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GROWING-SEASON MICROCLIMATIC GRADIENTS FROM CLEARCUT EDGES INTO OLD-GROWTH DOUGLAS-FIR FORESTS[1]

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Abstract. Edge is an important landscape feature of fragmented forest landscapes in the Pacific Northwest, USA. Our primary objective of this study is to characterize the changes in microclimatic variables from recent clearcut edges into the old-growth Douglas-fir forests as influenced by edge exposures and local weather conditions. Microclimatic gradients are described along transects extending from recently clearcut edges 240 m into stands of old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest west of the Cascade Range in the U.S. Pacific Northwest. Data for air temperature, soil temperature, relative humidity, short-wave radiation, and wind speed were collected over the course of the day from 16 different edges representing a range of edge orientations and local weather conditions over two growing seasons (1989–1990). Data for soil moisture were collected over three consecutive days in September 1990. Two indices, significance of edge influence (SEI) and depth of edge influence (DEI), were used to evaluate the effects of edges on microclimatic variables. Edge effects typically extended 30 to >240 m into the forest. From the edge into the forest, air temperatures decreased during the day and increased at night; the reversal produced mid-morning and late-afternoon periods when a gradient was absent. Changes in soil temperature from the edge into the forest were comparable to those for air temperature, except that edge effects did not extend as deeply into the forest. The gradient for relative humidity increased from the edge and was steepest in mid-afternoon. Humidity effects sometimes extended >240 m into the forest. Short-wave radiation decreased rapidly with distance from the edge, reaching interior forest levels by 30–60 m. Wind speed decreased exponentially from the edge into the forest, depending on the relationship of edge orientation to wind direction; stronger winds influenced conditions deeper inside the forest, sometimes >240 m from the edge. Edge orientation played a critical role for all variables; for air and soil temperature and humidity, it affected the times of day at which maximum and minimum values peaked. Influence of local weather conditions on gradients was highly variable. Overall, however, gradients generally were longest and steepest on partially clear, warm, dry days, at southwest-facing edges, and for air temperature, soil temperature, and relative humidity. SEI and DEI were found to be necessary measurements for evaluating edge effects on microclimatic variables, which responded differently depending on time of day, edge orientation, and local weather. No single value could be calculated for DEI. Because many ecological features near edges, such as tree stocking and regeneration, dispersal of flying insects, and decomposition of woody debris, seem related to microclimatic gradients, forest management to protect interior conditions should shift from the traditional charge ("create as much edge as possible") to a new charge in which the amount of edge is reduced at both the stand and landscape levels.

Key words: clearcut; Douglas-fir; edge; edge effects; edge exposure; landscape; microclimate; old growth.

INTRODUCTION

Edges and edge effects in ecosystems at landscape scales have received increasing attention in ecology, conservation biology, and ecosystem management. Wildlife managers traditionally attempted to "develop as much edge as possible because wildlife is a product of the places where two habitats meet" (Yoakum and Dasmann 1969, Thomas et al. 1979). However, such ideas have been challenged as scientists and managers consider maintaining biological diversity across entire landscapes. Forest edges provide suitable habitat for some species, such as deer and elk (Alverson et al. 1988), but appear detrimental to species requiring in-

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terior forest environment. The northern spotted owl (*Strix occidentalis caurina*), for example, occupies interior habitat within late-successional forest in the Pacific Northwest region of the United States (Johnson 1991, Johnson et al. 1991), and it is becoming apparent that other threatened or endangered species have similar requirements.

Edges play a critical role in controlling ecosystem interactions and landscape function. Since the pioneering research of Aldo Leopold in 1933, many aspects of edges and edge effects have been studied, including the distribution of plant and animal species (Gysel 1951, Wales 1972, Gates and Gysel 1978, Morgan and Gates 1982, Yahner 1988), vegetation structure (Ranney et al. 1981, Williams-Linera 1990, Chen et al. 1992, Frost 1992, Hansen et al. 1993), wildlife habitat conservation (Thomas et al. 1979, Lovejoy et al. 1986, Harris 1988, Schonewald-Cox 1988, Fuller and Warren 1991, Lehmkuhl and Ruggiero 1991, Angelstam 1992), physical environments (Wales 1967, Fritschen et al. 1970, Raynor 1971, Chen 1991, Chen et al. 1993*b*), and unique functions of edges in a landscape (Forman and Godron 1986, Franklin and Forman 1987, di Castri et al. 1988, Holland et al. 1991, Laurance and Yensen 1991, Hansen and di Castri 1992).

Automated weather equipment provides a good opportunity for investigating the dynamics of microclimatic patterns but also highlights problems unique to using large databases. It took 5 yr for Raynor (1971) to collect 362 field observations in his study of wind profile near the forest edge. In contrast, our six mobile weather stations logged 48 observations per day for each of five variables over two growing seasons. However, the data require many megabytes of computer storage and encode information about complex relationships, processes, and patterns that is not easily analyzed, synthesized, or generalized. Although biometeorological study has a long history, little is known about how to summarize huge amounts of meteorological data into a format simplified for the biological sciences and appropriate to further statistical analyses and computer simulations. For example, determining how truly representative our three "typical" days were for an entire growing season would require further data analysis (e.g., quantitative correlation analysis) before drawing final conclusions.

Microclimatic gradients from edge into interior forest create edge effects and are of increasing interest to both ecologists and land managers for predicting rates of processes such as litter decomposition and understory development. They are also important for addressing management questions regarding habitat suitability for various plant and animal species in fragmented forest landscapes such as those found in the Pacific Northwest (e.g., Franklin and Forman 1987, Lehmkuhl and Ruggiero 1991, Lehmkuhl et al. 1991, Morrison et al. 1991). A previous study indicated that there were highly contrasting microclimates among clearcut, edge, and interior old-growth forest (Chen et al. 1993*b*). In this study, we examined microclimatic gradients associated with edges of old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests adjacent to recent clearcuts (15–20 yr) on the western slope of the Cascade Range in the Pacific Northwest. More specifically, we studied diurnal changes in air temperature (T_a), soil temperature (T_s), relative humidity (h), short-wave radiation (R_t), wind speed (v), and volumetric soil moisture (Ψ) from edge into forest interior, considering effects of edge orientation (θ) and local weather conditions, over two growing seasons (June–September, 1989 and 1990). Many of the data presented for T_a, T_s, and h are for three selected days representing typical summer conditions at different edge orientations (exposure).

Methods

Study sites

The study was conducted at two locations: the Trout Creek Hill area of the Wind River Experimental Forest (45°48′ N and 121°55′ W) on the Gifford Pinchot National Forest in southern Washington; and the H.J. Andrews Experimental Forest (44°14′ N and 122°11′ W) on the Willamette National Forest in central Oregon. Elevation of the study areas ranges from 400 to 1000 m. Topography is gentle (<10° slopes). The forests at these two locations, representative of the old-growth Douglas-fir forests of western Oregon and Washington, are characterized by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), Pacific yew (*Taxus brevifolia* Nutt.), and western redcedar (*Thuja plicata* Donn ex D. Don) as well as Douglas-fir (Franklin et al. 1981). The forests occupy sites of the *Tsuga heterophylla* and the lower *Abies amabilis* zones (Franklin and Dyrness 1973). Dominant trees are typically 50–65 m tall.

We selected for study 16 edges (13 at the Wind River site and 3 at the H.J. Andrews site) between old-growth Douglas-fir forest patches and 10- to 15-yr-old clearcuts. The clearcuts had subsequently been replanted with several conifer species including Douglas-fir, western hemlock, western redcedar, and noble fir (*Abies procera*). Planted seedlings were generally <2.0 m tall. Coverage and height of successional shrubs and herbaceous vegetation ranged 55–75% and 20–120 cm, respectively. Because a preliminary study (Chen et al. 1990) indicated that edge could influence microclimate to a depth of 240 m into the forest, selected forest patches exceeded 500 m in diameter. From the edge into the interior forest, there were reductions in stocking density, as measured by canopy cover, number of stems per hectare, and basal area. There were also more Douglas-fir and western hemlock seedlings and saplings but fewer Pacific silver fir within 100 m inside the edge (Chen et al. 1992).

Data collection

In 1989 at each site, mobile weather stations were independently installed along a single transect perpendicular to the edge at distances of 0, 30, 60, 120, 180, and 240 m from the edge into the interior forest. Locations with unusual structures (e.g., large fallen logs, canopy gaps) were avoided when setting up weather stations. Since the influences of edge on solar radiation and soil moisture are limited to a relatively short distance (<60 m, Chen et al. 1990), in 1990 a short transect (0–120 m) was also used for sampling soil temperature and solar radiation with weather stations at 0, 15, 30, 60, 90, and 120 m from the edge. At each of the six stations of all transects, T_a, h, R_t, and v were measured 2 m above the ground, and T_s was measured 10 cm into the soil. Measurements for each variable were recorded every 15 s and averaged for 30-min intervals. Stations remained at each site for a short period of time (3–14 d) until local weather conditions (e.g., cloudy, sunny) were sampled; then, were moved to another site to sample edges with different orientations. In total, data were collected for 134 d over the two growing seasons.

Soil moisture data were collected during a 3-d period (18–20 September 1990) of stable weather via Time Domain Reflectometry (TDR) at 10 of the 13 sites. TDR was used because it measures water content of a volume of soil rather than a single point, as is the case with other soil-moisture sensors (Topp et al. 1980). The electrode pairs were built using stainless steel rods 3.18 mm in diameter and 30 cm long. These rods were individually driven into the soil at a 30° angle to determine the soil water content of the top 15 cm; wood guides ensured that rods were parallel to another and separated by 5 cm. Field measurements were repeated at five randomly chosen places at distances of 0, 15, 30, 45, 60, 90, 120, 180, and 240 m from the edge.

Instruments used were: automatic recording datalogger (Model 21x Micrologger, Campbell Scientific, Inc. (CSI), Logan, Utah, USA), temperature sensors (Model 101 and 107 Temperature Probes, CSI), relative humidity sensors (Model 207 Phys-Chem Temperature and RH Probes, CSI), pyranometers (Model Li200s Silicon Pyranometers, LI-COR, Lincoln, Nebraska, USA), cup anemometer (Model 12102 Gill 3-cup Anemometer, R. M. Youngs, Michigan, USA), and TDR (TEKTRONIX, Chicago, Illinois, USA). The thermocouples (chromel–constantan for T_a and copper–constantan for T_s) were custom-built in the laboratory.

All sensors, except for thermocouples, were calibrated before and after each field measurement. Temperature sensors (thermistors) were calibrated in a constant temperature chamber with a copper–constantan thermocouple as the standard. Relative humidity sensors were calibrated with a recycling system using saturated salts (Fritschen and Gay 1979). Anemometers were calibrated against a reliable photochopper anemometer (Fritschen 1967) in a wind tunnel. Pyranometers were calibrated by the manufacturer immediately before the field season. The TDR calibration was developed using the same soil cored in PVC (polyvinyl chloride plastic) pipes (Gray and Spies, *unpublished manuscript*). Linear regression techniques were used to develop all calibration equations.

Data analysis

Diurnal changes in T_a, T_s, h, R_t, and v were examined as a function of distance (δ) from the edge into the forest, local time of day, edge orientation, and local weather conditions. First, we plotted diurnal changes in each of the five variables for the entire database (134 d). Because equipment limitations did not allow for simultaneous measurement of multiple edges, we subjectively chose three sunny and cloudy days in 1989 (12 and 27 July, 25 August) to illustrate typical diurnal patterns for T_a, T_s, and h; 12 July represents an east-facing edge (θ = 90°), 25 August a south-facing edge (θ = 180°), and 27 July a west-facing edge (θ = 270°). Selections of these three days were based on findings from a previous study (Chen et al. 1993*b*) that clear edge effects will be detected.

Next, because our primary objective was to study microclimatic change along the transects, we calculated the relative values (ΔX_i) of T_a, T_s, and h as:

$$\Delta X_i = X_i - X_{240}$$

where X_i is the microclimatic value at a specific station i metres from the edge, X_{240} the value 240 m from the edge. The major reason for using relative values is because the primary goal of this study was to examine gradual changes from the edge into the forest rather than absolute values which have been reported previously (Chen et al. 1993*b*). Because values for R_t and v inside the forest were very low and highly variable, we used actual, rather than relative, values.

Then, we determined peak times of the day for differences in ΔT_a, ΔT_s, and Δh (i.e., when differences were maximal and minimal) and examined relationships between peak-difference times and edge orientation using nonlinear regression techniques. Chen (1991) found the most extreme differences to depend on θ. Microclimatic gradients during peak hours were evaluated over the 134-d sampling period for all edge orientations combined and for south-facing edges as a function of local weather condition. An F test (α = 0.05) was performed to test changes in soil moisture from the edge into the forest.

Finally, we evaluated edge effects on each microclimatic variable by two indices: significance of edge influence (SEI) and depth of edge influence (DEI). SEI reflects differences between edge and interior forest (i.e., ΔX_0); DEI, also known as edge width (Leopold 1933, Forman and Godron 1986), reflects how far into the forest edge effects extend. Decisions regarding the limit of DEI are arbitrary (Chen et al. 1992). We sub-

TABLE 1. Daily statistics for air temperature (T_a), soil temperature (T_s), and relative humidity (h) as a function of local weather conditions on three typical days in 1989 at three edge orientations (θ) relative to compass north along gradients from the edge into interior old-growth Douglas-fir forest.

Variable	12 July, 90°θ	27 July, 180°θ	25 Aug., 270°θ
T_a (°C)			
Max	28.6	20.7	24.9
Min	10.0	13.9	5.8
Mean	20.0	16.1	14.6
Difference	18.6	4.6	19.1
T_s (°C)			
Max	24.5	21.7	19.4
Min	17.4	17.5	12.7
Mean	20.9	19.3	15.9
Difference	7.1	4.2	6.7
h (%)			
Max	85.2	82.0	81.1
Min	34.2	43.9	31.2
Mean	60.4	64.3	67.3
Difference	51.0	38.1	49.9

jectively estimated DEI based on scatter plots of microclimatic variables with distance from the edge into the forest.

Correlation analysis was performed to examine the relationships between SEI for T_a, T_s, and h, as measured by daily averages, maximums, minimums, and differences (i.e., local weather conditions).

RESULTS

The three days used to illustrate typical diurnal patterns for T_a, T_s, and h at east-, south-, and west-facing edges were strongly representative of growing-season microclimate in the study area (Table 1, Fig. 1).

Air temperature

Relative air temperatures were maximum at the edge (SEI = 5.43, 4.8, and 4.43°C for the three typical days) and declined from the edge into old-growth Douglas-fir forest (Fig. 2). During the day, ΔT_a decreased from the edge into the forest, and DEI varied from 0 to >180 m depending on time of day. At night, ΔT_a decreased or slightly increased, and DEI was less than during the day (<60 m). The shift between day and night patterns provided two periods (mid-morning and late afternoon) during which air-temperature gradients were flat. The rough graph surface formed near the edge indicates higher variability in ΔT_a there, compared to relatively stable conditions inside the forest. For the rest of the sampling period, diurnal patterns of ΔT_a (Fig. 1) were similar to those in Fig. 2; maximum ΔT_a at the edge ranged from 1.3 to 7.8°C during the day and 0.5 to 4.9°C at night, and DEI varied from 30 to >240 m.

Diurnal gradients of ΔT_a were influenced by edge orientation for the three typical days. At the east-facing edge, ΔT_a peaked in the early morning (Fig. 2a). At the south-facing edge, it peaked around noon, the peak

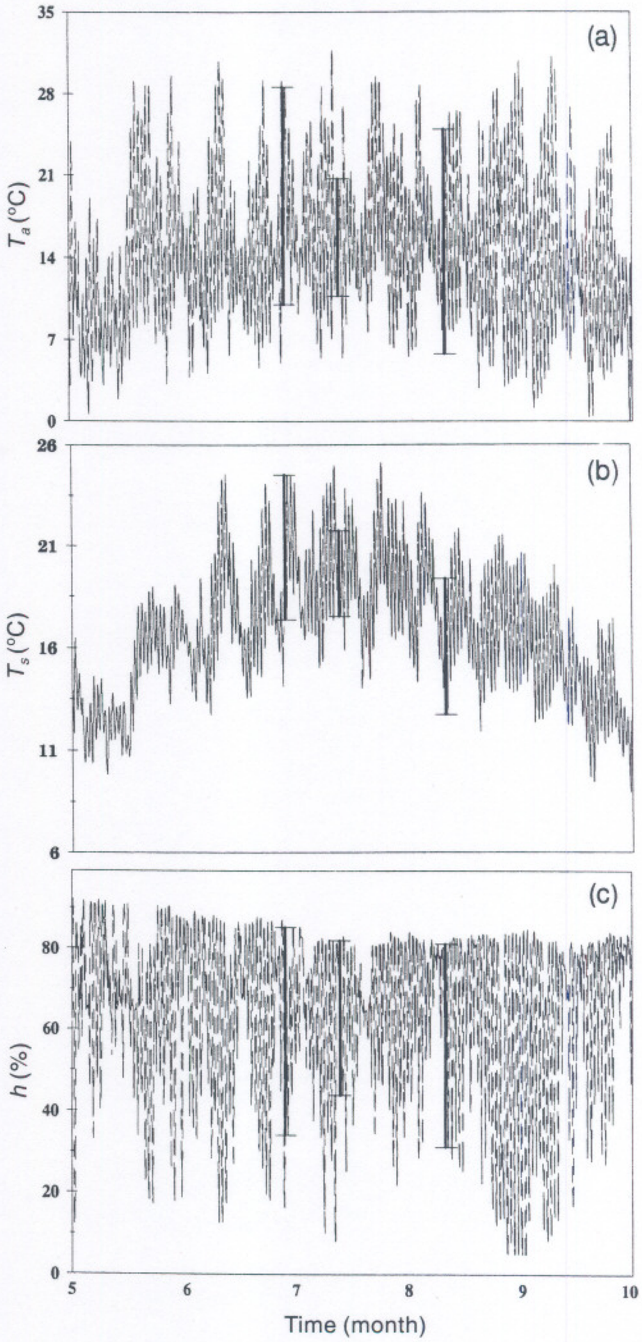

FIG. 1. Changes in (a) air temperature (T_a), (b) soil temperature (T_s), and (c) humidity (h) at the Wind River Experimental Forest during the 1989 growing season (15 May–15 October). Vertical bars indicate the range for each of the three days (12 and 27 July, 25 August) used to illustrate typical microclimatic gradients from edge into interior forest.

broader (Fig. 2b) than those at west- and east-facing edges. At the west-facing edge, ΔT_a was small in the morning, peaking in the late afternoon (Fig. 2c). The hours of the day at which differences in ΔT_a peaked clearly were related to edge orientation and were similar for the three typical days and the rest of the sampling period over all orientations. Values were maximum between 1000 and 1600, minimum between 0400 and 0500 (Fig. 3a, b).

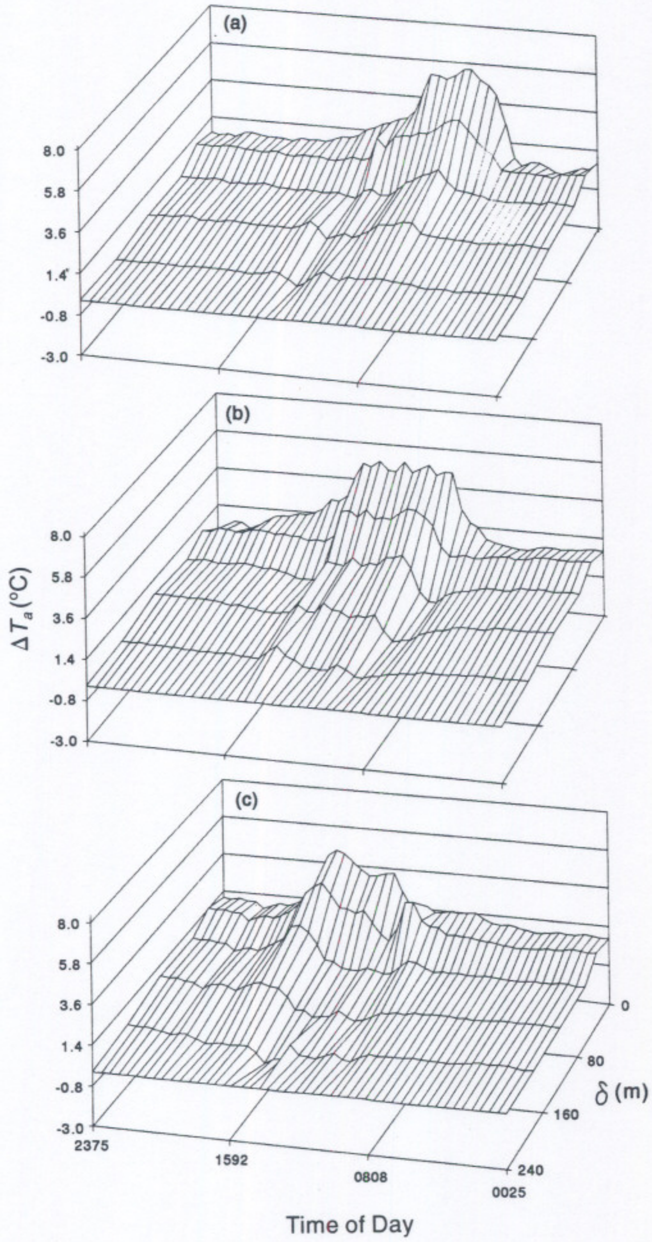

FIG. 2. Diurnal changes in relative air temperatures (ΔT_a) with distance (δ) from the edge (0 m) into old-growth Douglas-fir forest at (a) an east-facing edge on 12 July 1989, (b) a south-facing edge on 25 August 1989, and (c) a west-facing edge on 27 July 1989.

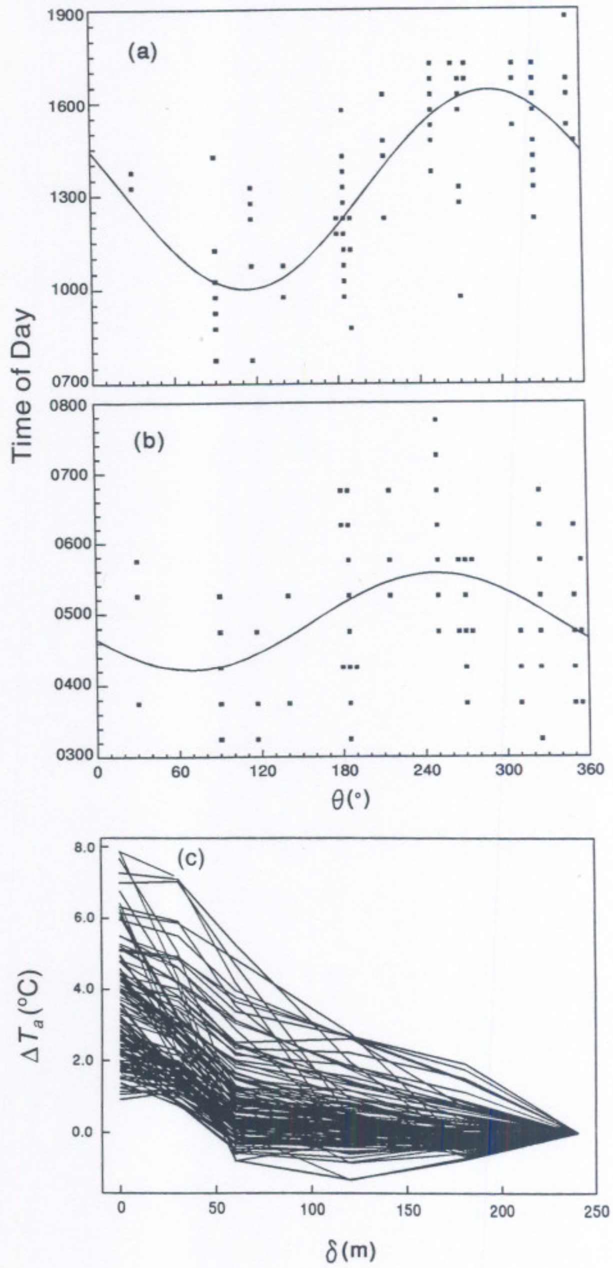

FIG. 3. Influence of edge orientation (θ) on the times at which (a) maximum and (b) minimum relative air temperatures (ΔT_a) peaked between the clearcut edge (0 m) and interior Douglas-fir forest (240 m) during the 134-d sampling period, and (c) 30-min average gradients of ΔT_a with distance (δ) from the edge into the forest near south-facing edges during peak times of day for maximum values (1000–1400).

Influences of local weather conditions were apparent. Overall, changes in ΔT_a, as indexed by SEI and DEI over 134 d, were much greater when weather shifted rapidly from, for example, sunny to cloudy. For south-facing edges, ΔT_a values were maximum between 1000 and 1400 and varied greatly. During the entire sampling period, SEI near south-facing edges ranged from 0.52 to 7.88°C; on most days, DEI ranged from 60 to 120 m but occasionally exceeded 240 m (Fig. 3c). Correlation analysis indicates that edges affected ΔT_a; that is, high SEI and DEI were positively related to higher daily maximums, minimums, and differences.

Soil temperature

Diurnal changes in ΔT_s from the edge into interior forest were similar to those of relative air temperature (Fig. 4). Values were maximum at the edge (SEI = 6.75, 15.11, and 9.27°C for the three typical days). During the day, SEI of ΔT_s was greater than that of ΔT_a over the same period. DEI varied during the day and was less (<60 m). At night, SEI and DEI were usually less than during the day. The smoother graph surfaces near the edge suggest less variability there

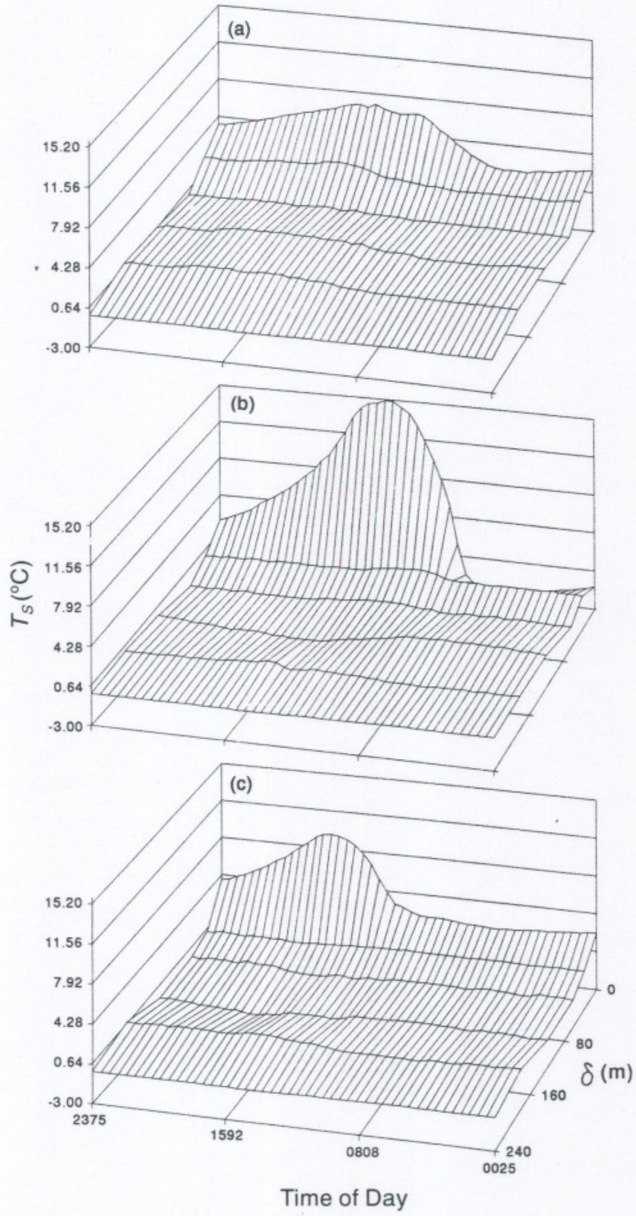

FIG. 4. Diurnal changes in relative soil temperatures (ΔT_s) with distance (δ) from the clearcut edge (0 m) into old-growth Douglas-fir forest at (a) an east-facing edge on 12 July 1989, (b) a south-facing edge on 25 August 1989, and (c) a west-facing edge on 27 July 1989.

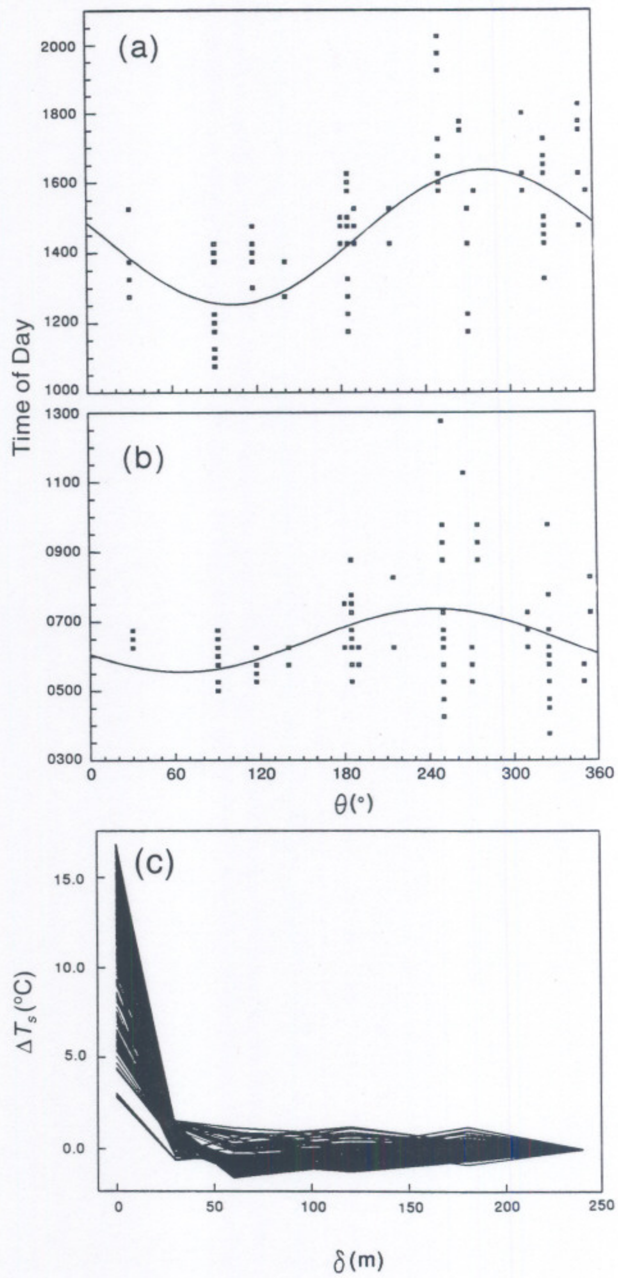

FIG. 5. Influence of edge orientation (θ) on the times at which (a) maximum and (b) minimum relative soil temperatures (ΔT_s) peaked between the clearcut edge (0 m) and interior forest (240 m) during the 134-d sampling period, and (c) 30-min average gradients of ΔT_s with distance (δ) from the edge into the forest near south-facing edges during peak times of day for maximum values (1200–1600).

than for ΔT_a. For the rest of the sampling period, diurnal patterns of ΔT_s (see Fig. 1) were similar to those in Fig. 4; maximum ΔT_s at the edge ranged from 1.66 to 15.52°C during the day and −1.5 to 4.35°C at night, and DEI varied from 15–120 m.

Diurnal gradients of ΔT_s were influenced by edge orientation for the three typical days (Fig. 4a–c). Mean differences between maximums and minimums were larger than those for ΔT_a, but variation was high. Peak times of day clearly were related to edge orientation and were similar for the three typical days and the rest of the sampling period. Values were maximum between 1200 and 1600, minimum between 0500 and 0700 (Fig. 5a, b).

Influences of local weather conditions were clear for SEI (Fig. 5a, b) but less apparent for DEI (Figs. 3c, 5c). For south-facing edges, ΔT_s values were maximum between 1200 and 1400 and varied less than those for ΔT_a (Fig. 5c). During the entire sampling period near south-facing edges, SEI ranged from 4.98 to 15.55°C, and DEI was limited to within 60 m of the edge (Fig. 5c). Correlation analysis indicates that edge effects on ΔT_s were weak compared with those on ΔT_a.

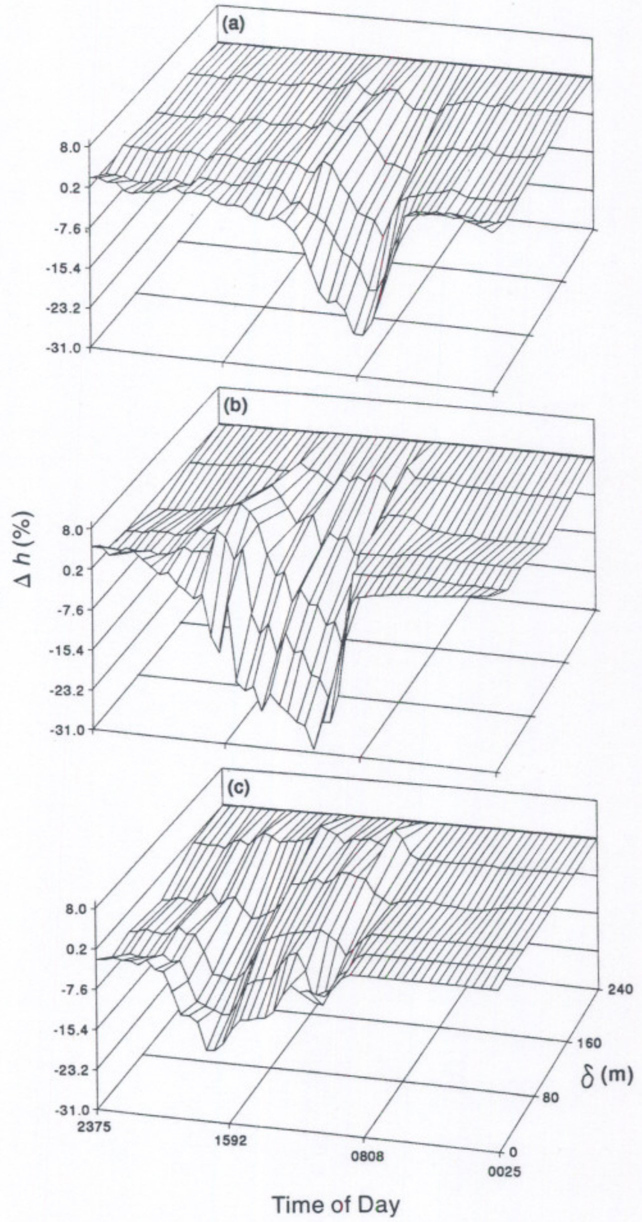

FIG. 6. Diurnal changes in relative humidities (Δh) with distance (δ) from the edge (0 m) into old-growth Douglas-fir forest at (a) an east-facing edge on 12 July 1989, (b) a south-facing edge on 25 August 1989, and (c) a west-facing edge on 27 July 1989.

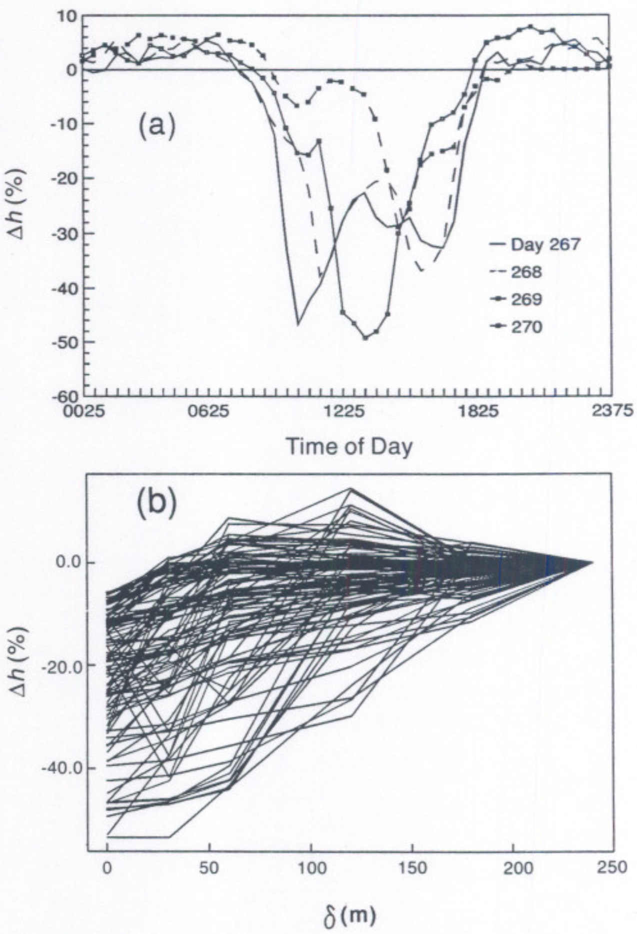

FIG. 7. Variation in diurnal changes in relative humidity, Δh (a) at a south-facing edge of a clearcut on four continuous days, and (b) 30-min average gradients with distance (δ) from the edge into the forest near south-facing edges during peak times of day for maximum values (0900–1600).

Relative humidity

Diurnal changes in Δh created a U-shaped pattern for the three typical days (Fig. 6). Values were maximum at the edge (SEI = 23.0, 30.4, and 17.1%). Edge effects occurred primarily during the day; DEI ranged from 30 to 240 m, depending on time of day and SEI. At night, when the air tended to be saturated, relative humidity was near 100%, producing a relatively flat graph surface from the edge into the forest. The maximum SEI could be as high as 60%.

Diurnal gradients of Δh were influenced by edge orientation for the three typical days. Increasing Δh from the edge into the forest began near the east-facing edge, then the south-facing edge, finally the west-facing edge (Fig. 6a–c, respectively). Unlike the diurnal patterns for ΔT_a and ΔT_s, Δh had twin troughs near the edge (Fig. 7a), one in late morning and the other in mid-afternoon, a phenomenon observed for many sampling days.

Influences of local weather conditions were apparent. For south-facing edges, Δh values were maximum between 0900 and 1600 and varied considerably (Fig. 7b). For most sampling days, SEI near south-facing edges ranged from 5.7 to 53.3%; DEI extended 120 m into the forest but could exceed 240 m. Correlation analysis suggests that edge effects were weakest (i.e., SEI and DEI were lowest) under cloudy and/or rainy conditions and strongest on partially clear, hot days.

Short-wave radiation

Total flux of short-wave radiation was significantly higher at the edge, rapidly decreasing within 30 to 60 m inside the forest, and varied in intensity and diurnal pattern as a function of edge orientation up to 60 m inside (Fig. 8a, b). Regardless of edge orientation, R_t

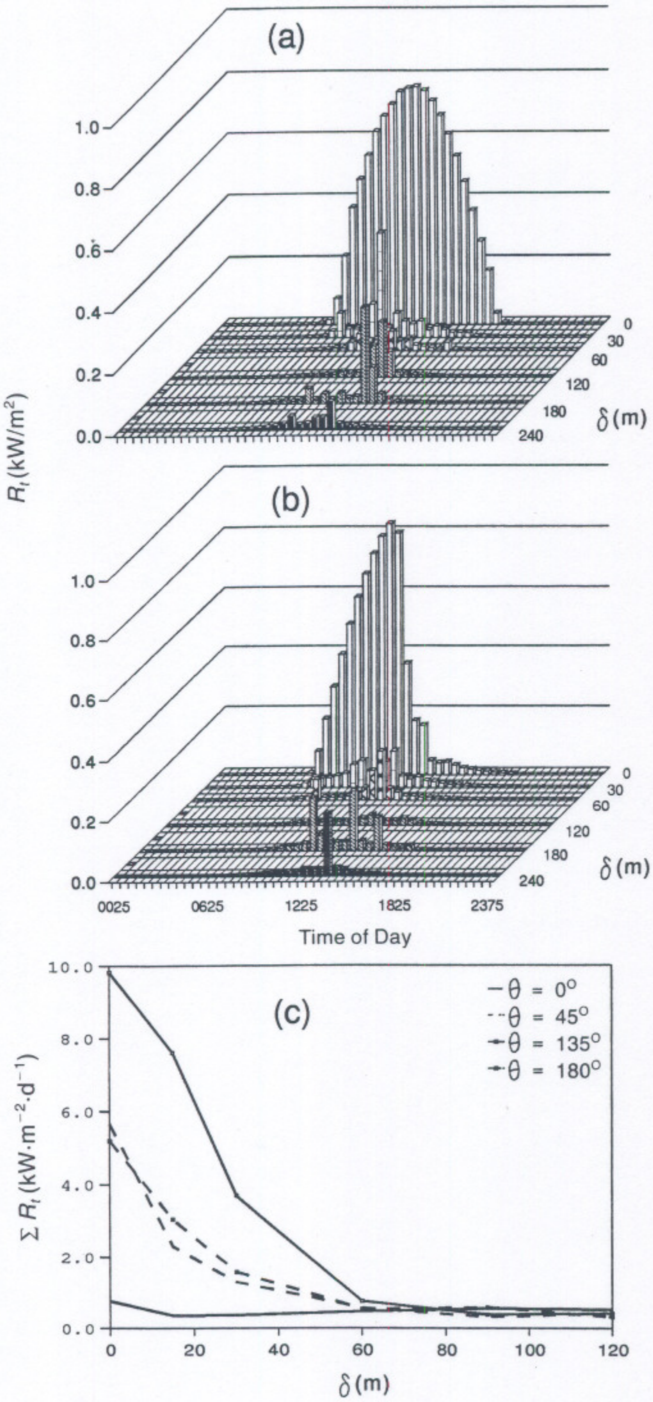

FIG. 8. Diurnal changes in total flux of short-wave radiation (R_t) with distance (δ) from the edge of a clearcut into old-growth Douglas-fir forest at (a) a south-facing and (b) an east-facing edge, and (c) daily accumulative radiation (Σ R_t) near four contrasting edges.

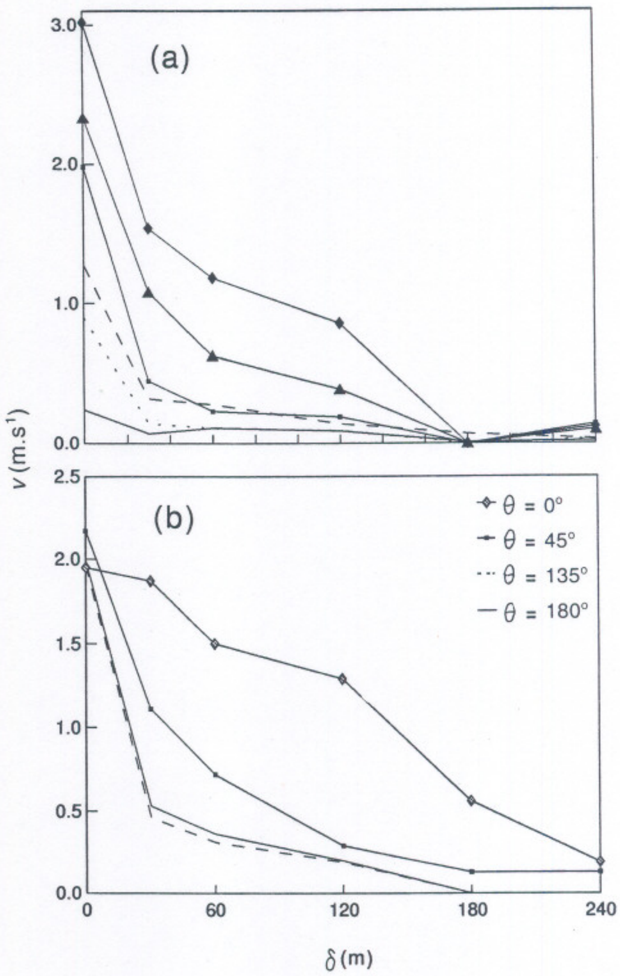

FIG. 9. Changes in wind speed (v) with distance (δ) from the edge into old-growth Douglas-fir forest as influenced by (a) external wind speed and (b) wind direction relative to the edge.

inside the forest was <15% of that at the edge at midday. R_t changed erratically over the day, the changes fundamentally associated with canopy structure; within <1 h, R_t could be very high or even the same inside as outside the forest. Daily accumulative solar radiation (i.e., flux density) decreased from the edge into the forest near four contrasting edges (Fig. 8c). DEI varied greatly among the edges, from <20 m at a north-facing edge to 60 m at a south-facing edge.

Wind speed

Wind speed from the edge into the forest decreased exponentially and was influenced by two other variables: external wind speed (i.e., wind speed in the clearcut) and wind direction (i.e., whether wind blows into, out of, or parallel to the forest) (Fig. 9). The magnitude of edge effects, as indexed by SEI and DEI, increased with external wind speed. For example, if external wind speed was 2–3 m/s, DEI could be as great as 180 m even with wind blowing out of the forest; however, if it was <1 m/s, DEI was limited to ≤30 m (Fig. 9a).

Wind direction and edge orientation influenced wind-speed gradients. For wind blowing into the forest at an external wind speed of 2 m/s (i.e., at edge), edge effects could extend >240 m into the forest; for wind blowing out of or parallel to the forest at the same speed (2 m/s), DEI was limited to 180 m (Fig. 9b).

TABLE 2. Changes in volumetric soil moisture with distance from the edge into old-growth Douglas-fir forest over three consecutive days in September 1990 (N = 50; 10 edges with edge orientations of 90–335°).

Distance from edge (m)	Soil moisture (%)			
	Mean	SE	Max	Min
0	17.3	0.5	31.6	12.1
15	16.1	0.3	23.8	11.3
30	16.4	0.3	20.5	12.0
45	15.4	0.2	19.2	11.9
60	16.4	0.3	23.6	11.1
90	15.3	0.2	18.7	11.3
120	14.7	0.2	18.3	12.1
180	16.3	0.3	22.0	8.0
240	16.1	0.2	19.3	13.3

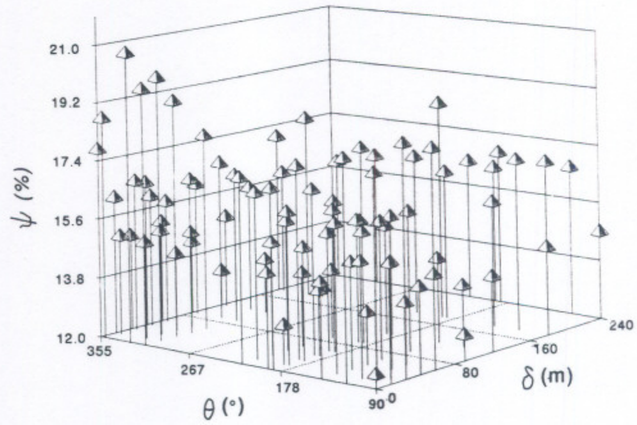

FIG. 10. Changes in volumetric soil moisture (Ψ) with edge orientation (θ) and distance (δ) from the edge into old-growth Douglas-fir forest sampled over three consecutive days in September 1990.

Soil moisture

Mean Ψ values measured from 10 edges over 3 d in 1990 did not significantly differ (α = 0.033, F test, N = 50; Table 2) from the edge into the forest. However, variability was high near the edge, stabilizing ≈15 m from it. Soil moisture was maximum at a north-facing edge (θ = 0°), minimum 60 m from a southwest-facing edge (θ = 140° from compass north).

For edges facing 90° to 220° from north, soil moisture was lower near the edge than inside the forest (Fig. 10). At south-facing edges, this low level persisted for 90 m into the forest; at all other edge orientations, soil moisture was slightly higher than or the same as that inside the forest.

DISCUSSION

Clearcut edges affected all six microclimatic variables along gradients into interior old-growth Douglas-fir forest. However, edge effects, as indexed by SEI and DEI, were highly dependent on the variable of interest. For example, DEI for T_a, T_s, h, R_t, v, and ψ ranged, respectively, from 180 to 240, 60 to 120, >240, 15 to 60, >240, and 0 to 90 m from the edge into the forest. Clearly, there is no single answer to the question, "How wide is the area influenced by edge?"

Our study demonstrates the importance of edge orientation and time of day to these microclimatic gradients. Edge orientation has generally been ignored in studies on microclimate (e.g., Williams-Linera 1990), and microclimatic variables in edge studies typically have been measured only once a day because of the expense of meteorological instruments. Yet our findings and a previous modeling exercise (Chen et al. 1993*a*) show that, at these latitudes, edge effects are strongest at southwest-facing edges and weakest at northeast-facing edges. This conclusion is logical: the time of day when a southwest-facing edge receives direct solar radiation (the early afternoon) is the time when local daily temperatures and moisture reach their upper extremes. Clearly, measurements should be taken at various edge orientations and over the course of the day to avoid biased conclusions.

Local weather conditions were also found to influence edge effects, although the values were highly variable and correlations therefore weak. Edge effects were greater (i.e., SEI and DEI were higher) under partially clear, hot, and windy weather conditions. However, further studies are needed to examine and quantify these relationships.

Generally, areas near edges receive more direct and diffuse solar radiation during the day and lose higher amounts of outgoing long-wave radiation at night (Geiger 1965, Ranney 1977). Inside the forest, the tall, deep canopies intercept both incoming solar and outgoing long-wave radiation (Gates 1965, Reifsnyder et al. 1971, Satterlund and Means 1978, Miller 1980). Differences in the amount of incoming and outgoing radiation cause temperature and moisture differences between the edge and interior forest, and the resultant heat exchange produces temperature and moisture gradients there, primarily through wind or turbulence (Miller et al. 1991). Such gradients have been observed in many other studies of forest edges (Aslyng 1958, Woodruff et al. 1959, Wales 1967, Raynor 1971, Chen et al. 1990, Williams-Linera 1990).

Wind is an important physical variable in studying edge effects because it significantly influences other physical (e.g., evapotranspiration) and biological (e.g., seed dispersal and pathway of flying insects) processes (Geiger 1965, Yoshino 1975, Lee 1978). It drives air circulation, which controls the balance between energy (heat) and materials (e.g., vapor) between the edge and interior forest (Lowry 1967, Rosenberg 1974). Results from various studies indicate that wind speed (1) generally is higher during the day than at night, though diurnal patterns are variable (Yoshino 1975), and (2) decreases from the edge into the forest (Geiger 1965) as a function of stand density, physical characteristics of the forest, wind direction, and external wind speed

(Fritschen et al. 1970, Raynor 1971, Kinerson and Fritschen 1973, Miller et al. 1991). Inside the forest, wind speed is largely a function of forest type and structure (Fons 1940) and, to a lesser extent, external wind speed (Allen 1968, Meroney 1968, Fritschen et al. 1970, Raynor 1971).

Reported DEI values for wind are highly variable. A DEI rule of two to three tree heights has been documented for wind speed (Reifsnyder 1955, Food and Agriculture Organization of the United Nations 1962, Fritschen et al. 1970) and used widely in other related studies (Franklin and Forman 1987, Morrison 1990, Ripple et al. 1991, Groom and Schumaker 1993). Larger values, however, also have been reported. Nageli (1953) claimed that wind velocity reached an equilibrium value at a distance of 8.5× tree height inside the forest; Raynor (1971) suggested 6× tree height. In a theoretical study using a plastic model forest in a wind tunnel, Meroney (1968) suggested 15× to 20× tree height. Recently, in a series of empirical and theoretical simulation studies, Miller and colleagues (Miller 1980, Miller et al. 1991) suggested 6–12× tree height. On the basis of these studies and our data (Fig. 9), it appears that maximum DEI is probably >5–6 tree heights with wind blowing into an old-growth Douglas-fir forest.

DEI for wind speed is highly related to vegetation type, understory structure (Reifsnyder 1955, Raynor 1971), and stand density. At the edge, most wind enters through the trunk region, only a small part flowing over the canopy (Reifsnyder 1955). Therefore, wind may penetrate only a short distance into the forest where canopy is continuous and understory dense (e.g., Reifsnyder 1955, Fritschen et al. 1970) but deep into the forest where tree branches are high and understory is sparse (e.g., Nageli 1953, Meroney 1968). Because old-growth Douglas-fir forest stands have low stem densities near clearcut edges (Chen et al. 1992) and considerable space between tree trunks, wind can be expected to penetrate deeply. In our study, with a moderate external wind speed of 2 m/s, wind reached equilibrium 240 m into the forest (Fig. 9). Results reported by Raynor (1971) and Nageli (1953) probably are appropriate for this forest. On the basis of their tree-height recommendations, DEI for wind speed may range from 330 to 510 m into the forest.

Relative wind-speed gradients (percentage of wind in the forest compared to that in the open) have been widely used (Geiger 1965, Raynor 1971, Yoshino 1975). However, this approach is problematical if absolute wind speed is not considered along with edge orientation and wind direction. In our study, with a light wind, DEI was limited to 30 m from the edge; but with a stronger wind, it might reach 240 m (Fig. 9). Use of relative values to characterize wind gradients near the edge will scale off this important feature and produce a biased conclusion.

As wind blows into or out of the forest, differences in energy and materials between the edge and interior will be reduced. Where DEI values for wind speed are large, so likely are those for air temperature and humidity. Our results show that DEI can be close to 240 m for T_a and >240 m for h. Since h is a function of T_a and is strongly influenced by v, DEI for h would be relatively larger than that of T_a. If strong winds penetrate deep (330–480 m) inside the forest, DEI for h also probably approximates those values. Obviously, under some weather conditions, equilibrium values for T_a and h are not achieved 240 m from the edge.

Many ecological features near clearcut edges seem related to microclimatic gradients. Increases in Pacific silver fir and declines in Douglas-fir and western hemlock seedlings and saplings from the edge into the forest, as well as decreased growth rates of Douglas-fir and western hemlock (Chen et al. 1992), are likely related to the gradients of solar radiation, temperature, and moisture from the edge into the forest. Other features include higher incidence of windthrow and dead wood caused by strong winds and environmental stress (Ruth and Yoder 1953, Chen et al. 1992), and different understory species composition and structure (Frost 1992).

Migration and dispersal of flying insects are significantly influenced by wind speed, temperature, humidity, and solar radiation (Johnson 1969). Wind strongly affects the flight of insects, depending on their size; smaller insects, for example, are sensitive to very light wind (e.g., 0.4 m/s). Air temperature, humidity, and light also influence wing beating for taking off and flying speed. The speed of the Douglas-fir beetle (*Dendroctonus pseudotsuga*) seems to be determined largely by wing-beat frequency, which is affected by air temperature and moisture (Atkins 1960). We suggest that dispersal of some flying insects follows microclimatic gradients that may extend >240 m from the edge into the forest.

Decomposition rates of fine litter and coarse woody debris near edges are influenced primarily by soil moisture and temperature (Harmon et al. 1986). Edmonds and Bigger (1984) found that litter decomposition rates were higher near edges than inside the forest and adjacent clearcut. We also found (J. Chen et al., *personal observations*) the depth of the organic layer to be much lower within 30 m of a southeast-facing edge than in interior Douglas-fir forest. These findings suggest gradients in decomposition processes of organic matter from the edge into the forest.

Traditionally, management of forest edges has mainly focused on wildlife (e.g., game species) habitat and biological diversity (Thomas et al. 1979, Rosenberg and Raphael 1986, Angelstam 1992, Lehmkuhl and Ruggiero 1991). However, because certain plants and animals are either interior species or need interior habitat, that view (i.e., creating as much edge as possible) needs to be reexamined. Given a 400-m DEI, there is probably too much area influenced by edge for an old-growth forest environment to be retained in a fragmented forest landscape such as that of the Pacific Northwest (Franklin and Forman 1987, Morrison et al. 1991, Groom and Schumaker 1993). Therefore, to maintain the biological diversity of old-growth forest, future management must shift from the traditional charge ("create as much edge as possible") to a new charge in which the amount of edge (length) is limited and the depth of edge influence (i.e., edge width) reduced at both stand and landscape levels.

Possible stand-level approaches include:

1) Creating a feathered edge instead of a high-contrast edge, and protecting forest structures (mainly understories including small trees and advanced regeneration) near the edge by limiting logging damage and forbidding salvage cutting. Forests with feathered edges and dense understories have higher resistance to many physical and biological variables (e.g., wind, moisture, heat, animals). Moreover, edge width will be narrower, ensuring more interior forest (Chen 1991);

2) Practicing partial cutting instead of clearcutting. Leaving a certain number of green trees in the cutover area, especially near the edge, may moderate the environment such that the differential between open area and interior forest is reduced (Ghuman and Lal 1987, Franklin 1992). As with the feathered edge, edge width would be narrower;

3) Planting and accelerating the growth of new trees in the cutover area. As secondary forest develops, the edge between cutover and original old-growth forest will gradually disappear (Oliver and Larson 1990).

Possible landscape-level approaches include:

1) Retaining larger forest patches. If DEI is large (e.g., 400 m), any forest patch <64 ha will be "all edge." Traditional practice is to cut 10- to 25-ha patches across the landscape, creating a patchwork of clearcuts and forest; but after 50% of the landscape is cut over, no interior forest environment remains (Franklin and Forman 1987);

2) Aggregating harvest. For a given amount of forest area, one large forest patch has far less edge than many smaller patches. One trade-off, however, is that the large cutovers that result from aggregation may have extremely harsh environments (Swanson et al. 1992);

3) Maintaining a circular or square patch shape, which has the least perimeter, instead of irregular shapes such as corridors and stars, thereby reducing the amount of edge (Laurance and Yensen 1991).

Conclusions

1) SEI and DEI are two indices of evaluating edge effects on microclimatic variables because they provide information about the magnitude and scale of edge effects on a given variable. It is clear that edge effects should be evaluated by both indices. Higher values of SEI and DEI surely indicate stronger edge effects. Cases can become more complicated, however, when SEI and DEI values diverge (e.g., high SEI and low DEI, as in Figs. 3c, 5c, and 7b).

2) Edge effects on microclimatic gradients, as indexed by SEI and DEI, are highly dependent on the variable of interest, time of day, edge orientation, and local weather. No single value can be calculated for edge width (i.e., DEI). Wind speed and relative humidity showed stronger responses to clearcut edges (DEIs of 180–480 m) than did the other four variables. Overall, edge effects on microclimate were strongest near southwest-facing edges under hot, partially clear to clear, windy conditions in the early afternoon.

3) We examined microclimatic gradients at individual edges and fine temporal scales (30 min to 24 h). To further understanding of edge dynamics and aid forest-management decision making, researchers need to examine the influences of edges at greater spatial (e.g., patch, landscape) and temporal (e.g., season) scales.

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