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HARVESTING EFFECTS ON MICROCLIMATIC GRADIENTS FROM SMALL STREAMS TO UPLANDS IN WESTERN WASHINGTON

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Abstract. Riparian zones are vital components of the landscape. Much attention has been focused on the question of how wide a buffer is needed to protect the original riparian environment. We sampled five streams 2–4 m wide and associated riparian ecosystems before and after clearcutting in western Washington. Buffers ranging from 17 to 72 m wide were left intact at all sites when harvesting. Our objectives were: (1) to characterize pre-harvest microclimatic gradients across riparian ecosystems, from the stream to the upland; (2) to identify effects of harvesting on these gradients; and (3) to describe effects of buffer width and near-stream microclimate on stream microclimate. Six weather stations measuring air temperature, soil temperature, surface air temperature, relative humidity, short-wave solar radiation, and wind speed were installed along transects running across the stream and into the upland, and two reference stations were established, one in an upland clearcut and one in an upland interior forest. Pairwise comparison tests were used to evaluate statistical differences between stations along transects for determination of gradient extent. Pre-harvest riparian gradients existed for all variables except solar radiation and wind speed, and values generally approached forest interior values within 31–62 m from the stream. After harvesting, microclimate values at the buffer edge and each subsequent location toward the upland began to approximate clearcut values instead of forest interior values, indicating an interruption or elimination of the stream–upland gradient. In addition, regression analyses showed that stream microclimate was affected to some degree by buffer width and microclimate in the surrounding area. We conclude that a buffer at least 45 m on each side of the stream is necessary to maintain a natural riparian microclimatic environment along the streams in our study, which were characterized by moderate to steep slopes, 70–80% overstory coverage (predominantly Douglas-fir and western hemlock), and a regional climate typified by hot, dry summers and mild, wet winters. This buffer width estimate is probably low, however, since it assumes that gradients stabilize within 30 m from the stream and that upslope edge effects extend no more than 15 m into the buffer (a low estimate based on other studies). Depending on the variable, required widths may extend up to 300 m, which is significantly greater than standard widths currently in use in the region (i.e., ~10–90 m). Our results indicate that even some of the more conservative standard buffer widths may not be adequate for preserving an unaltered microclimate near some streams. Additional site-specific data are needed for different site conditions in order to determine whether generalizations can be made regarding near-stream microclimate.

Key words: buffer width; microclimate; riparian ecosystem; streams; Washington State.

INTRODUCTION

Riparian forests play an important role in the landscape by providing plant and wildlife habitat, increasing landscape connectivity, and protecting water quality (Lowrance et al. 1984, Triquet et al. 1990, Gregory et al. 1991, Naiman et al. 1993, Gilliam 1994). The practice of leaving forested buffer strips on both sides of a stream or river when harvesting timber in order to preserve the functions of riparian forests was first implemented in the United States in the late 1960s (Calhoun 1988). Since then, numerous studies have suggested that ecological values in buffered streams and associated riparian areas are much higher than in unbuffered streams (Murphy et al. 1986, Triquet et al. 1990, Franklin 1992, Naiman 1992). Leaving riparian buffers along third and higher order streams has become a common practice on federal, state, and some private lands, thanks in part to the 1993 Forest Ecosystem Management Assessment Team (FEMAT) report, which specifies minimum buffer widths for streams based on fish-bearing characteristics and stream flow.

Standard riparian buffer widths, however, often do not take into account individual site characteristics, such as topography and various forest characteristics, that are known to influence the system. Although there is widespread agreement on the importance of buffer strips, many scientists disagree with applying a fixed-width buffer to all streams (e.g., Castelle et al. 1994,

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Forman 1995). The critical question has become: how wide is wide enough? Most agree that the answer to this question depends on stream and site conditions (e.g., vegetation, topography, hydrology), as well as management objectives. Castelle et al. (1994), for example, identified four criteria for determining adequate riparian buffer sizes: (1) resource functional value, (2) adjacent land use, (3) buffer characteristics, and (4) buffer functions desired. Current buffer width requirements tend to be arbitrary or based partially on climatic gradients collected across upland forest-clearcut edges (FEMAT 1993, Chen et al. 1995). Overprotection can result in loss of economic or other value in terms of nonharvestable timber, while inadequate protection reduces the quality of the site and may alter vital habitat or other functions (Levno and Rothacher 1967, Swift and Baker 1973, Murphy et al. 1986, Lockaby et al. 1994, Tang 1995).

Microclimate is important to consider when deciding management goals because of its effects on ecosystem processes and functions. Temperature, solar radiation, and humidity affect plant growth by influencing physiological processes such as photosynthesis, respiration, seed germination, mortality, and enzyme activity (Kramer and Kozlowski 1979, Levitt 1980, Tromp 1980, Harmon et al. 1986, Hungerford and Babbitt 1987, Fowells and Means 1990). Therefore, ecosystem processes such as decomposition, nutrient cycling, succession, and productivity are partially dependent on these variables. Many animals are also adapted to specific microclimatic conditions. Wind speed, air temperature, humidity, and solar radiation can influence migration and dispersal of flying insects (Johnson 1969). Soil microbe activity is affected by soil temperature and moisture. In addition, most fish have specific thermal ranges in which they are able to survive (Magnuson et al. 1979), suggesting that changes in variables that affect water temperature, such as solar radiation, can cause changes in habitat suitability for some organisms.

Gregory et al. (1991) defined riparian zones as interfaces between terrestrial and aquatic ecosystems, asserting that lateral riparian boundaries should be delineated at the limits of the area affected by water. However, many aspects of the ecosystem (e.g., vegetation, microclimate, wildlife, nutrients) may continue changing at differing rates toward the upland beyond this hydrologic limit. Changes in ecosystem composition, structure, and processes from streams to uplands are often gradual (Risser 1995, Chen et al. 1996) and vary with the rate of change of different variables. To understand interactions between riparian ecosystem properties and functions, attention should be given to the entire ecosystem, including transitional areas beyond the hydrologic limits. In addition, empirical data on many properties of near-stream environments are needed if we are to accurately assess the extent of riparian influence and answer practical questions concerning riparian management.

This study's focus is to provide information on physical components of the environments of small streams, which can help provide a base for understanding the characteristics and functions possible in managed riparian areas of differing sizes in the Pacific Northwest. Although significant attention has been focused on some aspects of streamside environments (Murphy et al. 1986, Nilsson et al. 1989, Triquet et al. 1990, Franklin 1991, Naiman and Rogers 1997), no previous attempts have been made to characterize the physical aspects of these systems, such as microclimate (FEMAT 1993, O'Laughlin and Belt 1995). This study addresses several microclimate variables important to the riparian ecosystem: air, water, soil, and surface air temperatures; relative humidity; short-wave solar radiation; and wind speed. Specific objectives of this paper are: (1) to characterize pre-harvest riparian microclimatic gradients from the stream to the upland; (2) to identify the effects of harvesting on these gradients; and (3) to describe the effects of buffer width and near-stream microclimate on stream microclimate.

METHODS

Study sites

We examined microclimate across small streams in western Washington, near Seattle and Olympia. The area lies in the foothills of the western slope of the Cascade Mountain Range, often with steep slopes culminating in constrained stream channels. Overstory vegetation at the study sites is comprised primarily of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), with occasional red alder (*Alnus rubra* Bong.), western red cedar (*Thuja plicata* Donn), and grand fir (*Abies grandis* [Dougl.] Lindl.). Ground vegetation is diverse, composed of both lowland and upland species.

We chose streams with similar size, vegetation, and physical characteristics in order to provide a legitimate basis for comparison between sites. Stream width ranged from 2 to 4 m, elevations ranged from ~150 to 600 m, and canopy coverage was ~70–80%. The stream sites varied in forested buffer width, valley formation, and orientation (see Table 1).

A total of 15 stream sites (20 transects) were monitored. Nine of these sites were monitored during the summer of 1993. Four had been harvested and planted in 1990–1991, with buffers of various widths left intact (range = 12–23 m). The remaining five sites were forested. These forested sites were clearcut during the winter of 1993–1994 and resampled in the summer of 1994 in order to compare the same site in both pre- and post-harvest conditions. Six additional streams (1–4-yr-old clearcut sites) were also monitored in 1994. A total of five forested sites, 14 clearcut and buffered sites (including the five forested sites following clear-

TABLE 1. Characteristics of sites examined in this study, where B indicates pre-harvest condition and A indicates post-harvest condition. Buffer widths (points at which the buffer station was located) for forested sites were obtained from harvest plans and do not indicate an actual buffer edge at that point, while those for post-harvest gradients were actual buffer widths. Opposite buffer width = the width of the buffer on the slope opposite that used for the gradient transect; CC = clearcut (year site was harvested); DF = Douglas-fir, RA = red alder, WH = western hemlock, GF = grand fir.

Transect	Sampling period	Structure	Buffer width, B_2 (m)	Opposite buffer width, B_1 (m)	Slope (%)	Aspect (°)	Dominant overstory species	Avg. dom. tree height (m)
1B	1993 (28 Jul–5 Aug)	forested	20	20	20	180	DF	32
1A	1994 (23–30 Jun)	CC (1993/1994)	23	17	18	180		
2B	1993 (5–16 Aug)	forested	20	20	35	360	DF	32
2A	1994 (30 Jun–7 Jul)	CC (1993/1994)	17	23	32	360		
3B	1993 (17–27 Aug)	forested	16	16	20	20	DF	48
3A	1994 (7–14 Jul)	CC (1993/1994)	25	60	34	20		
4B	1993 (27 Aug–6 Sep)	forested	16	16	22	200	DF	48
4A	1994 (14–21 Jul)	CC (1993/1994)	60	25	19	200		
5B	1993 8–17 Sep)	forested	32	44	25	180	DF, RA, WH	26
5A	1994 (7–16 Jun)	CC (1993/1994)	72	44	25	180		
6	1993 (12–28 Jun)	CC (1990)	12	12	33	319	WH	33
7	1993 (28 Jun–7 Jul)	CC (1990)	14	14	30	295	DF, RA, WH	33
8	1993 (7–15 Jul)	CC (1990)	14	14	15	115	DF, RA, WH	33
9	1993 (16–27 Jul)	CC (1990)	22	23	38	350	WH, GF	41
10	1994 (16–23 Jun)	CC (1993/1994)	44	72	35	30	DF, RA, WH	26
11†	1994 (22–28 Jul)	CC, burned (1990/1991)	0 (25)	0 (60)	42	40	WH (snag)	60
12	1994 (28 Jul–4 Aug)	CC (1991/1992)	10	22	3	239	DF, WH	39
13	1994 (4–11 Aug)	CC (1993/1994)	13	7	32	140	DF, RA, WH	41
14	1994 (11–18 Aug)	CC (1993/1994)	14	11	2	348	DF, RA, WH	41
15	1994 (18–25 Aug)	CC (1991/1992)	12	55	2	20	WH	38

† Site 11 was relatively unbuffered; the number in parentheses is the distance from the stream at which the weather station was placed.

cutting), and one clearcut, unbuffered (burned) site were sampled (Table 1). For the gradient analyses, we used only the sites for which we had pre- and post-harvest data, because our primary objective was to examine changes in riparian microclimate due to harvesting. All clearcut sites were included when analyzing the effects of buffer width and gradient variables on stream microclimate.

Data collection

At each site, a transect was established perpendicular to the stream. We collected microclimate measurements at six weather stations along each transect. One station was located in the center of the stream (S_0), one at the edge of the riparian buffer on the opposite side of the stream (B_1), one at the buffer edge on the slope being sampled (B_2), and one each at 15 m (B_2+15), 30 m (B_2+30), and 60 m (B_2+60) from the buffer edge (Fig. 1). At pre-harvest sites, the locations of the buffer edge stations were obtained from harvest plans and do not indicate actual edges at those spots (i.e., the entire gradient is forested). B_1 ranges from 16 to 44 m and B_2 ranges from 16 to 32 m from the stream at pre-harvest sites. At post-harvest sites, B_1 and B_2 were located at the actual buffer–clearcut edges, which ranged from 17 to 60 m from the stream (B_1) and 17 to 72 m from the stream (B_2). Weather-station locations were selected under consideration of equipment limitations and our desire to characterize the entire gradient from the stream into the upland. Because pre-harvest transects were under continuous canopy for their entire length, the gradient can be determined. Two additional stations were also established, one each in an interior forest (F_{int}) and interior clearcut (C_{int}), to serve as references for upland clearcut and forest conditions. Both F_{int} and C_{int} were located 180 m or more from the buffer edge.

Each weather station consisted of a 2 m tall metal tripod, a datalogger with protective housing, and microclimate measuring sensors (Table 2). The sensors included three replications each of air, surface, and soil temperature (measured in degrees Celsius); three replications of short-wave solar radiation (in kilowatts per square meter); relative humidity (as a percentage); and wind speed (in meters per second).

All measurements except for soil and surface temperatures were taken 2 m above the ground surface. The soil probe was driven 5 cm into the ground (mineral soil). Surface-temperature sensors were placed as close to the forest floor as possible without actually touching the ground or other objects. The tripod served as the location for measurements of relative humidity; wind velocity; one replication of air, soil, and surface temperatures; and all three replications of solar radiation. The other two replications of the temperature measurements were taken 15 m on each side of the tripod, parallel to the stream. At the stream station, soil and surface temperatures were not measured. Water temperature (degrees Celsius) was monitored instead.

During the 1993 field season, the clearcut and forest reference stations measured five of the six variables

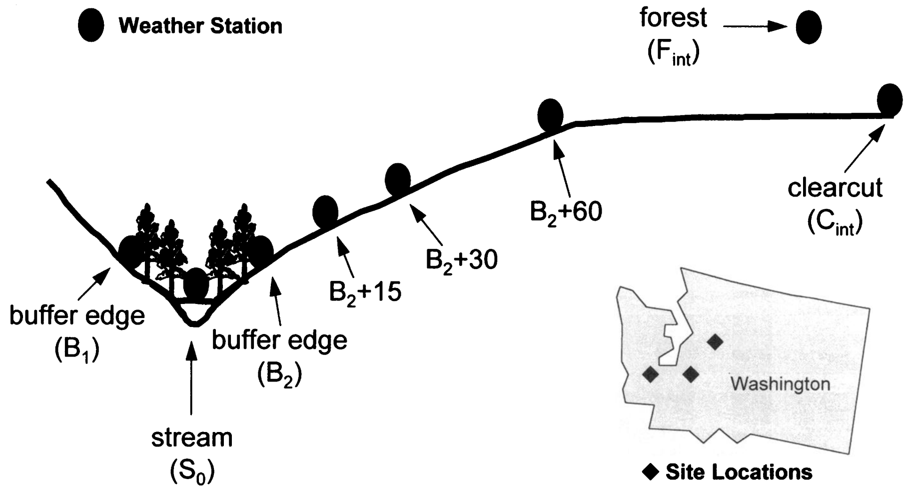

FIG. 1. Five streams in three locations in western Washington State were selected for pre- and post-harvest analysis. Six weather stations were installed along a gradient from the stream to the upland. Stations were located at each buffer edge (B_1 and B_2), in the center of the stream (S_0), and 15, 30, and 60 m from the buffer edge (B_2+15, B_2+30, B_2+60, respectively). At post-harvest sites, the clearcut station (C_{int}) was located 180 m from the buffer in the upland, and the forest station (F_{int}) was placed in a nearby upland interior forest. At pre-harvest sites, F_{int} was located along the transect and C_{int} was placed in a nearby upland clearcut.

(air and soil temperature, humidity, wind speed, and solar radiation). Due to datalogger constraints, ground surface temperature was not measured at these stations. In 1994, the reference stations measured the same six variables as the other stations, with the exception that only one replication of solar radiation was measured. Dataloggers sampled each variable every 15 s and averaged these values every 30 min for final storage. Weather stations collected data at each site for 6–15 d, then were moved to another site to repeat the data collection process.

Data analysis

For the gradient analyses, we plotted relative averages (e.g., $T_a(i)_{avg} = T_a(i) - \min[T_a(1, \ldots, 8)]$, where $T_a(i)$ is average air temperature at station i, and $\min[T_a(1, \ldots, 8)]$ represents the minimum average air temperature among the eight weather stations), against distance from the stream during two time periods (0000–0400 and 1200–1600) to obtain an initial visual assessment of the gradients. Relative values were used because the purpose was to examine gradual changes along the transects, not necessarily absolute values. The time periods chosen were considered to be representative of night and day conditions. We then used two-way ANOVA tests (model: variables = day, station, day × station) and pairwise Bonferroni comparisons to determine statistical differences ($P \leq 0.05$) between stations along each pre- and post-harvest transect during these two time periods. The microclimatic gradient was assumed to end at the point along the transect where statistical differences ended. For the sake of simplicity, reported results are primarily those obtained from combined data (i.e., all pre-harvest transects combined, all post-harvest transects combined). Harvesting effects were assessed by comparing post-harvest gradient patterns and statistical differences between stations to those found at the sites before harvest.

We used correlation and regression techniques to examine effects of buffer width and surrounding microclimate on stream microclimate. Each stream variable was used as the dependent variable, with buffer width

TABLE 2. Description of meteorological instruments used in this study.

Sensor	Manufacturer	Variable(s) measured or function
21X Micrologger	Campbell Scientific Inc., Logan, Utah	data accessories
CR21 Micrologger	Campbell Scientific Inc., Logan, Utah	data accessories
24 gauge E type thermocouples	custom-built	air temperature (°C)
24 gauge T type thermocouples	custom-built	soil and surface temperature (°C)
207 Phys-Chem Temperature and RH probe	Campbell Scientific Inc., Logan, Utah	air temperature (°C) and relative humidity (%)
12102 Gill 3 Cup Anemometer	RM Youngs Company, Traverse City, Michigan	wind speed (m/s)
Li-200s Silicon Pyranometer	LI-COR, Lincoln, Nebraska	solar radiation (kW/m²)
PC 208	Datalogger Support Software	programming and communication

and other microclimatic variables acting as independent variables. Several regression models were fit to the data, and the best-fit model, based on MSE and R^2 values, was used to describe the relationship. Data from all transects were included in these analyses, since we did not need pre-harvest data to compare the effects of buffer width and surrounding microclimate on the stream.

RESULTS

Statistical results showed clearly that significant microclimatic differences ($P = 0.0001$) occurred at some point along all transects in our study, including both pre- and post-harvest transects. Much of the variation in the data was due to location along the transect, as indicated by highly significant station effects ($P = 0.0001$). In addition, daily weather differences and interactions between daily weather and station location accounted for a statistically significant portion of the variation ($P = 0.0001$), although these effects generally accounted for less variation than did station location. When the sites were evaluated separately, daily weather differences were not significant for relative humidity at site 3B at night or for solar radiation at site 3A during the daytime period, but they were significant ($P = 0.0001$) for all other analyses. The interaction effect was significant ($P \leq 0.05$) for all ANOVAs except: humidity (time = 1200–1600) at sites 1A, 3A, 3B, 5B; air temperature (0000–0400) at sites 1A, 5A and (1200–1600) at sites 1A, 3A; soil temperature (1200–1600) at site 3A; surface temperature (0000–0400) at sites 1B, 2B, 4B, 5B, and (1200–1600) at site 3A; and wind speed (1200–1600) at site 3A.

Microclimatic gradients

Air temperature.—Relative average air temperature at the pre-harvest sites displayed a typical pattern of rising sharply from the stream to B_2 (16–32 m from the stream), then rising more slowly to B_2+15 (Fig. 2). Based on Bonferroni comparisons, there were no significant differences ($P \leq 0.05$) beyond B_2+15 (31–47 m from the stream), where temperatures approximated that inside the forest. Air temperature increased by an average of 17% from the stream to B_2+15 at night and by an average of ~18% during the day. However, C_{int} had significantly higher air temperature than any other station (6.8% higher than B_2+15 at night, 12.9% higher during the day).

After harvest, daytime patterns were similar to those found before harvest, except that air temperature increased to that of the clearcut instead of the forest. (Fig. 2). The gradient stabilized around B_2+15 (32–87 m from the stream) after increasing an average of 22.5% from the stream. Beyond this there were no significant differences. At night, however, the pattern was different. When all post-harvest sites were combined, statistical differences ($P \leq 0.05$) existed between all adjacent stations except between B_2+15 and B_2+30. There was variation by individual site, however. Two of the five post-harvest sites showed highest air temperature at the stream, with statistical differences between stations to B_2 (17–72 m from the stream). At the other three sites, no statistical differences were found between the stream and buffer stations. Two sites at night showed no differences from station to station along the gradient, while in one other site the only difference was from B_2+30 to B_2+60, where a slight decrease in air temperature occurred. The other two sites showed differences between the stream and buffer stations, but no statistical differences beyond B_2.

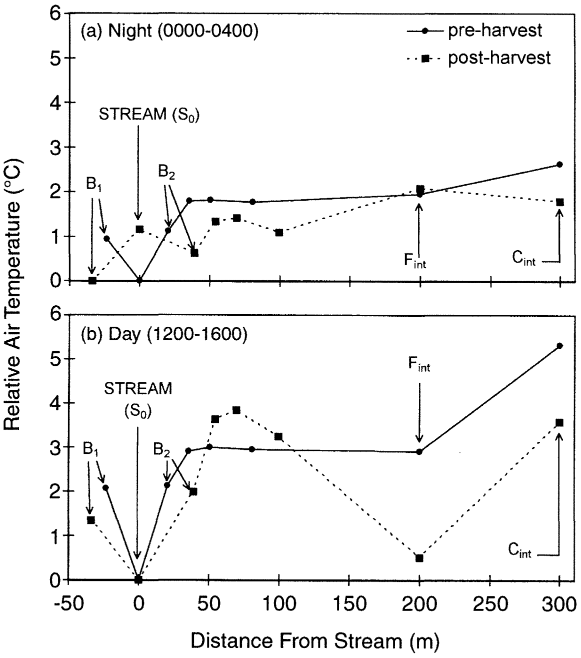

FIG. 2. Changes in average relative air temperature [$\Delta T_a(i)_{avg} = T_a(i) - \min[T_a(1, \ldots, 8)]$, where $T_a(i)$ is average air temperature at station i, and $\min[T_a(1, \ldots, 8)]$ represents the minimum average air temperature among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites during two time periods.

Soil temperature.—Nighttime soil temperature gradients at the pre-harvest sites followed two patterns. Soil temperature was lowest at B_1 at three of the sites, then rose steeply to B_2 (16–32 m from the stream), after which there was no significant change to the next station (B_2+15). The second pattern showed a drop in soil temperature from B_1 to B_2, then a sharp increase (~13%) to B_2+15 and a slight rise to B_2+30. When all sites were grouped (Fig. 3a), significant changes occurred between B_2 and B_2+15 (31–47 m from the stream), but not beyond this. During the day, changes along the gradient were significant to B_2+15 when all sites were grouped (Fig. 3b). Soil temperature increased by ~16% from the buffer to B_2+15 at two sites, but three sites showed no significant increase. The general patterns remained the same as at night. The forest

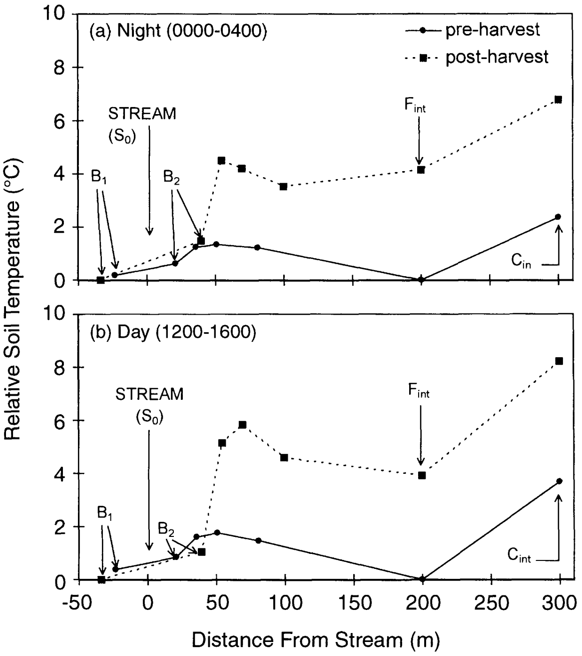

FIG. 3. Changes in average relative soil temperature [$\Delta T_s(i)_{avg} = T_s(i) - \min[T_s(1, \ldots, 8)]$, where $T_s(i)$ is average soil temperature at station *i*, and $\min[T_s(1, \ldots, 8)]$ represents the minimum average soil temperature among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites during two time periods. Note that there are no data for the stream (distance = 0).

interior and clearcut stations were statistically different from each other and all gradient stations during both night and day periods ($P < 0.0001$).

Gradients at the post-harvest sites were quite different (Fig. 3). The lowest soil temperature typically occurred at B_1 for all sites at night. Then there was a rise to B_2 (17–72 m from the stream) and a distinct increase (~24%) from the buffer edge into the harvested area. Significant changes were found along the gradient between B_2 and B_2+15 and between B_2+30 and B_2+60 (a decrease of ~4.4%). During the day, statistically significant changes occurred among all stations beyond the buffer edge and into the upland, although B_1 and B_2 were statistically similar. From B_2 to B_2+15, soil temperature increased by an average of 32%.

Surface air temperature.—Nighttime pre-harvest patterns showed that the lowest surface temperature was at the buffer edges, with a slight (~4%) increase at B_2+15 (31–47 m from the stream), where the microclimatic gradient appeared to end (Fig. 4a). Statistical differences ($P < 0.0001$) between subsequent stations also ended at B_2+15 during the night, but significant changes continued to occur throughout the length of the transect during the day (Fig. 4b), when all sites were grouped. However, only one individual site showed a significant change in surface temperature beyond B_2+30 (46–62 m from the stream). Surface temperature increased by an average of 7.3% from B_2 to B_2+30. No data were available for the stream, forest, or clearcut stations at pre-harvest sites.

After harvest, the minimum surface temperature occurred at B_2+60 at night (Fig. 4a). The difference between B_1 (17–60 m from the stream, opposite slope) and B_2 (17–72 m from the stream) was significant ($P < 0.05$) at night, although beyond B_2 there was no statistical change until B_2+60, which was significantly lower (~3%) than the preceding station. During the day, surface temperature increased by ~34% from B_2 to B_2+15, after which there were no significant changes (Fig. 4b). This was a much sharper increase than before harvest.

Short-wave solar radiation.—Gradient plots of relative solar radiation at the pre-harvest sites showed no statistical differences from station to station along the transect during the day, except at the clearcut, which was significantly different from all other stations ($P < 0.0001$) (Fig. 5). F_{int} was statistically similar to all other stations except C_{int}. One individual site did show significant differences along the gradient to B_2+15, but the other four sites did not. Night gradients were not analyzed, since all values were zero.

At post-harvest sites, significant changes in solar radiation were found along the gradient to B_2+30 (47–

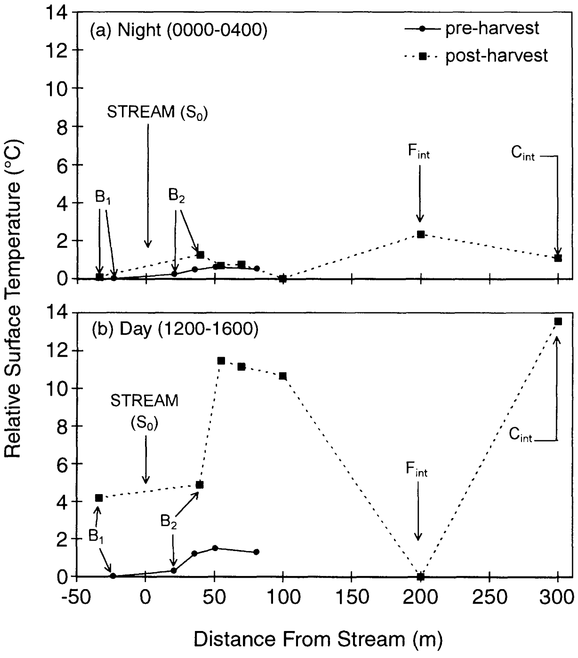

FIG. 4. Changes in average relative surface temperature [$\Delta T_{sf}(i)_{avg} = T_{sf}(i) - \min[T_{sf}(1, \ldots, 8)]$, where $T_{sf}(i)$ is average surface temperature at station *i*, and $\min[T_{sf}(1, \ldots, 8)]$ represents the minimum average surface temperature among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites during two time periods. Note that there are no data for the stream (distance = 0).

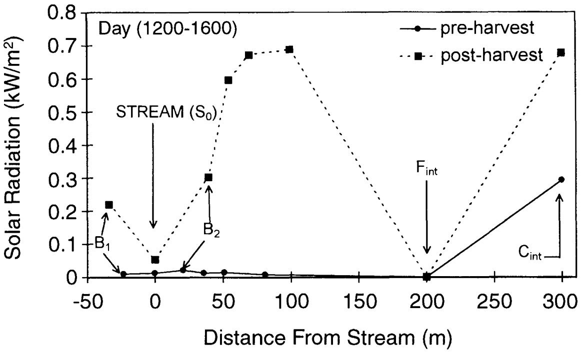

FIG. 5. Daytime changes in average relative solar radiation [$\Delta R_t(i)_{avg} = R_t(i) - \min[R_t(1, \ldots, 8)]$, where $R_t(i)$ is average solar radiation at station i, and $\min[R_t(1, \ldots, 8)]$ represents the minimum average solar radiation among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites. Nighttime data were not analyzed, since all values were zero. Pre-harvest light values were relatively constant but increased dramatically following the upland harvest.

102 m from the stream), beyond which light values were statistically similar to C_{int}. The forest interior station was significantly lower than all other stations ($P < 0.05$). The typical pattern involved a sharp increase in solar radiation from B_2 to B_2+15, then an additional increase to B_2+30. The total increase along the gradient from the stream to B_2+30 was, on average, 950% (i.e., from very small values to almost full sun).

Relative humidity.—Average nighttime humidity patterns at the pre-harvest sites showed no significant differences between the buffers and the stream (Fig. 6a). However, there was a relative decrease (~2.4%) in humidity from B_2 (16–32 m from the stream) to B_2+15, then an increase (~1.4%) to B_2+30. These differences were statistically significant ($P < 0.05$). Beyond B_2+30, there were no significant changes. The forest station was statistically different from all stations except B_2+15, and the clearcut was significantly different from all other stations. Daytime humidity increased from B_1 to the stream, then decreased along the gradient until B_2+15, where the gradient seemed to end (Fig. 6b). The total decrease was about 11% from the stream to B_2+15. Statistical differences between gradient stations ended at B_2+15, where values approximated those inside the forest. C_{int} had significantly lower relative humidity than all other stations ($P < 0.0001$).

Post-harvest gradients were not markedly different from pre-harvest gradients (Fig. 6), except that all transect stations had humidity values closer to that at C_{int} than they did before harvest. In addition, while the stream showed significantly higher humidity than F_{int} before harvest, at post-harvest sites these stations were not significantly different. Statistical differences were found between all consecutive transect stations to B_2+15 (~16.6% increase from the stream) during the day, and to B_2+30 (~1.5% decrease from the stream to B_2+15, then ~1.9% increase to B_2+30) at night ($P < 0.0001$). The only exception was that S_0 and B_2 (17–72 m from the stream) were not statistically different at night.

Wind speed.—Individual gradient plots of wind speed at pre-harvest sites showed no predominant pattern, although when all sites were grouped (Fig. 7), significant changes ($P < 0.05$) occurred along the transect except between B_2 (16–32 m from the stream) and B_2+15 at night. The forest station was statistically similar to all stations except B_2+30, B_1, and C_{int}. The clearcut had significantly higher wind speed than all other stations. During the day, significant changes occurred from B_1 to the stream and from B_2+30 to B_2+60, but no typical pattern could be described for individual sites. Wind-speed patterns varied widely at individual sites, and were possibly more sensitive to topographic or vegetational differences between sites than other variables. The only consistent feature of the pre-harvest gradients was that wind speed at C_{int} was significantly higher than any other station, and even this did not hold for site 5.

At post-harvest sites, wind speed increased significantly (~75% at four sites) from the buffer edge into the clearcut at night (Fig. 7). Statistical changes occurred between all adjacent transect stations except between B_2+15 and B_2+30, which were not significantly different from C_{int}. Again, however, there was much

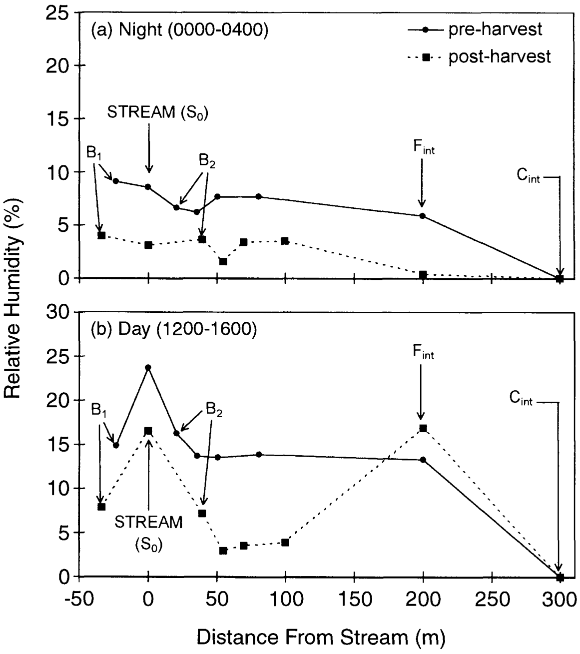

FIG. 6. Changes in average relative humidity [$\Delta h(i)_{avg} = h(i) - \min[h(1, \ldots, 8)]$, where $h(i)$ is average humidity at station i, and $\min[h(1, \ldots, 8)]$ represents the minimum average humidity among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites during two time periods.

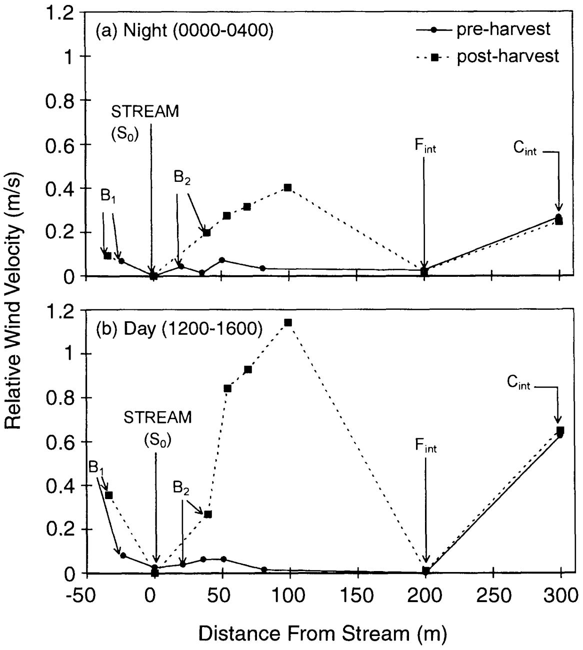

FIG. 7. Changes in average wind speed [$\Delta v(i)_{avg} = v(i) - \min[v(1, \ldots, 8)]$, where $v(i)$ is average wind speed at station i, and $\min[v(1, \ldots, 8)]$ represents the minimum average wind speed among the eight weather stations] with distance from the stream for combined pre-harvest and post-harvest sites during two time periods. Wind speed was highly variable, and no typical gradient could be identified at pre-harvest transects. Following harvest, wind speed increased dramatically along the gradient.

variation between patterns at individual sites, and three sites (3, 4, 5) showed patterns similar to those before harvest, except that wind speed at B_2+15, B_2+30, and B_2+60 was more similar to wind speed at C_{int} than to that at F_{int}. Daytime differences from pre-harvest patterns were clear at all sites. Lowest wind speed occurred at the stream and interior forest, followed by B_1 and B_2; wind speed then increased from the buffer edge (17–72 m from the stream) into the clearcut, with increases at each subsequent station. Statistically significant changes ($P < 0.05$) occurred along the entire length of the transect, with an average increase of ~400% from the stream to B_2+60.

Effects of buffer width and surrounding microclimate on stream microclimate

Buffer width did not appear to affect stream water temperature at our sites, except in the case of almost complete absence of streamside trees. At one site, where little or no buffer was left intact (i.e., buffer width = 0), water temperature was higher than at all other sites, but there was no clear pattern among data from the other sites. Similarly, we found no obvious dependencies on buffer width for air temperature or wind speed at the stream. However, solar radiation and relative humidity did appear to have some association with buffer width. Total solar radiation (R_t) decreased exponentially with increasing buffer width (R_t = exp[−2.5186 − 0.0409 × (buffer width)]; $R^2 = 0.60$) (Fig. 8a), and relative humidity displayed a positive exponential relationship with buffer width (h = exp[4.3671 + 0.0412 × ln(buffer width)]; $R^2 = 0.46$) (Fig. 8b), although this relationship was weaker.

Regression analyses between stream water temperature and microclimatic variables in the surrounding area (i.e., gradient stations) revealed that wind speed, relative humidity, and solar radiation had little or no relationship with stream water temperature. We found intermediate effects of air and surface temperatures on water temperature ($R^2 = 0.20$–0.70). Soil temperature, however, appeared to exert a strong influence on stream water temperature, especially at pre-harvest sites ($R^2 = 0.75$–0.98). R^2 values at post-harvest sites remained high but were usually slightly lower than those at pre-harvest sites.

The best-fit regression line for stream water temperature vs. soil temperature at pre-harvest sites typically had a steeper slope than that for post-harvest sites (Fig. 9), suggesting that the relationship between the two variables changed with harvesting. The difference in slopes was most prominent at stations inside the clearcut (i.e., B_2+15, B_2+30, B_2+60). At buffer stations, the slopes were often nearly equal or steeper at the post-harvest sites.

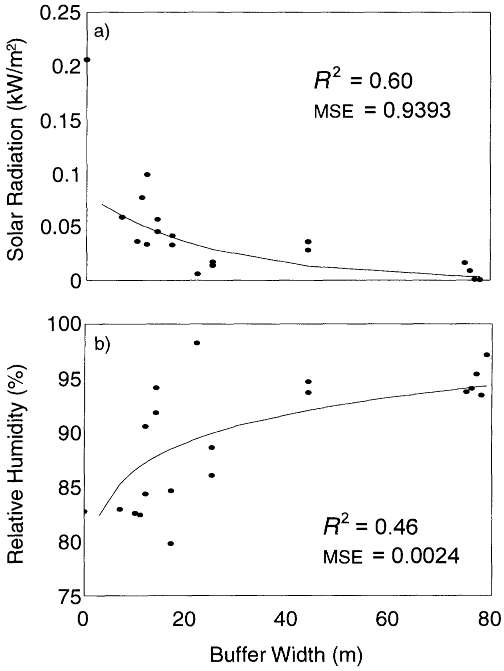

FIG. 8. Effects of buffer width on relative humidity and solar radiation at the stream. All 20 transects were used in analyses; the points grouped around 80 m represent pre-harvest data. Best-fit regression models are: R_t = exp[−2.5186 − 0.0409 × (buffer width)], $R^2 = 0.60$; and h = exp[4.3671 + 0.0412 × ln(buffer width)], $R^2 = 0.46$.

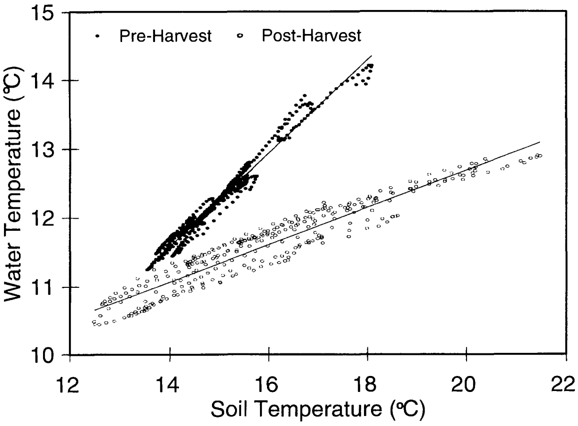

FIG. 9. Regression plots of water temperature vs. soil temperature at B_2+60 for pre-harvest (transect 2B) and post-harvest (transect 2A) data. The pre-harvest model is $T_w = 2.1058 + 0.6670(T_s)$, where T_w is stream water temperature and T_s is soil temperature at B_2+60. The post-harvest model is $T_w = 7.2777 + 0.2705(T_s)$. $R^2 = 0.98$ and 0.91 for the pre- and post-harvest models, respectively. Although this relationship was strong at our sites, it is probably highly variable depending on site-specific conditions, so extreme caution should be used in applying these results generally.

DISCUSSION

We found distinct riparian gradients at pre-harvest (forested) sites for air temperature, soil temperature, surface air temperature, and relative humidity. Gradient lengths (i.e., distances from the stream beyond which microclimate values showed no additional statistical differences and usually approximated upland interior forest values) ranged from 31 to 47 m for air and soil temperature and from 31 to 62 m for surface temperature and humidity. The temperature and humidity gradients were probably partially related to topography at our sites. Ross (1958) showed that lower temperatures and higher humidities often occur in valleys as compared with uplands. The presence of surface water probably influenced humidity at our sites.

We detected no obvious gradient for solar radiation or wind speed. The amount of solar radiation reaching the forest floor is primarily dependent on tree species, height, and overstory canopy cover, which influence how much light is intercepted (Gates 1965, Reifsnyder et al. 1971, Lee 1978, Chen et al. 1993). These variables were relatively constant throughout our sites, so it is not altogether surprising that solar radiation was relatively constant as well. Although significant changes in average wind speed were found, no predominant pattern emerged at pre-harvest sites, suggesting that this variable might have been more sensitive to individual site differences in topography or vegetation. Although wind speed is often lower in valleys, which are protected by the slopes (Linacre 1992), it is also slowed and dispersed by forest trees and understory (Chen et al. 1995). This effect might have had greater importance in determining station-to-station variation along our transects.

Harvesting affected near-stream microclimatic gradients at our sites. Its primary influence was to increase temperatures and decrease humidity along the gradient. If the gradient stabilized, it usually did so well into the clearcut at values closer to the interior clearcut station than the interior forest station. Buffer station values showed a large relative change toward clearcut values in most cases. This suggests that the riparian gradient was interrupted or at least affected by the transition from intact forest to clearcut conditions. Because the buffer station was situated at the edge of the clearcut at post-harvest sites, the surrounding forest structure had changed. Studies have shown that removal of trees increases direct solar radiation and air turbulence, elevating temperatures (during the day) and wind speeds, and lowering air moisture (Geiger 1965, Lee 1978). Hungerford and Babbitt (1987), for example, found that soil temperature up to 16 inches (40.6 cm) deep was significantly increased by clearcutting in Montana and Wyoming. The buffer station was exposed, at least partially, to these effects after harvesting had occurred.

These edge influences also appeared to penetrate the forested buffer and affect stream microclimate. Values at the stream station exhibited a slight change in the direction of the clearcut value after harvesting. Although we did not monitor the area between the stream and buffer edge due to equipment shortage, Chen et al. (1995) found that clearcut edges can affect microclimate up to 240 m into upland Douglas-fir forests. Because most buffers in this study were <30 m and none were >72 m wide, it is unlikely that any riparian microclimatic gradient retained an unaltered character within the buffer area due to these edge influences.

Changing the microclimate near the stream through harvesting in the upland can alter some functions of the riparian zone, including maintenance of high biodiversity. Amphibians rely on both the cooler temperatures, higher humidity, and reduced wind velocity of near-stream environments to prevent dehydration and allow respiratory functions (Petranka et al. 1993, Dupuis et al. 1995). Other taxa, such as many groups of small and large mammals (e.g., Feldhamer and Rochelle 1982, Raedeke et al. 1988), have also been shown to rely on riparian microclimates (e.g., humidity, cooler air) for physiological or other reasons. Although specific habitat needs for commonly known riparian species have not been widely studied, microclimate may well be a vital factor for many such animals. Because of these associations with habitat, changes in riparian microclimate caused by harvesting in the upland can reduce landscape connectivity and effectively fragment the landscape for species unable to cope well with the altered conditions.

Microclimate also plays a critical role in plant regeneration, growth, and distribution. For example, Hungerford and Babbitt (1987) found that higher ground surface temperatures caused by increased solar radiation due to logging resulted in an increase in seedling mortality. In addition, Ross (1958) found strong relationships between the distribution of some vegetation associations and various microclimatic factors. Although soil moisture was an important variable in many of his findings, air temperature and humidity were sometimes just as critical. Kramer and Kozlowski (1979) proposed that internal water budgets, which result from rates of both absorption of water from the soil and transpiration, are probably more important to plant growth than absorption alone. The high productivity and diversity of plants near streams (e.g., Nilsson 1992, DeFerrari and Naiman 1994, Naiman et al. 1997) might be partially accounted for by this combination of ideal microclimatic and moisture conditions. Changing these conditions may therefore affect plant composition, diversity, and succession near streams.

Stream variables are also important to consider in riparian studies because of the linkages that exist between terrestrial and aquatic environments. Altered conditions near the stream can affect stream microclimate, possibly changing aquatic functions. Water temperature, for example, affects stream biotic communities and water quality (e.g., dissolved oxygen content), and plays a critical role in fisheries management (Swift and Baker 1973, Magnuson et al. 1979, Hornbeck et al. 1984, Theurer et al. 1985, Brown and Binkley 1994). Although we did not find any relationship between water temperature and buffer width, we did find a strong influence of soil temperature in the surrounding land area on water temperature, suggesting a high predictive capability, at least for our sites. Extreme caution should be used, however, in applying these results to other sites, since the relationship is probably extremely variable. What made this result most interesting was that strong associations were found between stream water temperature and soil temperature, even at stations well away from the stream (e.g., B_2+60 and C_{int}). In fact, at pre-harvest sites, soil temperature at stations located 60 m upslope from the buffer station usually had a stronger influence on water temperature than did soil temperature at the buffer stations. This suggests that activity in the watershed up to or more than 180 m away may affect stream microclimate even when a buffer strip is left intact.

This strong relationship between soil temperature and stream water temperature also suggests that the streams in our study (low-order streams) were probably receiving much of their water input from the surrounding land area (particularly groundwater), rather than from upstream. Groundwater temperature is influenced by the temperature of the soil through which it passes. At our study sites, soils were relatively coarse and slopes were moderate to steep, which could help explain why soil temperature at locations closer to the upland was more influential than that at locations nearer the stream. Groundwater in the upland would probably move slowly through the soil and be strongly affected by it. Then it would move downslope to the stream relatively quickly due to the porous soils and steep slopes, preventing soils near the stream from influencing the groundwater temperature very much. Groundwater would enter the stream at temperatures closer to upland soil temperatures, and stream water temperature would therefore be more closely related to upland soil temperatures than to those near the stream.

The relationship between soil and water temperature grew slightly weaker, overall, after the sites were clearcut. Additionally, the regression lines usually showed a decreased slope after harvest, especially at soil temperature locations inside the clearcut. The diurnal patterns of soil temperature were generally less variable in forested conditions and similar to the diurnal variation found with stream water temperature (*data not shown*). After harvesting, soil temperature in the harvested areas increased in diurnal variation. Therefore, it makes sense that it would require a greater overall change in soil temperature at these stations to produce the same change in stream water temperature. These results suggest that microclimate changes caused by harvesting in the watershed even well away from the stream may affect the riparian microclimate and should not be ignored when developing management plans.

The influence of buffer width on microclimate at the stream was different for each variable. Air and water temperature seemed relatively unaffected, while relative humidity and solar radiation showed clear relationships. Wind speed was highly variable and provided no conclusive results. Although solar radiation is primarily affected by overstory canopy cover and tree height (Lee 1978), narrower buffer widths might provide an additional inlet, increasing light levels. As the buffer widens, the amount of solar radiation able to penetrate the vegetation and reach the stream station would decrease. Chen et al. (1995) found solar radiation gradients extending 15–60 m into upland old-growth Douglas-fir forest. They also reported humidity and wind-speed gradients at >240 m. Increased wind speed reaching the stream through narrower buffers would mix the air and consequently decrease humidity. Although wind speed showed no definite pattern because of high variability, it probably played a role in decreasing humidity at streams where buffers were narrower.

Managers need to consider multiple factors when determining appropriate buffer widths for harvesting near small stream environments. Because riparian microclimate can be influenced by activities that occur in the watershed outside the buffered area, management decisions should consider these as well. Selective harvesting instead of clearcutting in upland areas near small streams could help reduce the changes in those variables related to water temperature, as well as increasing the effectiveness of the buffer (Franklin 1992).

In addition, buffer widths sufficient to maintain unaltered riparian microclimatic gradients will include enough area to mitigate edge effects created by harvesting in upslope areas. For example, if management objectives include maintaining these gradients, a width sufficient to eliminate most of the microclimatic effects of the clearcut edge should be added to the width required for gradients to stabilize. This would mean that buffers for stream sites similar to ours would have to be >45 m on each side of the stream, based on our results and those of Chen et al. (1995). Microclimatic gradients and far-reaching edge effects, depending on individual variables, could extend necessary widths beyond 300 m, however. As discussed previously, Chen et al. (1995) found that humidity and wind speed were sometimes affected at distances >240 m from clearcut edges into old-growth Douglas fir forest. This, combined with our data showing near-stream gradients extending up to about 60 m, suggests that buffers may sometimes need to be ≥300 m wide to be adequate. Consequently, many standard buffer widths currently in use (e.g., ~10–90 m; MacDonald et al. 1991, 1993) may not effectively protect the full riparian and transitional microclimate. Additional research at sites with differing characteristics and research concerning microclimatic edge effects on steep slopes are needed before generalizations, if any, can be made.

This is not to say that buffer widths should be decided on the basis of microclimatic gradients alone. Microclimate is only one factor contributing to the unique conditions found near streams. However, because ecosystem components interact with one another, information on this and other components combined can help us better understand how the ecosystem and its functions may change in response to nearby land-use practices such as harvesting.

Our results and conclusions were limited by the intervals between stations along our transects, which were dictated largely by equipment limitations. Further refinement of the extent of riparian and transitional microclimate could be provided with finer scale studies of these gradients. This study, however, demonstrates a generally useful method for characterizing and comparing pre- and post-treatment gradients through riparian areas.

Conclusions

1) Riparian microclimatic gradients existed for air temperature, soil temperature, surface air temperature, and relative humidity. Short-wave solar radiation displayed no apparent riparian gradient, and wind speed, though differing along the transect, showed no definite pattern. Generally, pre-harvest gradients approached upland forest interior values within 31–47 m from the stream, although surface temperature and humidity gradients often extended further (31–62 m).

2) Harvesting influenced riparian microclimatic gradients. Variable values from the buffer and each subsequent station began to approximate clearcut values instead of forest interior values as before harvest, effectively interrupting or eliminating the riparian gradient. Taking upslope edge effects into account, buffers at least 45 m wide on each side of the stream are needed to maintain an unaltered microclimatic gradient near streams in our study, although necessary widths depend on several variables and could extend up to 300 m.

3) Buffer width influenced relative humidity and solar radiation at the stream, but appeared to have little effect on other variables. Relative humidity increased exponentially with increasing buffer width ($R^2 = 0.46$), and solar radiation decreased exponentially ($R^2 = 0.60$) with increasing buffer width.

4) Stream water temperature was strongly affected by soil temperature in the surrounding area at our sites. However, harvesting appeared to weaken the relationship and flatten the slope of the regression line, possibly because of increased diurnal variation in soil temperature as well as hydrologic differences between clearcuts and intact forests. Selective harvesting in the upland is strongly recommended at sites where the surrounding watershed exerts similar strong influences, so as to mitigate these indirect effects on stream water temperature.

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