# The Effectiveness of Different Buffer Widths for Protecting Headwater Stream Temperature in Maine

**Ethel Wilkerson, John M. Hagan, Darlene Siegel, and Andrew A. Whitman**

**Abstract:** We evaluated the effect of timber harvesting on summer water temperature in first-order headwater streams in western Maine. Fifteen streams were assigned to one of five treatments: (1) clearcutting with no stream buffer; (2) clearcutting with 11-m, partially harvested buffers, both sides; (3) clearcutting with 23-m, partially harvested buffers; (4) partial cuts with no designated buffer; and (5) unharvested controls. Over a 3-year period we measured summer water temperature hourly before and after harvesting, above and below the harvest zone. Streams without a buffer showed the greatest increase in mean weekly maximum temperatures following harvesting (1.4–4.4°C). Streams with an 11-m buffer showed minor, but not significant, increases (1.0–1.4°C). Streams with a 23-m buffer, partial-harvest treatment, and control streams showed no changes following harvest. The mean weekly maximum temperatures never exceeded the thermal stress limit for brook trout (25°C) in any treatment group. The mean daily temperature fluctuations for streams without buffers increased from 1.5°C/day to 3.8°C/day, while with 11-m buffers fluctuations increased nonsignificantly by 0.5–0.7°C/day. Water temperatures 100 m below the harvest zone in the no-buffer treatment were elevated above preharvest levels. We concluded that water temperature in small headwater streams is protected from the effects of clearcutting by an 11-m buffer (with >60% canopy retention). For. Sci. 52(3):221–231.

**Key Words:** Headwater stream, water temperature, riparian buffers, forest practices, buffer width.

Since passage of the United States Clean Water Act of 1972, much attention has been devoted to maintaining the ecological integrity of surface water, including a greater scrutiny of timber operations adjacent to watercourses. One forest management approach to minimize water quality impacts (e.g., temperature increases and sedimentation) has been to establish buffer zones with restrictions on timber harvest activities next to lakes, rivers, and large streams. This approach has addressed many water quality concerns associated with timber harvesting, but buffering waterways can represent a significant cost to landowners in terms of lost timber revenue.

Small headwater streams (intermittent and small first-order) often escape the regulatory mandates for riparian buffers (Sidle et al. 2000). For example, in the state of Maine, streams draining watersheds of less than 121 ha have no buffer or shade requirements under state law (Maine Department of Conservation 1999). Increasing awareness of the ecological importance of headwater streams (Richardson 2000) has raised questions about the amount and type of regulatory protection small streams should receive. Forest landowners and managers are concerned about potential regulations requiring buffers on small headwater streams because these features can be extremely common across the landscape. Headwater streams can account for 65–75% of the cumulative length of all stream and river channels in a watershed (Leopold et al. 1964), and establishing buffers on these streams would remove large portions of land from harvesting (Bren 1995), resulting in significant cost to landowners.

Studies of stream temperature after timber harvest have shown increases in summertime stream temperatures and diurnal fluctuations (Brown and Krygier 1967, Burton and Likens 1973, Lynch et al. 1984, Beschta et al. 1987, Kochenderfer and Edwards 1991, Johnson and Jones 2000, Murray et al. 2000, Jackson et al. 2001, Macdonald et al.

John M. Hagan, Director, Forest Conservation Program at Manomet Center for Conservation Sciences, 14 Maine St., Brunswick, ME 04011—Phone: (207) 721-9040; Fax: (207)-721–9144; jmhagan@ime.net. Ethel Wilkerson, Stream Project Manager, Manomet Center for Conservation Sciences, 14 Maine St., Brunswick, ME 04011—Phone: (207) 721-9040; Fax: (207) 721-9144; ewilkerson@prexar.com. Darlene Siegel, Fisheries Biologist, Tetra Tech, Inc., 1020 SW Taylor St., Suite 530, Portland, OR 97205—Phone: (503) 223-5388 ext. 226; Darlene.Siegel@tetratech.com. Andrew A. Whitman, Project Director, Manomet Center for Conservation Sciences, 14 Maine St., Brunswick, ME 04011—Phone: (207) 721-9040; awhitman@prexar.com.

Acknowledgments: Careful harvest planning and timing were essential to the success of this study. We are grateful to all of the foresters who implemented the difficult requirements of this study, including helping us locate candidate study streams and adjusting harvest crews and schedules to ensure harvesting occurred at the correct time: Frank Cuff, Tom Dodd, Steve Gettle, Pete Johnson, Dan Lamontagne, Ken McAllister, Kip Nichols, Kirk McDonald, Tom Short, and Jim Stewart. We also thank all the forest landowners who provided access to the streams for this study: Plum Creek Timber Company, Seven Islands Land Company, International Paper, and Mead-Westvaco. Carl Haag, Doug Denico (Plum Creek Timber Company), and Si Balch (Mead-Westvaco) were particularly helpful in making sure this study succeeded and proceeded as planned. Their advice, encouragement, and leadership played a major role in the success of this experiment. We also benefited greatly from the knowledge and experience of Jeff Light and Ron Steiner (Plum Creek Timber Company), and an earlier version of this manuscript was much improved by their thoughtful and careful attention to detail. We thank our many field assistants who deployed, monitored, and retrieved temperature probes, and collected other data that will be reported in subsequent manuscripts: Liane Beggs, Josh Campbell, Christopher Collins, Aimee Genung, Morgan Hall, Stephanie Hart, Corey Myers, Sacha Pealer, Matthew Peters, Anne Shilling, Crista Straub, Tara Trinko, and Eric Zell. Finally, we thank our funders: the National Council of Air and Stream Improvement, the Cooperative Forest Research Unit at the University of Maine, Plum Creek Timber Company, and the National Fish and Wildlife Foundation. Additional funding for manuscript preparation was provided by the Harold Whitworth Pierce Charitable Trust.

Manuscript received February 9, 2005, accepted December 6, 2005

2003). Elevation of water temperature is a concern for a number of reasons. Temperature is key in determining rates of metabolism, growth, decomposition, and solubility of gasses (Beitinger and Fitzpatrick 1979). Increases in temperature can result in increased decomposition rates and larger parasite populations (Brett 1956), decreased dissolved oxygen concentrations (Brown and Krygier 1967, Corbett et al. 1978), and increased metabolic rate, which causes increased oxygen consumption in biota (Cairns 1970).

Solar radiation is the dominant factor increasing stream temperatures after canopy removal (e.g., Brown and Krygier 1970, Sullivan et al. 1990). However, different studies examining canopy removal have yielded varying results and it is difficult to draw generalities. For example, in the absence of riparian buffers, temperature has been shown to increase from 3 to 4°C (Pacific Northwest, Brown and Krygier 1967, New Hampshire, Burton and Likens 1973, West Virginia, Kochenderfer and Edwards 1991) to 8°C (Washington, Caldwell et al. 1991). When buffers are retained, temperature changes are smaller. Riparian buffers between 15 and 20 m wide resulted in temperature increases of 2.0–2.6°C (Washington, Jackson et al. 2001), and buffers 20–30 m wide resulted in temperature increases between 1.0°C (Kochenderfer and Edwards 1991) and 2.5° C (Pennsylvania, Rishel et al. 1982, Pennsylvania, Lynch et al. 1984) of control watersheds.

The variability among studies can be attributed to a complex mix of factors, including the amount of shade retained within the buffers (Brown and Krygier 1970, Feller 1981, Lynch et al. 1985, Macdonald et al. 2003), site-specific attributes such as variability in stream size, depth, and water volume (Brown and Krygier 1967, Feller 1981, Lynch et al. 1985, Caldwell et al. 1991), geographic aspect (Kochenderfer and Edwards 1991, Macdonald et al. 2003), inputs of groundwater (Sullivan et al. 1990, Caldwell et al. 1991), and geographic location (latitude and elevation) (Hewlett and Fortson 1982, Caldwell et al. 1991). The purpose of our study was to examine the effectiveness of different buffer widths for protecting water temperature in small headwater streams in managed forest landscapes of western Maine. Most stream studies have no replicates within a treatment prescription, and often lack pre and posttreatment comparisons of dependent variables. Our study had multiple streams per treatment group as well as pre and posttreatment data. The objectives of our study were twofold: (1) to evaluate water temperature changes after timber harvest on streams with partially harvested buffer strips of various widths, and (2) to examine spatial temperature recovery (downstream of harvest zones).

# Methods

## *Study Layout and Design*

Western Maine is characterized by moderately rugged, forested topography with numerous streams, rivers, and lakes. Elevations of major peaks range from 900 to 1,300 m. The primary land use in the region is forestry, with large parcels of land managed primarily for timber products. The forest is typical of the Acadian Forest Region (Seymour and Hunter 1992), consisting of northern hardwood, spruce-fir, and mixed hardwood-softwood stands. Northern hardwood stands are dominated by sugar maple (*Acer saccharum* Marsh), beech (*Fagus grandifolia* Ehrh.), and white and yellow birch (*Betula papyrifera* Marsh and *Betula alleganiensis* Britton), while spruce-fir stands consist primarily of red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* [L.] Mill.). Softwood species tend to dominate along water courses.

We selected for study 15 headwater streams draining small watersheds with mature closed-canopy cover (>85%) at least 15 m tall and undisturbed by logging activity within the past >20 years. All streams were located within a 100-km radius of 45°00′00″ N, 70°20′00″ W (Figure 1). Watersheds ranged in area from 30 to 195 ha, with a mean of 82 ha. Along each stream we established 500-m study segments with the downstream end of the segment at least 20 m upstream from any human-made disturbance such as a logging road or timber harvest. Typically, the upper end of each study reach was within 500–1,000 m of the watershed divide. We marked the study reach with rebar on both sides of the stream at 100-m intervals (Figure 2) to monument the locations of temperature probe placement. Galvanized metal spikes (30 cm long) were placed every 20 m along the stream segment to monument locations for aspect, gradient, bankfull width (i.e., distance between stream banks), and canopy closure measurements.

## *Sampling Regime and Treatments*

Data were collected simultaneously at both treatment and control sites, both before and after the treatments were applied. Pretreatment sampling in 2001 established the relationship between the treatment sites and the control sites. After sampling in the pretreatment year, 200-m by 300-m (6 ha) harvest zones were created on both sides of each stream beginning at the 100-m station and extending upstream to

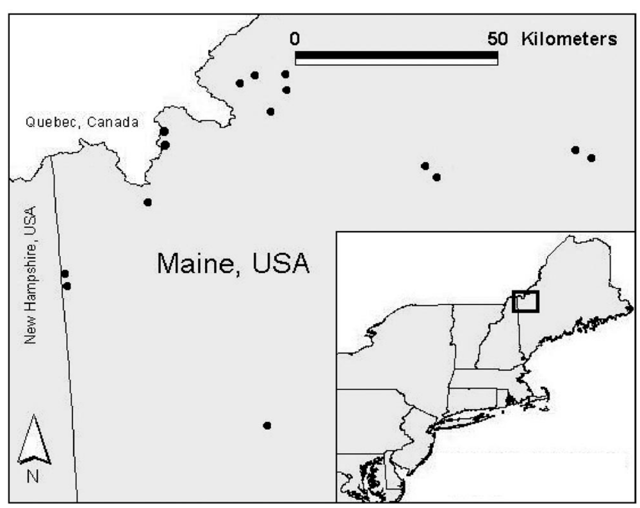


**Figure 1. Map of study streams.**

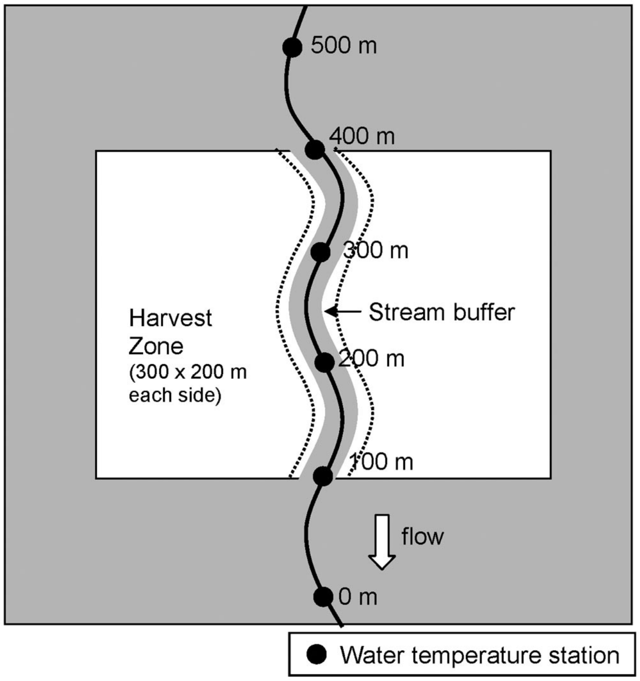


**Figure 2. Layout of study segments and harvest zones.**

the 400-m station (except for controls, Figure 2). There had been no recent harvesting (within the last 20 years) above the study reach within the watershed, and no harvesting was allowed upstream during the study. Forest canopy remained intact for at least 110 m below the harvest zone.

Each of the 15 study streams was randomly assigned to one of five treatment groups: (1) clearcut harvest (less than 6.8 $m^2$/ha residual basal area) leaving no buffer (0-m treatment); (2) clearcut harvest with 11-m buffers on both sides of the stream (11-m treatment); (3) clearcut harvest with 23-m buffers on both sides of the stream (23-m treatment); (4) selection cut harvest retaining at least 13.7 $m^2$/ha residual basal area in the harvest zone, without a specified buffer width (partial-harvest treatment); and (5) unharvested (control treatment). We chose a 23-m buffer for one treatment because it corresponded with existing state buffer width requirements for higher-order streams (Maine Department of Conservation 1999). To examine the capacity of a narrower buffer to protect stream temperature, we also selected an 11-m treatment (approximately one-half of 23 m). Partial harvesting was allowed in all buffers because timber removal within buffer zones is permitted and is a common practice in Maine. In this study we required at least 13.7 $m^2$/ha basal area to be retained (about 60% of a fully stocked stand) within the buffer zone. In all treatment groups, compaction and/or scarification of soil was not permitted within 8 m of the stream channel. Trees could be removed within 8 m of the stream channel if equipment could remove the trees without compacting or disturbing near stream soils. Harvesting occurred in the winter of 2001–2002 and posttreatment sampling occurred in 2002 and 2003.

## *Measurement Methods*

Aspect, gradient, and bankfull width measurements were taken every 20 m along each 500-m study segment. Canopy closure above the stream channel was measured using a concave spherical densiometer before and after harvest operations (Lemmon 1957). Canopy measurements were taken in the middle of the stream channel every 20 m within the harvest zone facing upstream, downstream, left, and right with the densiometer at elbow height (~1.4 m). We assessed tree (≥8 cm dbh) basal area within the buffer and within the adjacent harvest zones using a 15-factor prism both before the harvest (2001) and after the harvest (in 2002 only). Measurements of within-buffer basal area were taken from the middle of the stream channel. Basal area measurements for the harvest zone were taken along transects originating at the stream bank edge and extending perpendicularly into the harvest zone for 200 m. Prism readings were taken every 50 m and in the same locations in 2001 (pretreatment) and 2002 (posttreatment). Study site characteristics are presented in Table 1.

**Table 1. Descriptive statistics for the 15 study streams**

| Stream | Treatment | 0-m Station elevation (m) | 500-m Station elevation (m) | Watershed area (ha) | Average aspect | Average gradient (%) Mean (min, max) | Bankfull width (m) Mean (min, max) |
|---|---|---|---|---|---|---|---|
| Kibby | 0 m | 637 | 724 | 30 | SSE | 15 (4, 31) | 1.9 (0.9, 4.0) |
| Pierce 1 | 0 m | 469 | 518 | 52 | NW | 11 (3, 19) | 2.5 (1.0, 6.5) |
| Skinner 1 | 0 m | 616 | 678 | 41 | N | 12 (9, 17) | 3.1 (1.3, 5.5) |
| Bald Mt. | 11 m | 345 | 398 | 96 | NNW | 10 (5, 17) | 3.9 (2.3, 5.8) |
| Caratunk | 11 m | 408 | 442 | 80 | SE | 7 (0, 19) | 2.8 (1.3, 6.1) |
| Skinner 2 | 11 m | 619 | 676 | 37 | NW | 12 (12, 20) | 2.0 (0.7, 4.8) |
| Mass 2 | 23 m | 628 | 700 | 53 | NNE | 13 (3, 25) | 2.6 (1.3, 5.1) |
| Roxbury | 23 m | 371 | 407 | 67 | WNW | 6 (2, 11) | 2.4 (1.1, 3.4) |
| Sanderson | 23 m | 462 | 512 | 185 | E | 9 (2, 14) | 3.8 (2.2, 6.5) |
| Mass 1 | Partial | 598 | 648 | 58 | SSE | 12 (5, 31) | 2.0 (0.8, 4.9) |
| Pierce 2 | Partial | 436 | 529 | 44 | W | 18 (10, 31) | 2.3 (1.1, 5.2) |
| UpCup | Partial | 647 | 672 | 140 | S | 5 (2, 7) | 4.5 (2.1, 13.2) |
| Appleton | Control | 687 | 755 | 82 | NNW | 13 (6, 19) | 2.8 (1.4, 4.7) |
| Bryant | Control | 455 | 527 | 71 | SW | 11 (3, 16) | 3.6 (2.6, 5.5) |
| Dud | Control | 577 | 639 | 195 | SW | 11 (3, 17) | 4.2 (2.4, 7.6) |

Mean of 21 readings at 20-m intervals along each 500-m study reach.

At each of the 15 study streams, water temperature was measured hourly between June 15 and Aug. 15 of each year using automatic data loggers (OnSet Optic StowAway temperature loggers, Onset, Inc., Bourne, MA, error ±0.2°C). Clocks in all loggers were synchronized to the same launching computer on deployment. Data loggers were deployed at 100-m intervals along the 500-m study segment (see Figure 2). Loggers were placed inside 5-cm-diameter opaque PVC tubes to prevent possible influence of direct solar radiation on the logger casing. Loggers were secured by plastic cable ties to 30-cm galvanized metal spikes hammered into the streambed. For this study we only used data from loggers at the upper end of the harvest zone (400-m station), lower end of the harvest zone (100-m station), and 100 m below the harvest zone (0-m station).

During the summer in all 3 years of the study (2001–2003), portions of the 500-m study segment at many of the 15 streams began to dry, decreasing the wetted width and depth of the stream channel, sometimes completely. As a result, some water temperature data loggers became exposed to the air. Field personnel visited each stream every 1 to 3 weeks throughout the sample period. When dry data loggers were observed, if possible they were re-submerged in water as close as possible to the data logger's assigned location along the study segment. In addition, during each stream visit, the condition (wet or dry) of each probe was recorded. We eliminated from analysis any temperature data that we knew to represent, or we suspected to represent, dry conditions. If there was any question as to whether the probe was submerged, we eliminated the data from analysis. This was accomplished by using a combination of site visit data sheets and visual inspection of seasonal temperature traces to remove days with questionable data. Different streams had varying percentages of "wet days" in each year of study (Table 2), from a low of 23% wet days to a high of 100%.

## Temperature Analysis

Mean weekly maximum temperature at the 100-m station was calculated for each stream to show the pre and postharvest temperature range for streams in the study. Mean weekly maximum temperature is a 7-day average of daily maximum stream temperature and is often used in stream temperature studies because it is a more biologically meaningful metric than average daily temperature (Oliver and Fidler 2001) or daily maximum temperature (Washington Water Quality Program 2002).

For each treatment, we were interested in two primary questions: (1) how does temperature change within the harvest zone, and (2) if temperature changes, does it recover 100 m downstream of the harvest zone? To answer these questions we analyzed the following dependent variables: (1) mean maximum daily temperature difference between the 400-m and 100-m stations (i.e., the upstream and downstream boundaries of the harvest zone), (2) mean maximum daily temperature difference between the 400-m and 0-m stations (i.e., the upstream boundary of the harvest zone and 100 m below the downstream boundary of the harvest zone), and (3) mean daily temperature fluctuation (i.e., daily range) at the 100-m and 0-m station. The data set was restricted to days when the station (or multiple stations) was identified as being wet.

## Statistical Analyses

Differences in the percentage of wet days (Table 2) resulted in a variability in the number of observations among streams and years for each temperature metric. To minimize this variability we calculated a seasonal mean for each temperature metric and used this mean in the statistical analysis. The statistical analysis for each dependent variable was performed on one value for each stream per year of the study. This minimized the problem of missing data on days when a station was dry. A probe deployed at the 100-m station in one stream in the 11-m treatment group (Skinner 2) malfunctioned in the first postharvest year. The number of probes used in the analysis of each temperature metric is included in the data tables.

Because measurements were taken on the same experimental units (streams) before and after the application of a

**Table 2. Percentage of days during the 62-day sample window (June 15–Aug. 15) in the preharvest year (2001) and the postharvest years (2002 and 2003) for which the indicated temperature probe remained submerged**

| | | 400-m Probe | | | 100-m Probe | | | 0-m Probe | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Stream | Treatment | 2001 | 2002 | 2003 | 2001 | 2002 | 2003 | 2001 | 2002 | 2003 |
| Kibby | 0 m | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Pierce 1 | 0 m | 66 | 39 | 47 | 73 | 60 | 100 | 79 | 89 | 100 |
| Skinner 1 | 0 m | 100 | 100 | 100 | 100 | 100 | 98 | 100 | 100 | 100 |
| Bald Mt. | 11 m | 79 | 52 | 37 | 74 | 100 | 97 | 100 | 100 | 97 |
| Caratunk | 11 m | 79 | 73 | 100 | 79 | 97 | 100 | 77 | 90 | 100 |
| Skinner 2 | 11 m | 19 | 87 | 87 | 100 | nd | 100 | 100 | 100 | 100 |
| Mass 2 | 23 m | 13 | 44 | 27 | 100 | 100 | 100 | 100 | 100 | 100 |
| Roxbury | 23 m | 100 | 100 | 100 | 94 | 100 | 100 | 79 | 87 | 100 |
| Sanderson | 23 m | 79 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Mass 1 | Partial | 100 | 79 | 48 | 77 | 98 | 53 | 84 | 100 | 100 |
| Pierce 2 | Partial | 79 | 39 | 34 | 73 | 55 | 63 | 82 | 89 | 100 |
| UpCup | Partial | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Appleton | Control | 69 | 95 | 84 | 32 | 92 | 79 | 69 | 44 | 95 |
| Bryant | Control | 53 | 44 | 24 | 35 | 39 | 23 | 34 | 40 | 24 |
| Dud | Control | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

treatment (stream buffer prescription), we used repeated-measures analysis to examine differences among treatments for the various dependent variables (PROC MIXED, SAS 1999). Treatment and Year (1 preharvest year, 2 postharvest years) were both independent variables, and Year was the repeated variable in the analysis. The interaction term between Treatment and Year indicated whether there was a differential effect of year (pre versus postharvest) on the various buffer prescriptions. Because one treatment was a control (no harvest), and because the buffer prescriptions were quite different from one another, we expected the interaction term to be significant if harvesting had an effect on any dependent temperature variable.

If the interaction term was significant, we analyzed the main effects separately (by year among treatments, and by treatment among years) to examine which treatments and years were causing changes in the response of the dependent variable. Analysis of main effects was done using Dunnett's test (treatment effect among years) and the Dunn test (year effects among treatments). The Dunnett test (Dunnett 1955) determines whether the mean of the control group differs significantly from the mean of each treatment group (Zar 1996). The Dunn test (Dunn 1961) was used to analyze for year effects among treatments. The Dunn test analyzes differences between the pretreatment and posttreatment means within each treatment group using Bonferroni adjusted multiple *t*-tests (Howell 1982).

## Results

### *Pre and Postharvest Forest Conditions*

Basal area and buffer width measurements verified that our harvest specifications for the experimental treatments were achieved by foresters and loggers (Table 3). Basal areas of harvest zones involving clearcutting (the 0-m, 11-m, and 23-m buffer treatments) were reduced an average of 95% to well below the minimum basal area (6.9 $m^2$/ha) of the regulatory definition of a clearcut (Table 3). The harvest zones for the partial-harvest treatment maintained average residual basal areas ranging from 14.9 to 18.9 $m^2$/ha, meeting our prescribed criterion of at least 13.8 $m^2$/ha of residual basal area. The partial-harvest treatment reduced the residual basal area of the harvest zone by an average of 38%.

The 0-m treatment harvest prescription specified no streamside canopy tree retention. The streamside basal area of this treatment group was reduced by an average of 90% (Table 3). Removal of 100% of the streamside basal area was not achieved because loggers left occasional residual trees where soil and slope conditions would have resulted in compromising the stream bank or scarifying near-stream soils. The harvest prescription for the 11-m and 23-m treatment groups specified that a minimum of 13.8 $m^2$/ha of residual basal area should remain in the buffer. These specifications were met in five of the six streams in the 11-m and 23-m treatment groups. One stream in the 11-m treatment group had average riparian basal area reduced to 13.5 $m^2$/ha, slightly below the specified level (Table 3). Within-buffer basal area was reduced by an average of 31% in the 11-m treatment group, and 21% in the 23-m treatment group.

Following the harvest, stream canopy cover was reduced an average of 77% in the 0-m treatment group (Table 3). Canopy removal was not complete on this treatment, due to occasional residual trees left by loggers (see above). Canopy closure over the stream channel was reduced an average of 11% in the 11-m treatment group, and 4% in both the 23-m and partial-harvest treatment group. Mean canopy closure in the control treatment remained unchanged (Table 3).

### *Mean Weekly Maximum Temperature at the 100-m Station*

In the pretreatment year stream temperatures ranged from 11.9 to 15.6°C in the majority of the study streams

**Table 3. Average (minimum, maximum) basal area and canopy closure for preharvest year (2001) and the first postharvest year (2002) for each of the 15 study streams**

| | | Cut block basal area Mean (min, max) $m^2$/ha | | Riparian buffer basal area Mean (min, max) $m^2$/ha | | % Canopy closure Mean (min, max) | |
|---|---|---|---|---|---|---|---|
| Stream | Treatment | Preharvest 2001 | Postharvest 2002 | Preharvest 2001 | Postharvest 2002 | Preharvest 2001 | Postharvest 2002 |
| Kibby | 0 m | 23.9 (7.8, 46.8) | 1.5 (0.0, 6.2) | 30.1 (26.5, 32.7) | 0.0 (0.0, 0.0) | 95 (81, 99) | 1 (0, 4) |
| Pierce 1 | 0 m | 28.6 (6.2, 49.9) | 1.3 (0.0, 12.5) | 22.9 (9.4, 37.4) | 3.6 (1.6, 6.2) | 97 (90, 99) | 37 (4, 80) |
| Skinner 1 | 0 m | 25.9 (10.9, 40.0) | 2.1 (0.0, 9.4) | 22.3 (17.2, 28.1) | 3.1 (0.0, 6.2) | 95 (88, 98) | 27 (2,88) |
| Bald Mt. | 11 m | 22.0 (6.2, 35.9) | 0.0 (0.0, 0.0) | 24.9 (15.6, 39.0) | 15.1 (10.9, 18.7) | 98 (86, 99) | 84 (60, 93) |
| Caratunk | 11 m | 33.9 (20.3, 51.5) | 1.7 (0.0, 9.4) | 19.2 (10.9, 34.3) | 13.5 (9.4, 18.7) | 91 (53, 99) | 92 (68, 98) |
| Skinner 2 | 11 m | 26.0 (10.9, 39.0) | 1.9 (0.0, 9.4) | 21.8 (17.2, 28.1) | 16.6 (0.0, 31.2) | 93 (2, 99) | 75 (3, 97) |
| Mass 2 | 23 m | 32.7 (12.5, 54.6) | 0.7 (0.0, 3.1) | 29.6 (18.7, 42.1) | 24.9 (15.6, 34.3) | 95 (89, 98) | 91 (83, 95) |
| Roxbury | 23 m | 21.8 (0.0, 34.3) | 1.1 (0.0, 6.2) | 21.3 (15.6, 28.1) | 19.2 (15.6, 21.8) | 96 (92, 99) | 94 (89, 98) |
| Sanderson | 23 m | 20.4 (3.1, 42.1) | 1.0 (0.0, 9.4) | 24.9 (18.7, 29.6) | 15.6 (9.4, 18.7) | 91 (79, 98) | 86 (58, 98) |
| Mass 1 | Partial | 24.3 (3.1, 48.3) | 18.9 (3.1, 37.4) | 17.2 (9.4, 24.9) | 14.0 (6.2, 21.8) | 96 (86, 99) | 96 (88, 99) |
| Pierce 2 | Partial | 25.1 (12.5, 40.5) | 14.9 (3.1, 37.4) | 24.9 (17.2, 29.6) | 16.1 (14.0, 18.7) | 96 (93, 99) | 91 (71, 98) |
| UpCup | Partial | 33.8 (14.0, 59.3) | 16.1 (3.1, 51.5) | 22.3 (17.2, 29.6) | 17.2 (12.5, 21.8) | 87 (59, 98) | 82 (49, 98) |
| Appleton | Control | 22.3 (6.2, 37.4) | 21.3 (6.2, 34.3) | 14.6 (3.1, 21.8) | 15.1 (3.1, 21.8) | 93 (66, 99) | 90 (68, 99) |
| Bryant | Control | 23.1 (10.9, 32.7) | 24.1 (14.0, 37.4) | 19.2 (18.7, 20.3) | 19.2 (15.6, 21.8) | 97 (90, 99) | 96 (94, 97) |
| Dud | Control | 24.5 (12.5, 37.4) | 23.8 (6.2, 34.3) | 18.7 (14.0, 24.9) | 19.8 (15.6, 28.1) | 94 (76, 100) | 92 (50, 100) |

(Figure 3). One stream (Mass 2, 23-m treatment group), was much cooler, with mean weekly maximum temperatures at the 100-m station of 6.4°C. Following the harvest, temperatures increased 1.4–4.4°C in the 0-m treatment group and 1.0–1.4°C in the 11-m treatment group (Figure 3). Temperature in the 23-m, partial-harvest, and control treatment groups did not change following the harvest (Figure 3).

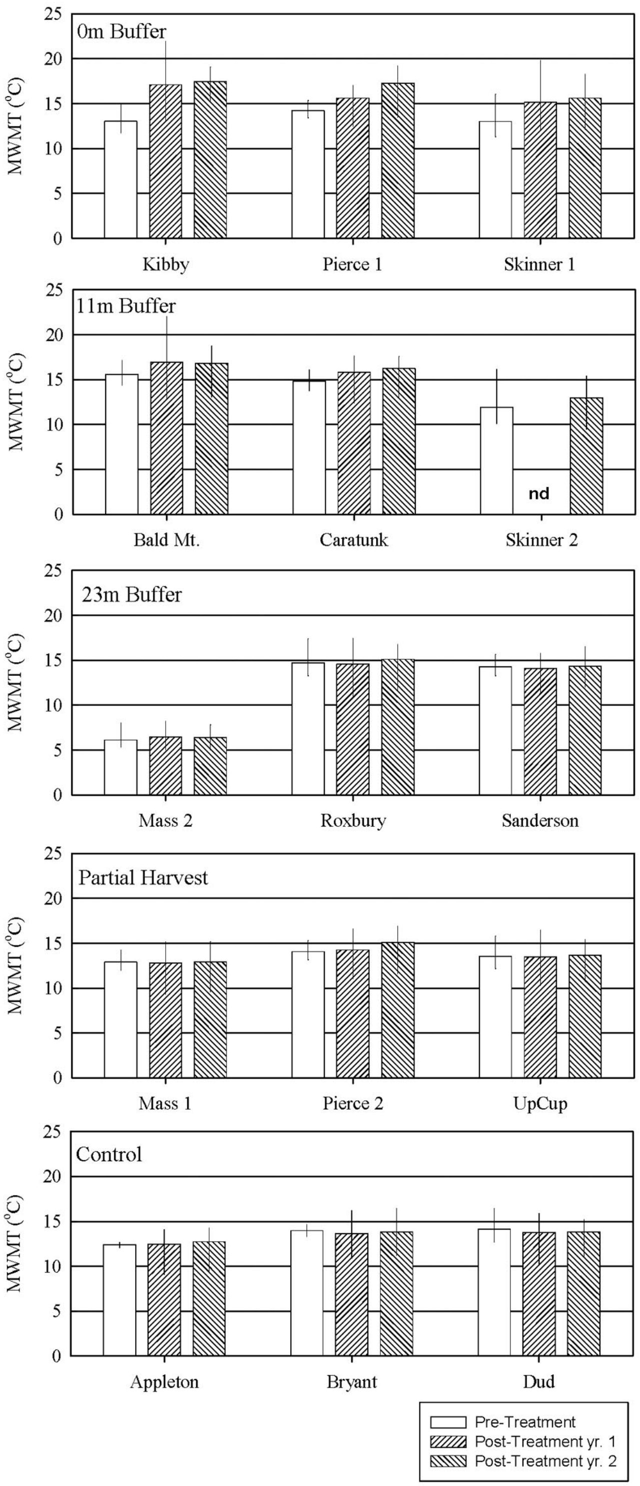


**Figure 3. Mean weekly maximum stream temperature at the 100-m station from June 15 through Aug. 15 in the preharvest (2001) and postharvest (2002–2003) years. The graphical bars represent the seasonal average of weekly mean weekly maximum temperatures and the vertical lines represent the seasonal maximum and minimum weekly maximum temperatures.**

## *Temperature Changes within the Harvest Zone: Differences between 100-m and 400-m Stations*

In the preharvest year, temperature changes between the 400-m and 100-m stations were small for all treatment groups (range = −1.0°C [cooling] to +0.8°C [warming]) (Table 4). Streams exhibited both slight warming and slight cooling within the planned 300-m harvest zone. Following the harvest, temperature change within the harvest zone increased 2.5–2.8°C in the 0-m treatment group and 1.4–2.5°C in the 11-m treatment group (Table 4). No temperature changes were observed in the 23-m, partial-harvest, or control treatment group (Table 4).

Water temperature changes within the harvest zone had a significant interaction between treatment and year ($P$ = 0.0034), indicating one or more of the harvest prescriptions affected stream temperature (the control was not expected to change). Further analysis of the main effects showed that for the 0-m treatment group water temperature changes within the harvest zone were significantly different from the control group in the first ($P$ = 0.0032) postharvest year (Table 4, Dunnett's test). In the second postharvest year changes within the harvest zone in the 0-m treatment group were significantly greater than preharvest values ($P$ = 0.0009) (Table 4, Dunn test). All other treatment groups (11-m, 23-m, and partial-harvest) did not significantly differ from the control group in either postharvest year nor did they show significant postharvest temperature increases within the harvest zone relative to preharvest values (Table 4).

**Table 4. Mean daily maximum temperature change by treatment between the 100- and 400-m stations (lower versus upper end of the harvest zone) from June 15 to Aug. 15 in the preharvest year and two postharvest years**

| | | 100 m *vs.* 400 m Station | | | | | |
|---|---|---|---|---|---|---|---|
| | | Preharvest | | Postharvest | | | |
| | | Year 1 | | Year 2 | | Year 3 | |
| Treatment | $n$ | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| 0-m | 3 | 0.8 | 0.2 | 3.6* | 0.5 | **3.3** | 0.4 |
| 11-m | 3[1] | −1.0 | 1.5 | 1.5 | 0.3 | 0.4 | 1.1 |
| 23-m | 3 | −0.3 | 0.3 | 0.3 | 0.3 | −0.3 | 0.6 |
| Partial-cut | 3 | 0.6 | 0.4 | 0.9 | 0.3 | 1.0 | 0.5 |
| Control | 3 | 0.6 | 0.3 | 0.7 | 0.3 | 0.6 | 0.2 |

Treatment means with an asterisk (*) are significantly different from the control treatment group based on Dunnett's test (Dunnett 1955). Treatment means in boldface type indicate significant differences from preharvest values within a treatment group based on Bonferroni adjusted multiple $t$-tests (Dunn 1961).

[1] $n$ = 3 in year 1 and year 3, $n$ = 2 in year 2 due to missing data.

## Temperature Changes within the Harvest Zone: Diurnal Fluctuation

In the preharvest year, the seasonal mean diurnal fluctuations at the 100-m stations were between 1.3 and 1.9°C for all treatment groups (Table 5). Following the harvest, diurnal temperature fluctuations at the 100-m stations increased by 2.3°C in the 0-m treatment group and by 0.5–0.7°C in the 11-m treatment group (Table 5). Diurnal fluctuation did not change in the 23-m, partial-harvest, and control treatment groups (Table 5).

Statistical analysis showed a significant interaction between treatment and year ($P < 0.0001$), indicating one or more harvest prescription had an effect on diurnal fluctuation at the 100-m station. Diurnal fluctuation in the 0-m treatment group was significantly greater than the control in both the first ($P = 0.0004$) and second ($P = 0.0007$) postharvest years (Table 5, Dunnett's test). No other treatment group was significantly different from the control (Table 5). In the 0-m treatment group diurnal fluctuation at the 100-m station was significantly greater than preharvest levels in both the first ($P < 0.0001$) and second ($P < 0.0001$) postharvest years (Table 5, Dunn test). No other treatment groups showed significant changes in diurnal fluctuations relative to preharvest levels. A continuous temperature trace for a 0-m buffer stream in the pre and postharvest years graphically depicts the change in amplitude of daily temperature fluctuations at the 100-m station (Figure 4).

## Downstream Recovery: Differences between 0-m and 400-m Stations

In the preharvest year temperature changes between the 400-m and 0-m (100 m below the harvest zone) stations ranged from −1.4°C (cooling) to 0.9°C (warming). Following the harvest, temperature changes between the two stations increased 1.3–1.8°C in the 0-m treatment group and 1.1–1.3°C in the 11-m treatment group. Temperature changes between the 0-m and 400-m station had a significant interaction term ($P = 0.0045$), indicating that temperature recovery 100 m below the harvest zone was not complete for all treatment groups. Analysis of the main effects showed that no treatment group had temperature changes between the 400-m station and the 0-m station that were significantly different than the control (Table 6, Dunnett's test). However, in the 0-m treatment group temperature changes between the two stations increased over the preharvest year in the first ($P = 0.0056$) postharvest year (Table 6, Dunn test). No other treatment group had temperature changes significantly different from the preharvest levels (Table 6).

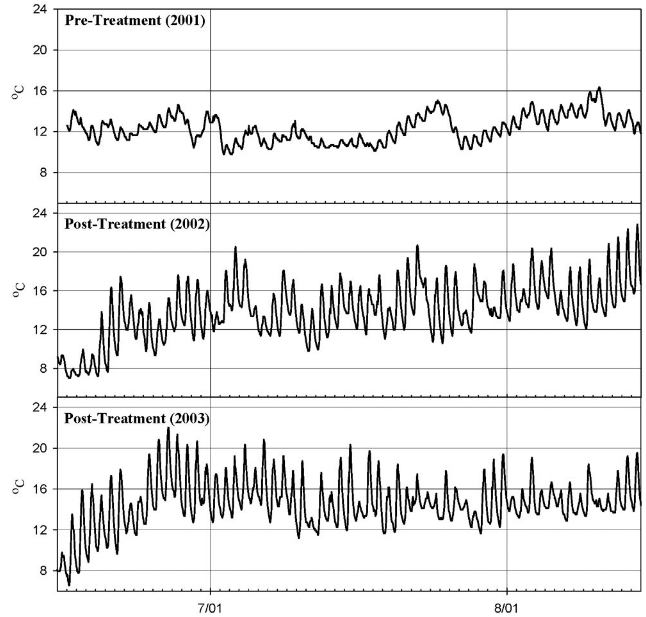


**Figure 4. Hourly temperature readings at the 100-m station of a stream in the 0-m treatment group (Kibby stream) from June 15 to Aug. 15 in the preharvest (2001) and both postharvest (2002–2003) years.**

**Table 5. Average maximum diurnal temperature change at the 100-m station from June 15 to Aug. 15 in the preharvest and two postharvest years**

| | | Preharvest | | Postharvest | | | |
|---|---|---|---|---|---|---|---|
| | | Year 1 | | Year 2 | | Year 3 | |
| Treatment | *n* | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| 0-m | 3 | 1.5 | 0.02 | **3.8*** | 0.8 | **3.8*** | 0.6 |
| 11-m | 3[1] | 1.9 | 0.1 | 2.6 | 0.1 | 2.4 | 0.1 |
| 23-m | 3 | 1.3 | 0.4 | 1.4 | 0.4 | 1.3 | 0.3 |
| Partial-cut | 3 | 1.9 | 0.3 | 2.1 | 0.05 | 1.6 | 0.1 |
| Control | 3 | 1.4 | 0.05 | 1.3 | 0.05 | 1.1 | 0.1 |

Treatment means with an asterisk (*) are significantly different from the control treatment group based on Dunnett's test (Dunnett 1955). Treatment means in boldface type indicate significant differences from preharvest values within a treatment group based on Bonferroni adjusted multiple *t*-tests (Dunn 1961).

[1] $n = 3$ in year 1 and year 3, $n = 2$ in year 2 due to missing data.

**Table 6. Mean daily maximum temperature change by treatment between the 0- and 400-m stations (100 m downstream of the lower end of the harvest zone vs. upper end of the harvest zone) from June 15 to Aug. 15 in the preharvest year and two postharvest years**

| | | 0 vs. 400 m Station | | | | | |
|---|---|---|---|---|---|---|---|
| | | Preharvest | | Postharvest | | | |
| | | Year 1 | | Year 2 | | Year 3 | |
| Treatment | *n* | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| 0-m | 3 | 0.7 | 0.5 | **2.5** | 0.6 | 2.0 | 0.7 |
| 11-m | 3 | −1.4 | 1.1 | −0.1 | 0.9 | −0.3 | 0.8 |
| 23-m | 3 | 0.5 | 0.4 | 0.9 | 0.4 | 0.5 | 0.5 |
| Partial-cut | 3 | 0.7 | 0.3 | 1.0 | 0.06 | 0.9 | 0.4 |
| Control | 3 | 0.9 | 0.2 | 0.8 | 0.2 | 0.7 | 0.2 |

Treatment means with an asterisk (*) are significantly different from the control treatment group based on Dunnett's test (Dunnett 1955). Treatment means in boldface type indicate significant differences from preharvest values within a treatment group based on Bonferroni adjusted multiple *t*-tests (Dunn 1961).

### *Downstream Temperature Recovery: Diurnal Fluctuation*

Following harvest, diurnal temperature fluctuations at the 0-m stations ranged from 2.0 to 2.5°C in the 0-m treatment group and 1.8–1.9°C in the 11-m treatment group (Table 7). These diurnal fluctuations are smaller than those observed at the 100-m stations, suggesting recovery of daily temperature fluctuations 100 m below the harvest zone. However, the interaction term between treatment and year was significant ($P = 0.0257$), indicating that recovery of diurnal fluctuations was not complete for all treatments. Analysis of the main effects showed no treatment groups had diurnal fluctuations that were significantly different from the control (Table 7, Dunnett's test). However, the diurnal fluctuations in the 0-m treatment group were significantly greater than preharvest levels in the first postharvest year ($P = 0.0316$, Table 7, Dunn test). No treatment group showed significant change in diurnal fluctuations from preharvest values in the second postharvest year (Table 7).

## Discussion

### *Stream Temperature Changes within the Harvest Zone*

This study demonstrated that leaving no buffers on small headwater streams for a 300-m harvest zone in a northern temperate forest region (~45° N latitude) resulted in postharvest increases in stream temperature. Streams in the 11-m treatment group had moderate, but statistically insignificant, increases in stream temperature while 23-m, partial-harvested, or control streams had no observable increases in temperature. Postharvest changes in stream temperatures and diurnal temperature fluctuations have been attributed primarily to increased levels of solar radiation reaching the stream channel (Brown and Krygier 1970). The extent of the increase in stream temperature following a harvest is significantly correlated with the amount of timber retained in the riparian buffer (Brown and Krygier 1970, Feller 1981, Lynch et al. 1985, Caldwell et al. 1991, Macdonald et al. 2003).

**Table 7. Average maximum diurnal temperature change at the 0-m station from June 15 to Aug. 15 in the preharvest and two postharvest years**

| | | Preharvest | | Postharvest | | | |
|---|---|---|---|---|---|---|---|
| | | Year 2 | | Year 2 | | Year 3 | |
| Treatment | $n$ | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| 0-m | 3 | 1.5 | 0.1 | **2.5** | 0.6 | 2.0 | 0.4 |
| 11-m | 3 | 1.8 | 0.1 | 1.9 | 0.2 | 1.8 | 0.2 |
| 23-m | 3 | 1.8 | 0.3 | 1.6 | 0.4 | 1.5 | 0.4 |
| Partial-cut | 3 | 2.1 | 0.2 | 2.0 | 0.4 | 1.7 | 0.1 |
| Control | 3 | 1.8 | 0.1 | 1.5 | 0.1 | 1.2 | 0.1 |

Treatment means with an asterisk (*) are significantly different from the control treatment group based on Dunnett's test (Dunnett 1955). Treatment means in boldface type indicate significant differences from preharvest values within a treatment group based on Bonferroni adjusted multiple $t$-tests (Dunn 1961).

The 0-m treatment group had the greatest reduction in mean canopy closure (77%), and the greatest increases in mean weekly maximum temperatures, temperature change within the harvest zone, and diurnal fluctuation following the timber harvest. In the 11-m treatment group, mean canopy closure decreased by 11% as a result of the harvest. Increases in temperature were smaller than in the 0-m treatment group. The 23-m and partial-harvest treatment groups both had 4% reductions in canopy closure. These treatment groups did not exhibit postharvest changes in temperature, indicating that such a small reduction in canopy closure did not significantly alter the amount of solar radiation reaching the stream channel.

Temperature increases observed in the 0-m treatment group were smaller or in the lower end of the range of temperature increases observed by other studies on unbuffered streams. Previous studies on unbuffered streams showed average temperature increases of 3.2–5.0°C (Brown and Krygier 1967, Burton and Likens 1973, Kochenderfer and Edwards 1991) as well as increases in diurnal fluctuation between 1.7–4.2°C (Pacific Northwest, Brown and Krygier 1970) and 6.1–7.5°C (Brown and Krygier 1967) above controls or preharvest conditions. In our study, streams in the 0-m buffer group showed 1.4–4.4°C increases in mean weekly maximum temperatures and 2.3°C increases in diurnal fluctuation.

Temperature increases in our 11-m treatment group were similar to other studies with wider buffers. The increases in diurnal fluctuation were smaller than observed in other studies with larger buffers. In the 11-m treatment group, postharvest increases in mean weekly maximum temperature ranged from 1.2 to 1.3°C, temperature changes within the harvest zone increased by 1.4–2.5°C, and diurnal fluctuation in temperature increased by 0.5–0.7°C. The 23-m and partial-harvest treatment groups did not exhibit postharvest changes in the temperature. Previous studies showed postharvest temperature increases of 1.0–2.6°C for buffers 15–30 m wide (Rishel et al. 1982, Lynch et al. 1984, Kochenderfer and Edwards 1991, Jackson et al. 2001). These studies also showed streams with 20–30-m wide buffers had 0.7–2.0°C increases in diurnal fluctuation (Rishel et al. 1982, Lynch et al. 1984, British Columbia, Macdonald et al. 2003) over preharvest or control conditions.

The smaller degree of temperature change relative to previous studies we observed in unbuffered streams might be partly attributed to groundwater inflow. Groundwater inputs can strongly influence stream temperature (Sullivan et al. 1990, Caldwell et al. 1991), and inflow can mitigate effects of canopy removal by slowing temperature increases (Poole and Berman 2001) and by aiding in stream temperature recovery (Ice 2001). The glacial till subsurface characteristic of our study region facilitates underground water flow. Also, the close proximity of our study reaches to the watershed divide suggests that a large proportion of groundwater feeds these stream systems. The importance of groundwater to stream temperatures in our study areas was illustrated by temperature measurements taken at 20-m intervals on a hot, sunny day (air temp = 31°C). We observed decreases in stream temperature between 1.2 and 3.2°C within 20 m of stream channel due to several cold groundwater inputs entering the stream channel. We suspect groundwater inflow played a significant role in mitigating the effect of canopy removal in our study. Variations in inflow among stream buffer studies could be a key factor for explaining observed differences in the effectiveness of different buffer widths.

Elevation of water temperature and diurnal fluctuation is a concern because aquatic organisms have adapted to living in systems within a particular temperature range in which body size, fecundity, and survival are optimized (Vannote and Sweeney 1980). Increased water temperature can result in physiological stress and potential death in brook trout (Grande and Anderson 1991). Documented lethal water temperature limits for brook trout range from 24.4°C (Brett 1956) to 26.2–27.2°C (Grande and Anderson 1991). The United States Environmental Protection Agency recommends that mean weekly maximum water temperatures do not exceed 24°C for even one week in streams with populations of brook trout (EPA 1986). In our study, mean weekly maximum temperatures never exceeded 22°C; even in the 0-m treatment group.

### *Downstream Temperature Recovery*

Temperature recovery downstream of a harvest zone is important to understand because a rapid decrease in temperature over a short distance can effectively limit the spatial impact of the harvest. In the 0-m treatment group, temperature changes between the 400-m (upstream of the harvest zone) and 0-m (100 m below the harvest zone) were significantly elevated over preharvest levels in one of the postharvest years. This indicates that without buffers, temperature increases persist for at least 100 m below the harvest zone in the first postharvest year. How far downstream the temperature increases persisted is not known.

Within the 100-m recovery zone we observed relatively large decreases in stream temperature. In the second postharvest year, temperature increases did not persist 100 m below the harvest zone despite being significantly elevated before entering the 100-m recovery zone. Previous studies of temperature recovery downstream of timber harvest showed large decreases in a relatively short downstream distance. Temperature decreases of approximately 1.5°C were observed within 130 m (Caldwell et al. 1991), 2.5°C within 200 m (British Columbia, Story et al. 2003), and 2.0°C within 300 m (Oregon, Zwieniecki and Newton 1999) after streams re-entered intact forest canopy. This common observation of relatively rapid reduction in temperature occurs because the intact forest canopy below the harvest zone shields the stream bed from direct solar radiation (Brown and Krygier 1970), while groundwater inflow and hyporheic exchange further mitigates temperature increases produced in the harvest zone (Sullivan et al. 1990, Caldwell et al. 1991, Johnson and Jones 2000).

### *Temporal Temperature Recovery*

Temperature recovery over time can also be important for forest management decision-making. We only had 2 years of postharvest data, and no temperature recovery was apparent in the 0-m treatment group at the 100-m stations within that time frame. However, shade from a regenerating shrub layer may function as effectively as mature canopy at shading the stream from solar radiation (Johnson and Jones 2000). Low vegetation (shrubs and saplings) and in-stream woody debris and slash can partially shade the stream from solar radiation and mitigate temperature changes associated with harvesting (Feller 1981, Rishel et al. 1982, Caldwell et al. 1991, Jackson et al. 2001). As a result, substantial moderation of stream temperature can occur only 7 years after harvesting, even along streams with no buffers (Ice 2001). We are measuring shrub height each year postharvest for a future study that discusses temperature recovery following timber harvesting.

## Conclusions

Forested buffers 11 m wide with ≥60% canopy closure on each side of the stream should protect against significant temperature increases in our study area. The small, statistically nonsignificant increases in temperature associated with 11-m buffers recovered after re-entering intact forest canopy for a distance of approximately one-third the length of the harvest zone. In watersheds with aquatic species that are of special ecological concern, an environmentally conservative management approach may be desirable. Buffers 23 m wide with ≥60% canopy closure on each side of the stream resulted in no detectable temperature changes.

## Literature Cited

BEITINGER, T.L., AND L.C. FITZPATRICK. 1979. Physiological and ecological correlates of preferred temperature in fish. Am. Zool. 19:319–329.

BESCHTA, R.L., R.E. BILBY, G.W. BROWN, L.B. HOLTBY, AND D. HOFSTRA. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. *In* Streamside management: Forestry and fishery interactions, Salo, E.O. and T.W. Cundy (eds.). College of Forest Resources, University of Washington, Seattle, WA.

BREN, L.J. 1995. Aspects of the geometry of riparian buffer strips and its significance to forestry operations. Forest Ecol. Manage. 75:1–10.

BRETT, J.R. 1956. Some principles in the thermal requirements of fishes. Q. Rev. Biol. 31:75–81.

BROWN, G.W., AND J.T. KRYGIER. 1967. Changing water temperatures in small mountain streams. J. Soil and Water Conserv. Nov.–Dec.:242–244.

BROWN, G.W., AND J.T. KRYGIER. 1970. Effects of clear-cutting on stream temperature. Water Resource Res. 6(4):1133–1139.

BURTON, T.M., AND G.E. LIKENS. 1973. The effect of strip-cutting on stream temperature in the Hubbard Brook Experimental Forest, New Hampshire. BioScience 23:433–435.

CAIRNS, J. 1970. Ecological management problems caused by heated wastewater discharged into the aquatic environment. Water Resource Bull. 6:868–878.

CALDWELL, J.E., K. DOUGHTY, AND K. SULLIVAN. 1991. Evaluation of downstream temperature effects of type 4/5 waters. Timber/Fish/Wildlife Rep. No. TFW -WQ5-91-004. Washington Department of Natural Resources, Olympia, WA. 71 p.

CORBETT, E.S., J.A. LYNCH, AND W.E. SOPPER. 1978. Timber harvesting practices and water quality in the eastern United States. J. For. 76:484–488.

ENVIRONMENTAL PROTECTION AGENCY. 1986. Water quality criteria. EPA 440/5-86-001. Office of Water Regulations and Standards, Washington, DC 477 p.

DUNN, O.J. 1961. Multiple comparisons among means. J. Am. Statist. Assoc. 56:52–64.

DUNNETT, C.W. 1955. A multiple comparison procedure for comparing several treatments with a control. J. Am. Statist. Assoc. 50:1096–1121.

FELLER, M.C. 1981. Effects of clearcutting and slashburning on stream temperature in southwestern British Columbia. Water Resource Bull. 17(5):863–867.

GRANDE, M., AND S. ANDERSON. 1991. Critical thermal maxima for young salmonids. J. Freshwater Ecol. 6(3):275–279.

HEWLETT, J.D., AND J.C. FORTSON. 1982. Stream temperature under an inadequate buffer strip in the southeastern piedmont. Water Resource Bull. 18(6):983–988.

HOWELL, D.C. 1982. Statistical methods of psychology. PWS Publishers, Boston.

ICE, G. 2001. How direct solar radiation and shade influences temperature in forest streams and relaxation of changes in stream temperature. Cooperative monitoring, evaluation and research (CMER) Workshop: Heat transfer processes in forested watersheds and their effects on surface water temperature, Oct. 2001. Washington Department of Fish and Wildlife, Lacey, WA.

JACKSON, C.R., C.A. STRUM, AND J.M. WARD. 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. J. Am. Water Resource Assoc. 37(6):1533–1549.

JOHNSON, S.L., AND J.A. JONES. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Aquat. Sci. 57(Suppl. 2):30–39.

KOCHENDERFER, J.N., AND P.J. EDWARDS. 1991. Effectiveness of three streamside management practices in the central Appalachians. *In* Proceedings of the 6th biennial southern silviculture research conference, Vol. 2. Memphis, TN, Oct. 30–Nov. 1, 1990, Coleman, S.S. and D.G. Neary (comps., eds.). Gen. Tech. Rep. SE-70, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Ashville, NC. 1:688–700.

LEMMON, P.E. 1957. A new instrument for measuring forest overstory density. J. For. 55(9):667–669.

LEOPOLD, L.B., M.G. WOLMAN, AND J.P. MILLER. 1964. Fluvial processes in geomorphology. Wlt. Freeman, San Francisco, CA. 134–150.

LYNCH, J.A., E.S. CORBETT, AND K. MUSSALLEM. 1985. Best management practices for controlling non-point source pollution on forested watersheds. J. Soil Water Conserv. Jan.–Feb.:64–67.

LYNCH, J.A., G.B. RISHEL, AND E.S. CORBETT. 1984. Thermal alteration of streams draining clearcut watersheds: Quantification and biological implications. Hydrobiologia 111:161–169.

MACDONALD, J.S., E.A. MACISAAC, AND H.E. HERUNTER. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Can. J. For. Res. 33:1371–1382.

MAINE DEPARTMENT OF CONSERVATION. 1999. The state of the forest and forest sustainability standards: Final report to the joint standing committee of the 119th legislature on agriculture, conservation, and forestry. Maine Department of Conservation, Augusta, ME. 39 p.

MURRAY, G.L.D., R.L. EDMONDS, AND J.L. MARRA. 2000. Influence of partial harvesting on stream temperatures in forests on the western Olympic Peninsula, Washington. Northwest Sci. 74(2):151–164.

OLIVER, G.G., AND L.E. FIDLER. 2001. Towards a water quality guideline for temperature in the province of British Columbia. Ministry of Environment, Lands, and Parks, Water Management Branch, Victoria, BC.

POOLE, G.C., AND C.H. BERMAN. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manage. 27(6):787–802.

RICHARDSON, J.S. 2000. Life beyond salmon streams: Communities of headwaters and their role in drainage networks. P. 473–476 *in* Proc. biology and management of species and habitats at risk, L.M. Darling (ed.). Kamloops, BC.

RISHEL, G.B., J.A. LYNCH, AND E.S. CORBETT. 1982. Seasonal stream temperature changes following forest harvesting. J. Environ. Qual. 11(1):112–116.

SAS INSTITUTE INC. 1999. SAS/STAT user's guide, version 8. SAS Institute Inc., Cary, NC. 3848 p.

SEYMOUR, R.S., AND M.L. HUNTER JR. 1992. New forestry in eastern spruce-fir forests: Principles and applications to Maine. Maine Agricultural and Forest Experiment Station, University of Maine, Orono, Maine.

SIDLE, R.C., Y. TSUBOYAMA, S. NOGUCHI, I. HOSODA, M. FUJIEDA, AND T. SHIMIZU. 2000. Stormflow generation in steep forested headwaters: A linked hydrogeomorphic paradigm. Hydrol. Process. 14:369–385.

STORY, A., R.D. MOORE, AND J.S. MACDONALD. 2003. Stream temperature in two shaded reaches below cutblocks and logging roads: Downstream cooling linked to subsurface hydrology. Can. J. For. Res. 33:1383–1396.

SULLIVAN, K., J. TOOLEY, K. DOUGHTY, J.E. CALDWELL, AND P. KNUDSEN. 1990. Evaluation of prediction models and characterization of stream temperatures regimes in Washington.

Timber/Fish/Wildlife Rep No. TFW-WQ3-90-006. Washington Department of Natural Resources, Olympia, WA. 224 p.

VANNOTE, R.L., AND B.W. SWEENEY. 1980. Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. Am. Nat. 115(5):667–695.

WASHINGTON WATER QUALITY PROGRAM. 2002. Evaluating standards for protecting aquatic life in Washington's surface water quality standards. Rep No. 00-10-070. Washington State Department of Ecology, Olympia, WA. 189 p.

ZAR, J.H. 1996. Biostatistical analysis. Prentice Hall, Upper Saddle River, NJ.

ZWIENIECKI, M.A., AND M. NEWTON. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. West. J. Appl. For. 14(2):106–113.