

# Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon

Paul D. Anderson, David J. Larson, and Samuel S. Chan

**Abstract:** Thinning of 30- to 70-year-old Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands is a common silvicultural activity on federal forest lands of the Pacific Northwest, United States. Empirical relationships among riparian functions, silvicultural treatments, and different riparian buffer widths are not well documented for small headwater streams. We investigated buffer width and density management effects on riparian microclimates of headwater streams in western Oregon. Spatial variations in stand density, canopy cover, and microclimate were measured along transects extending from stream center upslope into thinned stands, patch openings, or unthinned stands, with riparian buffers ranging from <5 m up to 150 m width. For treated stands, summer mean daily air and soil temperature maxima increased, and mean daily humidity minima decreased with distance from stream. Microclimate gradients were strongest within 10 m of stream center, a distinct area of stream influence within broader riparian areas. Thinning resulted in subtle changes in microclimate as mean air temperature maxima were 1 to 4°C higher than in unthinned stands. With buffers 15 m or greater width, daily maximum air temperature above stream center was less than 1°C greater, and daily minimum relative humidity was less than 5% lower than for unthinned stands. In contrast, air temperatures were significantly warmer within patch openings (+6 to +9°C), and within buffers adjacent to patch openings (+3°C) than within unthinned stands. Buffers of widths defined by the transition from riparian to upland vegetation or topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate above headwater streams. FOR. SCI. 53(2):254–269.

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**R**IPARIAN AREAS PROVIDE A VARIETY of ecological functions. They interact laterally between stream channel and upslope areas, longitudinally between upstream and downstream reaches, and vertically between surface and subsurface (Gomi et al. 2002). Vegetation, which regulates the exchange of energy, nutrients, and matter (Swanson et al. 1982, Gregory 1997), provides linkage of riparian areas with upland forests (Reeves et al. 1995). Riparian areas provide unique vegetative communities that tend to be more herbaceous than upslope habitats, but also provide cover in the form of many shrub species (Minore and Weatherly 1994, Pabst and Spies 1998). The diverse composition of vegetation in these areas provides structural characteristics that are important for survival and reproduction of many wildlife species (Kelsey and West 1998). Along with food, cover, and water for wildlife, riparian areas are also an important source of wood, soil, seed, and nutrient inputs to stream systems. Deciduous shrubs and overstory trees such as red alder (*Alnus rubra* [Bong.]) contribute detritus and invertebrates to stream systems (Piccolo and Wipfli 2002). Coarse wood in streams creates habitat for amphibians and aquatic invertebrates by controlling channel structure and stability, creating pools, storing sediment, and dissipating energy (Bilby and Bisson 1998, Gomi et al. 2001).

Headwater streams drain as much as 70 to 80% of watershed area (Sidle et al. 2000, Meyer and Wallace 2001). As summarized by Gomi et al. (2002), headwater streams are distinctly different from higher-order streams and rivers in the watershed network. The hydrology and geomorphology of headwater systems are more spatially heterogeneous (Gomi et al. 2002). A tighter coupling between hillslope storage and runoff results in headwater stream flows that are more responsive to precipitation events (Sidle et al. 2000, Gomi et al. 2002). Many headwater streams are seasonally intermittent due to variation in water table or alluvial deposition. While channel gradients tend to be steeper, coarse wood and boulders create channel steps and cascades (Gomi et al. 2002, May and Gresswell 2003). Given narrow channels and steeply constrained valleys, riparian vegetation and hillslopes often shade the full width of headwater streams (Gomi et al. 2002, Moore et al. 2005). These characteristics contribute to microclimates that are unique to headwater streams and that influence stream temperatures and habitats for terrestrial and aquatic organisms (Moore et al. 2005).

Regeneration harvesting and wildfire between 1930 and the early 1990s resulted in the establishment of hundreds of thousands of hectares of even-aged Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in western Oregon and Washington. These forests, now 30–80 years old, are

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frequently characterized by dense stands lacking in structural and compositional diversity. Lack of complexity makes these stands poorly suited for supporting many riparian-dependent species, the northern spotted owl (*Strix occidentalis cuarina* [Merriam]), and other wildlife species (Carey 1995, Linder Mayer and Franklin 2002, Curtis et al. 2004). Such stands will potentially remain in a stem-exclusion stage (Oliver and Larson 1996) for extended periods, perhaps a century or longer (Andrews et al. 2005), before mortality agents begin to create canopy gaps suitable for recruitment of understory vegetation and development of large crowns in overstory trees (Franklin and Van Pelt 2004).

It has been proposed that thinning of young Douglas-fir stands may be a means to create more heterogeneous forest structures conducive to development of understory vegetation (DeBell et al. 1997, Bailey and Tappeiner 1998) and more rapid development of large trees (McComb et al. 1993, Hayes et al. 1997, Carey et al. 1999a, b). Conventional application of thinning practices has focused on removing small or deformed stems and respacing of co-dominant trees to increase individual tree growth rates. Such practices can result in more uniform stand structures. In contrast, many contemporary partial harvest practices are designed to increase structural heterogeneity by such means as varying the intensity of thinning within a unit, incorporating dispersed or aggregate green-tree retention, or creating gaps and leave islands embedded within a thinned matrix (Aubry et al. 1999, Curtis et al. 2004, Cissel et al. 2006).

Buffering of streams and riparian areas is a common practice to mitigate potential negative impacts of harvest. Retention of streamside vegetation serves to maintain stream-bank stability, filter sediment transport to streams, reduce lateral air movement, and to intercept incoming solar radiation, the principle driver for heating of air and stream water (Moore et al. 2005). A variety of regulations and guidelines for buffer width delineation have been implemented across ownerships and jurisdictions within the Pacific Northwest (Gregory 1997). In general, buffer width requirements vary with stream size, flow volume, and the presence or absence of fish (Young 2000, Lee et al. 2004). The regulations represent societal compromise between ecological benefits of riparian protection and economic consequences of removing land from timber production. For example, under state regulations for private lands in California, Oregon, and Washington, some form of harvest is allowed directly adjacent to headwater streams with zones of restricted management ranging from 0 to 30 m (Young 2000). In contrast, guidelines applied to federal lands under the Northwest Forest Plan (USDA and USDI 1994) are directed toward maintaining a broad array of riparian and watershed functions with buffers of one or two site-potential tree heights being stipulated for nonfish-bearing and fish-bearing headwater streams, respectively. For Douglas-fir forests of western Oregon, one site-potential tree height may typically be 55 to 75 m (McArdle et al. 1961).

The studies of Chen et al. (1993a, b, 1995) provided a conceptual basis for defining the role of riparian buffers in moderating microclimate (FEMAT 1993). Their examination

of microclimate gradients from a clearcut into an old-growth Douglas-fir forest demonstrated that microclimate, particularly solar radiation and air temperature near the ground surface, was very sensitive to changes in canopy cover and is highly variable in space and time (Chen et al. 1999). Their work also demonstrated substantial differences among microclimate parameters in spatial and temporal responses to different forest structures. The distance from cut edge to which microclimate alterations could be detected within the forest interior varied from meters (e.g., soil moisture) to hundreds of meters (e.g., wind velocity). However, this body of research did not explicitly address microclimate gradients associated with streams, riparian buffers, or partial harvest, and therefore may not be directly applicable to issues of thinning in second-growth headwater forests.

Subsequently, a few studies have examined microclimate gradients associated with riparian areas and adjacent forest management. In wet-mesic forests of the west-side Cascades, Brososke et al. (1997) demonstrated that air and surface temperatures increased and relative humidity decreased, approaching interior forest conditions within 30 to 60 m of steeply constrained, small streams. Following clearcut harvest with buffers up to 72 m wide, trans-buffer and buffer-upslope gradients remained but upslope microclimate conditions approached those of the warmer, drier clearcuts. In the east-side Cascades, Danehy and Kirpes (2000) found strong near-stream gradients and increased diurnal variation in relative humidity in riparian zones of forests that had undergone selective harvest without an uncut buffer. They also surmised that topographic relief influenced the occurrence of near-stream microclimate gradients on these drier sites. In New Zealand, Meleason and Quinn (2004) evaluated air temperatures at the midpoints of a 5-m-wide and a 30-m-wide buffer and concluded that buffer effectiveness increased with increasing temperature in the adjacent forest clearing, and that although the 30-m buffer was cooler, the 5-m buffer provided substantial temperature moderation relative to open conditions. Although these studies demonstrated the effects of different stand conditions on near-stream microclimate, definitive information regarding the influence of thinning on headwater riparian microclimate and the relative effectiveness of various buffer widths for mitigating potential thinning effects is still lacking.

In this study we examined the effectiveness of riparian buffers of three types as implemented in an operational-scale study of density management. Our specific objectives were to (1) characterize variation in overstory density, canopy closure, and understory microclimate as a function of distance from headwater streams; and (2) for thinned stands, determine whether riparian buffers of varying width effectively maintain understory microclimates above the stream channel and in the riparian zones similar to those of unthinned stands.

## Methods

### *Locations and Treatments*

This study was undertaken as a component of the USDI Bureau of Land Management (BLM) Density Management

**Table 1. Locations and characteristics of riparian buffer microclimate and microsite study sites**

Site attribute*	Green Peak	Keel Mountain	Bottomline	O.M. Hubbard	North Soup Creek
Physiographic Province	Coast Range	Cascades Range	Coast Range	Coast Range	Coast Range
Latitude	44.37°N	44.53°N	43.77°N	43.29°N	43.57°N
Longitude	123.46°W	122.63°W	123.23°W	123.58°W	123.78°W
Elevation (m)	485–760	605–760	235–365	425–765	180–365
Aspect					
Unthinned unit	NE–SE	SW–NW	E–SE	N–NE	NW–N
Thinned unit	NE–SE	SW–W	NW–N	N–E	W–N
Site potential tree height (m)	75	82	72	61	68
Stand origin date	1933–1935	1949–1953	1939	1953–1955	~1948

\* Physiographic province from Franklin and Dyrness (1988); site information from Cissel et al. (2006).

Studies (DMS, Cissel et al. 2006). The DMS is a multidisciplinary, operational-scale evaluation of density management and riparian buffer alternatives applied to 30- to 80-year-old Douglas-fir stands characteristic of second growth forests predominant on BLM lands in western Oregon. The purpose of density management in the DMS is to increase structural heterogeneity of the overstory and thereby promote understory vegetation, development of dominant trees, recruitment of downed wood, and enhanced habitat quality for aquatic, riparian, and upland organisms.

The study was conducted at four sites along the Coast Range and at one site on the west-side Cascade Range of Oregon (Table 1). All five sites were within the western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) vegetation zone (Franklin and Dyrness 1988). Douglas-fir dominated the 45- to 65-year-old forests. Conifer associates included western hemlock and western redcedar (*Thuja plicata* Donn.). Hardwoods such as bigleaf maple (*Acer macrophyllum* Pursh) contributed generally less than 10% of stand density, and red alder (*Alnus rubra* Bong.) occurred in some riparian

areas. Site elevations ranged from approximately 200 m to 750 m, and aspect varied among sites and in some cases among treatment units within sites (Table 1). Historically, the two most northern sites, Green Peak and Keel Mountain, tended to receive more annual precipitation (Table 2). The Bottomline site tended to receive the least precipitation and had the highest annual and summer mean temperatures.

Physical and hydrologic characteristics of the streams at these sites are summarized in detail by Olson and Rugger (2007). In brief, they were topographically constrained first- and second-order streams. Active channel widths averaged 1.1 m (range 0.2–3.7 m), mean depth was less than 10 cm. Nearly 70% of the reaches were summer intermittent with a wetted surface over more than 80% of their length. Sampled reaches were 60 to 410 m in length (165 m average), as defined by internodal distances in the stream network, or transitions between adjacent density management units.

Stands ranging in size from 16 to 46 ha were either thinned to moderate density (T, 198 trees per hectare) or left unthinned (UT, approximately 500 to 865 trees per hectare).

**Table 2. Estimated climate conditions by study site; long-term annual and seasonal averages for 1980–2003 and for the period of sampling in 2001**

Site	Period	Mean daily temperature maximum (°C)	Mean daily temperature minimum (°C)	Mean daily temperature mean (°C)	Mean periodic precipitation (cm)
Annual and seasonal climate averages 1980–2003*					
Bottomline	Jan. 1–Dec. 31	17.2	5.1	13.9	138
	Jul. 15–Oct. 15	24.7	8.7	20.3	11.1
Green Peak	Jan. 1–Dec. 31	14.2	4.1	11.4	222
	Jul. 15–Oct. 15	21.3	8.2	17.7	15.7
Keel Mountain	Jan. 1–Dec. 31	14.0	2.9	11.0	200
	Jul. 15–Oct. 15	21.9	7.0	17.8	17.7
O.M. Hubbard	Jan. 1–Dec. 31	14.8	4.6	12.0	190
	Jul. 15–Oct. 15	20.8	8.1	17.3	12.5
North Soup Creek	Jan. 1–Dec. 31	15.9	5.7	13.1	172
	Jul. 15–Oct. 15	21.3	8.8	17.9	12.0
Climate during sampling†					
Bottomline	Aug. 14–Aug. 20, 2001	24.9	9.6	20.7	0.00
Green Peak	Aug. 30–Sep. 5, 2001	22.9	9.6	19.2	0.00
	Sep. 22–Oct. 3, 2001	24.6	6.9	19.7	0.11
Keel Mountain	Jul. 4–Jul. 9, 2001	26.5	7.1	21.2	0.00
	Jul. 15–Jul. 20, 2001	21.0	7.9	17.4	0.00
OM Hubbard	Sep. 25–Oct. 04, 2001	22.9	6.1	18.3	0.16
North Soup Creek	Oct. 16–Oct. 24, 2001	16.9	3.8	13.3	0.41

\*† Values are estimates based on a daily surface weather and climate summary model (DayMet) that calculates daily temperature, precipitation, humidity, and radiation for georeferenced locations within large regions of complex terrain. DayMet US Data Center, Numerical Terradynamic Simulation Group, University of Montana, www.daymet.org/default.jsp; Accessed 05/26/2006.

The thinnings primarily removed trees of small diameter or having defects. Within each thinned stand, 10% of the area was harvested to create patch openings (P) and 10% of the area was left as clusters of uncut trees (leave islands) (Figure 1).

Streams within the treated units were bounded by riparian buffers, strips of unharvested forest adjacent to the stream channel, averaging 69 m (one site-potential tree height, B1), 22 m (variable width, VB) or 9 m (streamside retention, SR) width as measured from stream center (Figure 1). The B1 buffers, ranging from 53 m to 73 m in width, were representative of riparian reserves specified for nonfish-bearing headwater streams under interim guidelines of the Northwest Forest Plan (USDA and USDI 1994). Variable-width buffers were delineated with a minimum width of 12 m from stream center and a maximum width up to 32 m based on features differentiating riparian and upland habitat, such as the transitions from channel to upland topographic position (slope break) or from riparian to upland vegetation. Streamside retention buffers consisted of retaining all trees having a portion of their crown extending directly over the stream. Ranging from less than 5 m to 14 m in width, SR buffers were presumed to provide greater bank stability and stream shading than a stand thinned up to the stream edge, but perhaps less moderation of microclimate within the stream and the riparian zones relative to VB and B1 buffers.

To enhance within-stand structural variation, the density management treatments included creation of patch openings (areas of complete overstory removal) embedded within the thinned stands (Figure 1). Patch openings (0.4 ha) directly adjacent to B1 and VB buffers were sampled as treatments

for two purposes. First, they provided a reference for assessing the impacts of thinning compared to complete overstory removal. Second, such features may become more common in young-stand management, and therefore there was a need to assess buffer efficacy in mitigating patch effects on riparian understory light and microclimate.

Six treatments, unique combinations of alternative buffer widths and adjacent density management condition, were evaluated: unthinned (UT), one site-potential tree height buffer adjacent to thinning (B1-T), one site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P), variable width buffer adjacent to thinning (VB-T), variable width buffer adjacent to a 0.4-ha patch opening (VB-P), and streamside retention buffer adjacent to thinning (SR-T).

Due to variability in the number of reaches among sites, not all six treatments were implemented at all sites (Table 3). At four sites, the 198 trees per hectare (tph) thinning treatment was nonrandomly assigned to the experimental treatment unit having the highest density of streams to accommodate as many of the buffer treatments as possible (Cissel et al. 2006).

### Sampling Design and Measurements

Microsite and microclimate responses to the treatments were characterized through repeated sampling of transects extending laterally from stream center through the riparian buffer and into the adjacent upland density management treatment. In general, there was one reach per treatment per site and one or two transects per reach (Table 3). Transects were located near the midpoints of the reaches. On some reaches, paired transects were installed to sample opposite

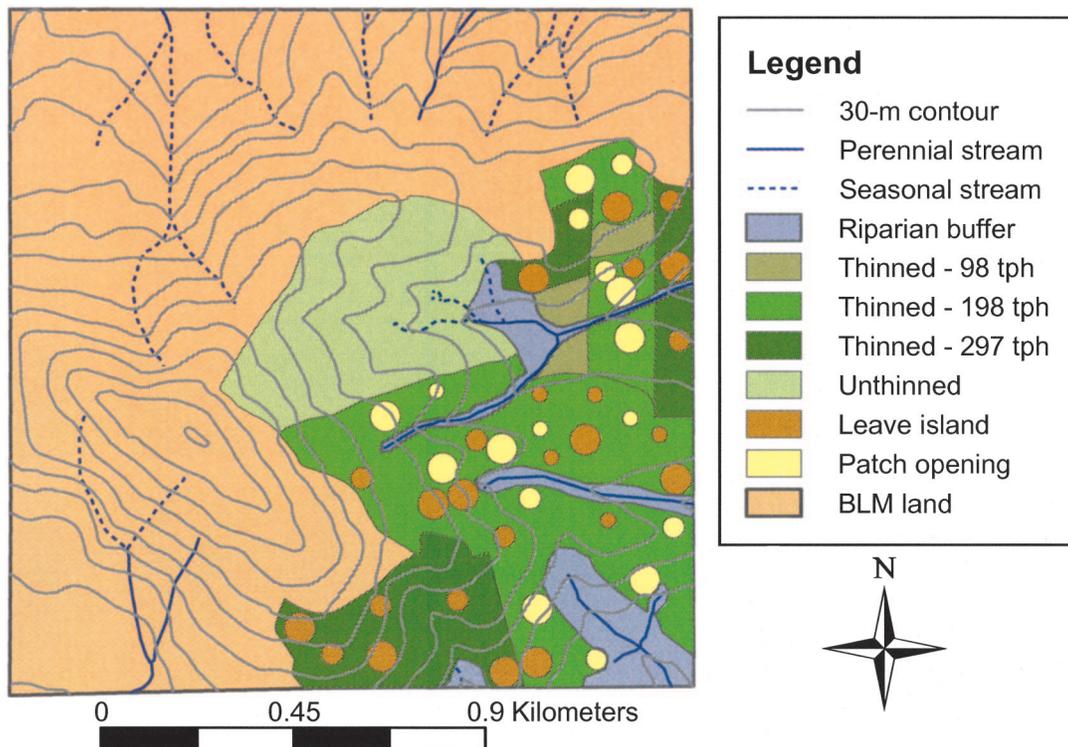


Figure 1. Experimental treatment layout at the Green Peak study site. The study was conducted within the stand thinned to 198 tph. This density management unit included streams with streamside retention, variable width, and one site-potential tree height buffers.

**Table 3. Number of study reaches (transects per reach) sampled by site and treatment**

Treatment*	Green Peak	Keel Mountain	Bottomline	O.M. Hubbard	North Soup Creek	Treatment Total
UT	1 (2)	1 (2)	1 (1)	1 (1)	1 (2)	5 (8)
B1-T	1 (2)	1 (1)	1 (1)	0	1 (2)	4 (6)
B1-P	1 (1)	1 (1)	1 (1)	0	1 (1)	4 (4)
VB-T	1 (2)	1 (2)	1 (1)	1 (1)	1 (1)	5 (7)
VB-P	1 (2)	1 (1)	1 (1)	1 (2)	1 (2)	5 (8)
SR-T	1 (2)	1 (2)	0	0	2 (2,1)	4 (7)
Site Total	6 (11)	6 (9)	5 (5)	3 (4)	6 (11)	

\* Treatments: unthinned stands (UT); 1 site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); 1 site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention buffer adjacent to a 198 tph thinning (SR-T).

sides of the stream. In total, data from 40 transects distributed among 26 reaches across five sites were used in the analyses (Table 3).

Transect lengths ranged from 41 m to 151 m (average 94 m), depending on the combination of buffer treatment and the potential dominant tree height. Where distance from stream to ridgeline permitted, transects extended a minimum of 65 m beyond the buffer into the adjacent upland treatment. Given the variation in stand density arising from patch openings and leave islands embedded within the thinned units, edge effects were likely in sampling of thinned stands and patch openings.

Each transect was anchored with a sample point at stream center. The nearest streamside sample point was generally located 4.6 m slope distance from stream center, although in a few instances it was located at 6.1 or 9.1 m slope distance due to local variation in channel morphology. From 4.6 to 22.9 m distance from stream center, sample points were spaced at 9.1 m slope distance. Beyond 22.9 m from stream center, sample points were spaced at 18.2 m slope distance. Sample points were more closely spaced near the stream because observations from a preliminary study indicated the presence of strong near-stream microclimate gradients in untreated stands. Each sample point served as a location for canopy closure and microclimate measurements. Stand density was measured at each sample point with the exception of stream center.

Stand basal area of trees greater than 12.7 cm dbh, a measure of overstory density, was estimated using variable-radius plot sampling based on 8.1- or 16.2-factor (metric) angle gauges. Canopy cover as quantified by the portion of visible sky (i.e., that portion of the overhead view unobstructed by foliage and limbs) was estimated from hemispherical photographs of the forest canopy during the summer, leaf-on period. Photographs were made using a 35 mm single-lens reflex camera with a 180° field of view (fisheye) lens mounted 1 m above the ground on a tripod. Images were recorded on high-contrast black and white film. To minimize potential errors associated with light reflectance from tree boles, branches, and foliage, images were recorded when the sun was low on the horizon or when the sky was uniformly overcast. Commercially developed black and white negatives were digitized and analyzed using CANOPY software (Rich 1989). Percentage visible skylight for each image was based on recorded diffuse light as a fraction of expected diffuse light for the entire field of view, given the geographic location.

Microclimate was monitored using three-channel humidity and dual-temperature data loggers (models GPSE 101 203 and GPSE 301 203, A.R. Harris, Ltd., Christchurch, NZ). Data loggers were mounted on Fiberglass rods and shielded from rain and direct sunlight with 1-liter ventilated white plastic cups. Air temperature and relative humidity were measured 1 m above the ground, and soil temperature (or at stream center, streambed temperature) at a subsurface depth of 0.15 m. Data loggers were simultaneously deployed at each transect point for continuous monitoring over an 8- to 10-day period. Data logged hourly for the four warmest precipitation-free days were analyzed. Limitations in the number of available sensors (approximately 200) resulted in sensors necessarily being rotated among sites. The majority of transects were sampled between mid-July and mid-September, with the exception of the North Soup Creek site, where sampling occurred in October, before the onset of autumnal rains (Table 2). It was presumed that summer would be the period of most extreme temperature and humidity, and therefore the period in which density management effects on microclimate would be most evident.

Density management treatments were applied between 1997 and 2000. As a result of variation among sites in the year of harvest and logistical constraints, we report data that were collected 2 to 5 years after harvest. Microclimate data were collected in 2001, canopy cover and overstory basal area in either 2002 or 2003.

## Analyses

Three forms of analyses were conducted with respect to overstory density, canopy cover, and microclimate response variables. First, variation with distance from stream was visually assessed based on plots of treatment mean values. Second, near-stream (0 to 30 m) gradients observed from graphical analysis were quantified and compared. Third, treatment effects were statistically evaluated for data stratified into stream center, buffer, and treated upslope zones.

Variation in stand basal area, canopy cover, and microclimate variables with respect to distance from stream was visually assessed from plots of treatment means by slope distance. Near-stream and riparian zone temperature gradients were calculated as the changes in temperature across the 0- to 10-m and the 10- to 30-m horizontal distances from stream center. These intervals were selected based on the

graphical evidence for substantial transitions in the temperature-distance relationship at approximately 10 m. The 30-m upper limit encompasses all data collected within the nominal riparian zones of average width for the study reaches.

Treatment effects were evaluated from three perspectives representing different spatial and resource contexts: (1) A stream-centric evaluation was made by comparing stream center microclimates between thinned and unthinned treatments. This assessment was analogous to the more common stream-centric studies of water temperature responses to forest management. (2) In recognition of the importance of riparian areas to a broad array of ecological processes and values, conditions within buffers of three widths were compared. (3) To evaluate the efficacy of riparian buffers, it was important to know the degree to which the mitigation capacity of the buffers was being challenged. This evaluation was made by comparing conditions between patch openings and thinnings adjacent to buffers.

A univariate linear modeling approach was used to detect buffer and density management treatment effects on basal area, canopy cover, and microclimate variables. Transect data were stratified into three zones: stream center, buffer, and upslope. For treated stands, the buffer and upslope zones were delineated by those portions of transects within the uncut buffer and those in the treated upslope, respectively. For each transect, means for the buffer and upslope zones were calculated as the average of individual point observations (e.g., mean daily maximum air temperature) weighted by the length of transect within the respective zone represented by each point. Weighted averaging of observations within the buffer and upslope zones eliminated bias associated with systematic variation in sample point spacing. For unthinned units in which there was by definition no distinct delineation in overstory density, buffer and upslope zones were subjectively defined as transect points within 22 m of, but excluding, stream center (buffer) and those more than 22 m distant from stream center (upslope). This delineation was based on the average VB buffer width.

Treatment effects were analyzed as a one-way treatment structure in a linear mixed-model analysis. The six buffer width/density management treatments were fixed effects. Site effects were random. Due to the general lack of treatment replication within locations, site effects served as the error term and estimates of site  $\times$  treatment interaction effects were not possible. Data from multiple sample reaches per treatment at a given site were averaged before analysis. Analyses for each zone and response variable were run separately. Stand basal area, percentage visible sky, and microclimate variables including daily maximum air temperature ( $T_{a_{max}}$ ), daily maximum soil or streambed temperature ( $T_{s_{max}}$ ), daily minimum relative humidity ( $Rh_{min}$ ), and a measure of absolute humidity, daily minimum water vapor pressure ( $Ah_{min}$ ) were the principal response variables. Basal area and visible sky data were log-transformed to stabilize variance.

Linear models were fitted using SAS Proc Mixed (Littell et al. 1996). Treatment main effects were considered significant at the  $P \leq 0.1$  level. Inferences regarding specific treatment differences were based on seven predefined con-

trasts. This set of contrasts tested differences between treated stands and unthinned units, between patch treatments and unthinned stands, and between thinning treatments with wide and narrow buffers. To control for experiment-wise error rates ( $P \leq 0.1$ ), inferences drawn from individual contrasts were based on Bonferroni adjusted significance values ( $P \leq 0.014$ ). Given restrictions on randomization in treatment implementation and the environmental confounding among replicates, the analyses should be interpreted as a compilation of case studies. The scope of inference is limited to the specific sites, treatments, and periods of measurement represented by the data.

## Results

### *Overstory Density and Canopy Cover*

For unthinned stands, mean basal area ranged from about 44 to 58  $m^2 ha^{-1}$  over the length of transects. While basal area of unthinned stands tended to increase with increasing distance from stream through 26 m, there was little variation among distances greater than 70 m (Figure 2a). For thinned treatments, basal areas within 5 to 10 m of the stream tended to be less than at 15 m, likely the result of the opening associated with the stream channel (Figure 2a). As expected, there was a substantial range in basal area for thinned treatments over distances from 15 to 70 m from stream center, indicative of different buffer widths and inherent near-stream density variation in unthinned buffer zones. Basal areas of thinned treatments (B1-T, VB-T, and SR-T) were relatively constant over distance in the upslope, treated portions of transects (Figure 2a). Unlike the modest variation with distance observed for the thinned treatments, the minimal basal areas associated with 0.4-ha patch openings were evident at approximate distances of 40 to 80 m and 85 to 105 m for the VB-P and B1-P treatments, respectively (Figure 2a).

Relative to the spatial patterns for basal area, canopy cover was relatively constant with increasing distance from stream for unthinned stands and for thinned stands regardless of buffer width (Figure 2b). In UT stands, percentage visible sky varied ranged from 5 to 7% with distance from stream. Visible sky of thinned stands (B1-T, VB-T) increased to 9 to 12% upslope from the buffer edge. In contrast, visible sky in the SR-T treatment was approximately 10% at stream center and did not increase more than 2% within 60 m of stream center (Figure 2b). Patch openings upslope of the VB or B1 edges were evident as increases to approximately 60% visible sky. Although buffers were unthinned, percentage visible sky values for the B1-P and VB-P treatments were increased within the buffer zone (Figure 2b), indicating an edge effect on canopy openness as measured from hemispherical imagery.

Basal area least-squares means (back-transformed from analysis of variance (ANOVA) model estimates) within the unthinned riparian buffers ranged among treatments from 28  $m^{-2} ha^{-1}$  (SR-T) treatment to 53  $m^{-2} ha^{-1}$  (B1-P) (Figure 3a). However, treatment differences in basal area of buffers were not significant ( $P = 0.145$ ). Given the lack of thinning within buffers, little difference in basal area of buffers among treatments might have been expected.

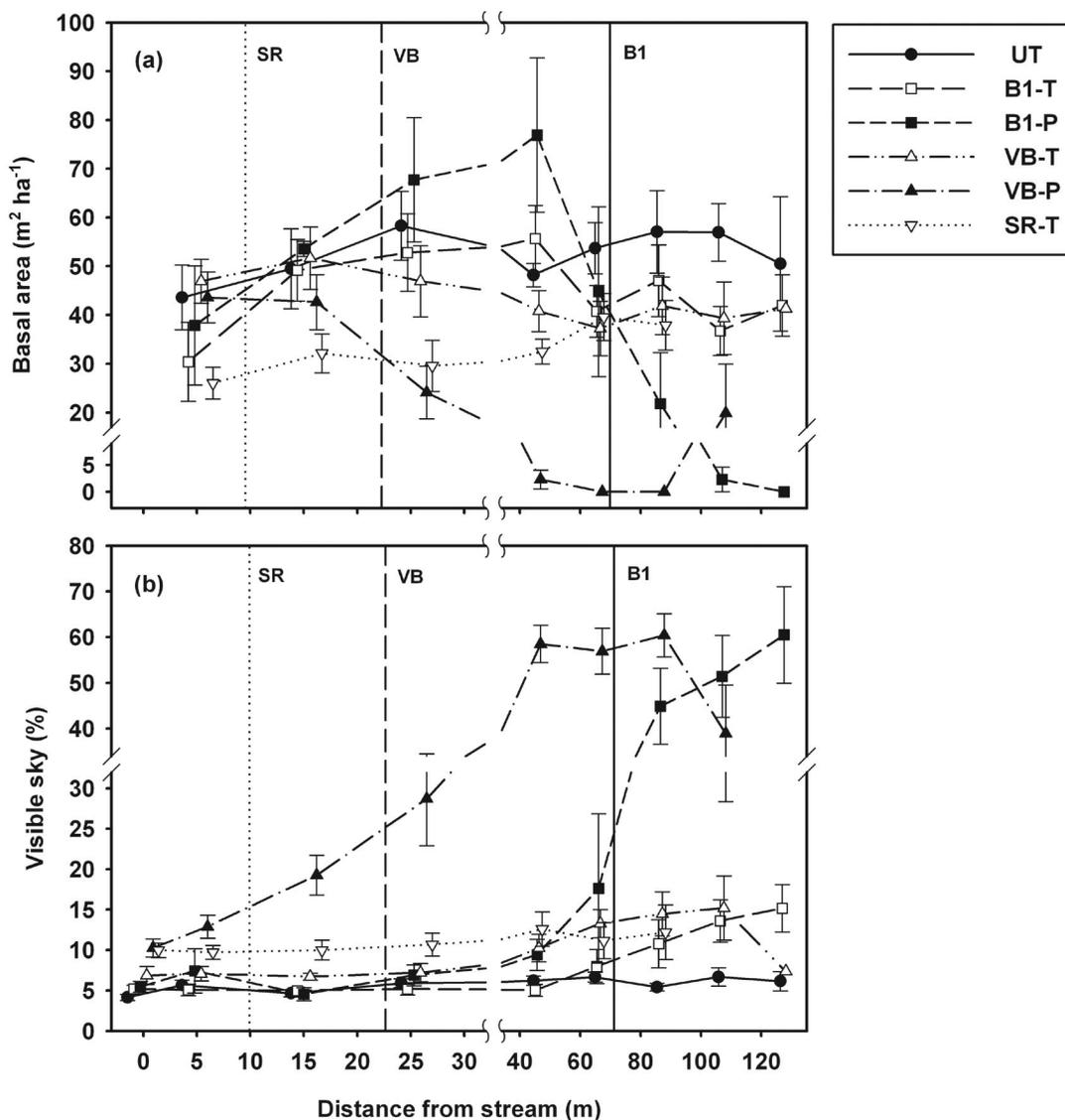


Figure 2. Variation in stand basal area (a) and percentage visible sky (b) with slope distance from stream center 3 to 5 years following implementation of density management treatments. Vertical lines indicate nominal distance from stream center to the buffer/upslope edge for streamside retention (SR, dotted line), variable width (VB, dashed line), and one site-potential tree height (B1, solid line) buffers. Values are means  $\pm 1$  standard error for  $n =$  two to five observations per treatment and distance. For enhanced clarity, data points at each distance are offset and data for distances greater than 128 m are excluded. Data for treatments: unthinned stands (UT); one site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); one site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention adjacent to a 198 tph thinning (SR-T).

However, the wide range of treatment mean basal area of buffers suggests that the lack of significance was also due in part to large within-treatment variation across reaches and sites.

For the upslope zone, mean basal area of patch openings was less than  $2 \text{ m}^{-2} \text{ ha}^{-1}$ , significantly less ( $P < 0.001$ ) than that for unthinned stands ( $49 \text{ m}^{-2} \text{ ha}^{-1}$ ) (Figure 3a). Basal areas for thinned stands ranged from 27 to  $31 \text{ m}^{-2} \text{ ha}^{-1}$  and did not differ significantly from UT stands or among thinned treatments (Table 4).

Variation in canopy cover among treatments was significant for stream center ( $P = 0.009$ ), buffer ( $P = 0.001$ ), and treated upslope ( $<0.001$ ) zones. At stream center the amount of visible sky increased with decreasing buffer width from about 4.2% for UT stands to approximately

9.6% for the SR-T treatment (Figure 3b). Stream center visible sky for the VB-P treatment, the only VB or B1 treatment to differ significantly, was about 5.1% greater than for UT stands ( $P = 0.002$ ).

Visible sky in the buffer zone ranged among treatments from 4.1% (B1-T) to 11.8% (VB-P), and was up to 3% greater than that at stream center for the corresponding treatments (Figure 3b). Percentage visible sky decreased with increasing buffer width, indicating a greater edge effect for narrow buffers. Canopy openness of SR buffers was significantly greater than that of UT buffer zones (Table 4). Patch openings were associated with increased mean visible sky in adjacent VB buffers, but not in adjacent B1 buffers (Table 4).

Upslope from the buffers, percentage visible sky averaged 5.6% for UT stands; 13.0% for SR-T, VB-T, and B1-T

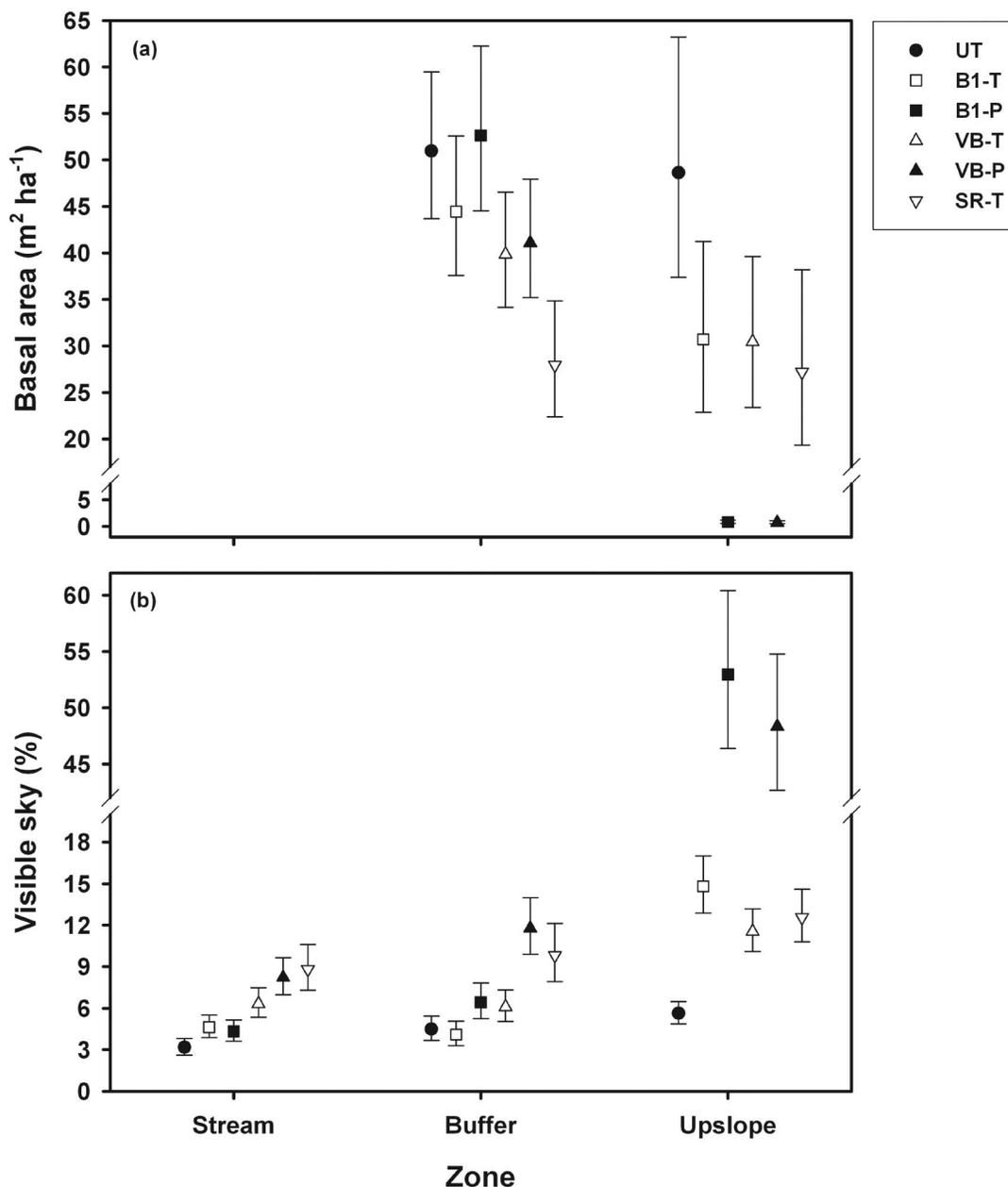


Figure 3. Treatment least-squares means ( $\pm 1$  standard error) for (a) basal area and (b) percentage visible sky as measured over stream center, within buffers, and within the upslope stands. Means and confidence intervals for  $n =$  four to five observations. Values are back-transformed from model estimates based on log-transformed data.

stands; and 51% for VB-P and B1-P treatments (Figure 3b). Canopy openness of thinned stands and patch openings was significantly greater than that of unthinned stands (Table 4).

### Microclimate

Daily maxima of air temperature ( $T_{a_{max}}$ ) and soil temperature ( $T_{s_{max}}$ ) in UT stands increased approximately 3°C and 2°C, respectively, with distance from stream center over 150-m transects (Figure 4). Temperature changes with distance were greatest within 10 m of stream center and temperatures were relatively constant beyond 10 m. Within 30 m of the stream, temperature patterns for thinned stands with VB and B1 buffers are similar to those of UT stands, with the exception that near-stream increases were greater

for the treated stands. In contrast,  $T_{a_{max}}$  above the stream for the SR-T treatment was similar to that in the thinned upslope at 21 m from the stream. Air and soil temperatures of thinned stands were elevated at distances upslope of the buffers. Within B1 buffers, temperatures increased with distance if adjacent to an upslope patch opening, but not if adjacent to thinning. Maximum air and soil temperatures were associated with 0.4-ha circular patch openings (approximately 35 m diameter) evident from 25 to 70 m (VB-P) or 80 to 140 m (B1-P) (Figure 4a, b).

Spatial patterns of relative humidity were generally the inverse of those for  $T_{a_{max}}$ , as expected given the dependence of saturation vapor pressure on temperature (Figure 5a). However, in contrast to  $T_{a_{max}}$ ,  $Rh_{min}$  in the UT treatment gradually declined continuously with distance over the

**Table 4. Significance of treatment main effects and single-degree of freedom contrasts for the mixed-model univariate analyses of basal area, canopy cover, and microclimate variables**

*Effect or Contrast	Significance (probability: $H = H_0$ )					
	†LnBA	LnSky	Ta <sub>max</sub>	Ts <sub>max</sub>	Rh <sub>min</sub>	Ah <sub>min</sub>
Stream center						
Treatment main effect	—	<b>0.009</b>	<b>0.096</b>	0.602	0.167	0.341
B1-T versus UT	—	0.168	0.729	0.455	0.836	0.372
VB-T versus UT	—	0.017	0.888	0.608	0.390	0.384
SR-T versus UT	—	<b>0.002</b>	0.021	0.860	0.053	0.555
B1-P versus UT	—	0.255	0.706	0.155	0.705	0.709
VB-P versus UT	—	<b>0.002</b>	0.299	0.947	0.686	0.085
B1-T versus VB-T	—	0.221	0.634	0.783	0.601	0.873
VB-T versus SR-T	—	0.211	0.026	0.544	<b>0.012</b>	0.194
Buffer						
Treatment main effect	0.145	<b>0.001</b>	<b>0.019</b>	<b>0.057</b>	<b>0.075</b>	<b>0.089</b>
B1-T versus UT	0.460	0.707	0.302	0.485	0.197	0.463
VB-T versus UT	0.164	0.160	0.048	0.310	0.329	0.272
SR-T versus UT	0.020	<b>0.005</b>	<b>0.011</b>	0.199	<b>0.010</b>	0.204
B1-P versus UT	0.861	0.125	<b>0.004</b>	0.022	<b>0.014</b>	0.133
VB-P versus UT	0.219	<b>&lt;0.001</b>	<b>0.006</b>	0.116	0.147	0.344
B1-T versus VB-T	0.555	0.098	0.371	0.801	0.685	0.089
VB-T versus SR-T	0.145	0.057	0.205	0.053	0.044	0.047
Upslope						
Treatment main effect	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>	<b>0.021</b>	<b>0.019</b>	0.234
B1-T versus UT	0.261	<b>&lt;0.001</b>	0.145	0.435	0.122	0.568
VB-T versus UT	0.226	<b>&lt;0.001</b>	0.044	0.453	0.078	0.798
SR-T versus UT	0.195	<b>&lt;0.001</b>	0.024	0.667	0.034	0.166
B1-P versus UT	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>	<b>&lt;0.001</b>	0.139
VB-P versus UT	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>	0.055	0.037	0.412
B1-T versus VB-T	0.983	0.060	0.627	0.931	0.911	0.738
VB-T versus SR-T	0.797	0.542	0.524	0.837	0.477	0.236

Values in boldface indicate significant differences for main effects ( $P \leq 0.1$ ) or, following Bonferroni adjustment, treatment contrasts ( $P \leq 0.014$ ). All tests based on 16 error degrees of freedom.

\* Treatments: unthinned stands (UT); 1 site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); 1 site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention adjacent to a 198 tph thinning (SR-T).

† LnBA = natural logarithm of basal area, LnSky = natural logarithm of percentage visible sky, Ta<sub>max</sub> = mean daily maximum air temperature, Ts<sub>max</sub> = mean daily maximum soil/streambed temperature, Rh<sub>min</sub> = mean daily minimum relative humidity, Ah<sub>min</sub> = mean daily minimum atmospheric water vapor pressure.

150 m distance sampled. Daily minimum water vapor pressure (Ah<sub>min</sub>), a measure of absolute humidity independent of air temperature, also declined with distance from stream. However, like Ta<sub>max</sub> and Ts<sub>max</sub>, change in Ah<sub>min</sub> was greatest near the stream and mean values varied less among distances greater than 10 m (Figure 5b).

To more easily interpret near-stream patterns presented in Figure 4a, air temperature gradients were estimated for distance from stream intervals of 0 to 10 m and 10 to 30 m (Table 5). For unthinned stands, the change in Ta<sub>max</sub> per unit horizontal distance from stream was 0.15°C m<sup>-1</sup> over the 0- to 10-m distance and 0.0°C m<sup>-1</sup> over the 10- to 30-m distance, indicative of a strong transition in microclimate. Air temperature gradients over the 0- to 10-m distance tended to be greater for thinned stands with VB and B1 buffers (0.28 to 0.35°C m<sup>-1</sup>), while gradients over the 10- to 30-m distance were similar for all treatments (0.0 to 0.08°C m<sup>-1</sup>). Near-stream temperature gradients for the SR-T treatment were unique in that they were uniformly small across the 0- to 30-m distance, indicating that temperatures over the stream channel were not substantially lower than that in the thinned upslope. Estimates of topographic slope (change in elevation per unit horizontal distance from stream) tended to be similar for the 0- to 10-m

(38 to 71%) and 10- to 30-m (30 to 54%) distances (Table 5). This indicates that the valley hillslopes were relatively uniform through 30 m, and that the observed transitions in temperature profile at 10 m were likely not due to topographic transitions, such as a slope break. Furthermore, it indicates that the stream has a distinct zone of influence within the broader riparian areas of these headwater reaches.

Although canopy cover at stream center differed among treatments, above-stream microclimate generally did not differ among treatments (Table 4). Compared to UT stands, Ta<sub>max</sub> above the stream for stands having B1 and VB buffers differed by -0.7°C (B1-P) to 1.6°C (VB-P) (Figure 6a). Although statistically insignificant, Ta<sub>max</sub> of the SR-T treatment exceeded that for UT stands by 4.5°C (Figure 6). Similarly, there was little difference in stream center mean Ts<sub>max</sub>, Rh<sub>min</sub>, and Ah<sub>min</sub> for B1-T and VB-T treatments compared to UT stands (Figure 6b–d). As with Ta<sub>max</sub>, above-stream Rh<sub>min</sub> in the SR-T treatment was 13% less than in the UT stands, but the difference was not statistically significant (Figure 6c).

Within the buffer zone, treatment differences were evident for Ta<sub>max</sub> ( $P = 0.019$ ), and to a lesser extent, for Rh<sub>min</sub> ( $P = 0.075$ ) (Figures 6a and 6c). Compared to UT stands, Ta<sub>max</sub> for buffers of thinned stands tended to be greater by 1.1°C (B1-T) to 4.0°C (SR-T), but only the SR-T treatment

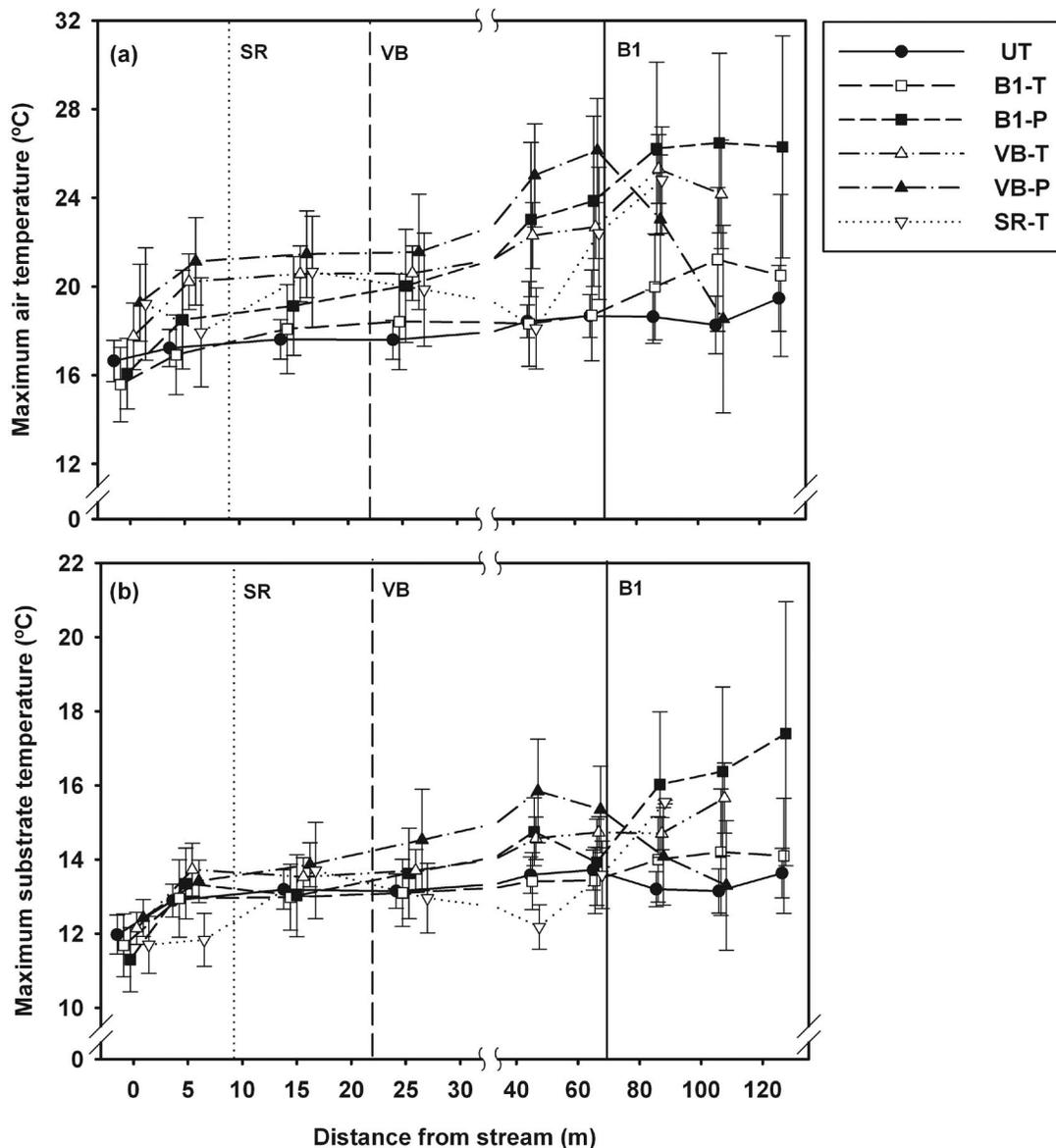


Figure 4. Variation in summer daily maximum air temperature (a) and daily maximum soil/streambed temperature (b) with slope distance from stream center for stands having different buffer widths in combination with moderate intensity thinning and patch openings. Vertical lines indicate nominal distance from stream center to the buffer/upslope edge for SR (dotted line), VB (dashed line), and B1 buffers (solid line). Values are daily maximum hourly means  $\pm 1$  standard error of  $n =$  two to five observations per treatment and distance for the four warmest, rainless days within a 6- to 10-day sampling period. For enhanced clarity, data points at each distance are offset and data for distances greater than 128 m are excluded. Treatments: unthinned stands (UT); one site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); one site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention adjacent to a 198 tph thinning (SR-T).

differed significantly ( $P = 0.011$ ). Air temperature maxima for buffers adjacent to patch openings averaged  $3.5^{\circ}\text{C}$  greater than in UT stands (Figure 6a, Table 4). Relative humidity minima in buffers adjacent to treated stands ranged from 5.1% (VB-T) to 20.5% (SR-T) less than that of UT stands with  $\text{Rh}_{\min}$  of the B1-P and SR-T treatments being significantly lower (Table 4).

Stand density treatments significantly influenced  $T_{\text{a,max}}$ ,  $T_{\text{s,max}}$ , and  $\text{Rh}_{\min}$  of the upslope forest (Table 4). Air temperature maxima of treated stands exceeded those of UT stands by 2.6 to  $9.0^{\circ}\text{C}$ , with the greatest differences being associated with the B1-P ( $P < 0.001$ ) and VB-P ( $P = 0.002$ ) treatments (Figure 6a). Compared to thinned stands

(B1-T, VB-T, SR-T), air and soil temperature maxima in patch openings (B1-P, VB-P) averaged  $8.8^{\circ}\text{C}$  and  $3.6^{\circ}\text{C}$  warmer, respectively. Relative humidity responses to the treatments generally mirrored those of  $T_{\text{a,max}}$ , as  $\text{Rh}_{\min}$  of treated stands was 8.6% (B1-T) to 22.4% (B1-P) less than UT stands. However,  $\text{Rh}_{\min}$  of the treated upslope forest differed from UT only for the B1-P treatment ( $P < 0.001$ ).

## Discussion

### Microclimate

Headwater riparian zones are characterized by microclimate gradients extending from the stream into the upslope

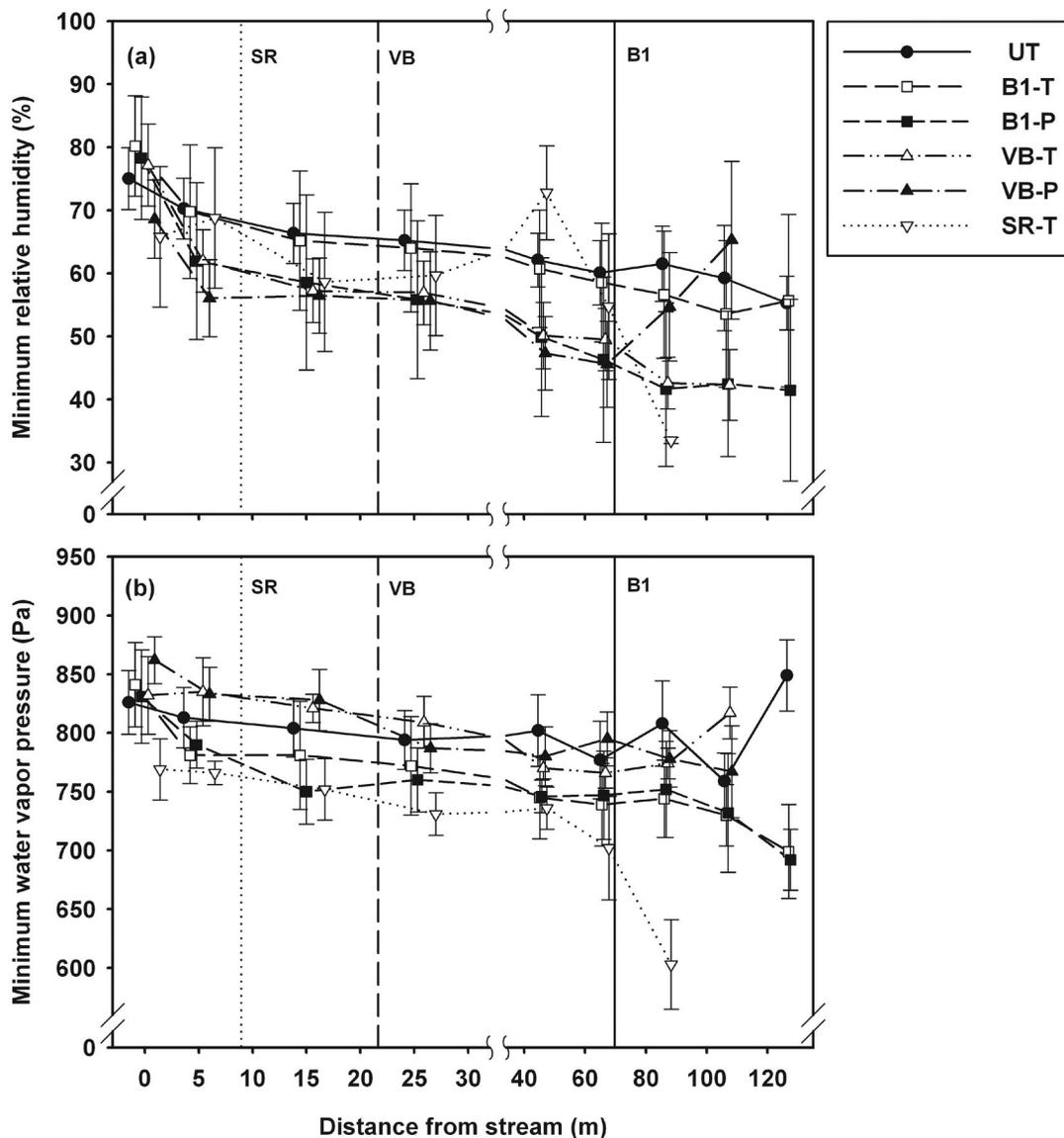


Figure 5. Variation in summer daily minimum relative humidity (a) and daily minimum atmospheric water vapor pressure (b) with slope distance from stream center for stands having different buffer widths in combination with moderate intensity thinning and patch openings. Vertical lines indicate nominal distance from stream center to the buffer/upslope edge for SR (dotted line), VB (dashed line), and B1 buffers (solid line). Values are daily minimum hourly means  $\pm 1$  standard error of  $n =$  two to five observations per treatment and distance for the four warmest, rainless days within a 6- to 10-day sampling period. For enhanced clarity, data points at each distance are offset and data for distances greater than 128 m are excluded. Treatments: unthinned stands (UT); one site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); one site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention adjacent to a 198 tph thinning (SR-T).

forest. The observation of steep near-stream temperature and relative humidity gradients is consistent with findings of two Pacific Northwest riparian microclimate studies: one in the eastern Cascades (Danehy and Kirpes 2000) and the other in the western Cascades (Brosfoske et al. 1997). Near-stream relative humidity gradients reported by Danehy and Kirpes (2000) for riparian areas on the east side of the Cascades were strongest in the first 5 m from the stream, one-half the distance observed in this study. The eastern Cascades study sites were more xeric than those of the western Cascades and Coast Range, and the adjacent forest had been selectively harvested to a range of residual stockings without retaining buffers. They concluded that the drier

upslope environment, low rates of transpiration by streamside vegetation, and local steep topography contributed to the relatively compressed zone of stream influence.

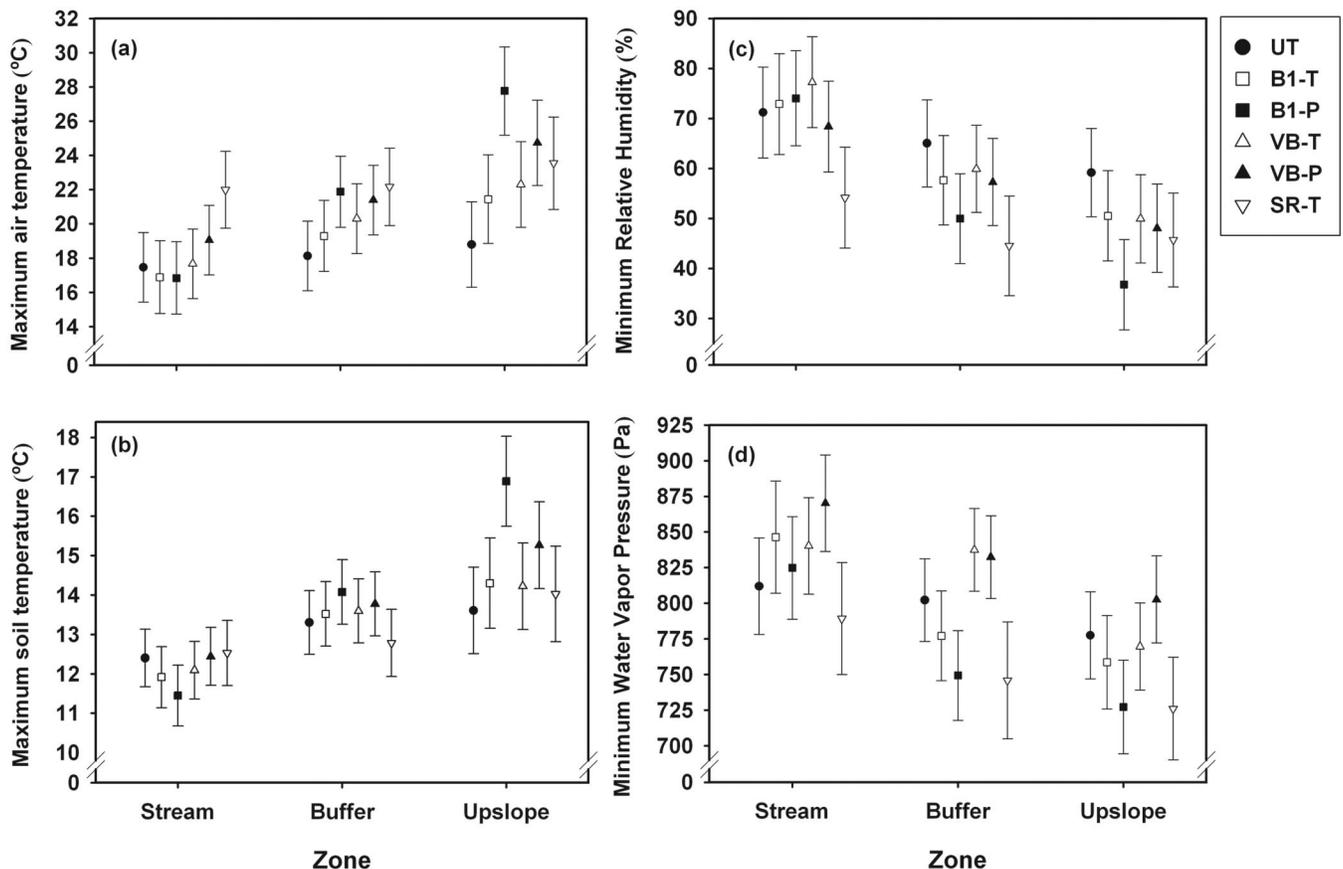
In more mesic western Cascade forests, Brosfoske et al. (1997) did not observe a consistent influence of buffer width on air temperature at the stream following clearcut harvest with retention of buffers ranging in width from less than 10 to 60 m. Relative humidity increased and solar radiation decreased with increasing buffer width. A modeling analysis of the same data led Dong et al. (1998) to conclude that air temperature in the stream channel had increased following harvest by up to 4°C, and that buffer effectiveness in moderating air temperature above the

**Table 5. Mean ( $\pm$ SE) air temperature and hillslope gradients in relation to distance from stream by treatment**

Treatment*	n	Air temperature gradient 0–10 m ( $^{\circ}\text{C m}^{-1}$ )		Air temperature gradient 10–30 m ( $^{\circ}\text{C m}^{-1}$ )		Hillslope gradient 0–10 m (%)		Hillslope gradient 10–30 m (%)	
		Mean	(SE)	Mean	(SE)	Mean	(SE)	Mean	(SE)
UT	5	0.154	(0.068)	−0.001	(0.011)	45.9	(11.4)	35.3	(9.6)
B1-T	4	0.327	(0.131)	0.062	(0.029)	48.0	(11.3)	47.8	(10.3)
B1-P	4	0.351	(0.102)	0.081	(0.035)	70.5	(10.3)	54.2	(8.6)
VB-T	5	0.318	(0.104)	0.016	(0.025)	41.4	(5.9)	29.7	(4.6)
VB-P	4	0.275	(0.115)	0.026	(0.070)	38.4	(5.4)	35.5	(8.7)
SR-T	4	0.056	(0.067)	0.029	(0.015)	44.0	(13.0)	47.0	(15.8)

Temperature gradient is the change in temperature per unit horizontal distance from stream center. Hillslope gradient is the change in elevation above the stream per unit horizontal distance from stream center;  $n$  = number of reaches sampled.

\* Treatments: unthinned stands (UT); 1 site-potential tree height buffer adjacent to a 198 tph thinning (B1-T); 1 site-potential tree height buffer adjacent to a 0.4-ha patch opening (B1-P); variable break buffer adjacent to a 198 tph thinning (VB-T); variable break buffer adjacent to a 0.4-ha patch opening (VB-P); and streamside retention adjacent to a 198 tph thinning (SR-T).



**Figure 6. Treatment least-squares means ( $\pm$ 1 standard error) for (a) daily maximum air temperature, (b) daily maximum soil/streambed temperature, (c) daily minimum relative humidity, and (d) daily minimum atmospheric water vapor pressure as measured over stream center, within buffers, and within the upslope stands. Means and confidence intervals for  $n$  = four to five observations.**

stream was greatest early and late in the growing season, and negligible during mid-growing season. These results contrast with our observations that indicated temperature increases above the stream associated with thinning retaining buffers of minimum 15 m width (B1-T, VB-T) were approximately  $1^{\circ}\text{C}$  and statistically insignificant (Figure 6a, Table 4). This inconsistency is likely the result of two contrasting intensities of upslope harvest: clearcut versus thinning. Patch openings, which were essentially small clearcuts, were associated with elevated air temperatures within buffers (approximately  $3^{\circ}\text{C}$ ) that

were similar to the temperature differences between buffer-clearcut edge and intact forest reported by Dong et al. (1998).

The effectiveness of narrow, streamside retention buffers in moderating stream microclimate from harvest effects is questionable. Daily maximum air temperature and daily minimum relative humidity at stream center for the SR-T treatment were extreme among the treatments. It was also the only treatment that lacked a near-stream temperature gradient in excess of that for unthinned stands. It had a weak temperature gradient that was similar for the 0- to 10-m and

the 10- to 30-m distances from stream center. This indicates that the stream center and buffer microclimates were essentially the same as that upslope in the thinned stand. Although the temperature and humidity values observed in this study may have been confounded by site and season, the presence of near-stream gradients was generally consistent across sites for a given treatment. A lack of strong near-stream microclimate gradients may have diagnostic value as an indicator of ecosystem disturbance.

In treated stands, transects traversed two edges: a stream channel-buffer edge and a buffer-upslope forest edge. Sampling was designed to characterize the strong near-stream gradients. This design was successful in capturing the microclimate transitions that delineate a narrow zone of stream influence within a broader riparian zone. However, the wider spacing of sample points with increased distance from stream did not allow an explicit evaluation of microclimate gradients about the boundary delineating buffer from thinned zones. Edges have bidirectional effects evident as alterations in abiotic characteristics that extend beyond the physical edge defined by an abrupt habitat transition (Cadenasso et al. 1997), such as a forest harvest boundary. This was best illustrated in our data by the distinct elevation of air and soil temperatures at the center of 0.4-ha patch openings (Figure 2). The lower temperatures near the interior perimeter of patches at both upper and lower patch boundaries indicates an external influence of the buffer and thinned stand on the patch environment. Although buffers are also likely to exert an influence on an adjacent thinned stand, the structural differences are less pronounced, resulting in weaker environmental gradients, and therefore less obvious edge influence (Harper et al. 2005).

Direct solar radiation is a driving source of air and soil heating. In eastern hardwood forests, edge gradients for parameters associated with direct beam radiation (temperature, vapor pressure deficit, litter moisture content) were found to be aspect-dependent, whereas gradients in humidity and shrub cover were not (Matlack 1993). Direct radiation along edges between forest and openings is particularly important at low sun angles when direct radiation penetrates through bole space. In thinned stands having shallow crowns, or on slopes of southern aspect, this low-angle direct radiation may be important (Hagan and Whitman 2000). As edges mature with the development of an understory vertically connected to the canopy, the edge porosity may decline, decreasing the extent of edge influence (Mourelle et al. 2001). Moderate thinning, as implemented in this study, provides a low contrast in canopy density at the buffer-upslope edge. These edges are relatively closed and microclimate transitions are likely not much influenced by aspect or slope. However, for patch openings adjacent to buffers, microclimate gradients along relatively open edges are likely subject to strong influence of aspect and slope.

Microclimates in patch openings differed from those of thinned stands. Although thinned stands and patch openings demonstrated increased air temperature and decreased relative humidity, the magnitude was greater in patch openings. Soil temperature responses were evident only in the patch openings. With complete overstory removal, more solar radiation reached the forest floor. Whether because of patch

size or the development of vegetation within patches, air movement was insufficient to dissipate the heat. Although it cannot be discerned precisely from Figure 4b, it is reasonable based on Chen et al. (1995) to expect that elevated soil temperatures extend from patch openings at least a few meters into adjacent buffers.

Canopy cover provided a more precise measure of overstory condition than did basal area. Two possible explanations are that (1) estimates of canopy cover by hemispherical photographs integrate over a greater area of the stand and are less subject to local variation, and (2) variation in growth potential among and within sites may have resulted in different average tree sizes. Thus, a thinning prescription targeting a specific stem density may have resulted in dissimilar basal areas across sites. Although stand density and basal area are common metrics in forest management, the relationships between these measures and canopy cover are nonlinear (Chan et al. 2006) and often not well defined for specific sites or stand conditions. Canopy cover is a more direct measure of solar radiation transmission and therefore may be a preferred metric for assessing potential thinning impacts on understory microclimate. In the Pacific Northwest, canopy cover criteria have been incorporated into streamside management regulations for state and private lands in California (Young 2000).

Our measures of canopy cover were based on the estimated proportion of diffuse beam radiation that is transmitted through the canopy. The premise is that canopy cover is an index for solar energy penetration to the understory or stream channel. However, total energy received comprises both diffuse and direct beam radiation. Direct beam transmittance is dependent on the solar path, and therefore its relationship to canopy shading of streams or microclimate variation along forest edges is aspect-dependent (Matlack 1993, Dignan and Bren 2003). We observed across these sites that percentage transmittances of indirect and direct light were strongly correlated in the buffer and in the upslope zones, but less so at stream center (data not shown). This suggests that while canopy cover may be a useful index of potential shading, aspect should also be accounted for, particularly under conditions where direct and indirect light are not strongly coupled.

Measurements of canopy cover were made one or two growing seasons later than microclimate measurements. How might this affect the relationships between canopy cover and microclimate data presented here? A recent thinning study for similar stands in the Coast Range indicated that rates of canopy closure during the first 8 years following thinning averaged 1 to 3% per year (Chan et al. 2006). Visible sky at the time of microclimate sampling was likely 2 to 5% greater than reported here. In that situation net radiation within thinned stands would have been greater, leading to potentially stronger contrast with unthinned stands. For the levels of canopy closure measured in 2002 and 2003, it is reasonable to expect that microclimate differences between thinned stands and unthinned stands would have been less, while differences between patch openings and thinned stands may have been greater.

The importance of headwater streams and riparian areas to species diversity and ecological function is increasingly

being recognized. Within forested landscapes of western Oregon, riparian areas of headwater streams are characterized by high abundance and diversity of macroinvertebrates (Progar and Moldenke, unpublished data) and diversity of aquatic-dependent vertebrates such as amphibians (Olson and Rugger 2007). Microclimate variables are frequently among the suite of environmental factors influencing assemblages of fauna, such as amphibians (Sheridan and Olson 2003), or riparian plant communities (Pabst and Spies 1998). Although buffers may be sufficient to maintain above-stream and buffer microclimates similar to unthinned stands, the question remains as to the biological implications of these statistically insignificant microclimate changes. For some aquatic organisms, particularly fish, physiological tolerances to changes in stream temperature and water chemistry are fairly well known. For example, Huff et al. (2005) determined the thermal tolerances for 16 aquatic vertebrates in four ecoregions of Oregon. Their data not only identified minimum and maximum temperature limits that differed among species, but they also demonstrated that a species' range of thermal tolerance varied among ecoregions. Small changes in microclimate leading to stream water heating may threaten local populations when initial water temperatures are near the thermal maxima and when discontinuities in headwater systems inhibit relocation to cooler waters by sensitive aquatic vertebrates. In contrast, Herlihy et al. (2005) surmised that increased canopy opening leading to increased primary productivity following harvest was responsible for a general increase in aquatic macroinvertebrate abundance for headwater streams in Oregon. MacCracken (2002) found positive, negative, and neutral responses by various salamander species to small changes in air temperature and humidity associated with thinning of riparian alder. Although definitive information is generally lacking, the influence of small changes in microclimate for aquatic and riparian species will likely be influenced by life stage and their ability to reach suitable refuge such as stream banks, shade, down wood, or soil.

## Conclusions

Headwater riparian zones are characterized by microclimate gradients extending from the stream into the upslope forest. These gradients appear strongest within 10 m of the stream center. Although thinned stands may have buffer and stream-center light environments that differ from unthinned stands, the stream exerts a strong influence on near-stream microclimate. In general, thinned stands are warmer and drier, but upslope thinning has little detectable effect on stream-center microclimate. Furthermore, thinnings as practiced in this study were associated with substantially less alteration of canopy cover and understory microclimate than were patch openings. Buffers of widths defined by the transition from riparian to upland vegetation or significant topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate above the stream; there was no apparent increase in mitigation associated with wider buffers. Cross-disciplinary research to better understand relationships among forest structure, mi-

croclimate, and habitat suitability for headwater riparian organisms such as amphibians and invertebrates is needed.

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