NC-4153
Staff: VMPR Problem: 01
Code: 1.41 Reprints: Y

Microclimate in Forest Ecosystem and Landscape Ecology

Variations in local climate can be used to monitor and compare the effects of different management regimes

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Chen, Jiquan; Saunders, Sari C.; Crow, Thomas R.; Naiman, Robert J.; Brosofske, Kimberley D.; et al. 1999. Microclimate in forest ecosystem and landscape ecology BioScience. 49(4): 288-297.

Microclimate is the suite of climatic conditions measured in localized areas near the earth's surface (Geiger 1965). These environmental variables, which include temperature, light, wind speed, and moisture, have been critical throughout human history, providing meaningful indicators for habitat selection and other activities. For example, for 2600 years the Chinese have used localized seasonal changes in temperature and precipitation to schedule their agricultural activities. In seminal studies, Shirley (1929, 1945) emphasized microclimate as a determinant of ecological patterns in both plant and animal communities and a driver of such processes as the growth and mortality of organisms. The importance of microclimate in influencing ecological processes such as plant regeneration and growth, soil respiration, nutrient cycling, and wildlife habitat selection has became an essential component of current ecological research (Perry 1994).

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Microclimate directly influences ecological processes and reflects subtle changes in ecosystem function and landscape structure across scales

Human activities, such as agriculture and forestry, and natural disturbances, such as outbreaks of insects and diseases, can modify the physical environment of an ecosystem (i.e., the patterns of temperature, moisture, wind, and light) by altering structural features. Typically, forest structure is described at the stand and landscape levels. Stand structure is well defined in forestry (e.g., stocking densities, overstory coverage, and species composition). Landscape structure can be defined by the spatial arrangement (pattern) of elements of topography, vegetation, soil, or the physical environment itself. However, vegetative features are also commonly used at the landscape scale, and it is at this level that we focus in this article.

Each component of the microclimatic environment exhibits unique spatial and temporal responses to changes in structural elements. Furthermore, the dynamics of these responses differ with the choice of metric used to quantify microclimate. Therefore, the sensitivity of the microclimate to structural transformation (e.g., timber harvesting and the resultant stand-level changes in overstory height and landscape-level fragmentation) offers strong potential for monitoring ecosystem and landscape changes at multiple spatial scales.

Relationships between microclimate and biological processes are complex and often nonlinear. For example, decomposition rates of organic material within pits, mounds, and the floor of a wetland are strongly related to soil temperature and moisture. The association between decomposition and soil temperature is linear, whereas that between decomposition and soil moisture is nonlinear (Figure 1). Clearly, effects of soil microclimate on the activities of soil biota and, thus, indirectly on decomposition depend on the combination of temperature and moisture, suggesting that a nonlinear model is needed to develop empirical relationships. For most ecological processes, such complex relationships are common (e.g., plant distribution as a function of light, temperature, moisture, and vapor deficit; avian foraging site selection as a function of wind speed and temperature; Wachob 1996).

Microclimatic information is, therefore, vital for empirical field studies, theoretical modeling exercises, and management decision-making. However, microclimatic studies have traditionally focused on

statistical summaries (i.e., daily, monthly, and annual). Less attention has been given to variability in microclimate or to the differences among microclimatic patterns across spatial and temporal scales. In this article, we present microclimatic characteristics associated with the structure of forest ecosystems and landscapes. We synthesize the variability of microclimate related to major management practices in patches of interior forest, across the edges of forest clearcuts (Figure 2), through riparian buffers (Figure 3), within different management units (e.g., green-tree retention, or partial cut, during which 5–60 live trees per hectare are retained after logging; Figure 2), and across entire landscapes in the Pacific Northwest, northern Wisconsin, and southeast Missouri. We discuss the importance of monitoring multiple microclimatic variables when characterizing the physical environment, and we demonstrate how these measurements can be used to monitor and compare changes among landscapes and under varying management regimes.

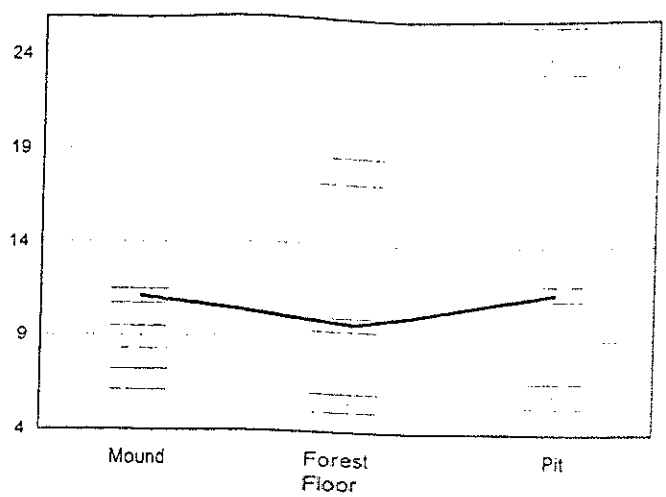

Figure 1. Microclimate in three distinct microhabitats of a wetland in the Upper Peninsula of Michigan. Mean soil temperature (°C; dashed line), soil moisture (%; thin line), and decomposition rates (tensile strength, kN/m²; thick line) are indicated. Bars indicate high and low values for each microclimatic variable at each microtopographic feature (scales are numerically equivalent for all three variables). Data were collected from 18 September 1995 to 14 November 1995.

Variability of microclimate in forested landscapes

The importance of understory microclimate for production in the overstory canopy, for the distribution of understory species, and for the maintenance of belowground processes is well documented (Geiger 1965). For example, short-lived sun flecks (i.e., those lasting an average of 6–12 minutes) can provide from 37% to 68% of the total seasonal photosynthetically active radiation in temperate hardwood and coniferous forests (Canham et al. 1990). Both horizontal and vertical gradients in photosynthetically active radiation influence the development of understory vegetation and its spatial distribution (Chazdon 1986, Brandani et al. 1988). However, the role and importance of microclimate vary widely among forests over time and under different weather conditions. For example, in lowland tropical forests, the percentage of understory radiation that comes from sun flecks is substantially lower in the wet season than the dry season (Smith et al. 1992). However, seasonal effects on light environment seem less pronounced in other forest ecosystems, such as Australian rainforests (both temperate and tropical), which have largely deciduous, multilayered canopies (Lowman 1986).

Microclimatic variables, particularly solar radiation, air temperature at the ground surface (hereafter referred to as surface temperature), and soil temperature, are highly sensitive to changes in the overstory canopy and exhibit relatively high spatial and temporal variability within a forest (Reifsnyder et al. 1971, Chen and Franklin 1997). Diurnal patterns of shortwave radiation (Figure 4a) and air temperature (2 m above the ground; Figure 4b) after three different types of canopy removals—clearcut, dispersed retention (i.e., partial cut), and aggregated retention (patch) harvesting (see also Figure 2)—are clearly different from those in intact, mature Douglas-fir (*Pseudotsuga menziesii*) forests. The influence of silvicultural treatments also differs among climatic variables; a new environment, characterized by a distinct combination of climatic responses, is created by altering canopy structure. For example, in one study of Douglas-fir forests in Washington, air temperature did not differ distinctly among clearcut, partial cut, and aggregated harvesting sites (Figure 4b), whereas patterns in light levels were unique at all sites (Figure 4a). Relative humidity, wind speed, and air temperature all responded similarly to harvesting. However, soil temperature and moisture changed in distinct ways and were less variable. Quantification of the differential responses of microclimatic variables to structural changes is a vital initial step in integrated ecosystem research because, as these results show, such variables respond uniquely to management activities.

The degree of spatial variability in microclimate also differs greatly among forest ecosystems. For example, Reifsnyder et al. (1971) found that it was difficult to sample, much less confidently quantify, the spatial and temporal variability of direct shortwave radiation in both oak and pine forests in central Connecticut. Old-growth Douglas-fir forests in southern Washington (Chen and Franklin 1997) and mature mixed-oak forests in the Ozarks of southeastern Missouri (Chen et al. 1997, Xu et al. 1997), also exhibited spatial variation in climatic variables, including air and soil temperatures, shortwave radiation, wind speed, and soil water content. The diurnal patterns in these variables differed as functions of daily local weather conditions (e.g., hot versus cool or wet versus dry days). In general, soil temperature was more variable spatially than air temperature or soil moisture. In the old-growth Douglas-fir forests, air temperature (maximum–minimum) varied by 2.7 °C along a 200 m transect in southern Washington on a typical summer day, whereas soil temperature varied by 5.9 °C (Chen

Figure 2. A landscape mosaic of management patches in the Pacific Northwest showing edges between residual forest (closed canopy) and clearcut areas, and between aggregated and dispersed greentree retention patches (see North et al. 1996 for site description).

and Franklin 1997). However, in the mature oak forests of the Ozarks, where forest canopies are less structurally diverse and summer weather is characteristically hot and humid, air and soil temperatures at nine points within a 0.64 ha area generally varied by less than 1.6 °C and 2.5 °C, respectively. Differences in shortwave radiation among nine measurement points in southern Washington were as high as 0.8 kW/m^2. Soil temperature and moisture in Washington were predictable from local weather conditions, but wind speed and shortwave radiation had weak relationships to local weather (Chen et al. 1993a, Dong et al. 1998).

The microclimate of the old-growth Douglas-fir forest varied more than that of the mature hardwood stands in Missouri, probably because the relatively even-aged, single-layered canopy of the oak forests is relatively more homogeneous, both horizontally and vertically; 30–60% of the old-growth forest is occupied by canopy openings of various ages and sizes.

Consideration of temporal dynamics in microclimatic variation can provide insights into ecological phenomena (e.g., soil respiration, flowering, and seed production) and the dynamics of species or individuals (e.g., wildlife dispersal and foraging behavior). The dynamics of these patterns in microclimatic variation are distinct from the dynamics of microclimatic mean values in both the Douglas-fir and oak forest systems. Thus, it is important to select the appropriate metric for any ecological phenomenon under study. For example, the significant differences in diurnal air temperature between the interior forest and harvested stands (Figure 4b) will not be clear when daily means are used because forest temperatures are lower in the day and relatively warmer at night (see also Reifsnyder et al. 1971). Mean air and soil temperatures usually reach their minima before sunrise and their maxima in the mid- or late afternoon, depending on geographic location, position in the landscape, and overstory structure. Variabilities in air and soil temperatures are also greater during the day than at night, and variation is greatest in the mid-morning and/or the late afternoon, with twin-peak patterns for temperature and moisture (Chen and Franklin 1997). At broader temporal scales (i.e., weeks or months), microclimatic variation within forest canopies is not always related directly to daily weather extremes; instead, especially in the spring and autumn, it may be related to dramatic weather changes (Chen and Franklin 1997). However, weekly or monthly mean values of microclimate measurements are influenced by daily temperature fluctuations. Thus, the choice of a microclimatic summary variable can significantly affect the perceptions and conclusions of a study.

Figure 3. Riparian buffers are common elements of landscape structure in the Pacific Northwest. Buffer strips are generally retained after logging in North America; however, the appropriate width is still debated.

Microclimate relationships to landscape structure

Landscape structure, as delineated by topographic features, is well known to directly affect temporal

and spatial patterns of microclimate at broad spatial scales, through gradients of elevation, slope, and aspect (Geiger 1965, Swanson et al. 1988). We expand this concept to suggest that, at finer scales, microclimate and its dynamics are directly related to all components of the landscape, including patches (defined in this article by vegetation), corridors (e.g., streams, roads, and power lines), and transitional zones between patches (e.g., edges between forests and openings; Forman 1995, Chen et al. 1996).

Landform modifies climate at local and regional scales. The height and distribution of land masses influence gradients of temperature and affect the channeling of air masses (i.e., wind patterns; Swanson et al. 1988). The intensity and duration of solar energy received, and the reception, retention, and movement of precipitation are also affected by landform. For example, temperature, moisture, wind speed, and light levels were found to differ among three landforms sampled in the southeast Missouri Ozarks—southwest slope, northeast slope, and ridge top—although the vegetation characteristics of the sites were similar (Xu et al. 1997). These differences, which were caused largely by the patterns of air flow and levels of incident shortwave radiation (Swanson et al. 1988), were generally smaller between south- and west-facing slopes and ridge tops than between north- and east-facing slopes and ridge tops (Figure 5).

In forested landscapes, patches (the basic units of landscape structure) result from disturbance and variation in the physical and geomorphical environment; they are frequently delineated using vegetation and soil properties (Forman 1995). The microclimate within each patch type is distinctive (Chen et al. 1996). Because microclimatic differences directly determine the distribution of species within patches (i.e., biological diversity) and the movement of species among patches (Forman 1995), there is strong interest in understanding the microclimates of harvested versus naturally disturbed patches, pre- versus post-management patches, and patches versus the surrounding landscape matrix. Patches that have been recently disturbed by human-induced or natural processes tend to have higher daytime shortwave radiation, temperature, and wind speed than undisturbed patches; in addition, these variables show greater spatial and temporal variability (Figure 4; see also Hungerford and Babbitt 1987, Chen et al. 1993b, Xu et al. 1997). This increased variability arises largely because removal of overstory vegetation destroys the ability of canopies to "buffer" the understory, moderating levels of incoming and outgoing energy components (Chen et al. 1996), including radiation, sensible heat, and latent heat.

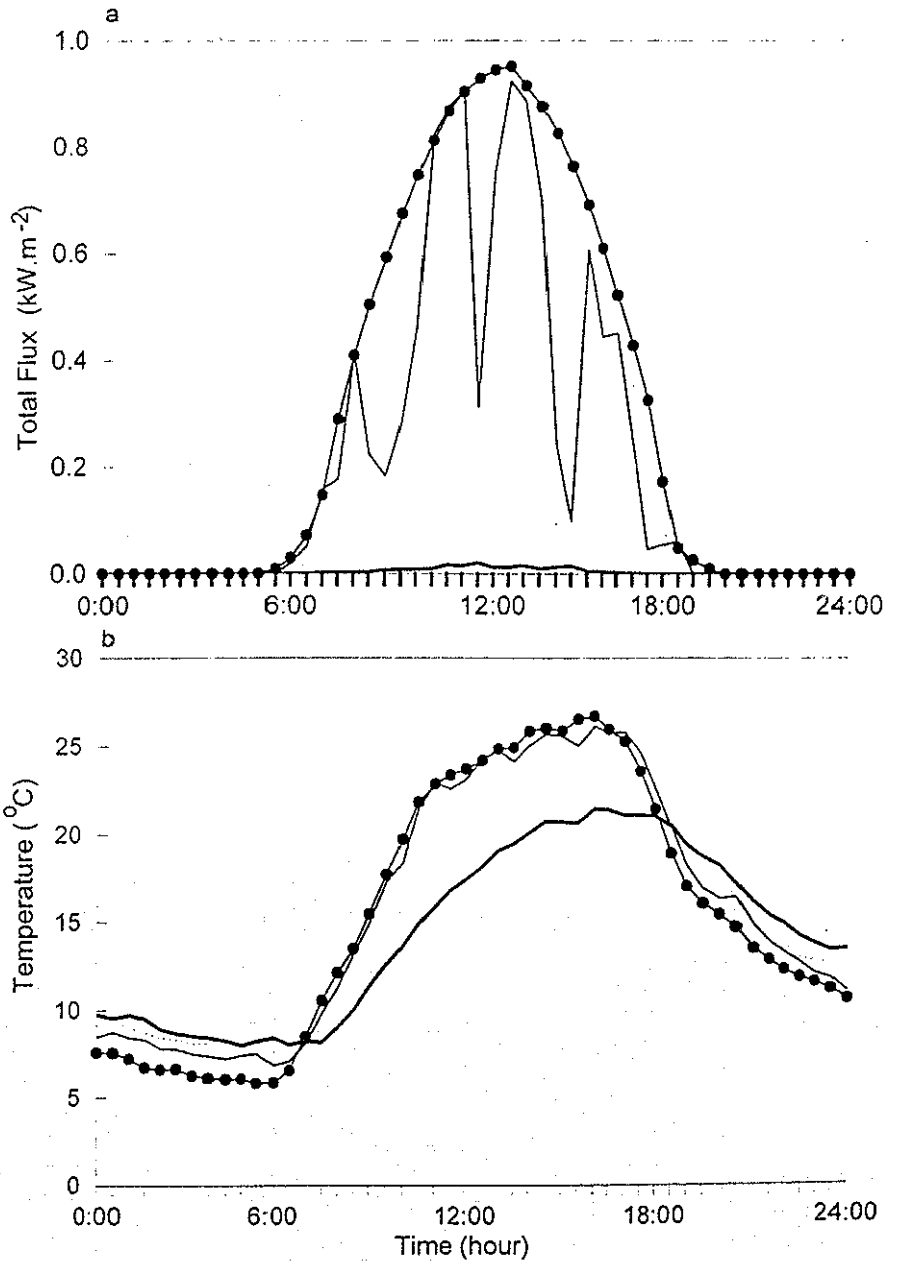

Figure 4. Diurnal changes in microclimate under different harvest regimes. (a) Patterns of shortwave radiation (kW/m²) for a 70-year-old Douglas-fir (*Pseudotsuga menziesii*) forest (thick black line) and three sites recently harvested using clearcut (solid line with circles), dispersed green-tree retention (partial cut; solid line), and aggregated green-tree retention (patch; dashed line) techniques. (b) Patterns of air temperature (°C) at 2 m above the ground for the same sites. Data were collected in western Washington on 25 August 1992 (the study sites are shown in Figure 2).

Quantification of microclimatic variance within a structural patch may provide direct causal explanations of structural or compositional

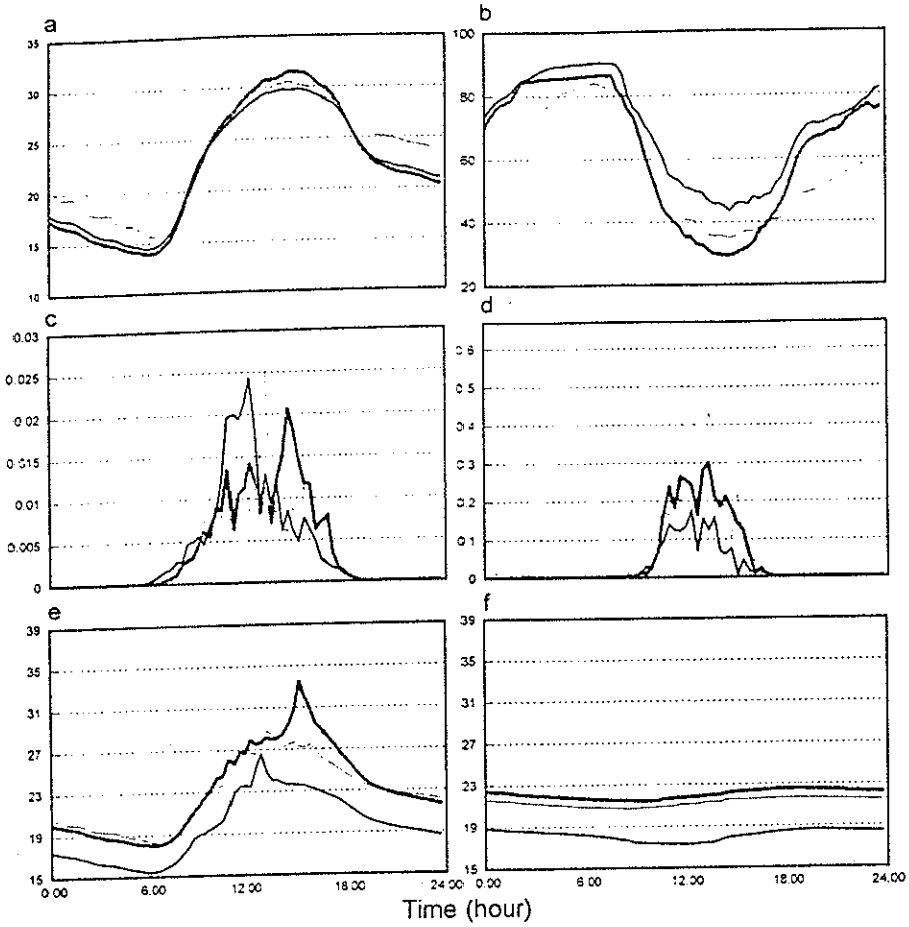

Figure 5. Diurnal changes in microclimatic variables at three landforms: ridge tops (solid black line), south- and west-facing slopes (thick gray line), and north- and east-facing slopes (thin black line). Variables monitored included (a) air temperature at 2 m height, (b) relative humidity, (c) shortwave radiation, (d) wind velocity, (e) air temperature at ground surface, and (f) soil temperature at 5 cm depth. Data were collected on 24 August 1995.

dynamics and can increase the ability to accurately predict the dynamics of an ecosystem. Microclimate can vary gradually from patch interior to edge and into neighboring patches, depending on edge orientation and the abruptness of changes in vegetative composition and density (Murcia 1995). Thus, boundaries defined by microclimatic criteria are not always the same as edges defined by structural criteria (Chen et al. 1996).

Microclimatic variance is especially dramatic in ecotones, which are distinct environments within the transitional zone between adjacent ecosystems (Gosz 1991). These edge environments are manifested in climatic and biotic (e.g., vegetal) changes (Harris 1988, Saunders et al. 1991). Such edge effects have been a focus of recent research because the increased rate of forest fragmentation in many landscapes has led to areas-of-edge influence becoming a major portion of fragmented landscapes (Franklin and Forman 1987, Chen et al. 1996). The changes in physical and biotic environments created within ecotones affect ecological processes as varied as seed dispersal, plant regeneration, nutrient cycling, and wildlife interactions (Saunders et al. 1991). When one moves from an open area, through an edge zone, and into a forest remnant, there is generally a decrease in daytime summer temperatures but an increase in humidity (Figure 6). The temporal range in microclimatic conditions created near an edge is significantly higher than the natural variation within a patch (e.g., up to 8 °C for air temperature in forest patches influenced by edge versus a natural within-patch range of 2.7 °C in a Douglas-fir forest in southern Washington; Chen et al. 1995).

These changes in microclimatic condition near edges can modify or impair ecosystem functions. For example, more extreme temperatures can be reached at the structural boundary between two patches than in either of their interiors because of stable air masses created at the edge (e.g., in tropical premontane wet forests, Williams-Linera 1990; in northern temperate conifer stands, Saunders et al. in press). These high soil and surface temperatures (more than 50 °C) can limit dispersal of insects and herpetofauna across the landscape. Similarly, strong winds near abrupt edges can be the primary cause of tree mortality, through windthrow (Chen et al. 1992) and desiccation (Essen 1994). Low humidity near edges can reduce production of biomass and recruitment for many moisture-limited species (e.g., herbaceous understory plants, Frost 1997; hypogeous fungi, Clarkson and Mills 1994). However, changes in microclimatic conditions near the edge are highly dependent on the variable of interest, time of day and season, edge orientation, edge position in the landscape or landform, and current weather conditions (e.g., in temperate oak-deciduous forests, Matlack 1993; in Pacific Northwest conifer systems, Chen et al. 1995). Recognizing the unique nature of microclimate on both sides of a patch transition and the influence of this microclimatic zone on landscape processes is, therefore, a critical component of landscape studies.

The depth-of-edge influence, or edge width, associated with microclimatic zones across abrupt edges in a landscape can result in broad areas-of-edge influence, which can constitute a significant portion of a fragmented landscape. The depth-of-edge influence, although it varies over time and with edge characteristics, can extend four to six tree heights into the forest from a recent clearcut forest edge, equivalent to approximately 60 m in eastern red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) forests (Raynor 1971) and

over 400 m in Pacific Northwest Douglas-fir forests (Figure 6; Chen et al. 1995). Edge width for some variables, such as air movement, can extend up to 15 tree heights into the clearcut (Rosenberg et al. 1983). When these numbers are translated to an area-of-edge influence, it becomes clear that the percentage of area-of-edge influence in a typical checkerboard clearcut landscape of the Pacific Northwest, for example, is much higher than the percentage in either forested or harvested areas alone (Chen et al. 1996).

Stream and river corridors—a special type of edge zone, or ecotone, between terrestrial and aquatic ecosystems—are other common structural features in a landscape. In the last two decades, it has become increasingly common to leave forested buffer strips along streams and around other aquatic ecosystems during harvesting (Figure 3; FEMAT 1993). These buffer strips are critical for maintaining the species composition and ecological functions of both aquatic and terrestrial ecosystems in managed landscapes (Naiman and Décamps 1997, Naiman et al. 1997). However, there is no consensus about how wide buffers must be to function effectively. Microclimatic variables provide one of the most sensitive and immediate sources of information available for examining the impacts of forested buffer strips and making appropriate management decisions. For example, riparian forests directly affect the amount of solar radiation reaching streams; therefore, low stream temperatures can be maintained by retaining the buffers (Brown 1969).

Harvesting riparian forests also affects microclimatic variables other than stream temperature. Before harvesting, stream and riparian environments in Washington are generally characterized by cool air and soil temperatures, high humidity, and low wind speed relative to forest interior conditions in the upland (Figure 7). These conditions extend approximately 50 m from the stream before they change to approximate the environment of the upland forest. Following clearcutting, the riparian microclimate shifts to approximate clearcut values rather than forest interior conditions (Brosofske et al. 1997). Although only relative humidity at stream center (positive association; $r^2 = 0.46$) and shortwave radiation at stream center (negative association; $r^2 = 0.60$) correlate with buffer width (Brosofske et al. 1997), harvesting near the stream results in overall changes in microclimate at the stream, even when buffers are wide (i.e., up to 74 m). For example, standardized values show that harvesting at 17 m or more from the stream results in an increase in air temperature of 2–4 °C and a decrease in relative humidity of 2.5–13.8% at the stream.

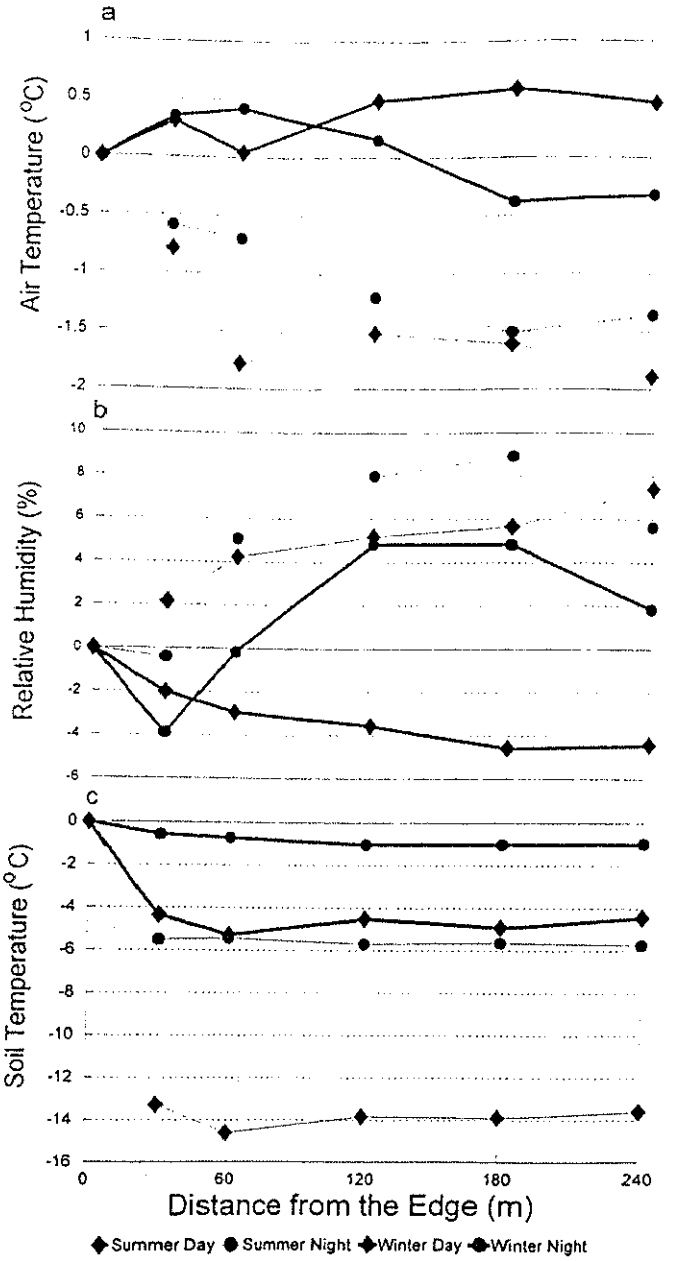

Figure 6. Gradients in microclimate from a clearcut into a forest stand. Changes in (a) air temperature (°C), (b) relative humidity (%), and (c) soil temperature (°C) at 5 cm depth were measured from an open edge (south facing) into an old-growth Douglas-fir forest during the day (diamonds) and at night (circles). Data were collected in southern Washington on 19–24 June 1990 for summer conditions (thin lines) and 2–11 April 1991 for winter conditions (thick lines).

The changing microclimate associated with the opening of canopies in riparian zones may result in modification of climate and landscape processes at the coarser scale of the drainage basin. For example, the increased air temperatures in the riparian zone may alter the channeling of air masses through river corridors. Furthermore, the regional diversity of vascular plants, which is related to the natural gradient in climate from the headwaters to lower reaches of streams (Naiman et al. 1993), may be modified by disruptions to this climatic heterogeneity. Moreover, modification of stream and air temperatures affects the productivity of stream invertebrate (e.g., Newbold et al. 1980) and vertebrate (e.g., Holtby 1988) populations.

The widespread implications of changes in microclimate from manipulation of forest and landscape structure require serious attention. Field studies suggest that increases in both air and soil temperatures created by forest clearing (i.e., more than 2 °C) are of similar magnitude or even greater than some predictions of the increased temperatures associated with increased atmospheric CO_2 and other greenhouse gases within the next century (Houghton et al. 1996). At the land-

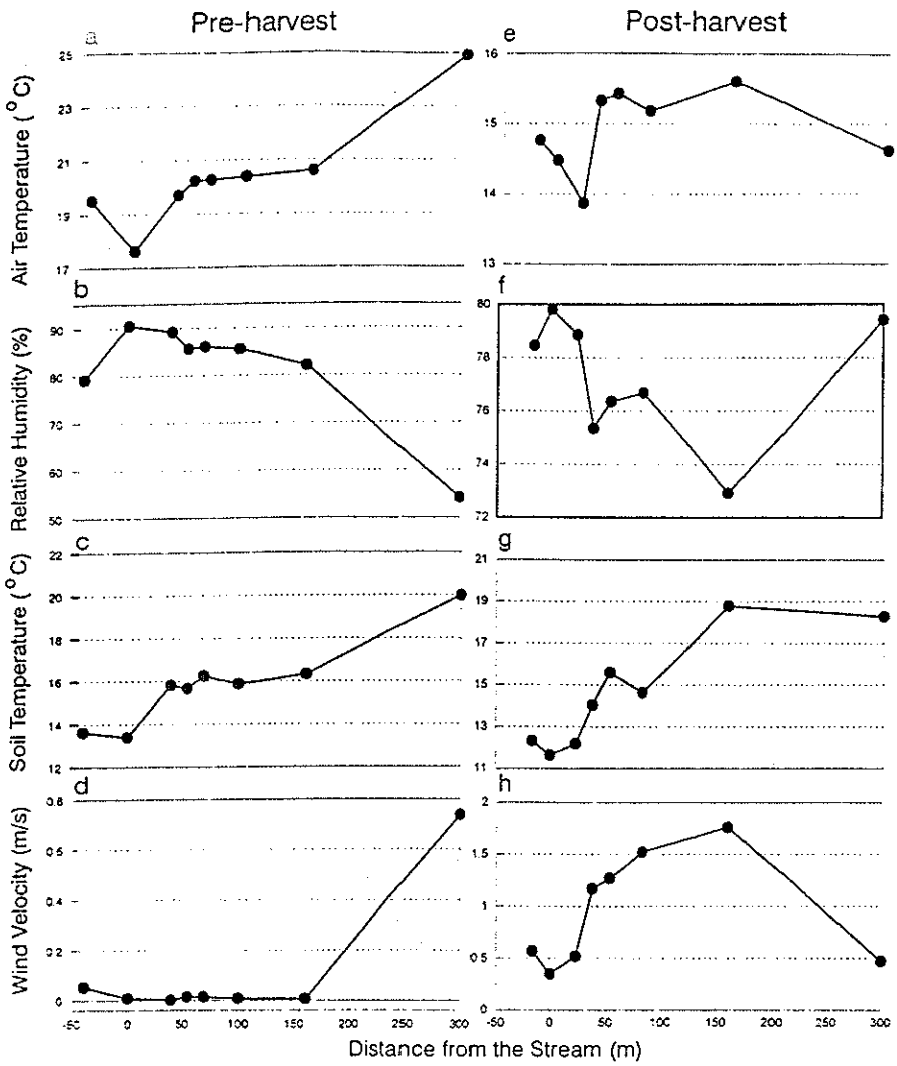

Figure 7. Microclimatic gradients across a small stream before and after harvesting in western Washington. Variables monitored include: (a and e) mean air temperature (°C), (b and f) relative humidity (%), (c and g) soil temperature (°C), and (d and h) wind speed (m/s). The center of the stream is at 0 m, and the points to the immediate left and right represent the buffer edges (i.e., planned buffer edges for pre-harvest sites, and actual buffer edges for post-harvest sites) at which microclimate was monitored. The retained buffer was a similar width (23 m) on both sides of the stream. Microclimatic data are averages (3-day) relative to the minimum average for the same variable measured at all the monitoring stations for the stream (n = 8; 7 stations along the stream gradient, 1 in the upland forest interior). Relative data are provided to minimize the confounding effects of changing macroclimate between years. Data were collected between 3 and 5 August 1993 and between 27 and 29 June 1994 for the pre- and post-harvest environment, respectively. Data are for one stream; however, results were qualitatively similar for four other streams examined before and after harvest (see Brosofske et al. 1997).

scape scale, these changes in temperature are occurring within a much shorter time span (i.e., over one harvesting period), and their cumulative impacts at broader spatial and temporal scales are not well understood. Thus, climate changes (e.g., temperature increase) caused by extensive land-use alteration may have greater impacts at both local and regional scales than modifications predicted from the greenhouse effect.

Importance of scaling

The microclimatic environment and its relative importance for driving biological processes vary with temporal and spatial scales because ecosystem structure and function are scale dependent (Meentemeyer and Box 1987). Thus, relationships between microclimate and structural landscape features or ecosystem processes developed at any single scale of study may not be applicable at other scales (Levin 1992). Across space, microclimate responds at the stand level to canopy structure (Reifsnyder et al. 1971, Chen and Franklin 1997), varies distinctly among patch types (Geiger 1965, Hungerford and Babbitt 1987, Chen et al. 1993b), changes gradually among patches through transitional zones or ecotones (e.g., riparian zones and forest-open edges), and forms a temporally dynamic pattern across the entire landscape. Although microclimatic responses to ecosystem structure differ significantly across these spatial scales, these responses are seldom examined as a hierarchical continuum across continuous scales, largely because of difficulties associated with simultaneous sampling of large areas and lack of appropriate quantitative methods for data analysis.

Fortunately, rapid technological development over the last three decades has greatly expanded the potential for field studies on microclimate. For example, it is now possible to use multiple data loggers and custom-made thermocouples to simultaneously record information on multiple microclimatic variables every 5 m across long transects (e.g., up to 760 m, as in the Chequamegon National Forest in northern Wisconsin; Figure 8). By moving measuring devices along transects during the growing season, it is possible to measure temperature gradients over approximately 3–4 km of fragmented forest landscapes. Such data make it possible to determine the importance of spatial scale in structure–climate relationships (Saunders et al. 1998).

Wavelet analysis has recently been used in ecological research to examine dynamics over continuous spatial scales or to detect patchiness at multiple scales (Bradshaw and Spies 1992, Gao and Li 1993, Saunders et al. 1998). We used this technique to detect multiscale patterns in and associations between canopy structure

and microclimate along a 760 m transect through mixed-pine stands in the Chequamegon National Forest (Figures 9a and 9b). Wavelet analysis allows for the examination of patterns at multiple resolutions while retaining information on the location along study transects (i.e., structural data; Bradshaw and Spies 1992). The data (collected every 5 m) suggested that at fine scales, overstory coverage and air temperature at the ground surface have a weak negative correlation (Figure 9c); Pearson correlations confirmed this limited structure–temperature association ($r^2 = -0.09$ at 10 m scale; $r^2 = -0.04$ at 50 m scale). However, the wavelet transforms of canopy structure (Figure 9a) and temperature (Figure 9b) indicated that temperature–overstory relationships might be stronger at broader scales. At a resolution of 200 m, there was a more distinct association between overstory structure and temperature, and correlations were stronger ($r^2 = -0.74$). A patch of relatively high temperature (darker area from approximately 200 m to 350 m along the transect in Figure 9a) corresponded to a region of relatively open canopy associated with old harvest landings at this same scale and location (lighter region of transform in Figure 9b).

Figure 8. Multiple microclimatic variables are measured concurrently every 5 m along a 760 m transect in the Chequamegon National Forest, northern Wisconsin.

Conclusions and implications

Scientists traditionally use microclimatic information to explain the behavior, distribution, development, and movement of organisms in natural systems. Major ecological processes, such as production, mineralization, and the spread of diseases, insects, and natural disturbances (e.g., fire), are controlled directly or have been related empirically to microclimatic conditions (Perry 1994, Waring and Running 1998). Microclimate influences the distribution of taxa as varied as butterflies (Weiss et al. 1991), lizards (Vitt et al. 1998), and birds (e.g., Wachob 1996). Manipulating microclimate by altering the structural environment can thus be a useful tool in both wildlife and ecosystem conservation.

In addition, the dynamics, across scales, of the relationships among microclimatic and structural landscape features should be considered in management and conservation planning. For example, when designating the size of harvest units (or reserve areas), managers wanting to retain a specific amount of interior forest on the landscape should be aware that interior conditions delineated by microclimate often differ in extent from interior zones delineated by vegetative cover (e.g., Chen et al. 1996). However, at the local (i.e., stand) scale, the impact of a management unit—for example, a clearcut—on microclimatic conditions will be similar at different locations. However, characteristics of adjacent stands will influence climatic conditions at the landscape scale. Roads and other landscape features can also influence microclimate at broad scales (i.e., at more than 100 m resolution), depending on the vegetation and topography of the patch types that they border (Saunders et al. 1998). As ecologists become more aware of the importance of scaling in studying biological responses, there is a need to examine microclimatic characteristics concurrently at multiple scales and to consider cumulative effects, rather than to simply assess the importance of microclimate independently at each scale.

Traditional climatic summaries can frequently be misleading, depending on research objectives and the microclimatic variables of interest. When undertaking any study of climate or climate–structure relationships, it is essential to recognize that microclimate is temporally and spatially variable; that microclimate has distinct spatial characteristics at multiple scales, corresponding to unique structural components of the landscape—within patch, between patches, through ecotones, and across the landscape; and that microclimatic environments and patterns across landscape elements are highly specific to an ecosystem due to differences in landform, species composition, and structure among ecosystems.

Empirical studies within patches and across patch boundaries suggest that landscape structure can also be defined and delineated using microclimate information. Indeed, patch patterns delineated on the basis of microclimate may provide ecologists with improved insights into biological responses to management and landscape design. Gradients of microclimatic conditions across edges and around residual habitat patches are associated with changes in vegetation composition and growth, in rates of ecosystem processes (e.g., decomposition), and in movement of wildlife. Microclimatic information provides significant insights when in-

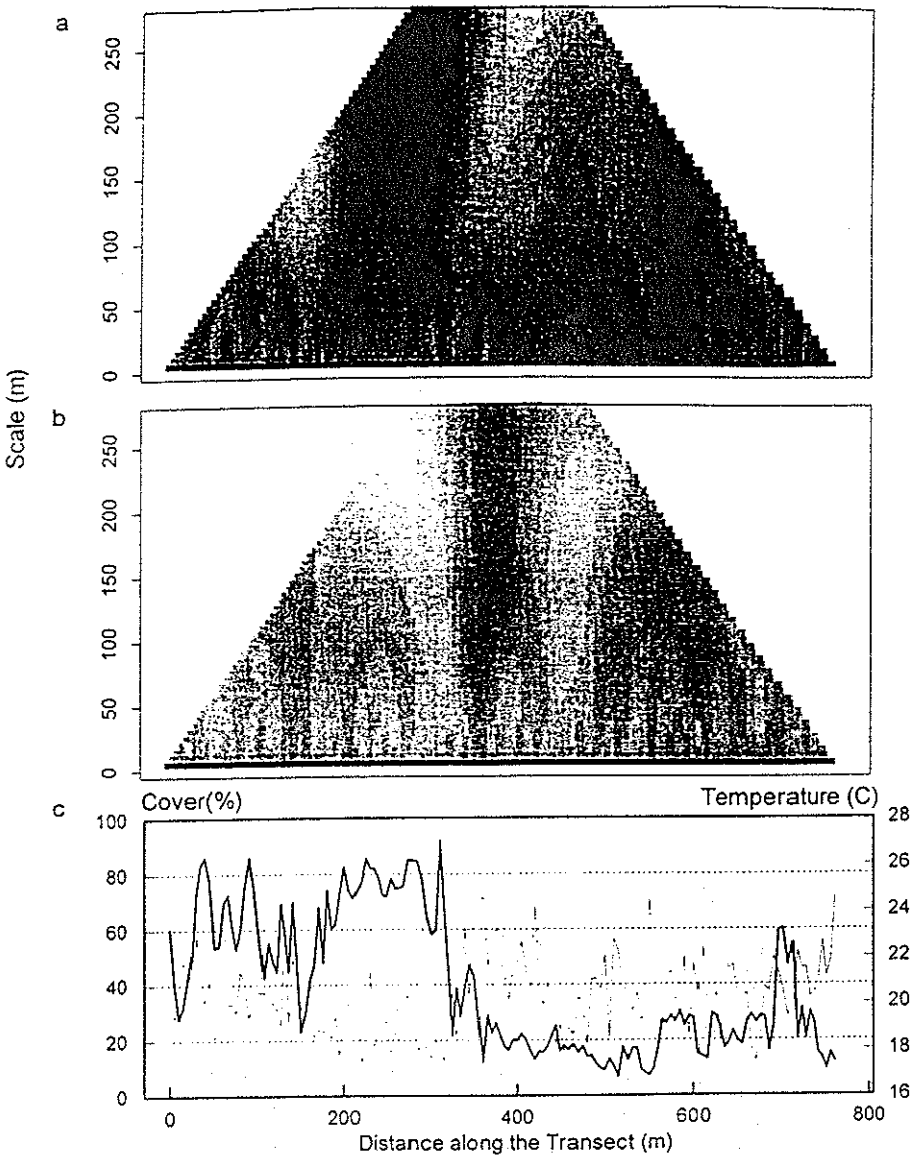

Figure 9. Patterns of overstory cover and air temperature at ground surface along a 760 m transect in a jack and red pine forest landscape in the Chequamegon National Forest, northern Wisconsin. The wavelet transforms for (a) canopy cover and (b) temperature were produced using the Mexican Hat function to reveal patterns at multiple resolutions (5–250 m) that are not apparent from the original data for (c) overstory (% cover; bold line) and air temperature (°C; thin line). Data were collected from 30 June 1995 through 3 July 1995.

terpreting other ecological processes and vital information when developing management options for a landscape.

Finally, three additional critical issues should be emphasized in any microclimate-related study to encourage sound examination and complete understanding of these multiscale relationships: the frequency of nonlinear combinations of microclimatic variables, the intensity of direct microclimatic monitoring required to adequately describe a study site, and the importance of quality-control procedures for climatic measurements.

Acknowledgments

This research was partially supported by the Landscape Ecology and Ecosystem Management program of North Central Forest Experiment Station (23-94-12), the Missouri Department of Conservation, the WESTGEC/NIGEC program of the US Department of Energy, Michigan's Research Excellence Funds at Michigan Technological University, the New Perspectives and Water–Land Interactions Programs of the Pacific Northwest Forest and Research Station (PNW-94-0541 and PNW-378409), the USDA National Research Initiative (97-35101-4315), and the Mead Publishing Paper Division. We thank Vernon Meentemeyer, Fred Swanson, Rebecca Chasan, and three anonymous reviewers for their helpful comments.

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