Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada

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Received 3 April 2005; revised 28 February 2006; accepted 9 May 2006; published 30 August 2006.

[1] A 6-year study documented the effects of clear-cut harvesting with and without riparian buffers (10 m and 30 m wide) on headwater stream temperature in coastal British Columbia. The experiment involved a replicated paired catchment design. Pretreatment calibration relations between the treatment and control streams were fitted using time series of daily minimum, mean, and maximum temperatures. Generalized least squares (GLS) regression was used to account for autocorrelation in the residuals. While water temperature in streams with 10 and 30 m buffers did not exhibit marked warming, daily maximum temperature in summer increased by up to 2°–8°C in the streams with no buffer. The effectiveness of the buffers may have been maximized by the north-south orientation of the streams, which meant that the streams would be well shaded from late morning to early afternoon by the overhead canopy, even under the 10 m buffer. The variation in response for the no-buffer treatments is consistent with the differences in channel morphology that influence their exposure to solar radiation and their depth. Relations between treatment effect and daily maximum air temperature suggested that recovery toward preharvest temperature conditions was occurring, with rates appearing to vary with stream and by season.

Citation: Gomi, T., R. D. Moore, and A. S. Dhakal (2006), Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada, *Water Resour. Res.*, *42*, W08437, doi:10.1029/2005WR004162.

1. Introduction

[2] The effects of forest harvesting on hydrology and water quality have been the focus of management concern and scientific research for decades [e.g., *Bates and Henry*, 1928; *Hewlett*, 1982; *Beschta et al.*, 2000]. The effects on water temperature have been of particular concern [*Titcomb*, 1926; *Burton and Likens*, 1973; *Beschta et al.*, 1987; *Poole and Berman*, 2001] because it is one of the dominant controls on biological processes in streams [*Vannote and Sweeney*, 1980; *Ward and Stanford*, 1982]. Experiments conducted throughout North America have documented postharvest increases in summer maximum stream temperature ranging from 0° to 13°C [*Beschta et al.*, 1987; *Moore et al.*, 2005a]. Retention of trees in riparian buffers is the most common management approach to minimizing the effects of forest harvesting on stream temperature and to maintaining other ecological processes, such as input of organic matter [*Young*, 2000; *Dignan and Bren*, 2003]. However, warming of several degrees Celsius has been observed in some cases where buffers were retained [*Hewlett and Fortson*, 1982; *Jackson et al.*, 2001; *Macdonald et al.*, 2003], and there is ongoing debate and uncertainty about how wide buffers need to be, what amount of retention is required within them, and how far up the stream network they should extend.

[3] The most statistically rigorous approach to quantifying the effect of forest practices on hydrology and water quality is the paired catchment experiment, in which data are collected both before and after treatment for both the treatment stream(s) and at least one untreated control [*Hewlett*, 1982]. This approach is commonly applied to response variables measured at an annual time interval, such as annual peak flows and summer maximum temperature, to avoid problems with autocorrelation, which would violate the assumptions underlying ordinary least squares (OLS) regression and analysis of covariance [*Neter et al.*, 1996], the conventional approaches to analyzing paired catchment studies. However, a focus on metrics such as summer maximum temperature ignores much of the information available in the full time series. For example, by analyzing daily streamflow time series, *Jones and Post* [2004] were able to document posttreatment changes in hydrologic conditions on both seasonal and interannual timescales. Another aspect of the conventional approach is that several years of preharvest data are required to develop a regression relation between the treatment and control streams for a specific response metric. In many cases, relatively short pretreatment periods have been available for calibration due to the inability of researchers to influence harvesting schedules [e.g., *Macdonald et al.*, 2003], prompting some studies to use regressions based on daily time series for calibration [e.g., *Jackson et al.*, 2001; *Mellina et al.*, 2002].

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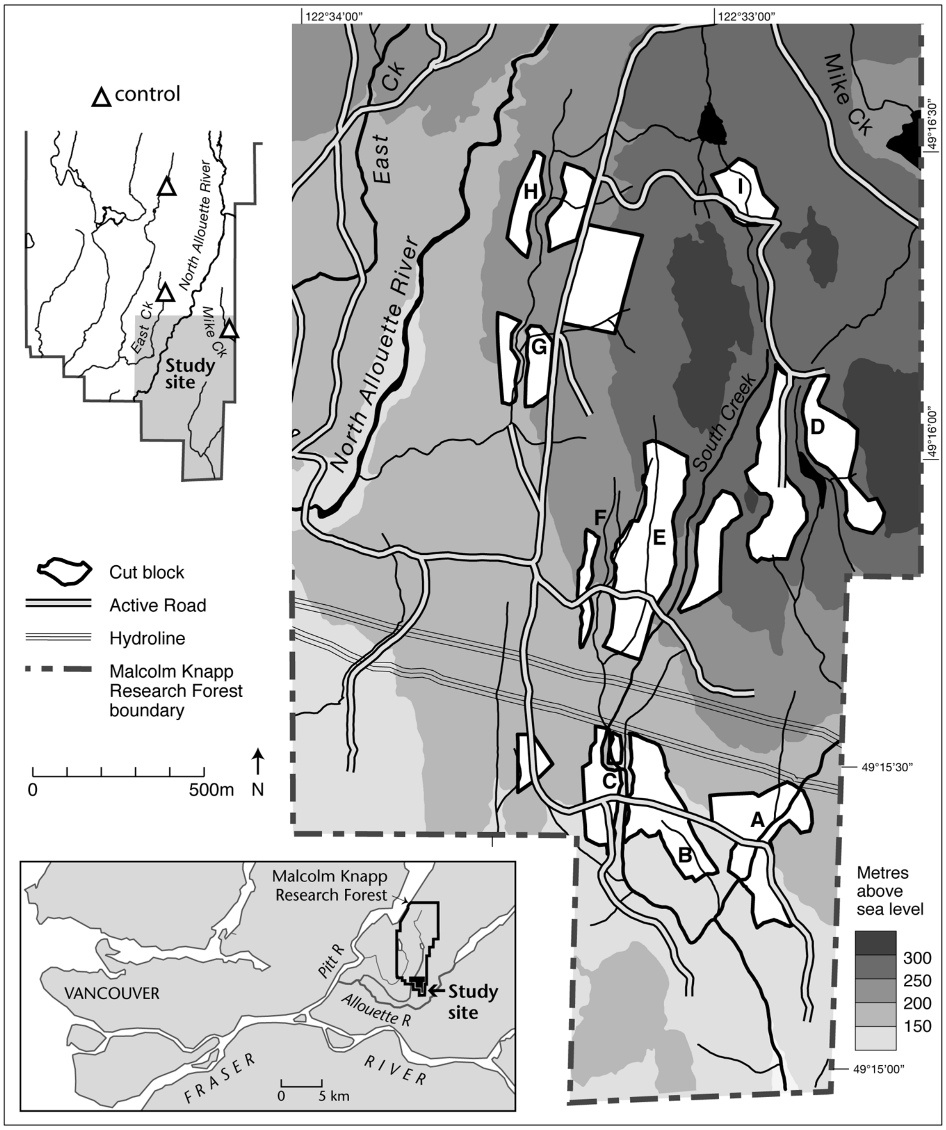

Figure 1. Study area and locations.

[4] Only two studies appear to have addressed the problem of autocorrelation that arises from using subannual timescales for catchment calibration. In a study of forest harvesting effects on monthly streamflow, *Watson et al.* [2001] used OLS regression following a logarithmic transformation to fit the preharvest regression, then adjusted the residuals to account for first-order autocorrelation prior to computing 95% prediction intervals. Generalized least squares (GLS) regression provides an alternative solution to the problem of autocorrelated residuals, but only one study, which focused on forestry effects on streamflow, appears to have applied this approach to catchment calibration [*Troendle et al.*, 2001]. In that study, *Troendle et al.* [2001] did not assess the statistical significance of the differences between observed and predicted discharge following treatment.

[5] The main objective of this study is to evaluate headwater stream temperature response to clear-cut logging with different riparian treatments based on a replicated paried catchment design. To achieve this objective, we introduce the application of generalized least squares regression using daily time series for catchment calibration, in order to maximize the use of the information available in a short pretreatment period, and provide more detailed information on the variability of treatment effect both within and among seasons.

2. Methods

2.1. Study Site

[6] This study was conducted in the University of British Columbia Malcolm Knapp Research Forest, located approximately 60 km east of Vancouver, BC (Figure 1). The climate is temperate with wet, mild winters and warm, dry summers. Mean annual precipitation over the study catchments ranges from about 2000 to 2500 mm, of which approximately 70% falls between October and April as a result of Pacific frontal systems. Snowfall accounts for only about 15% of mean annual precipitation. Soils are dominantly podzols formed in ablation till or colluvium overly-

Table 1. Characteristics of Study Streams[a]

Creek	Buffer Width, m	Drainage Area, ha	Mean Channel Gradient	Mean Bankfull Width, m	Channel Reach Type[b]	Period of Logging	Impacted Stream Length, m	Impacted Area, %	Comments
A	0	58.5	0.11	2.3	step-pool	19 Oct 1998 to 8 Jan 1999	325	20.5	seasonally discontinuous
B	0	13.5	0.07	1.1	pool-riffle	2 Nov 1998 to 5 Feb 1999	250	24.4	
E	0	12.2	0.11	0.5	pool-riffle	1 Apr 1998 to 12 Feb 1999	650	53.3	
I	0	12.6	0.08	1.9	cascade-pool	10 Aug to 11 Sep 98	215	21.4	swamps in upper channel reach
C	10	89.1	0.07	2.4	step-pool	11 Sep to 11 Dec 1998	335	21.2	seasonally discontinuous
D	30	43.3	0.08	2.1	step-pool	6 Apr to 4 Dec 1998	450	21.9	
H	30	55.4	0.06	4.0	pool-riffle	23 Feb to 30 Oct 1998	300	22.0	
East	control	44.0	0.08	2.7	step-pool	-	-	-	
Spring	control	111.0	0.02	1.6	step-pool-riffle	-	-	-	
Mike	control	29.7	0.08	1.5	step-pool	-	-	-	

[a]From *Winfield* [2002].
[b]Based on categories described by *Montgomery and Buffington* [1997].

ing relatively impermeable basal till or granitic bedrock, and average about 1 m in depth [*Hutchinson and Moore*, 2000]. Forest cover is dominated by second growth (80 years old) western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and Douglas fir (*Pseudotsuga menziesii*). Tree height is about 30 to 40 m, and crown closure ranges from about 70% to 90%.

[7] Catchment elevations for the study streams range from about 100 to 400 masl. Mean bankfull widths range from 0.5 to 4.0 m and channel gradients range from 2 to 11% [*Winfield*, 2002]. While most of the streams are perennial, sections with discontinuous flow were observed during summer dry periods in some streams (Table 1). Drainage areas at the downstream ends of study reaches range from 12 to 89 ha. Logging slash was left in the channels and riparian zones of no-buffer streams. However, slash did not accumulate over the stream and provide significant shade as has been observed, for example, in the Coast Range [*Jackson et al.*, 2001]. Large wood pieces (up to 100 years old) recruited during and after old logging activities were also present in the channels [*Winfield*, 2002]. Creeks A and C provide habitat for both juvenile Coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Oncorhynchus clarki*).

2.2. Experimental Design and Treatments

[8] This study was conducted as part of a broader experiment investigating the ecological response of headwater stream and riparian zones to forest harvesting with different riparian treatments [*Kiffney et al.*, 2003]. It involves three control reaches and ten subject to clear-cut harvest: four with no buffer, three with 10 m buffers and three with 30 m buffers. In each treatment unit, harvesting occurred in a single cut block that straddled the treatment reach. The fraction of catchment logged and roaded was intended to be fixed at 20 to 25% in an attempt to keep effects on discharge relatively small and constant among streams, and thus to minimize confounding between harvesting and riparian treatments (Table 1). However, the harvested fraction unintentionally ended up being higher for E Creek (affected area became 53%). Because three of the study streams had less than one year of preharvest temperature data, our analysis focused on seven streams: four no buffer treatments (A, B, E, and I), one 10 m buffer treatment (C), and two 30 m buffer treatments (D and H) (Table 1). Thus not all treatments were replicated. All channels but I Creek flow from north to south; I Creek flows from south to north (Figure 1).

[9] Given that some treatments were executed on tributaries of other treatment streams, not all are strictly independent. For example, the D Creek treatment is upstream of the A Creek unit (Figure 1), while the C Creek unit lies downstream of three experimental units (E, F, and South Creeks). The potential for confounding effects will be considered in the discussion. Treatment units were logged from April 1998 to January 1999 with cable yarding (Table 1). Cut blocks and logging roads occupied approximately 20 to 50% of the catchment areas. East, Spring and Mike Creeks were used as control streams because no harvesting activities had been conducted for the last 80 years and their catchments are currently covered by second growth conifer forest.

2.3. Field Methods

[10] Stream temperature was recorded from 1997 to 2002 using submersible temperature loggers with ±0.2°C accuracy (Stowaway Tidbit and HOBO Loggers, Onset Computer Application). Loss of loggers during high-flow events resulted in some data gaps, mainly in winter. Data loggers were placed at the downstream ends of the cut blocks in flowing water deep enough to ensure complete coverage of water. To minimize the potential for heating by solar radiation absorption, the loggers were housed in PVC pipe with multiple holes drilled through to promote water exchange and were placed at shaded locations (e.g., below undercut banks or large wood). Time series of daily maximum, mean, and minimum temperatures in each stream were extracted for analysis. Recording intervals were initially 30 min in 1997, but were increased to 192 min later in the study. While this increase in recording interval can result in underestimation and overestimation of the daily maxima and minima, respectively, the diurnal temperature waves had sufficiently broad peaks and troughs that this error is not critical, even for the no-buffer treatments. Examination of higher-resolution data (10–15 min intervals) collected in 2001 for A Creek [*Moore et al.*, 2005b] and 2003 for I Creek (unpublished data) indicate maximum errors of about 0.5°C and 1°C, respectively, assuming worst-case timing of sampling relative to the timing of the daily maximum temperature. On most days, the error would be substantially less than the maximum. The net effect is that the estimated treatment effects will slightly underestimate the true values,

but the relative magnitudes among treatments should not be affected.

[11] Climate measurements were recorded at the Research Forest Headquarters station, including daily maximum and minimum temperature, as well as hourly and daily precipitation. Stream discharge for the entire experimental period was available only for East Creek.

[12] Regeneration and growth of riparian vegetation have been measured since 1999 along transects located 2 m apart and oriented parallel to the channels. Average plant height and coverage were estimated at 15 points in the transects (S. Mitchell, Department of Forest Science, University of British Columbia, unpublished data).

2.4. Data Analysis

[13] Data analysis included the following steps: (1) establishment of regression relations between treatment and control streams for the pretreatment periods (calibration), (2) calculation of the differences between observed and predicted temperatures for both preharvest and postharvest periods, (3) testing of the statistical significance of the differences between observed and predicted temperatures for the preharvest and postharvest periods, and (4) analysis of the daily, seasonal, and annual variations of postharvest differences between observed and predicted temperatures, which provide estimates of the effects of the treatments. Stream temperature data during logging activity (shown in Table 1) were excluded from analysis.

[14] Preharvest regression relations were developed for daily maximum, mean, and minimum stream temperatures at each treatment stream as a function of the corresponding values at an unlogged control. East Creek was used as the control stream because it had the longest pretreatment period of record. Generalized least squares (GLS) regression was used to account for residual autocorrelation, using the implementation in the software package S-Plus [*Pinheiro and Bates*, 2000]. The fitted model was:

$$y_t = \beta_o + \beta_1 x_t + \beta_2 \sin(2\pi j/T) + \beta_3 \cos(2\pi j/T) + \varepsilon_t \quad (1)$$

where y_t is the temperature at a treatment stream on day t; x_t is the corresponding temperature at the control stream (East Creek); β_0, β_1, β_2 and β_3 are coefficients to be estimated by regression; j is day of the year (j = 1 on Jan. 1); T = 365.25, the number of days in a year; and ε_t is an error term, which was modeled as an autoregressive process of order "k":

$$\varepsilon_t = \rho_1 \varepsilon_{t-1} + \rho_2 \varepsilon_{t-2} + \ldots.. + \rho_k \varepsilon_{t-k} + u_t \quad (2)$$

where ρ_i is the autocorrelation between error terms at a lag of "i" days, ε_{t-i} is the error term "i" days before day "t," and u_t is a random disturbance (white noise), assumed to be normally distributed with constant variance. The order k was determined by examining partial autocorrelation functions and plots of the prelogging residuals and retaining only the terms with statistically significant partial autocorrelation coefficients [*Venables and Ripley*, 1997]. The sine and cosine terms in equation (1) account for seasonality in the residuals [*Watson et al.*, 2001].

[15] The treatment effect on a given day in the postharvesting period (T_e) was estimated as

$$T_e = y_t - \hat{y}_t \quad (3)$$

where y_t and $\hat{y}_t$ are the observed and predicted temperatures on day t. To provide an approximate assessment of the statistical significance of the treatment effect, we followed an approach similar to that of *Watson et al.* [2001]. This procedure first removes the autocorrelation from the residuals to provide an estimate of the random disturbances:

$$\hat{u}_t = (y_t - \hat{y}_t) - \hat{\rho}_1(y_{t-1} - \hat{y}_{t-1}) - \hat{\rho}_2(y_{t-2} - \hat{y}_{t-2}) - \ldots - \hat{\rho}_k \cdot (y_{t-k} - \hat{y}_{t-k}) \quad (4)$$

where $\hat{u}_t$ is an estimate of the random disturbance on day t and $\hat{\rho}_i$ is an estimate of the lag i autocorrelation coefficient from the GLS regression fit. Given that these disturbances will be independent, then if they are also approximately normally distributed, 95% prediction limits can be estimated as ±1.96 s_u, where s_u is the standard deviation of $\hat{u}_t$. Under the null hypothesis of no treatment effect, the distribution of $\hat{u}_t$ should be the same both pretreatment and posttreatment. To assess the significance of logging impacts on stream temperature, we applied the two-sample Kolmogorov-Smirnov test for the distribution of disturbances between the prelogging period and each posttreatment year. This test does not require normality or equality of variance.

[16] To test the interannual stability of the calibration relations between the pretreatment and posttreatment periods, we used GLS regression to fit calibrations between the other control streams (Spring Creek and Mike Creek) and East Creek. Data collected before 1 April 1999 were used to fit the GLS regressions, which were then used to predict stream temperature for the period following 1 April 1999. Under the null hypothesis of no treatment effect (true in the case of regressions between two control streams), the distributions of residuals and disturbances should be the same in both the calibration and test periods.

[17] To examine the patterns of variability in the treatment effect both within and among seasons, we fitted relations between treatment effects and air temperature using linear regression. Air temperature represents a surrogate for the net heat input to the water, because, even though solar radiation should be the dominant daytime input at a stream with no buffer [*Brown*, 1969], days with strong solar heating are associated with high air temperatures. Thus changes in the relation between treatment effect and air temperature should reflect nonclimatic influences on stream temperature, such as recovery of riparian vegetation. In the regression model, we included year as a categorical variable and the interaction between air temperature and year.

3. Results

3.1. Overview of the Study Period

[18] The prelogging period (1997–1998) was generally warmer than the postlogging period (Table 2). Riparian vegetation rapidly reestablished adjacent to the no-buffer streams following harvest, in terms of both percentage ground cover and height (Figure 2). Riparian vegetation was dominated by deciduous shrubs such as Stink currant (*Ribes bracteosum*), Thimbleberry (*Rubus parviflorus*), Salmonberry (*Rubus spectabilis*), Devil's club (*Oplopanax horridus*), Vine Maple (*Acer circinatum*) and *Vaccinium* spp.

Table 2. Climate Data (Total Precipitation and Air Temperature) at the Headquarters Station and Mean Streamflow and Maximum Water Temperature at East Creek for July and August

Variable	Year					
	1997	1998	1999	2000	2001	2002
P, mm	258	89	201	136	224	57
Air T_{max}, °C	31.0	34.0	28.0	29.0	30.5	32.0
Air T_{mean}	18.2	18.9	17.3	16.4	17.3	17.8
Air T_{min}	9.5	9.5	8.0	6.5	8.0	7.0
Q_{mean}, m^3 s^{-1}	0.017	0.004	0.010	0.003	0.007	0.003
Stream T_{max}, °C	14.7	16.1	14.0	13.8	14.0	14.3

3.2. Regression Analysis

[19] Significant ($p < 0.05$) residual autocorrelation in the preharvest regressions was found for all streams and all three temperature variables. For daily maximum stream temperature, residuals were autocorrelated to order one in all streams but Spring Creek, for which the residuals exhibited autocorrelation to two lags. Lag one autocorrelation coefficients ranged from about 0.54 to 0.97. For daily mean temperatures, autocorrelation was significant ($p < 0.05$) to lag two for six streams and to lag one for three. For daily minimum temperature, residual autocorrelation was significant up to lag three for three streams, lag two for two streams, and lag one for four streams.

[20] For the control streams Mike Creek and Spring Creek, deviations from the calibration regression were similar for both the calibration and test periods, as were the random disturbances (Figure 3). The Kolmogorov-Smirnov test indicated no significant change (at $\alpha = 0.05$) in the disturbances between the calibration and test periods for summer (July–August) for Spring Creek, but there appeared to be significant differences for Mike Creek for 2000 and 2002. However, more than 70% of the deviations for the test period were less than 0.5°C in absolute value (Figure 3), and fewer than 3% exceeded 1°C in absolute value. These results suggest that the preharvest regressions are reasonably stable and should provide a basis for identifying postharvest treatment effects that exceed 1°C.

3.3. Magnitude and Significance of Treatment Effects

[21] Treatment effects, estimated as deviations between the observed and predicted temperatures, were most strongly expressed for daily maximum temperature, particularly in summer (Figure 4). The response in daily maximum temperature varied dramatically among the four no-buffer treatments, with maximum effects varying from 1.9°C for E Creek to 8.8°C for I Creek (Figures 4 and 5 and Table 3). The observed preharvesting and postharvesting maximum temperature did not vary notably although the magnitude of the maximum treatment effect was significant. For example, the maximum temperature recorded at B Creek was similar between the preharvest and postharvest periods (17.1° versus 17.3°C), despite a maximum treatment effect of 5.2°C. This apparent discrepancy is partly due to climatic differences between the preharvest and postharvest periods, as well as the fact that the maximum deviations from the predicted values did not necessarily occur on the day of maximum temperature. The treatment effects for the no-buffer streams during summer (July–August) were mainly statistically significant ($p < 0.05$) throughout the postharvest period for A, B and I Creeks (Table 4). Changes in the disturbances are not necessarily evident in the mean, but can be expressed by an increase in the variance following treatment (Figure 4 and Table 4). The effect for E Creek appeared to be significant only for the first year following harvest.

[22] Treatment effects were more subdued for the streams with 30 m buffers, with maximum effects for maximum daily temperature of less than 2°C (Figure 5 and Table 3). The effects appeared to be statistically significant only for the first posttreatment year at H Creek (Table 4). The maximum treatment effect at C Creek (10 m buffer) was relatively large (4.1°C) and statistically significant, but large deviations from the regression also occurred in the pretreatment period (Figure 5). During low-flow periods, C Creek breaks up into a series of poorly connected or disconnected pools, which may promote anomalous warming.

3.4. Temporal Variation of Treatment Effects

[23] Treatment effects were correlated with air temperature in most streams for maximum and mean stream temperature, whereas air temperature was less important for minimum temperature in some streams. In the regression model, the effects of "year" and "air temperature times year interaction" were significant ($p < 0.05$) for all streams. However, interpretation of significance is complicated by the presence of residual autocorrelation in the regressions. Consequently, we consider the relations in Figure 6 as an exploration of possible patterns of recovery rather than as a definitive test. Relations

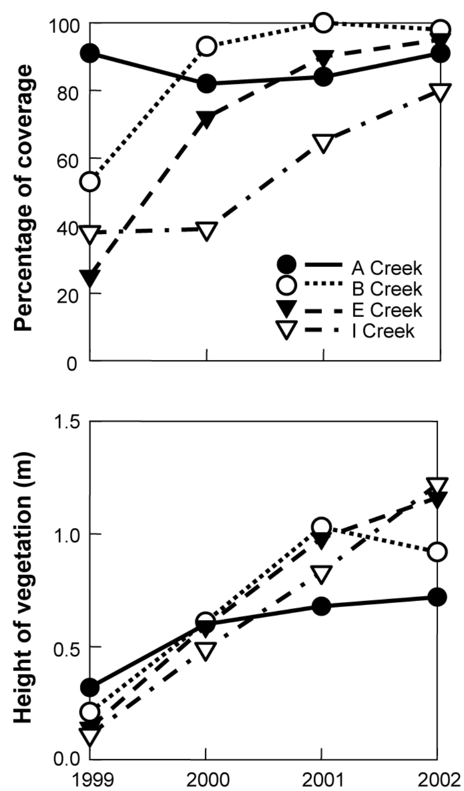

Figure 2. Postharvest changes in ground coverage and height of vegetation in riparian zones of streams with no buffer (S. Mitchell, Department of Forest Science, UBC, unpublished data).

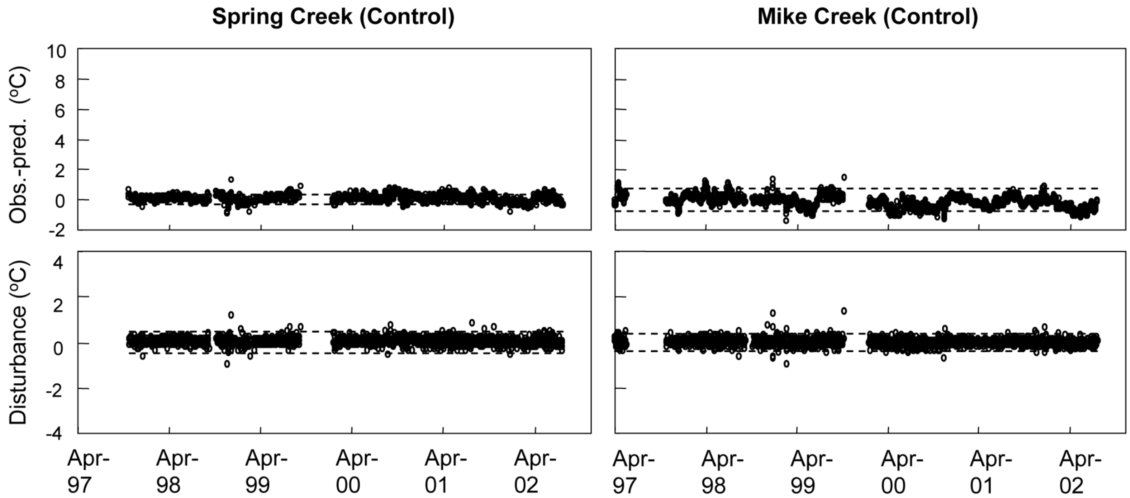

Figure 3. (top) Difference between observed and predicted daily maximum temperature and (bottom) random disturbances in Spring Creek and Mike Creek. Data before 1 April 1999 were used to calibrate the regression model, while data from 1 April 1999 onward were used to test the interannual stability of the model. Dashed horizontal lines in the disturbance plots indicate 95% prediction limits estimated as ±1.96 s_u, (s_u = standard deviation of $\hat{u}_t$); dashed horizontal lines in plots of treatment effects show bands of ±1.96 s_e (where s_e is the standard error of the residuals from the regression).

between treatment effect and air temperature also varied seasonally (Figure 6). The relations between treatment effects and air temperatures did not differ between spring (May and June) and summer (July and August) for A and I Creeks in 1999 and 2000, while treatment effects in May and June appeared to be greater than those in summer for 2001 and 2002. For B creek, treatment effects in summer appeared to diminish to preharvest conditions by the second year following harvest, while spring temperatures remained elevated, but with a weaker relation with air temperature (Figure 6). Although treatment effects for E Creek were located around the upper approximate prediction limit during the first postharvest year for both spring and summer, treatment effects in summer 2000 were distributed within the prediction limits. By the third postharvest year (2001), both summer and spring treatment effects were within the ± 1.96 s_e bounds (Figure 6).

4. Discussion

4.1. Effects of Harvesting With No Buffer on Stream Temperature

[24] Stream temperature response to harvesting with no buffer varied among the treatment streams, with maximum effects on maximum temperature ranging from about 2°–

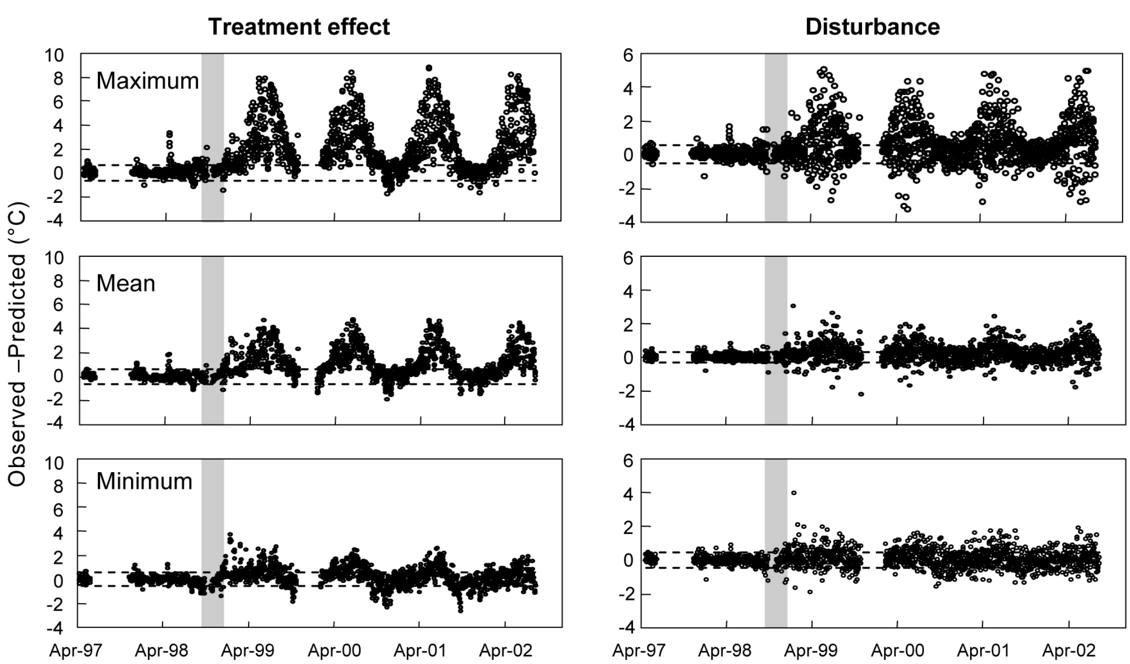

Figure 4. Treatment effects and disturbances for daily maximum, mean, and minimum temperatures for I Creek. See the Figure 3 caption for an explanation of dashed horizontal lines.

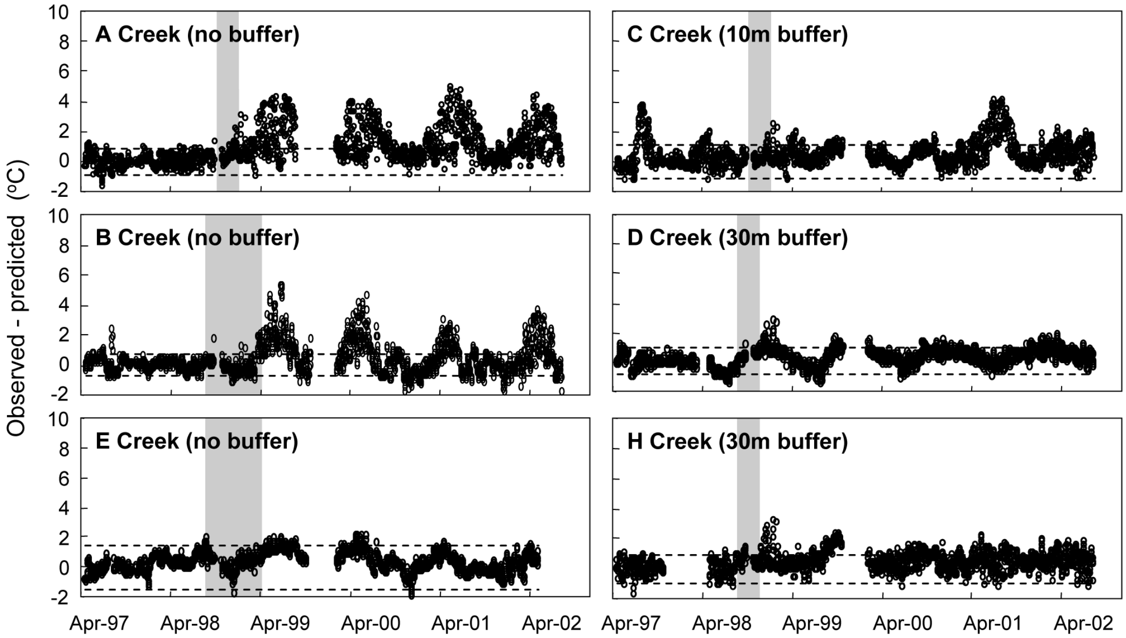

Figure 5. Difference between observed and predicted daily maximum temperatures in streams A, B, C, D, E, and H. Shaded areas indicate period of logging activities. See the Figure 3 caption for an explanation of dashed horizontal lines.

8°C, thus lying within the range of values found in previous studies [*Moore et al.*, 2005a]. Because solar radiation is the greatest source of energy for summertime warming in unshaded streams [*Brown*, 1969], differences in treatment response should, in part, reflect differences in stream shading associated with different channel morphologies. Because A and I Creeks are relatively wide (Table 1), they would be less shaded by their banks and thus more exposed to direct solar radiation input, compared to the narrower, somewhat incised B and E Creeks [*Webb and Zhang*, 1997]. Another important factor is that small wetlands located in the upper parts of I Creek are shallow and slow flowing, maximizing the opportunity for warming. Other factors that could influence the magnitude of temperature response include groundwater inflow, hyporheic exchange and bed heat conduction, which tend to counteract solar heating during the daytime [*Mellina et al.*, 2002; *Story et al.*, 2003; *Johnson*, 2004; *Hannah et al.*, 2004]. Although *Moore et al.*

Table 3. Summary Statistics of Maximum Daily Temperature and Treatment Effect for Spring (May and June) and Summer (July and August) Daily Maximum Temperature

	Prelogging Temperature				Postlogging Temperature				Treatment Effect			
	Mean	SD	Maximum	Minimum	Mean	SD	Maximum	Minimum	Mean	SD	Maximum	Minimum
							Spring					
A	11.8	1.2	15.2	7.9	11.6	2.7	19.2	7.6	1.5	1.3	4.9	−0.5
B	11.0	1.0	13.0	8.4	11.8	1.6	15.9	8.2	1.9	1.0	4.6	0.0
E	9.6	1.4	11.4	6.6	10.5	1.4	13.1	8.1	1.2	0.5	2.1	0.2
I	10.9	1.6	14.7	7.3	12.7	3.4	22.2	7.3	3.6	2.2	8.8	0.4
C	11.7	1.5	15.6	7.9	10.4	2.0	14.3	7.6	0.1	0.8	2.2	−0.9
D	10.6	1.5	12.6	7.0	9.1	1.7	12.9	6.3	−0.1	0.4	0.7	−1.2
H	12.1	1.6	14.0	8.2	10.9	2.2	16.8	7.5	0.3	0.6	2.2	−0.9
Spring	9.9	1.2	12.4	6.0	8.1	1.6	12.6	5.1	0.1	0.2	0.8	−0.2
Mike	10.2	1.3	12.9	6.5	8.4	1.6	13.2	5.9	−0.6	0.3	0.3	−1.1
							Summer					
A	15.4	1.6	19.4	11.4	16.3	1.8	20.4	10.2	2.1	1.1	4.8	−0.7
B	13.7	1.0	17.1	11.8	13.4	1.3	17.3	11.2	0.4	1.3	5.2	−1.8
E	14.2	1.5	17.7	11.3	13.4	1.0	15.4	11.3	0.4	0.8	1.9	−0.7
I	15.0	1.3	18.0	12.5	17.3	2.3	22.0	10.2	3.9	1.8	7.3	−0.1
C	16.1	2.0	20.5	11.8	15.2	1.7	20.1	10.6	1.0	1.3	4.1	−0.6
D	13.6	1.3	16.0	10.8	12.9	1.1	15.5	9.4	−0.2	0.5	1.1	−1.6
H	15.9	1.5	19.8	12.1	15.1	1.4	18.4	11.4	0.4	0.7	1.8	−1.3
Spring	13.8	1.5	16.9	11.2	11.8	1.0	14.1	8.5	0.1	0.2	0.7	−0.4
Mike	13.9	1.2	16.7	11.8	12.4	1.1	14.9	9.0	−0.3	0.4	−0.3	−1.1

Table 4. Summary and Statistical Significance of Disturbances in July and August for Daily Maximum Temperature[a]

	Creek								
	A	B	E	I	C	D	H	Spring	Mike
1997									
Mean	−0.1	0.0	0.0	-	0.4	0.0	0.0	-	-
SD	0.3	0.4	0.2	-	0.7	0.2	0.4	-	-
1998									
Mean	0.0	0.0	-	0.0	0.0	-	-	0.0	0.0
SD	0.3	0.2	-	0.2	0.4	-	-	0.1	0.2
1999									
Mean	**0.6**	**0.3**	**0.0**	**1.2**	**0.1**	−0.1	**0.2**	0.1	0.0
SD	**1.1**	**0.9**	**0.2**	**1.6**	**0.3**	0.3	**0.3**	0.2	0.2
2000									
Mean	**0.5**	**0.0**	0.0	**1.0**	**0.0**	0.0	0.1	0.0	**−0.1**
SD	**0.6**	**0.3**	0.2	**1.2**	**0.2**	0.3	0.5	0.1	**0.2**
2001									
Mean	**0.5**	0.0	0.0	**1.0**	**0.8**	0.0	0.1	0.0	0.0
SD	**0.7**	0.3	0.1	**1.1**	**0.6**	0.3	0.5	0.2	0.1
2002									
Mean	**0.3**	**0.0**	-	**1.0**	0.2	0.0	0.1	0.0	**−0.1**
SD	**0.6**	**0.5**	-	**1.5**	0.6	0.3	0.5	0.1	**0.1**

[a]Bold values for 1999–2002 indicate significant differences ($p < 0.05$) in distribution of disturbance based on two-sample Kolmogorov-Smirnov test between prelogging and postlogging disturbances.

[2005b] estimated these effects for A Creek, comparable data are unavailable for the other streams.

[25] Differential streamflow responses to harvesting could also have influenced the relative effects for the different streams. Even though the experimental design attempted to control for this effect by keeping the harvested fraction roughly constant, differences in riparian vegetation conditions could have influenced the magnitude of low flows for the no buffer treatments [*Hicks et al.*, 1991]. An indication of the magnitude of this effect can be made for A Creek, where regression analysis suggested that doubling (halving) stream discharge would decrease (increase) daily maximum stream temperature by only about 0.7°C [*Moore et al.*, 2005b, Table III]. However, the effect of differential streamflow response to harvesting cannot be definitively estimated in the absence of streamflow data.

[26] The relations between treatment effect and air temperature suggest that thermal recovery was occurring in the four no-buffer streams (Figure 6), although at different rates. Recovery appeared to occur more rapidly for summer (July and August), possibly due to the greater leaf area of riparian shrubs and the associated increase in shading, especially as solar elevation angle decreases through the summer. For the relatively narrow B and E Creeks, summer recovery appeared to occur within two years. For the wider A and I Creeks, partial recovery in summer (July–August) temperatures occurred through the four postharvest years (Figure 6), broadly consistent with several previous studies at rain-dominated catchments in the Pacific Northwest, where temperature recovery occurred, or was at least underway, within 5–10 years [*Brown and Krygier*, 1970; *Harris*, 1977; *Feller*, 1981; *Harr and Fredriksen*, 1988]. However, *Feller* [1981] reported one stream for which recovery was not detectable in the 7 year postharvest period, while *Johnson and Jones* [2000] found that recovery occurred in about 15 years after debris flows disturbed the riparian zones of two streams. The apparently more rapid thermal recovery observed for B and E Creeks, as compared to other studies [see *Moore et al.*, 2005a], likely relates to the potential for greater shading by riparian vegetation in those narrow streams.

4.2. Effectiveness of Riparian Buffers for Minimizing Stream Temperature Response

[27] The 30 m wide riparian buffers appeared to be effective at minimizing postharvest stream warming in this study. The 10 m buffer also appeared to minimize warming, although the data are confounded by short-term temperature increases that occurred both preharvest and postharvest. The effectiveness of the buffers may have been maximized by the north-south orientation of the streams, such that the streams would be well shaded from late morning to early afternoon by the overhead canopy, even under the 10 m buffer. These results contrast with those from some other studies, where substantial postharvest warming was observed despite retention of riparian buffers [*Hewlett and Fortson*, 1982; *Jackson et al.*, 2001; *Macdonald et al.*, 2003]. More research is clearly needed to quantify stream temperature response to harvesting with buffers, combined with more information on the heat exchanges that control temperature response.

4.3. Potential Confounding by Upstream Treatments

[28] As mentioned earlier, some of the treatment reaches were located downstream of other treatment units, potentially confounding the treatment effect. However, the errors associated with this situation are likely to be minor. For example, the D Creek treatment resulted in maximum warming of less than 2°C. Furthermore, this warming effect for D Creek would have been diluted through groundwater and tributary inflow and modified by the effects of energy exchanges under a complete canopy in the reach above the A Creek cut block [*Story et al.*, 2003; *Rutherford et al.*, 2004]. The H Creek unit is located downstream of I Creek, which did exhibit significant warming after harvesting. However, much of this warming would likely have been lost due to the effects of the lake into which I Creek flowed, upstream of H Creek, in accordance with the serial discontinuity concept [*Ward and Stanford*, 1983]. In any event, the effects of upstream treatments at C and H Creeks would have been to increase the apparent effect at those reaches, so that the observed responses, which were relatively small, would be exaggerated. Thus the qualitative conclusion that the streams with buffers did not exhibit substantial warming would remain valid.

4.4. Experimental Design and Data Analysis

[29] The use of GLS regression for fitting prelogging relations using daily time series proved to be an effective approach for maximizing the information available in a relatively short pretreatment period, as well as for providing information on the within- and between-season variations in the treatment effect. In particular, by regressing treatment effect against air temperature to account for variations in meteorological conditions that control surface energy inputs, the effects of nonclimatic controls could be tentatively identified. However, availability of streamflow, both preharvest and postharvest, would be required to quantify

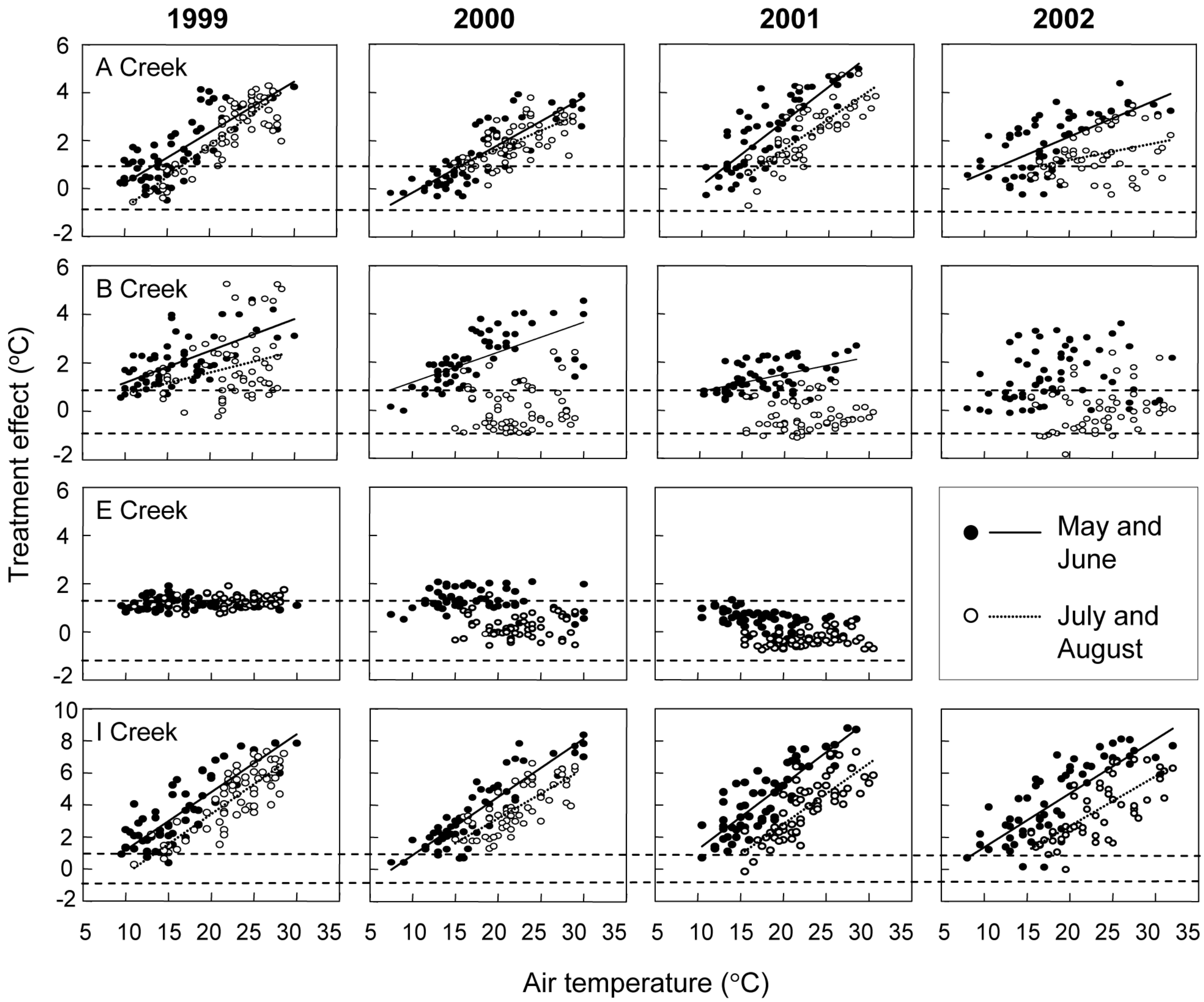

Figure 6. Relations between treatment effects and air temperature in spring (May–June) and summer (July–August). Regression lines in figures indicate significant relations between treatment effect and air temperature at $\alpha = 0.05$. Dashed horizontal lines indicate bands of ± 1.96 s_e (where s_e is the standard error of the residuals from the GLS regression).

effects of hydrologic changes on stream temperature response.

[30] The use of multiple control streams in this study provided a basis for assessing the stability of the pretreatment calibrations. However, stability for two controls does not guarantee stability for other streams, and more confidence could be gained by including more controls and longer pretreatment data collection. The replication of treatments, insofar as treatments can be replicated given the unique attributes of any catchment, highlighted the variability of response among streams, which is likely due to variations in channel morphology as well as differences in stream-subsurface exchanges of heat and water. The integration of process studies, conducted both preharvest and postharvest, would be valuable for identifying more conclusively the dominant processes causing the observed variability in treatment effect.

[31] An issue that does not appear to have been addressed in previous experiments is spatial heterogeneity of stream temperatures, which has been well documented for larger stream reaches [e.g., *Arscott et al.*, 2001; *Ebersole et al.*, 2003]. Such variability within a reach could confound the comparison of treatment effects among reaches. *Moore et al.* [2005b] documented summertime spatial variations of up to 2°C within a single step-pool unit at A Creek, associated with locally upwelling hyporheic and/or groundwater flow, as well as distinct longitudinal warming and cooling trends over distances of tens of meters. Future studies should sample stream temperature at different locations within the treatment unit, and not just at the downstream end, to provide a more accurate measure of the effects of harvesting on aquatic habitat throughout the treatment reach and the variability of response across streams.

5. Conclusions

[32] This study examined headwater stream temperature response to clear-cut logging with and without riparian buffers using a replicated paried catchment experimental design. Generalized least squares regression provided an

effective method for establishing prelogging calibrations using daily time series, for which residual autocorrelation needs to be taken into account. Analyzing daily time series of stream temperature allowed the use of relatively short preharvest periods for calibration (less than two years) and also permitted tentative identification of the daily, seasonal, and annual variation of harvesting effects, in particular the nature of postharvest recovery. The use of multiple control streams allowed an assessment of the year-to-year stability of the preharvest regression.

[33] Daily maximum temperatures increased from 2° to 8°C in four streams with no riparian buffer. Apparent recovery toward preharvest temperature regimes occurred at different rates in the four streams, with more rapid recovery in July and August than in May and June. This seasonal difference in apparent recovery rates is consistent with the seasonal variation in leaf area of shrubby riparian vegetation, in combination with changing solar angles. Variations in treatment effect and rates of recovery among streams are also likely related to channel morphology and its influence on shading by the stream banks and shrubby riparian vegetation. Narrower channels exhibited less warming and recovered more rapidly through time.

[34] Both 10 and 30 m wide riparian buffers appeared to be effective for minimizing stream temperature increases. Particularly for the 10 m buffer, this effectiveness may have been enhanced by the north-south orientation of the streams, such that they would be well shaded from late morning to early afternoon by the overhead canopy. A caveat to the results for the 10 m buffer is that anomalous warming occurred both preharvest and postharvest during low-flow periods, confounding interpretation.

[35] **Acknowledgments.** John Richardson, Peter Kiffney, Michael Feller, and Steve Mitchell supplied data. Funding was provided by operating grants to RDM from Forest Renewal British Columbia (FRBC) and Natural Sciences and Engineering Research Council. TG and ASD were supported by funding through grants from FRBC and Forestry Investment Initiative (FII). This project is part of a broader FRBC- and FII-funded project titled "Ecology and management of riparian - stream ecosystems: a large scale experiment using alternative streamside management techniques" (P.I. John Richardson). Jennifer Bull assisted with field data collection and processing. E. Leinberger produced the location map. Anthony Story, three anonymous referees and Associate Editor Aaron Packman provided constructive reviews of earlier versions of the manuscript.

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