a and T_{sf}, and east-facing slopes had the lowest DTR for soil (Table 1). Flat areas (neutral) had

Table 1. Effects of aspect on temperatures (°C) and soil moisture (%) along a 10 km transect in the SE Missouri Ozarks

Aspect	Sample size	Seasonal mean temperature			Diurnal temperature range			Soil moisture
		Soil surface	Air	Soil	Soil surface	Air	Soil	
Neutral	131	20.33	20.87	19.79	6.15	13.09	2.78	13.17
North	235	20.10	21.23	19.41	5.17	11.40	2.01	11.43
East	243	19.99	21.01	19.27	5.26	11.51	1.97	11.26
South	201	20.47	21.19	19.74	5.91	11.71	2.22	10.42
West	196	20.66	21.26	20.01	5.98	11.99	2.32	11.06

Table 2. Effects of slope position on temperatures (°C) and soil moisture (%) along a 10 km transect in SE Missouri Ozarks

Slope position	Sample size	Seasonal mean temperature			Diurnal temperature range			Soil moisture
		Soil surface	Air	Soil	Soil surface	Air	Soil	
Crest	29	20.92	21.66	20.08	6.09	11.17	2.37	12.24
Upper	296	20.61	21.58	19.85	5.53	11.07	1.92	10.29
Middle	212	20.40	21.20	19.69	5.97	11.90	2.33	10.80
Lower	233	19.93	20.81	19.28	5.26	11.92	2.06	11.17
Toe	107	19.72	20.62	19.19	5.23	12.17	2.33	13.21
Level	129	20.33	20.85	19.79	6.14	13.13	2.77	13.18

the highest soil moisture (13.2 %), and south-facing slopes had the lowest soil moisture (10.4 %). However, there were no significant differences in soil moisture between north-, east-, and west-facing slopes according to Duncan's multiple range tests ($\alpha = 0.05$).

Slope had limited influence on microclimate based on the data collected at 10 m intervals. Slope was not significant in accounting for the variance in T_a, T_{sf}, T_s and soil-surface DTR ($n = 1006$, $p > 0.50$), and it accounted for no more than 5 % ($r^2 < 0.05$, $n = 1006$, $p < 0.002$) of the variation in the other variables. However, slope position was important in affecting microclimate. In general, temperature decreased from crest to slope bottom, except in flat valleys. Upper slopes had the lowest values of DTR and soil moisture and flat valleys had the highest values (Table 2).

The elevation was about 170 m at the south end of the transect and increased variably to about 320 m at the north end of the transect. The highest elevation was about 340 m. The abrupt changes of elevation along the transect indicated the variable topography of the study area. Fig. 7a shows the elevation profile along the transect. At the scale of 10 m, elevation accounted for no more than 23 % ($r^2 < 0.23$, $n = 1006$) of the total variance of each microclimate variable examined. Elevation and all the microclimate variables were negatively correlated, except for seasonal mean T_a and seasonal minimum temperatures. Elevation accounted for 23 % of the variation in soil moisture and 20 % in seasonal minimum T_a ($n = 1006$, $p < 0.01$). The higher the elevation the lower the soil moisture, but the higher the seasonal minimum temperatures.

3.4. Temperature and soil moisture versus landscape structure

Temperature and soil moisture in different patch types were significantly different. Road and power-line corridors had the highest T_a, T_s and T_{sf}. Most of the roads in the study area were unpaved with a width of 4 to 10 m. The power-line corridors were mainly covered by shrubs, with a typical width of 20 to 30 m. Hickory-dogwood, hickory-oak, and oak-dogwood forests had the lowest T_a, T_s and T_{sf} (Table 3). Forest edges, roadsides, and forest openings (gaps) had the second highest T_{sf}. Oak-pine forest, shrubs, mixed oak, and maple forest had the third highest T_{sf}, and the seasonal mean T_{sf} between these patch types were not statistically different. Forest edges, gaps, oak-pine, mixed oak, pine-oak, and oak-hickory forests had the second highest T_a. Roadsides and forest edges had the second highest T_s. Oak-hickory and oak-pine forests had the second lowest T_s (Table 3).

The sparse forest canopy coverage, not the ground flora coverage, was responsible for the large DTR (Fig. 1, Table 3). Roads, power-line corridors, roadsides, shrub land and forest openings had the highest air, soil, and soil-surface DTR, though the understory coverage was high for these patch types (Table 3). The average DTR for patch types without forest cover (types 2, 3, and 4 in Table 3) for T_a, T_{sf} and T_s was 13.3, 8.3, and 4.0°C respectively, while the corresponding values were 11.7, 5.5 and 2.1°C for patch types with forest cover. Maple forest had the lowest soil-surface DTR, and pine-oak, oak-dogwood, and oak-pine forests had the lowest air

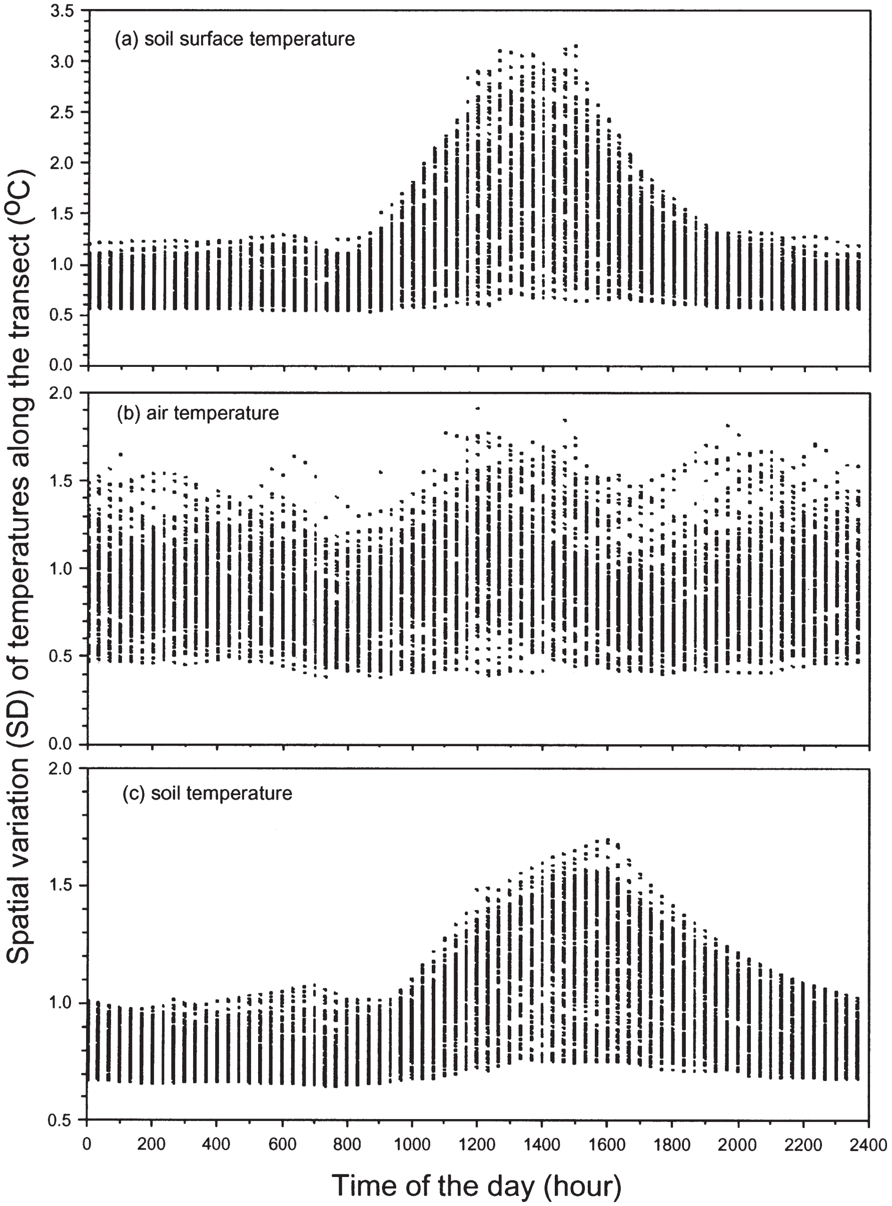

Fig. 5. Diurnal pattern of the spatial variation (standard deviation) of (a) T_{sf}, (b) T_a and (c) T_s along the transect

DTR. The lowest soil DTR occurred in pine-oak, oak-dogwood, and hickory-dogwood forests (Table 3).

Soil moisture in patch types with low/no forest canopy cover was generally higher than in forest patch types. For example, the soil moisture averaged over patch types 2, 3, and 4 (Table 3) was 13.8%, and it was only 12.0% averaged over the rest of the patch types in Table 3. However, the highest mean soil moisture occurred in maple forests (19.4%), and the minimum mean soil moisture in oak-pine and pine-oak forests (~9.0%) (Table 3).

In general, lower canopy coverage correlates with higher maximum temperature. The overstory canopy coverage ranged between 0 and 99%, with an average of about 80% along the transect (Fig. 7b). Low canopy coverage occurred along road and power-line corridors and at forest edges and gaps. The canopy coverage was better correlated with seasonal maximum temperatures than with the other temperatures. Canopy coverage explained about 10, 15, and 10% of the variation in seasonal maximum T_{sf}, T_a and T_s, respectively. But it explained no more than 8% of the variation in each of the other temperatures (mean, minimum, and DTR) ($r^2 < 0.08$, n = 1006). The seasonal maximum temperature averaged over patch types 2, 3, and 4 in Table 3 was 38.1, 36.2, and 27.6°C for T_a, T_{sf}

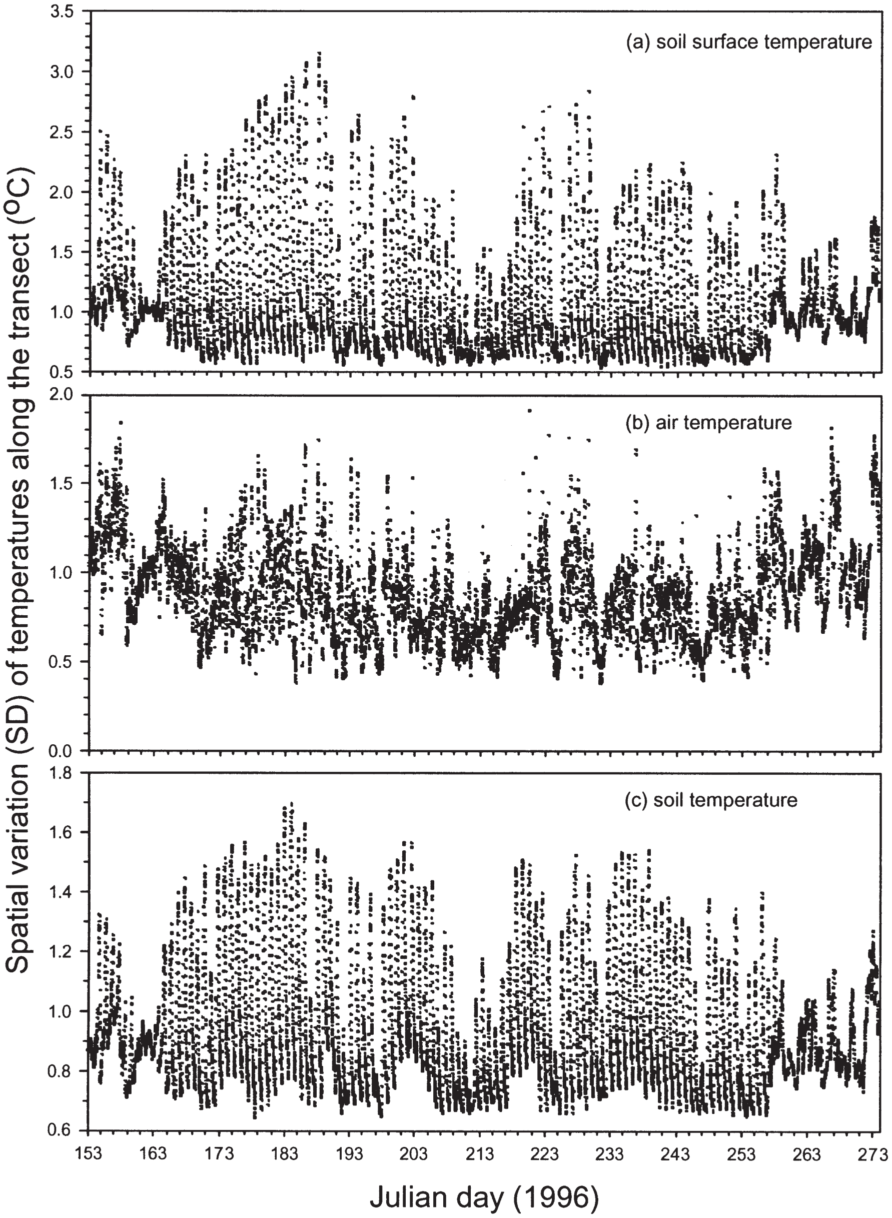

Fig. 6. Seasonal pattern of the spatial variation (standard deviation) of (a) T_{sf}, (b) T_a and (c) T_s along the transect

and T_s respectively, while the corresponding temperature for the forest patch types was 36.3, 29.6, and 23.9°C, respectively.

4. DISCUSSION

Temperature and soil moisture at the landscape level demonstrated significant spatial variations along the 10 km transect. The seasonal mean T_a along the transect ranged from 19.6 to 22.7°C. This range is equivalent to the seasonal temperature gradients observed over a latitudinal gradient of 3 to 5° or over altitudinal changes of 300 to 500 m in mid-latitude. However, the differentiation of vegetation at the landscape level is smaller than at regional and larger scales. This suggests that microclimate-vegetation relationships may change with scale. In a separate study, we examined the interactions between landscape structure and microclimate at different spatial scales (M. Xu, Y. Qi & J. Chen unpubl.). Landscape structure plays a critical role in shaping the subtle microclimate patterns across a landscape. The effect of landscape structure on microclimate operates mainly through influences on

Table 3. Seasonal mean temperature (°C), daily temperature range (DTR; °C), soil moisture (%), and overstory (OCC; %) and understory (UCC; %) canopy coverage in different patch types along a 10 km transect in the SE Missouri Ozarks. Patch types: 1 – hickory + oak forest (hickory dominant); 2 – road and power-line corridor; 3 – forest edge; 4 – forest opening (gap); 5 – hickory + dogwood + blackgum forest (hickory dominant); 6 – maple + oak forest (maple dominant); 7 – mixed oak forest; 8 – oak + dogwood forest (oak dominant); 9 – oak + hickory forest (oak dominant); 10 – oak + shortleaf pine forest (oak dominant); 11 – shortleaf pine + oak forest (shortleaf pine dominant); 12 – shrubs

Patch type	Sample size	Seasonal mean temperature			Diurnal temperature range			Soil moisture	OCC	UCC
		Soil surface	Air	Soil	Soil surface	Air	Soil			
1	52	19.71	20.67	19.26	5.08	12.24	2.06	12.41	77.5	45.8
2	12	22.24	21.71	21.64	8.04	12.71	3.43	12.97	41.6	82.3
3	29	21.31	21.23	20.67	8.43	13.31	4.43	14.07	47.5	79.7
4	6	20.93	21.29	20.09	8.45	14.66	3.46	14.47	18.9	89.5
5	13	19.62	20.71	19.08	5.33	12.00	1.97	11.11	73.1	–
6	13	20.39	21.04	19.98	4.45	12.07	2.29	19.42	78.3	71.9
7	70	20.41	21.29	19.64	5.79	11.63	2.16	10.95	76.9	32.9
8	81	19.88	20.92	19.39	4.73	11.44	1.89	11.54	77.7	22.7
9	390	20.16	21.04	19.47	5.52	11.87	2.27	11.92	75.3	30.3
10	275	20.49	21.33	19.74	5.71	11.50	2.01	9.96	73.9	13.4
11	52	20.22	21.27	19.46	5.36	11.23	1.69	9.12	74.5	7.3
12	13	20.53	20.86	19.98	6.51	15.63	2.60	11.86	46.4	–

ground surface energy balance, a driving force in shaping microclimate patterns. These biophysical processes can happen on short timescales of seconds to days. On the other hand, the counteraction of microclimate on vegetation structure is usually a slow ecological process of regeneration and succession which may take up to hundreds of years (except for extreme events such as hurricanes or flooding).

The higher maximum temperature and larger DTR for patch types with low/no vegetation cover versus the forest patch types reflect the effects of forest canopy on ground surface energy balance. Denser canopies can absorb and reflect more solar radiation, resulting in less solar energy reaching the ground. The net solar radiation reaching the ground surface is further partitioned to sensible heat, latent heat, and soil heat fluxes which are used to heat the air, evaporate soil water, and warm the soil, respectively. T_a attained higher maximum values than T_{sf} (Fig. 1). This phenomenon can be explained by the following facts: First, a majority of the sections of the transect are under forest cover (Fig. 7b), and energy absorption/reflection by the canopy greatly reduces the amount of energy reaching the forest floor. Second, our T_{sf} were measured under the litter layer, just above soil surface, in the vegetated patch types. The 'buffer-effect' of the litter layer may reduce T_{sf} and its diurnal variation. Third, the turbulent mixing is much stronger in the air than within the litter layer where the T_{sf} was measured.

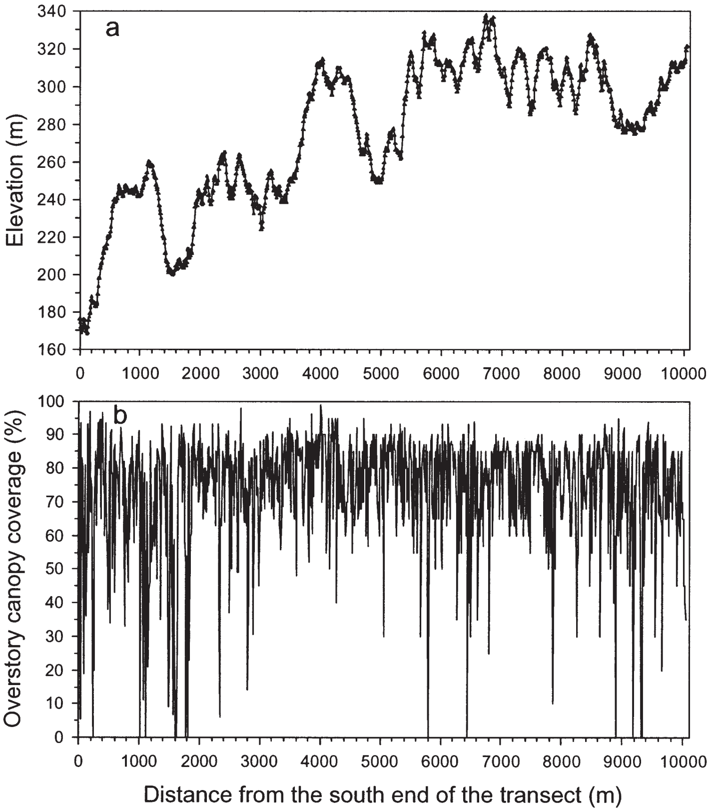

Fig. 7. (a) Elevation measured with GPS and (b) overstory canopy coverage measured at a height of 1.5 m with densitometer every 10 m along the transect

The higher soil moisture in the patch types with low/no vegetation cover demonstrated the effects of vegetation (transpiration) on the terrestrial water balance. Although the low/no vegetation covered patch types had a higher T_s and probably a greater evaporation rate from the soil surface, the soil moisture was generally higher within these patch types than the vegetated patch types, suggesting transpiration through vegetation is a major component of the water balance on the landscape. The exceptionally high soil moisture in the maple-oak forest (Table 3) does not necessarily mean the maple-oak forest has high water use efficiency, because maple trees are often seen in the bottom valley or on north-facing slopes, where the soils are usually deeper, hold more water, and receive less solar radiation.

To test if temperature and soil moisture and their spatial variation at the landscape level are different from those at the stand level, we chose a stand of 200 m along the transect to represent a typical oak-hickory forest in the area. By comparing temperature and soil moisture at the landscape level with those at the stand level, we found that seasonal mean values of temperatures at the landscape level (10 km) were not much different from those at the stand level (200 m); the differences were no more than 3 % of their average values. However, the soil moisture and the spatial variation of temperatures at the 2 scales were quite different, and the differences existed in both magnitude and diurnal patterns (Table 4). First, the spatial variations of temperature and soil moisture at the landscape level were larger than those at the stand level. SDs of T_{sf} and T_s at the landscape level were about 30 and 60 % greater than those at the stand level, respectively. The SD of soil moisture at the landscape level was also about 60 % greater than that at the stand level (Table 4). Second, the diurnal patterns of the SD at the 2 scales were different. In general, the peaks of SD at the stand level occurred earlier in the day than those at the landscape level, especially for T_s (Figs. 5 & 8). For T_{sf}, the peak of SD appeared around 14:00 h at the landscape level, while it occurred from 12:00 to 13:00 h at the stand level (Figs. 5a & 8a). Although the diurnal peak was readily apparent for T_a, a small peak was identified around 12:00 h at the landscape level (Fig. 5b), whereas at the stand level, a small peak for T_a occurred from 09:00 to 10:00 h (Fig. 8b). The peak shift was most apparent for the SD of T_s. At the landscape level, the peak occurred at about 16:00 h (Fig. 5c), whereas it appeared around 13:00 h at the stand level (Fig. 8c).

We must point out that the diurnal pattern of the spatial variation of T_a was not a typical bell-shaped pattern as reported in our previous study (Xu et al. 1997a). Chen & Franklin (1997) also found that the spatial variation of T_a peaked in the mid-morning from 09:00 to 10:00 h along a 200 m transect in an old-growth Douglas-fir forest in Washington. Zheng et al. (1999) found that the peak shift in the diurnal pattern of the spatial variation of T_a was related to vegetation structure and management practices. The asymmetric diurnal patterns of temperature and its spatial variation resulted from the energy partition at the ground-atmosphere interface. The rapid increase of near-ground temperature in the morning is caused by (1) the strong turbulent exchange under and above the canopy; (2) the higher penetrability of the plant canopy to daytime shortwave radiation as compared to the nighttime longwave radiation; and (3) the air-mixing advection. Similarly, the slow decrease in temperature from late afternoon to the following early morning can be explained by the weak turbulent mixing during the night and the canopy interception of longwave radiation emitted from forest floor during the nighttime. This canopy effect is similar to the 'greenhouse effect', making the T_a inside forests warmer than outside during the nighttime. Therefore, the buffer effect of the canopy makes the T_a inside the canopy more homogenous, and the temperature decreases slowly during the nighttime.

Why were the SDs of T_{sf} and T_s larger during the daytime and smaller during the nighttime (Fig. 5)? The decrease in T_s during the nighttime occurs through the loss of energy as longwave radiation from the soil surface. The landscape patch types with high daytime T_s are often those patches absorbing the most energy at the soil surface and featuring little or no vegetation cover. These patches lose energy rapidly in the late afternoon and early evening through longwave radiation; therefore, their T_s drops quickly during this period. Meanwhile, the patch types with low T_s are

Table 4. Comparison of temperature (°C) and soil moisture (%) and their spatial variations at landscape (10 050 m) and stand levels (200 m). SSD: spatial variation (standard deviation) of seasonal mean

Scale	Variable	Seasonal mean temperature			Diurnal temperature range			Soil
		Soil surface	Air	Soil	Soil surface	Air	Soil	moisture
10050	Mean	20.29	21.13	19.61	5.63	11.82	2.20	11.34
	SSD	0.79	0.54	0.78	1.80	1.20	0.92	4.02
200	Mean	20.26	20.89	19.39	5.78	11.25	2.15	9.92
	SSD	0.59	0.50	0.32	1.66	0.52	0.62	1.59

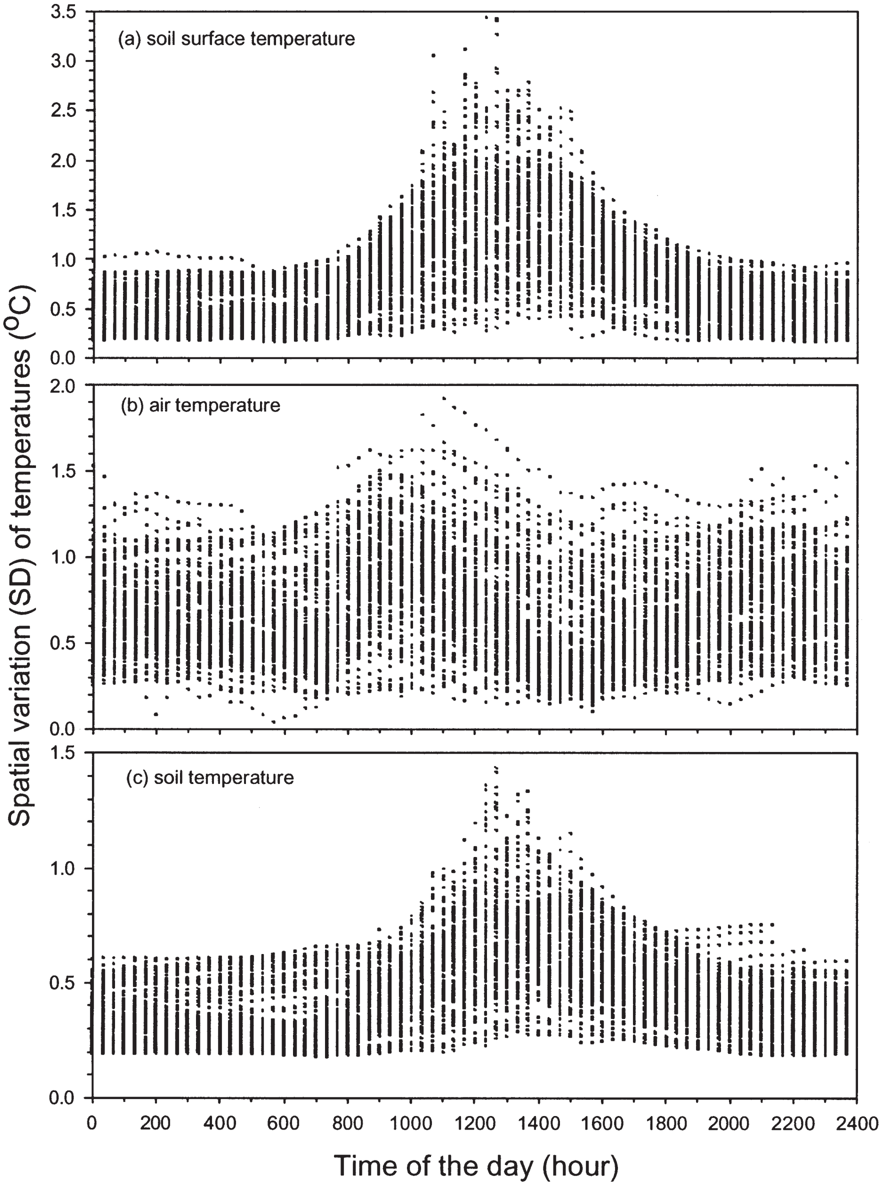

Fig. 8. Diurnal pattern of the spatial variation (standard deviation) of (a) T_{sf}, (b) T_a and (c) T_s at the stand (200 m) level

often forest patches, where the canopy intercepts the longwave radiation emitted from the soil surface and reradiates it back to the forest floor. By absorbing the returning longwave radiation, the soils under the forest canopy will maintain warmer nighttime temperatures. Therefore, the spatial heterogeneity of T_s and T_{sf} is reduced between forest and non-forest patch types during the night. Similarly, the spatial variations of T_s and T_{sf} are enhanced during the daytime because the vegetation canopy reduces the input of solar radiation to the forest floor during the daytime. Therefore, the differences in T_s and T_{sf} between forest and non-forest patch types increase during the daytime. The lack of a distinct diurnal pattern in the spatial variation of T_a is mainly due to the movement of the air in both vertical (turbulent mixing) and horizontal (advection) directions. T_a differences between different patch types are reduced through the mixing process.

According to our general linear models, landscape structure variables, including topography, patch type, and overstory canopy coverage, explained only 22 to 52% of the variation in each microclimatic variable. Because the microclimate measured at each 10 m interval may be influenced not only by the topography and vegetation structure at that point but also by the landscape structure of adjacent points, the topographic and microclimatic data collected at 10 m intervals were not spatially random. Furthermore, surface microclimate was also influenced by the vertical structure of the landscape. Near-surface T_a and T_s in forests were negatively correlated with canopy coverage, because the forest canopy significantly influenced the amount of solar radiation reaching the ground, therefore driving the near-surface temperatures. The correlation between canopy coverage and temperatures and soil moisture was poor at the scale of 10 m, because the solar energy reaching a single point on the forest floor was not only controlled by the forest canopy over that point, but also by the energy passing through the adjacent canopies, especially for the case of a small solar-elevation angle. This result suggests that the point sampling of microclimatic variables may provide a different spatial representation of the ecosystem. In other words, the representative area (or 'footprint') of different sampling locations may be significantly different. In addition, the 'footprints' of different variables can also be highly variable, even for the same sampling location. For example, T_a may represent a few meters in diameter around the sampling point and T_s may represent only a few centimeters around the same point. Therefore, ecologists must be cautious when using point sampling of a microclimate to examine the relationship between microclimate and ecological processes. Biased and even wrong conclusions are easily drawn if the 'footprints' of the measured microclimatic variables do not match the scale of the ecological processes examined. In addition, we have found that spatial scale is critical in examining the relationships between microclimate and landscape structure (M. Xu, Y. Qi & J. Chen unpubl.).

Weather conditions are critical in affecting the spatial variations of temperature and soil moisture. We observed 2 periods with low spatial variations in temperatures during the growing season that corresponded with cloudy and rainy days. Young et al. (1997) also found that microclimate differences between slopes was significantly reduced during cloudy periods because diffuse rather than direct solar radiation prevailed under cloudy conditions.

Landscape management activities can significantly change surface temperature and soil moisture across the landscape. Road and power-line construction will not only increase the landscape fragmentation but also the surface T_a and T_s. Vegetation removal along the roads and power-line corridors allows more solar energy to reach the ground surface, providing ample resources and appropriate habitats for edge and shade-intolerant species. Species richness of the ground flora along the corridors is significantly higher than in the interior forests (Xu & Qi 2000b). However, some core species which require a typical forest environment may be influenced by the corridors, because the edge effect on some microclimatic variables can extend hundreds of meters into the forest (Chen et al. 1995). In addition, wind and turbulence are stronger along the corridors than within the forests, and more animals use the corridors as well. Therefore, the seed and pollen dispersal is facilitated by wind and animals along the corridors, which may help the regeneration of some species and hence change the species composition and vegetation structure along the corridors.

Forest openings, or natural gaps, act as 'heat islands' during the daytime because the gaps receive more solar radiation during daytime and lose more energy through long-wave radiation during nighttime than the typical forests. This is evidenced by the high seasonal mean temperature and greater DTR in the forest openings along our transect. The high soil moisture content in the forest openings may result from the low evapotranspiration rate in the gaps where vegetation cover is absent or sparse. Monitoring temperature and soil moisture in the natural gaps may help forest managers better formulate management scenarios. For example, group opening is a common practice in timber harvesting. Determining the opening size is often empirical because of the lack of ecologically sound knowledge of different ecosystems. Microclimate measurements from natural gaps may provide a reference for forest managers to maintain microclimate fluctuations in the harvested openings with an average similar to those of the natural gaps. This will allow the forests to sustain a stable forest structure and species composition in a post-harvest regeneration, because microclimate is important to seed dispersal, germination, and colonization at the harvested openings. However, by directly applying the natural gap size results to the group opening harvest practice may introduce bias, because most natural gaps develop some short vegetation before they are physically created.

5. CONCLUSIONS

The spatial variations of air, soil, and soil surface temperatures and soil moisture were large along a 10 km transect, ranging from 19.6 to 22.7°C for seasonal mean air temperature and from 3.5 to 28.6% for gravimetric soil moisture. Topography, such as aspect, slope position, and elevation, and landscape patch type were important factors contributing to the spatial variations of the above microclimatic variables. The high spatial variations of temperature and soil moisture suggest that some important ecological processes, such as productivity, decomposition, and soil carbon dynamics, may also vary substantially across the landscape, because most ecological processes are greatly controlled by temperature and soil moisture. Based on the data collected at every 10 m interval, landscape structure, including topography, patch type, and canopy coverage, explained 22 to 52 % of the variation in the different microclimatic variables examined. The differences of temperature and soil moisture among different landscape patch types may provide valuable information to forest/landscape managers evaluating different landscape management scenarios and examining the effects of management practices on microclimate and ecological processes. For example, canopy coverage has significant effects on temperature, diurnal temperature range, and soil moisture, and forest managers can use this information to determine an appropriate harvesting intensity that would create a suitable microclimatic and ecological environment for important species and ecological functions, such as nutrient cycling and soil carbon emissions.

Although the results of this study were based on a specific transect, the spatial patterns of temperature and soil moisture and their relationships with landscape structure are applicable to other parts of the Ozark area because of the similar topography and vegetation in the area. In addition, some results, such as the diurnal patterns of the spatial variation of temperatures, may be applicable to even larger scales outside the Ozark area. However, caution must be taken when applying our results to the whole Ozark and other areas, because our transect covered a limited number of patch types. Therefore, analysis of additional transects is recommended in order to study the entire landscape. In this study, we focused on air, soil and soil-surface temperatures and soil moisture, but other microclimatic variables may be derived from temperature and soil moisture measurements. For example, we found that air temperature and relative humidity were well correlated in this area in our previous study (Chen et al. 1997).

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