Agricultural and Forest Meteorology, 63 (1993) 219–237
Elsevier Science Publishers B.V., Amsterdam

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Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest

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(Received 1 April 1992; revision accepted 18 September 1992)

ABSTRACT

Chen, J., Franklin, J.F. and Spies, T.A., 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agric. For. Meteorol., 63: 219–237.

Clearcut, remnant old-growth forest patch, and edge are the three primary landscape elements in northwestern North America. Microclimatic information on this forest landscape is needed for both research and resources management purposes. In this paper, seasonal summaries and diurnal changes in air temperature and moisture, soil temperature and moisture, short-wave radiation, and wind velocity are quantified for recent clearcut (10–15 years old), edge, and adjacent interior old-growth Douglas-fir forest environments in southern Washington state, USA, over two growing seasons. Influences of local weather condition and edge orientation (relationship of edge to the azimuth) are also assessed. Over the growing season, daily averages of air and soil temperatures, wind velocity, and short-wave radiation are consistently lower, and soil and air moisture are higher, inside the forest than in the clearcut or at the edge. Daily differences (i.e. maximums minus minimums) of all variables are consistently lower in the forest. The microclimates at the edge and the clearcut show a variable relationship with regard to averages and differences. Between the edge and the forest, greater differences occur under clear sky conditions for air temperature, but under partial cloudy conditions for relative humidity and soil temperature. Edge orientation is critical in assessing solar radiation, soil moisture, and relative humidity. The highest variability in microclimate exists at the edge, rather than in either clearcut or interior forest, primarily because of the influences related to edge orientation. The supposition that edge microclimates are intermediate between clearcut and interior forest is consistently true only for wind velocity and solar radiation, not for temperature and moisture.

INTRODUCTION

The extensive contiguous old-growth coniferous forests that once dominated the landscape of the Pacific Northwest have been transformed into a mosaic of remnant forest patches surrounded by clearcuts (Harris, 1984; Franklin

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0168-1923/93/$06.00

and Forman, 1987; Lehmkuhl and Ruggiero, 1991; Morrison et al., 1991). Only about 10% of the original forest remains.

Large amounts of area subject to edge influences have been created during this process of regional forest fragmentation. Edges and adjacent areas provide ecological conditions that contrast markedly with general conditions within the central portions of clearcut or forest patches. For example, edges impact ecosystem structure and productivity (Chen et al., 1992), understory species (Frost, 1992), wildlife habitat, composition and distribution (Thomas et al., 1979; Hansen and Horvah, 1990), and microclimatic conditions (Fritschen et al., 1970; Chen, 1991).

In effect, in many forested regions, including the Pacific Northwest, forest fragmentation has produced a landscape in which edges are a dominant feature and most forested tracts are subject to extensive edge influences (Chen, 1991). Indeed, theoretical models of dispersed forest clearcutting (Franklin and Forman, 1987) indicate that all interior forest habitat (areas free of edge influences) may be lost with as much as 50% of the original forest remaining. It is increasingly clear that a better understanding of edge effects is essential for both research on and management of forest resources (Franklin and Forman, 1987; Morrison, 1990; Ripple et al., 1991).

High-contrast edges between forest and cutover greatly influence physical conditions and biological processes. Both the composition of organisms and ecosystem processes are dramatically altered. For example, many wildlife species respond positively to edges while many others, which require protected forest conditions, are negatively impacted (Thomas et al., 1979; Yahner, 1988; Hunter, 1990; Hansen and Horvah, 1990). These responses relate to a variety of factors including microclimate, predation, and food resources. Regeneration and growth of plants is also affected (Frost, 1992; Chen et al., 1992) as is tree mortality (Ruth and Yoder, 1953; Gratkowski, 1956). Ecosystem processes, such as productivity and decomposition, are profoundly influenced by edges.

Microclimatic conditions in edge environments are critical to understanding and predicting biological responses. Microclimatic parameters, such as moisture, temperature, and solar radiation, drive biological processes and control the distribution of organisms (Geiger, 1965; Whittaker, 1975; Zobel et al., 1976; Waring and Schlesinger, 1985; Szujecki, 1987; Chapin et al., 1987). Soil moisture and temperature largely control decomposition rates (Edmonds, 1980; Edmonds and Bigger, 1984; Moore, 1986). Solar radiation directly controls rates of photosynthesis and, indirectly, development of understory vegetation.

Unfortunately, despite their importance, microclimatic conditions and their temporal dynamics at forest edges have been the subject of very few studies. Except for some European studies early in the 20th century (Ranney, 1977) no systematic studies of microclimates at and near forest cutover edges have been undertaken. Fragmentary data do exist in a variety of sources, however (Kittredge, 1948; Geiger, 1965; Wales, 1967; Raynor, 1971; Lee, 1978; Ghuman and Lal, 1987; Hugerford and Babbitt, 1987; Williams-Linera, 1990). Recent concerns about edges and their effect on ecosystem and landscape functions (Forman and Godron, 1986; Gosz, 1992)—including impacts on forest productivity, wildlife, and biological diversity—make microclimatic quantification of edges and adjacent clearcut and forest ecosystems increasingly important.

In this paper we report on the growing season microclimates of recent clearcut, edge, and interior old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest in the Pacific Northwest. Specifically, we investigated the relationships of daily averages and differences of air and soil temperature, relative humidity, vapor pressure deficit, soil moisture, wind velocity, and short-wave radiation in the clearcut, edge, and interior forest based on field measurements during the growing season; we explored and discussed their diurnal patterns among these three locations; and we studied the influences of edge orientation on the diurnal changes in solar radiation and relative humidity as well as soil moisture. The ultimate goal was to provide general information on microclimates among the clearcut, edge, and interior forest in order to assist in interpretation and prediction of biological phenomena associated with old-growth forest edges and improve current management practices in these forest landscapes.

METHODS

The study was conducted in 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. Elevation of the study area ranges from 400 to 750 m, and topography is gentle (< 10°). Vegetation is intermediate between the *Tsuga heterophylla* and lower *Abies amabilis* zones (Franklin and Dyrness, 1973). Portions of the forest, 450 year-old-growth Douglas-fir western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), were clearcut 10–15 years ago. The clearcuts were subsequently replanted with several conifer species. Conditions within old-growth forests are described by DeBell and Franklin (1987); dominant trees within forest patches are typically 55–65 m tall. Thirteen study sites including clearcuts, edge, and interior forest environments were used in this study. Some edges utilized a common clearcut.

Weather stations were independently installed at three locations on each site: the center of the clearcut, at the forest edge, and in the interior of the forest patch (i.e. at least 250 m from any edge), on the assumption that this is a sufficient distance to provide interior forest conditions (Chen, 1991). At each location, air temperature, relative humidity, wind velocity, and short-wave radiation sensors were mounted 2 m above the ground, and soil temperature at 10 cm in the soil. Measurements for each variable were recorded every 15 s and averaged for 30-min intervals. Vapor pressure deficit was computed from relative humidity and corresponding air temperature (Campbell, 1986) using the empirical parameters estimated by Lowe (1977). Precipitation was not recorded because the measurements were taken during the dry season when rain events are very rare (Phillips, 1964; Bierlmaier and McKee, 1989). Stations remained at each site for 2–3 days and were then moved to another site to allow for more sampling of edges with different orientations (relationship of edge to the azimuth). Field data collection was conducted over the two growing seasons (late June–September) of 1989 and 1990 for a total of 35 completed sample days.

Soil moisture data was collected during a 3-day period (18–20 September 1990) of stable weather via Time Domain Reflectometry (TDR) at ten of 13 study 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. The electrode pairs were built using 3.18 mm in diameter and 30 cm long stainless steel rods. These rods were individually driven into the soil at a 30° angle to determine the soilwater content of the top 15 cm through a woody guide that insured the rods were parallel to each other and had 5 cm separation. Field measurements were repeated at five random places in each of the three locations (i.e. clearcut, edge, and forest). The daily weather conditions were recorded as clear, partly cloudy, or cloudy (and/or rainy).

Instruments used were: automatic recording datalogger (Model 21x and CR21 Micrologger, Campbell Scientific (CSI), Logan, UT), temperature sensors (Model 101 and 107 Temperature Probes, CSI), relative humidity sensor (Model 207 Phys-Chem Temperature and RH Probe, CSI), pyranometers (Model Li-200S Silicon Pyranometer, LI-COR, Lincoln, NE); cup anemometer (Model 12102 Gill 3 Cup Anemometer, R.M. Youngs Company, MI); and TDR (TEKTRONIX, Inc., Chicago, IL). The thermocouples (chromel-constantan and copper constantan) used for repeated measurements of air and soil temperatures 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 polyvinyl chloride pipes (Gray and Spies, 1992). Linear regression techniques were used to develop all calibration equations.

The daily average, maximum, minimum, and difference (i.e. maximum–minimum, a measure of variability) of air and soil temperature, relative

TABLE 1

Means (and standard errors) of daily average and differences (maximum minus minimum, Δ) for air temperature (T_a), soil temperature (T_s) relative humidity (h), and vapor pressure deficit (D) in clearcut, edge, and old-growth Douglas-fir forest over the 35-day measurement period (June–September 1989 and 1990)

	T_a	ΔT_a	T_s	ΔT_s	h	Δh	D	ΔD
Clearcut	16.33	14.75	18.34	10.36	70.90	41.30	0.669	1.504
	(0.42)	(1.06)	(0.46)	(0.64)	(3.41)	(2.86)	(0.075)	(0.145)
Edge	16.67	14.17	17.08	11.08	75.99	44.57	0.617	1.538
	(0.40)	(1.01)	(0.43)	(0.86)	(2.88)	(3.02)	(0.073)	(0.156)
Forest	15.72	10.05	13.93	2.44	79.38	31.71	0.425	0.934
	(0.40)	(0.67)	(0.23)	(0.26)	(2.63)	(2.31)	(0.060)	(0.087)

humidity, vapor pressure deficit, and wind velocity were computed. Based on this daily information, means and standard errors over 35 measurement days were further calculated. By visually investigating the relationships of daily averages and differences among the three locations for all 35 days, we identified different relationships among locations (named pattern) and categorized each day into an appropriate pattern. Mean and standard error for each pattern were then computed. To stress the microclimate at the edge under different weather conditions, we compared the basic statistics of the differences in air temperature, relative humidity, and soil temperature of the edge relative to the forest during the day and at night. The comparison was not made for short-wave radiation and wind velocity because of the strong influence of edge orientation.

The diurnal changes in soil and air temperature, relative humidity, vapor pressure deficit, wind velocity, and solar radiation were explored choosing one of the standard days after visual examinations on all 35 days. The influences of local weather condition were also considered, based on 35 diurnal changes and associated local weather conditions. Comparisons of the diurnal pattern among three locations were made by selecting a typical clear day of the Pacific Northwest. The influences of edge orientation on the diurnal changes were examined for short-wave radiation, relative humidity, and soil moisture.

RESULTS

General pattern

Mean daily average air temperatures (T_a) among the clearcut, edge, and forest varied slightly and standard errors around these means were about the same (Table 1). Three major patterns emerged relating T_a, to location (Fig. 1(a)). Most commonly (for 18 of 35 days, Pattern 1), T_a was highest at the edge

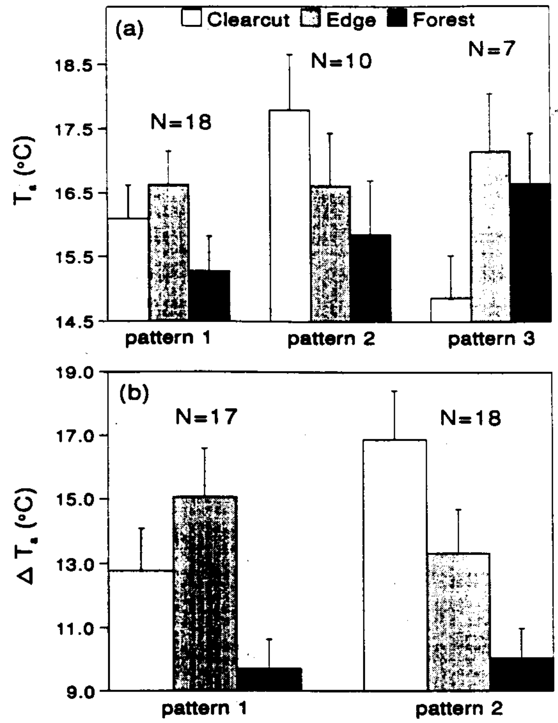

Fig. 1. Means and standard errors of (a) daily average air temperatures and (b) daily air temperature differences in the clearcut, edge, and old-growth Douglas-fir forest. N, indicates the number of days that follow the associated pattern over the 35-day measurement period (June–September 1989 and 1990).

and lowest in the interior forest. For 10 of 35 days (Pattern 2), T_a declined from the clearcut into the forest. For 7 of 35 days (Pattern 3), air temperature was lowest in the clearcut and highest at the edge. No clear relationship has been found between these patterns and local weather conditions in the data analysis.

Mean daily air temperature differences (ΔT_a) were higher in the clearcut and at the edge than in the forest as were the associated standard errors (Table 1). Under unstable weather conditions (e.g. during the change from hot, sunny to windy, cloudy weather), ΔT_a was as high as 25–28°C in the clearcut and at the edge, but considerably smaller (15–17°C) inside the forest. Two patterns emerged relative to location: ΔT_a of the clearcut was either higher than that of the edge or vice versa and, in any case, was lowest in the forest (Fig. 1(b)). Patterns of T_a and ΔT_a were not clearly related (Figs. 1(a) and 1(b)).

Mean daily average soil temperatures (T_s) were the highest in the clearcut, moderate at the edge, and the lowest in the forest, as were the associated standard errors (Table 1). Two patterns emerged relating T_s to locations, although T_s was always lowest in the forest (Fig. 2(a)). For 21 of 35 days (Pattern 1), T_s was higher in the clearcut than at the edge, but for the rest of the days (Pattern 2), this relationship was reversed. Over the same period, T_s

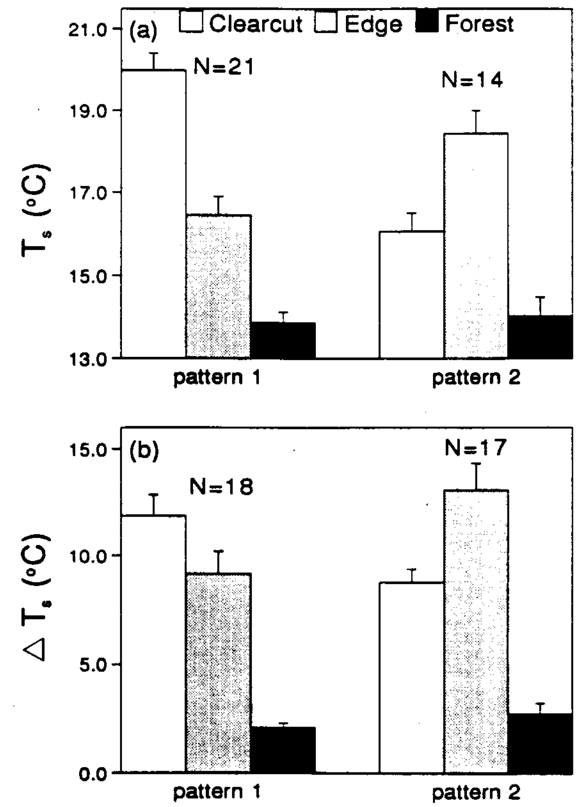

Fig. 2. Means and standard errors of (a) daily average soil temperatures and (b) daily soil temperature differences in the clearcut, edge, and old-growth Douglas-fir forest. N, indicates the number of days that follow the associated pattern over the 35-day measurement period (June–September 1989 and 1990).

in the clearcut and at the edge was consistently higher than T_a but always lower inside the forest; hence, the difference in air temperature between forest and clearcut was less than that in soil temperature.

Mean daily soil temperature differences (ΔT_s) and the associated standard errors were much higher in the clearcut and at the edge than in the forest (Table 1) where soil temperature varied diurnally in the narrow range of 1–4°C. Under extreme weather conditions (e.g. a very hot, sunny day), ΔT_s was as great as 20–24°C in the clearcut and at the edge, but much smaller (< 8°C) inside the forest. As for ΔT_a, two patterns emerged relating to locations: ΔT_s of the clearcut was either higher than that of the edge or vice versa and, in any case, was lowest in the forest (Fig. 2(b)).

Mean daily average relative humidity (h) increased from the clearcut into the forest, but the standard errors decreased (Table 1); i.e. daily growing-season changes in h were smaller inside the forest than in the clearcut and at the edge. Two patterns emerged relating h to locations (Fig. 3(a)). For 25 of 35 days (Pattern 1), h was higher at the edge than in the clearcut while remaining lowest in the forest. This was the pattern under more humid

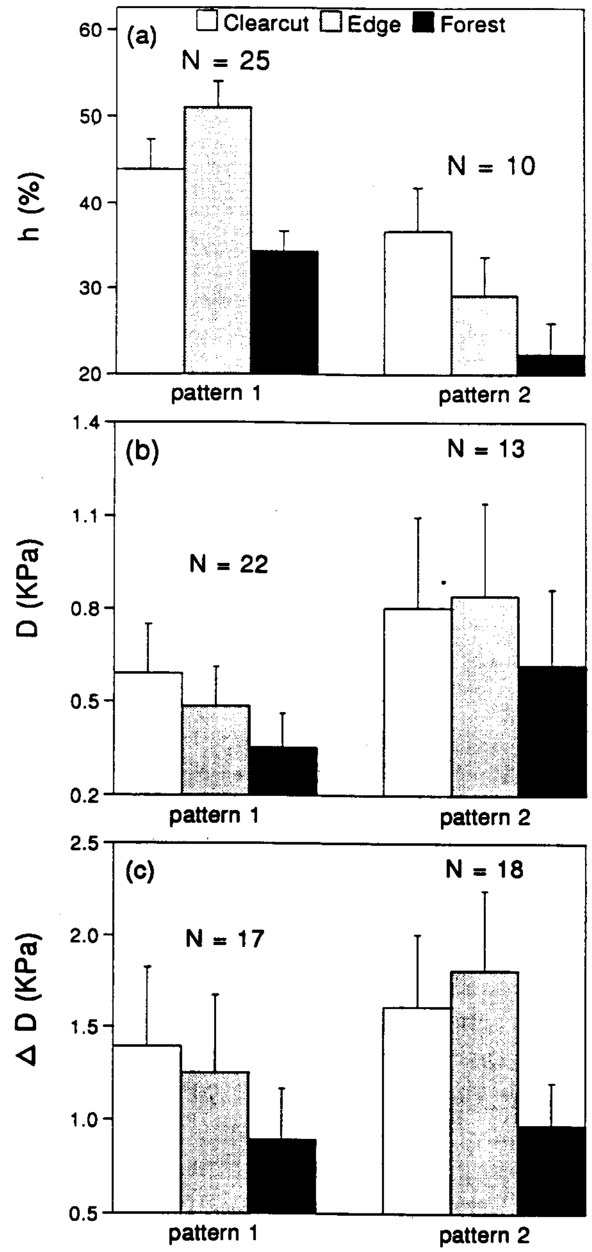

Fig. 3. Means and standard errors of (a) daily average relative humidity (h), (b) vapor pressure deficit (D) and (c) its daily difference (ΔD) in the clearcut, edge, and old-growth Douglas-fir forest. Nm indicates the number of days that follow the associated pattern over the 35-day measurement period (June–September 1989 and 1990).

weather conditions. For 10 of 35 days (i.e. drier weather condition, or Pattern 2), h decreased from the clearcut into the forest. Differences in daily relative humidity (Δh): expressed by the daily minimum because the maximum, which occurs before sunrise, is usually close to the saturation point; were consistently greatest at the edge and least in the forest (Table 1).

Similar results for absolute air moisture were found by examining vapor pressure deficit (D) among three locations. The decreasing trend in D from the clearcut into the forest—lowest air moisture in the clearcut, moderate at the edge, and the highest in the forest (Table 1)—was most common (22 of 35 days, Pattern 1). For the rest of the sampling days (Pattern 2), the edges had the least air moisture (Pattern 2, Fig. 3(b), drier weather conditions). This relationship to the local weather condition was not found for the diurnal difference (ΔD) and associated variation (Table 1). For 17 of 35 days (Pattern 1), ΔD decreased from the clearcut into the forest; for the other days (Pattern 2), it was higher at the edge than in the clearcut while the forest remained the lowest (Fig. 3(c)).

Mean volumetric soil moisture and variability (SE) from 45 repeated measurements in each environment was highest at the edge (17.3%, SE = 0.490), intermediate in the forest (15.7%, SE = 0.256), and lowest in the clearcut (13.8%, SE = 0.357) (Fig. 4(a)). However, the driest (i.e. most extreme) individual measurement was taken in the forest (8.0%) and the wettest at the edge (25.3.0%). This greater variability in soil moisture at the edge was primarily caused by edge orientation (Fig. 4(b)). Soil moisture was the lowest at south- and east-facing edges and the highest at northwest-facing edges. At the east- and south-facing edges, soil moisture was even lower than in the clearcut, while it was higher than in the forest at northwest-facing edges.

Means and associated standard errors for daily average wind speed were consistently highest in the clearcut, intermediate at the edge, and lowest within the forest (Fig. 5). The relative decline in wind velocity was greater between clearcut and edge than between edge and forest.

Diurnal changes

Diurnal changes in air temperature among the three locations had a strongly sinusoidal pattern (Fig. 6(a)), with the minimum temperature occurring at around 06:00 h and the maximum at around 15:00 h. Ratios of air temperature over time among the locations differed considerably for clear and partly cloudy conditions, but little for cloudy conditions. By examining diurnal changes during all 35 days, we found temperatures peaked higher at the south- and west-facing edges than in the clearcut. At other edges, the daily maximum was found at the clearcut.

Air temperature in the clearcut and at the edge rose faster following the early morning low than in the forest. By the time temperatures in the clearcut

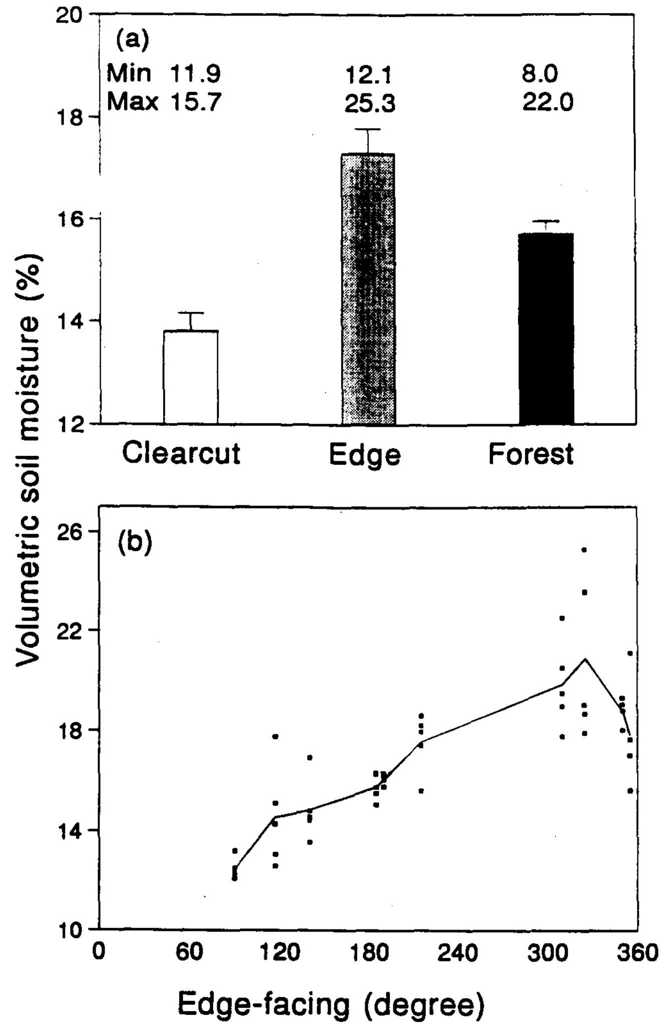

Fig. 4. Means and standard errors of volumetric soil moisture (%) in (a) clearcut, edge, and old-growth Douglas-fir forest and (b) its changes with edge orientation based on the measurements from 50 measurements at ten different edges.

peaked (around 14:30–15:00 h), temperatures at the edge were still rising and continued to rise to a higher maximum. In mid-afternoon, they were much higher at the edge, but still lowest inside the forest. Therefore, all temperature curves declined, but the rates of decline in the clearcut and at the edge were faster than in the forest. This trend continued until early morning of the next day, when the lowest temperature was attained in the clearcut. Early morning minimums were higher inside the forest than in the other two locations.

During the day, maximum air temperature at the edge relative to the forest averaged about 3.5°C higher under clear and partly cloudy weather conditions, and slightly less under cloudy skies (Table 2). However, variation was

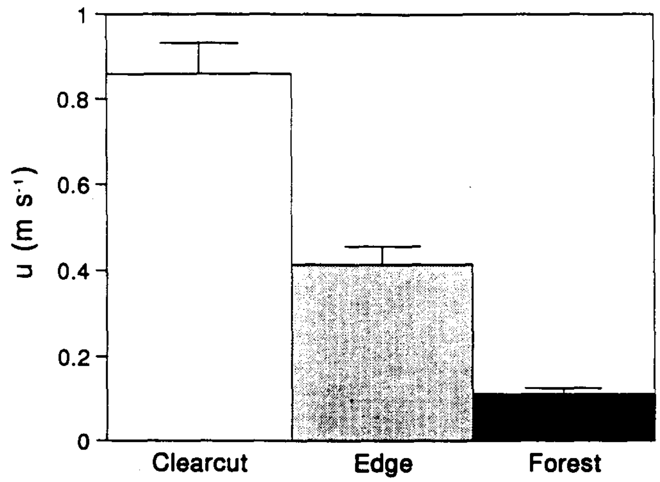

Fig. 5. Mean and standard errors of wind velocity in the clearcut, edge, and old-growth Douglas-fir forest over the 35-day measurement period (June–September 1989 and 1990).

as high as 7.8°C and as low as 0.5°C. During the night, air temperature was slightly cooler at the edge, but could be warmer under special conditions, such as during a period of local warming process.

Diurnal changes in soil temperature were similar to the those of air temperature (Fig. 6(b)). Soil temperature fluctuated far less in the forest than in the clearcut and at the edge, and was higher in the clearcut and at the edge during the day but slightly lower at night (Table 2). In contrast to air temperature, soil temperature in the clearcut was always higher than at the edge under clear and partly cloudy conditions. This temperature difference between clearcut and edge was very small under cloudy or rainy conditions. Differences in soil temperature between the edge and the forest were much greater than those in air temperature under all weather conditions (Table 2); mean differences were much higher during the day than at night and were greatest under clear skies.

Diurnal changes in relative humidity were the reverse of those in air temperature (compare Figs. 5(a) and 5(b)). At night, relative humidity was high, usually close to the saturation point; it began to decline at around 08:00 h and reached its minimum at 16:00–16:30 h (Fig. 5(b)). During the day, relative humidity was much lower in the clearcut and at the edge than inside the forest; at night, it was the lowest in the forest, moderate at the edge, and highest in the clearcut, but the difference was minimal, especially between the edge and the clearcut. Differences in relative humidity between the clearcut and the forest were greater under clear skies, but negligible under cloudy or rainy conditions. Differences in relative humidity at the edge relative to the forest were considerably greater during the day than at night (Table 2) and could increase up to 33% under extreme (e.g. very dry) weather conditions

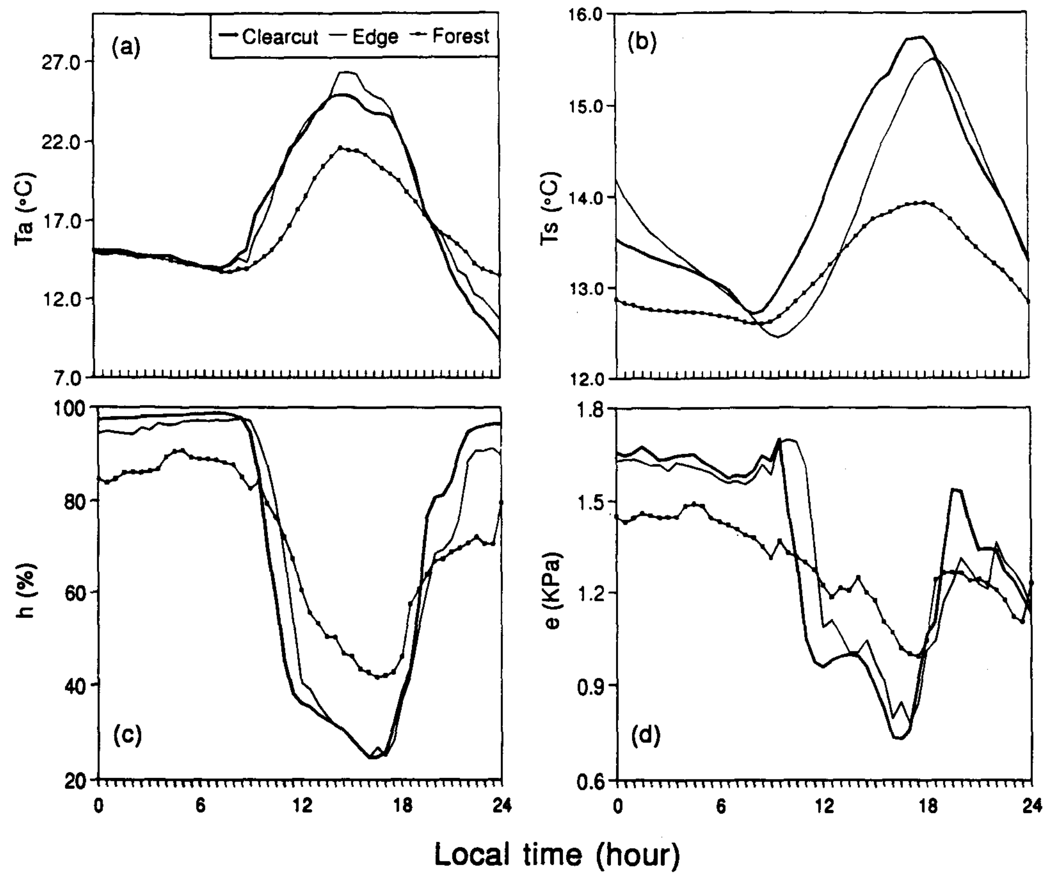

Fig. 6. Diurnal changes in (a) air temperature; (b), soil temperature; (c) relative humidity; (d) vapor pressure in the clearcut, edge (south-facing) and old-growth Douglas-fir forest.

during the day. Vapor pressure had the same pattern (Fig. 6(d)), indicating a minor influence of air temperature on the air moisture when comparing the differences among three locations. Both relative humidity and vapor pressure at the edge decreased later in the morning than at the clearcut, primarily because measurements were at a south-facing edge.

Diurnal changes in wind velocity were similar for a strong and a weak wind: lower at night and higher during the day. Generally, velocity decreased in the afternoon and was lowest at night (usually calm) and in the early morning; it was consistently highest and most erratic in the clearcut, moderate at the edge, and calmest and least variable in the forest (Fig. 7(a)). The wind velocity as a percentage of that in the clearcut was about 15–20% in the forest and 60–70% at the edge.

Diurnal changes in short-wave solar radiation were considerably greater in the clearcut than at the edge and inside the forest regardless of sky conditions (Fig. 7(b)). On a clear day, the radiation curve was bell-shaped in the clearcut,

TABLE 2

Temperature and humidity differences at the edge relative to the interior forest under three local weather conditions (clear, partly cloudy, and cloudy/rainy) during the 1989 and 1990 growing seasons

Variable weather by time	Condition	No. measured	Mean difference	Standard error	Max.	Min.
Air temperature (°C)						
Day	Clear	24	3.62	0.34	7.04	0.95
	P/Cloudy	17	3.53	0.44	7.80	1.29
	Cloudy	13	2.67	0.38	4.89	0.54
Night	Clear	26	−1.51	0.26	−0.15	−5.83
	P/Cloudy	18	−1.47	0.40	0.25	−5.52
	Cloudy	14	−1.29	0.46	0.28	−6.69
Relative humidity (%)						
Day	Clear	23	15.00	1.50	28.49	4.24
	P/Cloudy	17	15.39	1.93	32.77	6.95
	Cloudy	14	13.06	1.99	28.68	2.98
Night	Clear	24	6.05	1.61	35.97	−1.63
	P/Cloudy	16	6.65	2.27	26.93	−2.05
	Cloudy	14	5.75	1.98	25.87	−1.61
Soil temperature (°C)						
Day	Clear	36	8.09	0.58	15.52	1.66
	P/Cloudy	21	9.14	0.75	14.73	2.41
	Cloudy	18	7.17	0.85	14.90	2.68
Night	Clear	39	0.72	0.21	3.55	−2.55
	P/Cloudy	21	1.10	0.33	4.34	−1.51
	Cloudy	19	0.62	0.33	2.64	−1.91

but erratic at the edge, where sunlight is partially blocked by the forest canopy. With increasing cloud cover, however, the forest floor receives only a small amount of light, and the influence of sky condition was minimal. The local fluctuation (i.e. white noise between 30-min time periods) in radiation patterns owing to the sky condition was greater in the clearcut and at the edge than in the forest.

These relationships in short-wave radiation were strongly influenced by edge orientation (Fig. 8(a)). At a south-facing edge, total radiation flux for a clear day produced a bell-shaped curve similar to that at the clearcut (compare Figs. 7(b) and 8(a)). However, at east- and west-facing edges, the bell curve was essentially halved. At an east-facing edge, radiation flux increased earlier in the day and at a faster rate than it did at a south-facing edge; at around 09:30 h, there was almost the same amount of radiation at both sites. Then, the rate of increase at the east-facing edge began to decline, dropping precipitously around noon. Within 1–2 h, the light condition approximated that at

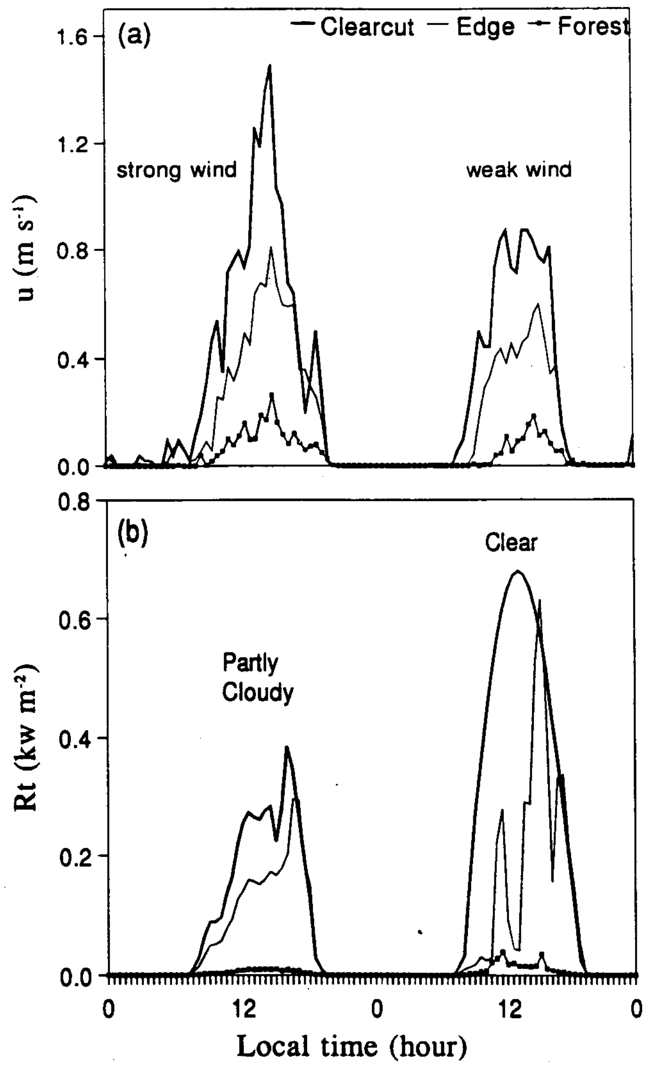

Fig. 7. Diurnal changes in wind velocity with (a) strong and weak wind; (b) short-wave radiation under clear and partly cloudy skies in the clearcut, edge and old-growth Douglas-fir forest (the edge faces west).

a north-facing edge (diffuse and reflective light only). Radiation flux at a west-facing edge virtually mirrored that at an east-facing edge (Fig. 8(a)). At a north-facing edge, radiation levels remained relatively low throughout the day, but were highest in late afternoon, when it was similar to that at a west-facing edge during the long days of the growing season.

Diurnal changes in relative humidity were also influenced by edge orientation, and these influences were seen more strongly during the day and weakly at night (Fig. 8(b)). During the day, relative humidity at the north and east edges decreased more gradually from early morning on, and was considerably

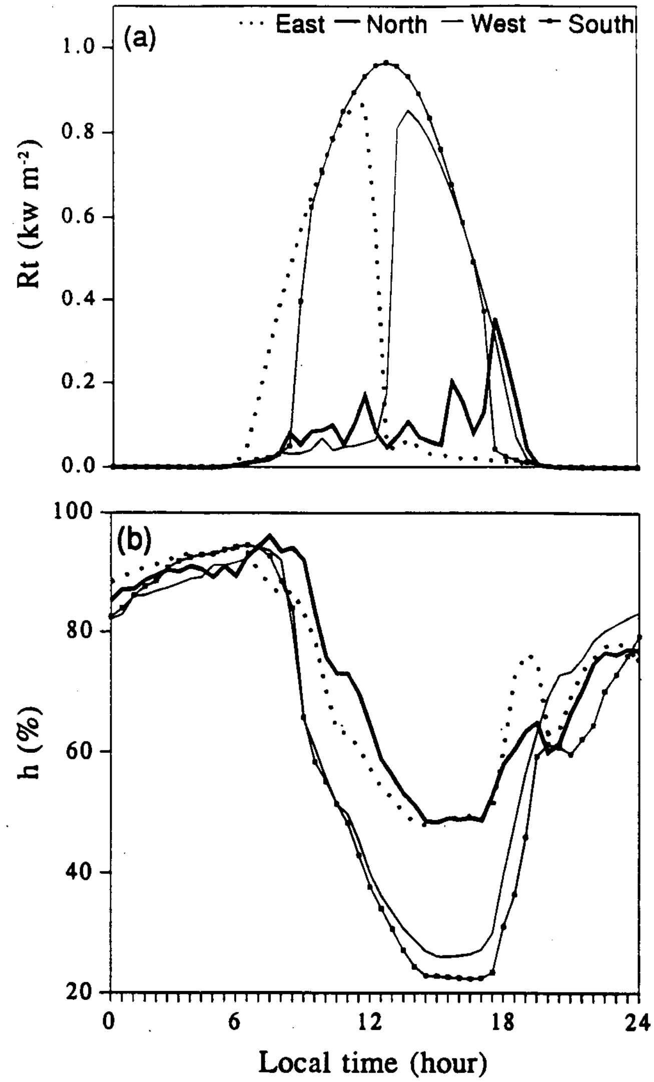

Fig. 8. Diurnal changes (a) in short-wave radiation; (b) relative humidity at four contrasting edges that face east, north, west, and south under clear sky conditions.

higher in the afternoon than at south and west edges. At night, the influences of orientation weakened and few differences existed among the four edges.

DISCUSSION

Clearcutting and associated forest practices significantly alter the surface thermal properties (e.g. albedo) and energy and material balances (e.g. solar radiation and precipitation) near the ground owing to the removal of forest canopy and ground materials (understory shrubs, coarse woody debris, etc.). Generally, a clearcut receives more direct solar radiation and precipitation, loses more outgoing long-wave radiation, and shows higher rates of evapotranspiration than an adjacent forested area. Hence, there is typically a sunnier, warmer, windier, and drier environment outside the forest than in the forest during summer days (Geiger, 1965; Wales, 1967; Lee, 1978; Ghuman and Lal, 1987) and a cooler, wetter environment at night (Chen, 1991). The data from both the 1989 and 1990 growing seasons in this study illustrated these patterns for clearcut, edge, and forest environments associated with old-growth Douglas-fir forests in the Cascades of southern Washington (Table 1). However, the influences of local weather conditions were such that, on cloudy or rainy days, microclimates among the three locations differed little and relationships among them varied.

Additional evidence that local weather conditions affect microclimate was found in the diurnal changes of temperature and relative humidity for the clearcut and adjacent forest. Generally, the daily maximums, minimums, and variations were greater during clear than cloudy weather conditions (Raynor, 1971; Ranney, 1977; Lee, 1978; Chen, 1991). However, in our study, these parameters also were more variable under partly cloudy skies (Fig. 6, Table 2) because the dynamics of such weather conditions creates an unstable microclimate near the ground. Our weather records for the 1989 and 1990 growing seasons showed that roughly 51.4% of this period was clear, 28.0% was partly cloudy, and 20.6% was cloudy or rainy, indicating then the relative importance during the study period.

Although microclimates outside and inside the forest have been compared previously (Geiger, 1965; Lee, 1978), it is important to consider the edge as both a separate microclimate and a climatic mediator between clearcut and forest. However, studies of the microclimate at edges have been rare. Because the edge is physically located between clearcut and forest, it might logically be assumed that its microclimate would be intermediate between the clearcut and forest (e.g. Geiger, 1965; Wales, 1967; Ranney, 1977). We found this to be the case for wind velocity and solar radiation, which were always highest in the clearcut and lowest in the forest, but not for temperature and moisture variables. The most extreme day time air temperatures and relative humidities occurred at the edge rather than in the clearcut (Figs., 1(a), 2, 5(a), 5(b)). Both means and standard errors for soil moisture also were highest at the edge.

Wind influences temperature and moisture regimes at the edge. In the clearcut, winds are stronger; this helps mix air, which carries heat energy and moisture to the surrounding areas and thereby reduces variation in air temperature and relative humidity. Near the edge winds are weaker; this produces relative stable air which, in turn, allows more extreme air temperatures and humidity. Although they were not studied, soil surface cover (e.g. litter, vegetation), which influences soil thermal properties, and precipitation probably have major influences on soil moisture patterns at the edge because there tends to be more surface cover and precipitation (i.e. condensation) at forest edges than inside the forest and on the clearcut (Waring and Schlesinger, 1985; Weathers et al., 1990).

We found microclimate to be strongly related to edge orientation, as have others (Wales, 1967; Ranney, 1977). Since solar radiation is the only heat source, changes in radiation flux associated with edge orientation will alter the diurnal patterns of other microclimatic variables such as air temperature, soil temperature, and relative humidity. The contrasting patterns of diurnal changes in relative humidity as influenced by edge orientation (Fig. 8(b)), for example, can be explained by the corresponding patterns of solar radiation and air temperature.

Many biological features near the forest edge seem related to these unique microclimatic conditions well. Fastest decomposition rates of litter near the edge are probably owing to high available soil moisture and higher temperatures, which speed up the activity of fungi and other decomposer organisms (Edmonds and Bigger, 1984). Abundance regeneration and higher growth rates of western hemlock and Douglas-fir are likely caused by greater light and higher air temperatures (Chen et al., 1992). Other apparent relationships include greater wind damage (Ruth and Yoder, 1953; Chen et al., 1992), unique understory species composition (Frost, 1992), and use of edges as insect pathways (Wood and Samways, 1991), etc.

Precise microclimatic data have been difficult to collect because of the high cost of instrumentation (Pinker, 1980; Ghuman and Lal, 1987). Indeed, traditionally, microclimatic information used in studying, e.g. species distribution or ecological processes, was either measured once a day or averaged over a period, inadvertently biasing the data base because important values might have been hidden or lost. We believe that our continuous-monitoring approach, with many replications among sites, environment, and weather conditions, has provided reliable data on microclimate. Moreover, although Chen (1991) originally hypothesized that the most variable microclimatic conditions would occur in the clearcut, our measurements of temperature and moisture data indicate that such conditions are actually found at the edge. This phenomenon might be explained by the complex interactions among microclimatic variables and forest structure. However, such an explanation needs to be verified in other forest types from further, detailed study of energy budgets.

ACKNOWLEDGMENTS

This study was supported by a collaborative research program with Willamette National Forest, the Bloedel Professorship at the University of Washington, and the Olympic Natural Resources Center of the University of Washington, with funding from USDA Forest Service New Perspectives

Program Grant No. PNW 90-342, Amendment No. 1. We thank Carol Perry and Stephanie Martin for reviews of the draft of this manuscript.

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