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Riparian Forest Harvesting Effects on Maximum Water Temperatures in Wetland-sourced Headwater Streams from the Nicola River Watershed, British Columbia, Canada

Sierra Rayne • Gregory Henderson • Paramjit Gill • Kaya Forest

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Abstract Water temperature was continuously recorded during the ice-free season between June/July and October/November at 90 sites with lentic and lotic stream sources distributed throughout the Nicola River watershed (British Columbia, Canada) in 1999, 2000, and 2001. The eight lentic-sourced stream temperature monitoring sites were located in two adjacent watersheds. The headwaters and riparian areas around the wetland outlet of the treatment watershed were harvested during the overwinter period between 1999 and 2000. Areas around and downstream of the headwater wetland outlet in the control watershed were not harvested. Reducing riparian shade by harvesting activities increased maximum stream temperatures in the treatment watershed by up to 1–2°C relative to the control watershed. Because of the general downstream cooling trends in lentic-sourced headwater streams, riparian harvesting activities in these regions have a reduced thermal impact relative to similar harvesting alongside lotic-sourced headwater streams, whose maximum stream temperatures may warm by up to 8°C following harvesting. The downstream influence of elevated maximum stream temperatures from riparian harvesting of lentic-sourced headwater streams appears to be localized, but persists for at least 2 years following harvesting. Both lentic-sourced treatment and control streams in the current study relaxed

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S. Rayne (✉)
Chemistry, Earth and Environmental Sciences, Irving K. Barber School of Arts and Sciences,
The University of British Columbia at Okanagan, 3333 University Way,
Kelowna, British Columbia V1V 1V7, Canada
e-mail: sierra.rayne@ubc.ca

G. Henderson
Matrix Solutions, Inc., #118 319-2nd Avenue S.W., Calgary, Alberta T2P 0C5, Canada

P. Gill
Mathematics, Statistics, and Physics, Irving K. Barber School of Arts and Sciences,
The University of British Columbia at Okanagan, 3333 University Way,
Kelowna, British Columbia V1V 1V7, Canada

K. Forest
Department of Chemistry, Okanagan College, 583 Duncan Avenue West,
Penticton, British Columbia V2A 8E1, Canada

towards baseline equilibrium temperature estimated by the lotic-sourced watershed trend within several hundred meters of downstream travel distance, with cooling rates proportional to the distance from expected thermal equilibrium. Due to the heating in wetland-sourced stream reaches adjacent to riparian harvesting, the regions downstream of treatment areas cool more rapidly than similar regions in control watersheds as the stream attempts to achieve thermal equilibrium.

Keywords Stream temperature · Headwater streams · Riparian harvesting activities · Thermal equilibrium · Water quality

1 Introduction

In recent years, the form and function of headwaters streams has received increased attention worldwide. Historically, such streams have received relatively less research attention than their larger, fish-bearing downstream counterparts. Although headwater streams are generally small in terms of discharge, their large numbers make them a significant portion of the stream system, thereby raising concerns about the cumulative and downstream impacts of anthropogenic headwater activities such as riparian forest harvesting (Brown 1985). Among the numerous variables influenced by riparian harvesting activities in a river's watershed, the temperature of headwater streams is of great interest because of its influence on biota and stream chemistry (Johnson 2004). In particular, maximum stream temperatures are often of focus due to their potential deleterious effects on aquatic biota (Barton et al. 1985; Beschta et al. 1987).

Spatial and temporal variations in stream temperature result from a number of interactive hydrological, meteorological, and landscape factors (Brown 1969). Direct solar radiation on the stream surface is a major thermal input (Beschta et al. 1987; Sinokrot and Stefan 1993; Webb and Zhang 1997; Johnson 2004). Other influences include energy exchange by conduction between stream water, substrate, and hyporheic fluxes (Crittenden 1978; Hondzo and Stefan 1994; Evans et al. 1995; Johnson 2004), evaporation and sensible heat exchange with the atmosphere (Sinokrot and Stefan 1993; Webb and Zhang 1997), and advection of groundwater and upstream flow (Ingebritsen et al. 1992; Webb and Zhang 1997).

A dominant pattern of temperature at the watershed scale that has been observed worldwide is a warming trend in the downstream direction (Hynes 1970; Vannote et al. 1980; Sullivan and Adams 1989). Lotic-sourced streams tend to have the lowest water temperatures near headwater sources where groundwater has recently emerged from subsurface flow pathways and riparian vegetation along narrow channels is capable of blocking incoming solar radiation (Brown 1969; Black 2000). This general trend in increasing stream temperature with distance from the watershed divide reflects the systematic change in average conditions of the dominant factors that control water temperature. Together, the combination of these characteristics at each site determine its equilibrium temperature (Sullivan and Adams 1989; Caissie et al. 2005) and produce a spatially and temporally resolved watershed scale thermal regime.

In contrast to lotic-sourced streams, lentic-sourced streams arising from lakes, wetlands, swamps, etc., generally undergo initial cooling in the downstream direction (Brownlee et al. 1988; Hendricks and White 1995; Mellina et al. 1999, 2002; Maxted et al. 2005). Studies characterizing the range of potential impacts on headwater stream temperatures from riparian harvesting activities have primarily focused on those with lotic sources (see e.g., Brown and Krygier 1970; Quinn et al. 1997; Johnson and Jones 2000; Macdonald et al. 2003a, b; Johnson 2004), with the remainder of the literature investigating the effects large reservoirs have on major high-order river ecosystems (Baxter 1977). To the best of our knowledge, only a limited number of investigations have examined riparian harvesting effects on temperatures in headwater streams with lentic sources (e.g., wetlands, lakes, etc.) (Mellina et al. 1999, 2002), and the potential impacts remain poorly understood.

To help fill this research gap, we undertook a 3-year study in the Nicola River watershed in British Columbia, Canada using a paired treatment-control watershed approach on two wetland-sourced headwater streams, combined with a regionally distributed water temperature monitoring network on lotic-sourced streams to better contextualize any potential impacts of riparian harvesting in the lentic-sourced system. Although maximum stream temperatures are known to be affected by riparian vegetation removal (see e.g., Beschta et al. 1987), there is disagreement in the literature regarding the effect (if any) on minimum water temperatures (no change: Johnson 2004; Rutherford et al. 2004; change: Rishel et al. 1982; Lynch and Rishel 1984; Sweeney 1992; Johnson and Jones 2000). Because of the biological effects of maximum stream temperatures (Beschta et al. 1987), and the regulatory focus in this regard, our work was concentrated on potential changes to the upper thermal regime in the study area.

2 Study Area

The Nicola River is located in south-central British Columbia, Canada, with a watershed area of >7,000 km^2 (Fig. 1). The Nicola River watershed occupies the Thompson Plateau physiographic region (Holland 1976) where the topography is mainly upland rolling hills, except in the southwest where the transition between the Plateau and the Cascade Mountains is sharp, and steep mountain slopes drain to the Spius and Coldwater Creeks. Headwater streams in the Nicola watershed are low order (i.e., zero-, first-, or second-order on a 1:30,000 scale map), often located at elevations higher than 1,220 m with steep (>5%) gradients, and typically within 5–20 km distance from the top of the watershed divide. Forest types in the study area above 1,200 m elevation fall into the Engelmann Spruce Subalpine Fir, Montane Spruce, and Interior Douglas Fir biogeoclimatic zones. Such biogeoclimatic zones are geographic areas with broadly homogeneous climates and plant species (Mitchell and Green 1981; Lloyd et al. 1990). The summer climate in the region is characterized as hot and dry with daily maximum air temperatures exceeding 40°C at times and approximately 20–25 mm of average monthly precipitation between March and October (Walthers and Nener 1998). Annual precipitation averages 314 mm, of which 223 mm (or 71%) is rainfall. The warm summer climate of this semi-arid region consistently produces annual hydrographs with the lowest flows (typically about 20% of peak flows) in August and September (Rood and Hamilton 1995) .

3 Materials and Methods

3.1 Water Temperature Monitoring

Water temperature was continuously recorded during the ice-free season between June/July and October/November at 90 sites with lentic (e.g., wetland, pond, lake; $n=8$) and lotic (e.g.,

Fig. 1 Map showing the location of the study area

groundwater; $n=82$) stream sources distributed throughout the Nicola River watershed in 1999, 2000, and 2001. Air temperature was also monitored at eight of the sites. Because of concentrated forest harvesting activities in the southwestern and southeastern regions of the Nicola River watershed, water and air temperature monitoring was more intensively monitored in these areas rather than evenly distributed throughout the watershed. All sites were visited monthly to ensure stations were functioning.

Of the 82 lotic-sourced stream temperature monitoring sites, the distribution as a function of distance from the watershed divide was as follows: 0–5 km ($n=17$), 5–10 km ($n=16$), 10–15 km ($n=12$), 15–20 km ($n=12$), 20–30 km ($n=11$), 30–40 km ($n=5$), 40–50 km ($n=2$), 50–60 km ($n=4$), 60–70 km ($n=2$), and 70–80 km ($n=1$). The range of distances from a watershed divide was 0.7–78.4 km. These sites were located in stream reaches not affected by riparian forest harvesting, and contained non-anthropogenically influenced levels of stream shading.

The eight lentic-sourced stream temperature monitoring sites were located in two adjacent watersheds (North Tributary Creek [NTC] and West Tributary Creek [WTC]). The headwaters of the NTC watershed was harvested (including riparian areas around the wetland outlet of the stream) during the overwinter period between 1999 and 2000. Areas downstream of the headwater wetland outlet in the NTC watershed were not harvested. Water temperature monitoring sites were located in the NTC watershed at distances of 0 m (wetland outlet; NTC1), 340 m (NTC2), 590 m (NTC3), and 1,690 m (NTC4) downstream of the headwater wetland outlet. The WTC watershed was treated as a paired control watershed for the study, and water temperature monitoring sites were located at distances of

0 m (WTC1), 1,400 m (WTC2), 1,900 m (WTC3), and 2,300 m (WTC4) downstream of headwater wetland outlet.

Water temperature was monitored at each of the 88 sites with a waterproof Stowaway Tidbit™ datalogger (Onset Computer Corporation; Bourne, MA, USA) capable of recording temperature in the range of −4 to 37°C with an accuracy of ±0.2°C. Prior to field installation, the dataloggers were tested over a range of temperatures from 0°C to approximately 40°C and compared with those from a certified mercury thermometer. Water temperature was also recorded at each field visit using a certified mercury thermometer and compared to values measured by the dataloggers. Good agreement was observed between laboratory and field based temperatures reported by the datalogger and that of the certified mercury thermometer.

At each site, the datalogger was situated in turbulent water flow to ensure maximum mixing of water layers and a representative stream temperature profile. Pools and quiescent backwater channels were avoided. The datalogger was connected by rigid metal wire to a lead or brick weight or a metal rod (depending on stream velocity and conditions) to prevent downstream movement and situated away from direct sunlight if water was shallow. Underwater thermistors were not housed in radiation shields, and may have been in direct sunlight at some locations for a few hours each day. However, it is considered unlikely they would have absorbed heat and measured a different temperature from the water because the water flow was strong at each site, resulting in rapid heat conduction between the thermistor casing and surrounding water (Rutherford et al. 2004). In addition, the datalogger was suspended above the channel bed to avoid collision with mobile bedload. Dataloggers were programmed to measure stream temperature every hour over the annual study periods.

Air temperature was also measured at eight selected stream sites using a Stowaway Tidbit™ datalogger mounted inside an air shelter. The air shelters were made of a half-section of PVC pipe and were erected 1.5 m above the water surface on a wood stake. The dataloggers were suspended on a hook within the shelters to reduce conductive heat transfer between the datalogger and the exposed shelter. Air shelters were positioned in a north-south direction to avoid direct sunlight from a setting or rising sun. Regional air temperatures in the Nicola River watershed were also acquired for 1999, 2000, and 2001 from the Environment Canada climate station at the nearby city of Merritt (http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html).

3.2 Stream Reach Surveying

Stream reach surveys were carried out at low flow in mid- to late-August above each water temperature datalogger site to inventory the following channel and riparian characteristics that may directly or indirectly influence observed stream temperature profiles: wetted width, thalweg and average depth, channel morphology, channel gradient, stream aspect, shade cover, stream discharge, and groundwater discharge. Field methods were based on those published elsewhere (Sullivan et al. 1990). Survey length was a minimum of 200 channel widths, a distance estimated to average the upstream physical and morphological features that affect stream temperature. Survey distance ranged from 225 to 1,270 m above the downstream datalogger. Field sketches were also made to describe stream system morphology and to document other factors that may influence or explain stream temperature characteristics (e.g., beaver dams, presence of fish, riparian vegetation, groundwater seepages, tributary inputs, and aggraded channel conditions). Shade cover was estimated as the influence of riparian vegetation and topography blocking the stream's view-to-the-sky (Adams and Sullivan 1989). Shade was measured as the spherical canopy density (SCD) with the Lemmon Model A spherical densiometer (Lemmon 1957). Measurements were taken in four cardinal points (north, south, east, and west) and averaged. Stream shading was also evaluated as the angular canopy density (ACD), which measures blocking in the south direction only, as described elsewhere (Teti 2001). No difference was observed in the measure of shade determined by the ACD and SCD methods.

Stream velocity and flow was measured by a constant rate salt dilution injection method (Johnstone 1988) following field guide procedures for small streams (Moore 2001). Electrical conductivity was measured with a WTW LF 330 conductivity meter (WTW Measurement Systems, Inc.; Ft. Myers, FL, USA) utilizing automatic temperature compensation. The constant rate salt dilution injection was not applicable where still pools and channel morphology (e.g., where water depth was too shallow [often less than 0.10 m]) prevented full mixing of the salt injection. In these locations, streamflow into a bucket inserted below natural or constructed channel steps was timed to estimate discharge within ±10–20%. Stream velocity was also estimated by timing float objects as a check on results obtained from the salt injection technique. Error associated with the salt dilution injection method is approximately ±5%, whereas error for the float estimation method is approximately ±10–15%. Groundwater temperatures were estimated by field measurements at seeps and stream banks using a digital thermometer. Groundwater inflow and streamflow lost to groundwater was estimated as the difference in discharge between upstream and downstream points in a stream reach, and will have an error on the order of streamflow measurements obtained by the salt dilution injection method (±5%).

3.3 Statistical Methods

To determine the potential effects of riparian harvesting on the wetland-sourced NTC at the four downstream water temperature monitoring sites (NTC1, NTC2, NTC3, and NTC4), observed post-harvesting average maximum stream temperatures during the warmest seven consecutive days ($T_{\text{max, 7-day avg}}$) in 2000 and 2001 were compared to pre-harvesting $T_{\text{max, 7-day avg}}$ values during 1999. The one-way ANOVA statistical test compared the difference in the $T_{\text{max, 7-day avg}}$ during a particular year between each treatment site (NTC1, NTC2, NTC3, and NTC4) and the corresponding reference sites (WTC1, WTC2, and WTC3) with the difference in $T_{\text{max, 7-day avg}}$ between the particular treatment site/reference site pair during 1999 (the pre-harvesting control year). The approach accounts for year-to-year microclimatic variability in stream temperatures within the paired watersheds, allowing the thermal effects of riparian harvesting on wetland-sourced headwater streams to be differentiated from natural variances. WTC1 (0 m downstream from wetland outlet in the control watershed) was used as the reference site for sites NTC1 (0 m), NTC2 (340 m), and NTC3 (590 m) in the treatment watershed. An average of WTC2 (1,400 m) and WTC3 (1,900 m) was used as the reference site for NTC4 (1,690 m).

4 Results and Discussion

Maximum stream temperatures were compared at four sites in North Tributary Creek (NTC) between pre- (1999) and post-harvesting (2000 and 2001) years, and in reference to undisturbed control sites in the adjacent West Tributary Creek (WTC) watershed over this period (1999 through 2001). The analyses involved a statistical comparison (see Section 3 for details) of $T_{\text{max, 7-day avg}}$ values during the study years at a site on NTC where riparian harvesting occurred within the reach during the overwinter of 1999/2000 (NTC1 [0 m downstream from harvesting at the wetland outlet]) and three sites downstream of riparian harvesting (NTC2 [340 m downstream], NTC3 [590 m downstream], and NTC4 [1,690 m downstream]), relative to three undisturbed reference sites having no nearby riparian harvesting activities or anthropogenic influences on stream shading or hydrology/hydrogeology in the adjacent WTC watershed (sites WTC1, WTC2, and WTC3). Additional stream temperature data was collected at a further downstream site in the WTC watershed (WTC4 [2,300 m]). This site was not used as a reference location for any of the NTC sites due to its significantly greater downstream distance (2,300 m) from the WTC wetland outlet relative to the farthest downstream site in the NTC watershed (NTC4 at 1,690 m, which made WTC2 [1,400 m] and WTC3 [1,900 m] more suitable reference sites than WTC4).

A systematic downstream decrease in the $T_{\text{max, 7-day avg}}$ from NTC1 to NTC4 in the impacted watershed, and from WTC1 to WTC4 in the control watershed, was observed in each of the three study years (Table 1 and Fig. 3). This trend reflects the expected downstream cooling pattern for headwater streams near a wetland source (Brownlee et al. 1988; Hendricks and White 1995; Mellina et al. 1999, 2002). However, statistically significant stream temperature increases (+0.6°C in 2000 and +1.9°C in 2001; $p<0.0001$ for both years) were present in the harvested reach (NTC1) relative to the pre-harvesting 1999 year. No statistically significant difference in $T_{\text{max,7-day avg}}$ during 2000 or 2001 was found at NTC2 (340 m downstream of harvesting; $p=0.51$ in 2000 and $p=0.32$ in 2001), NTC3 (590 m; $p=0.17$ in 2000 and $p=0.21$ in 2001), or NTC4 (1,690 m; $p=0.25$ in 2000 and $p=0.39$ in 2001) relative to the 1999 pre-harvest year, indicating a limited downstream impact (<300 m) of riparian harvesting on summer maximum temperatures in this lentic-sourced headwater stream.

Table 1 Average maximum stream temperature during the warmest seven consecutive days ($T_{\text{max, 7-day avg}}$) in wetland sourced headwater stream reaches directly impacted by riparian harvesting activities (NTC1) and downstream of these impacts (NTC2, NTC3, and NTC4), and at four reference sites (WTC1, WTC2, WTC3, and WTC4) in an adjacent wetland sourced headwater stream not impacted by riparian harvesting activities

	Pre-harvesting	Post-harvesting	
	1999 (°C)	2000 (°C)	2001 (°C)
Harvested and downstream sites			
NTC1 (0 m)	18.6±0.4	21.8±0.6*	20.1±0.6*
NTC2 (340 m)	15.3±0.3	17.0±0.4	13.4±0.3
NTC3 (590 m)	13.1±0.2	14.3±0.3	12.5±0.2
NTC4 (1,690 m)	12.4±0.1	13.3±0.3	10.9±0.2
Reference sites			
WTC1 (0 m)	19.1±0.4	20.8±0.4	18.6±0.5
WTC2 (1,400 m)	15.7±0.3	17.2±0.4	14.8±0.4
WTC3 (1,900 m)	14.4±0.2	16.2±0.2	13.9±0.1
WTC4 (2,300 m)	14.2±0.2	16.1±0.2	13.8±0.1

Error bars are standard deviations about the mean, and values in parentheses represent distances downstream of the respective wetland outlets for the impacted and reference watersheds.

*Significant (at $p<0.0001$) increase in $T_{\text{max, 7-day avg}}$ relative to pre-harvesting condition. No other year-site combinations had statistically significant ($\alpha=0.05$) differences in $T_{\text{max, 7-day avg}}$ values relative to the pre-harvesting condition.

In contrast to riparian harvesting in lotic-sourced streams which, in the absence of anthropogenic perturbations, are already warming in the downstream direction, the localized increases in daily maximum temperatures of up to 1–2°C we observed in lentic-sources streams affected by riparian harvesting are generally lower in magnitude and reduced in downstream impact. Summer daily maximum stream temperature increases of from 3 to 8°C have been reported where riparian harvesting along lotic-sourced streams has occurred (Brown and Krygier 1970; Graynoth 1979; Quinn et al. 1997; Johnson and Jones 2000; Macdonald et al. 2003a, b; Johnson 2004; Rutherford et al. 2004). Summer maximum temperatures have also been reported to occur earlier in the calendar year (and closer to the summer equinox) after riparian harvesting (Brown and Krygier 1970; Holtby 1988; Johnson and Jones 2000), since the dominant forcing for increased stream temperatures is believed the higher solar inputs (Johnson and Jones 2000; Johnson 2003). We did not observe any statistically significant temporal shift in the $T_{\text{max,7-day avg}}$ date in the two watershed under study following riparian harvesting along NTC during 2000, but our sample size was small and a larger study could make more definitive conclusions. It is of note that other work has reported groundwater-driven increases in stream temperature due to riparian harvesting (Curry et al. 2002), consistent with the increased heat flux into groundwater in cut blocks (St-Hilaire et al. 2000). To the best of our knowledge, only one previous study (Mellina et al. 2002) has specifically considered the effects of riparian harvesting on downstream temperature patterns in headwater streams from wetlands and other small lentic systems. This previous work found a temperature increase of about 0.1–1.0°C due to riparian harvesting activities, in the range of what we report in the present study. Our study appears to be one of the first, however, to more completely define the downstream extent of stream temperature impacts from riparian harvesting (<300 m) in lentic-sourced headstream streams.

To better understand the cooling rates observed in the treatment and control watersheds downstream of their respective wetland source outlets, we sought to develop a quantitative understanding of factors controlling the $T_{\text{max, 7-day avg}}$ values among the lotic-sourced water temperature monitoring sites in our study. In contrast to lentic-sourced streams, lotic-sourced streams generally warm down their entire length (Vannote et al. 1980), making them good models for investigating local- and watershed-scale meteorological, hydrological, and landscape processes that govern downstream water temperature trends. As noted in Section 3, at each of the 82 lotic-sourced stream temperature monitoring sites, we collected data regarding elevation, slope, aspect, streamflow and groundwater inflows/outflows, velocity, wetted width, thalweg and average depth, channel morphology, and shade cover. Air temperature was monitored at only eight sites throughout the study area, and thus could not be used for site-specific predictions of stream temperature. Efforts were made to develop multiple regression relationships using the available variables for predicting $T_{\text{max, 7-day avg}}$ values in each of 1999, 2000, and 2001. However, the best predictive approach that could be obtained using our extensive site-specific dataset was a regression between the $T_{\text{max, 7-day avg}}$ value and the distance the site was from the watershed divide (D_{WD}).

For example, in 2000, lotic-sourced streams containing the 82 stream temperature monitoring sites not influenced by riparian harvesting activities in the Nicola River watershed were found to have $T_{\text{max, 7-day avg}}$ values best represented as a single exponential association regression equation with *x*- and *y*-axis offsets of the form $T_{\text{max,7-day avg}} = 14.9 \times (1 - \exp(-0.0267 \times (\text{DWD} + 3.73))) + 10.6$ with an $r^2 = 0.903$ (Fig. 2). Similar relationships between D_{WD} and $T_{\text{max, 7-day avg}}$ were also observed in 1999 ($15.0 \times (1 - \exp(-0.0261 \times (D_{\text{WD}} + 3.52))) + 9.9$; $r^2 = 0.878$) and 2001 ($15.2 \times (1 - \exp(-0.0274 \times (D_{\text{WD}} + 3.86))) + 8.5$; $r^2 = 0.890$). Analogous downstream distance-stream temperature metrics have

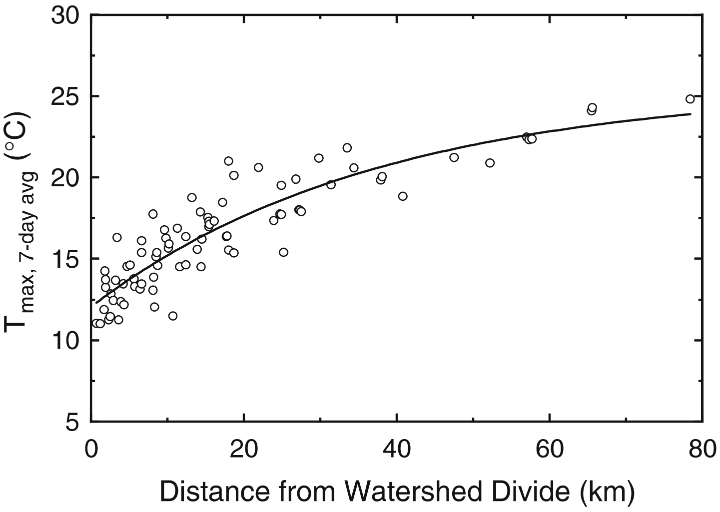


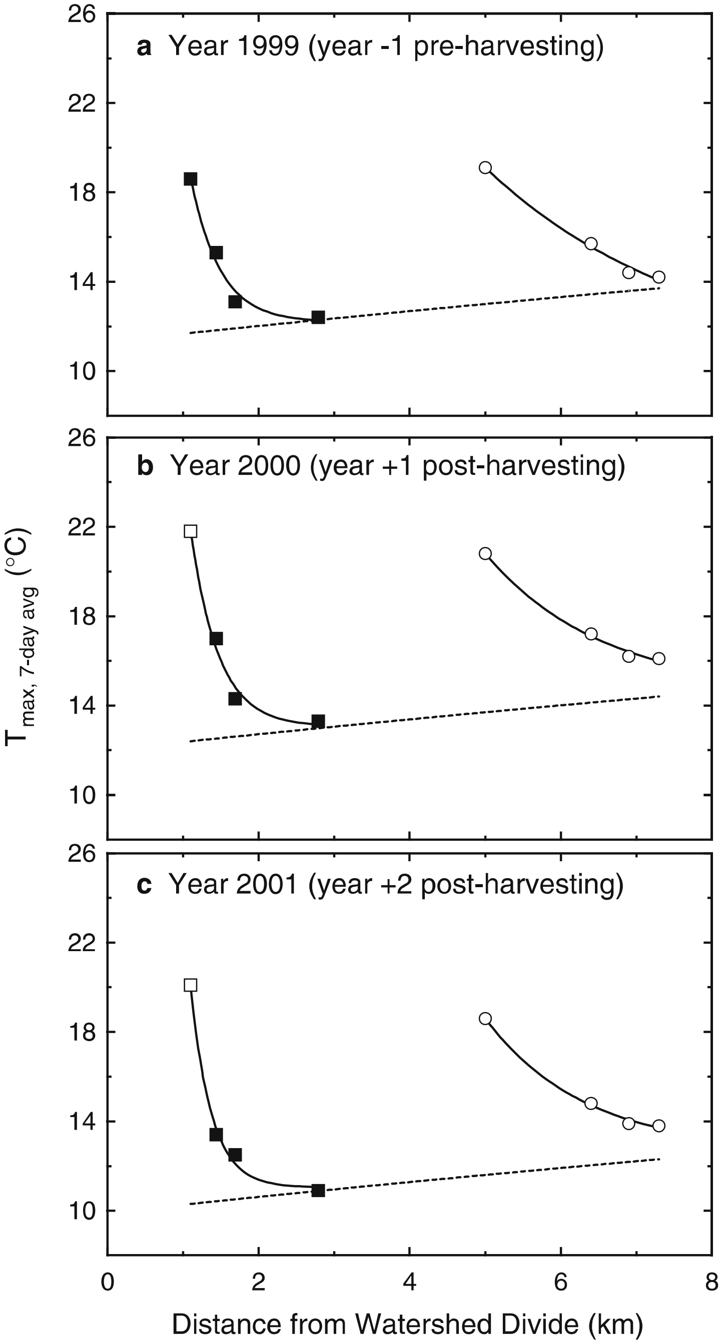
Fig. 2 $T_{max,\ 7\text{-day avg}}$ values in 2000 at 82 lotic-sourced stream sites in the Nicola River watershed unaffected by riparian forest harvesting activities as a function of distance from watershed divide (D_{WD}). A single exponential association regression equation with *x*- and *y*-axis offsets of the form $T_{max,7\text{-day avg}} = 14.9 \times (1 - \exp(-0.0267 \times (DWD + 3.73))) + 10.6$ with an $r^2 = 0.903$ is shown

been previously reported (Gardner et al. 2003), but it is accepted they do not accurately describe the levels of downstream heterogeneity in stream temperatures that can be observed via aerial remote sensing surveys (see Rayne and Henderson 2004, for studies in the Nicola River watershed; Loheide and Gorelick 2006). For these reasons, some authors have questioned the use of average longitudinal temperature trends for determining whether stream temperature has "recovered" from an upstream perturbation (Zwieniecki and Newton 1999). The equilibrium temperature (T_e) concept (Edinger et al. 1968; Novotny and Krenkel 1973; Caissie et al. 2005) has also been used in a number of studies to describe the thermal state a stream is seeking. However, calculations for T_e require detailed spatial knowledge of air temperatures at each site under consideration, and our dataset did not contain this information.

For both the treatment and control watersheds, streams of wetland origin displayed downstream cooling with $T_{max,\ 7\text{-day avg}}$ values progressively decreasing downstream towards the "expected" $T_{max,\ 7\text{-day avg}}$ value for that particular location in the watershed (i.e., based on the D_{WD} at a site) obtained via the predictive relationship for lotic-sourced streams (Fig. 3). In addition to the increase in stream temperature from riparian harvesting, stream cooling rates (calculated using the $T_{max,\ 7\text{-day avg}}$ values in adjacent reaches) immediately downstream from the riparian harvesting in NTC1 (i.e., from NTC1 to NTC2) increased significantly ($p<0.0001$) during the 2000 and 2001 post-harvest years relative to the 1999 pre-harvest year (Table 2). The cooling rate in the NTC1-NTC2 reach was also higher ($p<0.05$) in 2001 (year +2 after harvesting) relative to 2000 (year +1 after harvesting). Other than the significantly increased ($p<0.05$) cooling rate between NTC2 and NTC3 during 2000 (relative to both 1999 and 2001), no other reaches downstream of NTC2 had cooling rates that differed between any combination of pre- and post-harvest years, or among the two post-harvest years.

The higher cooling rate for the NTC1-NTC2 segment nearest the riparian harvesting treatment site in the post-harvesting years of 2000 and 2001 relative to the pre-harvesting 1999 year is consistent with an increased gradient for conductive, convective, and radiative heat loss from the stream. The maximum cooling rates we observed (from 1 to 2°C/100 m) are consistent with other studies downstream of small lentic source waters (Rutherford et al. 2004; Maxted et al. 2005), which have suggested that such high cooling rates apply only over short distances and travel times because downstream water temperatures adjust to the new level of shade and reach a dynamic equilibrium (Rutherford et al. 2004). This new

Fig. 3 $T_{max,\ 7\text{-}day\ avg}$ values in **a** 1999, **b** 2000, and **c** 2001 along two headwater streams with wetland sources. West Tributary Creek (WTC) sites were not influenced by riparian harvesting activities in this unlogged watershed (*open circle*); North Tributary Creek (NTC) sites were located below the source wetland (most upstream monitoring site immediately downstream of wetland outlet) in a unit harvested during the winter of 1999/2000 (given the *open square* in 2000 and 2001 to reflect harvesting effects, and the *filled square* in 1999 to indicate pre-treatment condition) with downstream sites (*filled square*) having non-anthropogenically affected levels of riparian vegetation and stream shading. The *dashed line* represents the watershed trend lines of $T_{max,\ 7\text{-}day\ avg}$ as a function of distance from watershed divide during the corresponding years



dynamic equilibrium, in our watersheds, is best illustrated by the D_{WD} versus $T_{max,\ 7\text{-}day\ avg}$ regression line.

However, cooling and heating rates in streams are influenced by a number of factors, including catchment area, cloud cover, air temperature, wind speed, channel width, water depth and velocity, hydraulic residence time, and shading (Rutherford et al. 1997, 2004). Because of the limited number of study watersheds in our investigation, coupled with a lack of stream instrumentation for heat flux measurements, we did not attempt to rigorously determine the relative importance of these physical factors on cooling rates. Previous work has established that in harvested blocks, evaporation rates can be up to twice as high as in forested areas (Deardoff 1978), and thus, water draining through harvested blocks will have

Table 2 Average cooling rates (°C/100 m) in stream reaches downstream of a harvested riparian area and the wetland outlet (at NTC1) during the warmest seven consecutive days ($T_{max,\ 31\text{-}day\ avg}$) in the NTC wetland sourced headwater stream. Cooling rates in reaches downstream of the wetland outlet (at WTCI) in the control WTC watershed are also presented for comparison

	Pre-harvesting	Post-harvesting	
	1999	2000	2001
Harvested and downstream stream segments			
NTC1 to NTC2 (0–340 m downstream)	1.0 ± 0.4^a	1.4 ± 0.4^b	2.0 ± 0.5^c
NTC2 to NTC3 (340–590 m downstream)	0.9 ± 0.3^a	1.1 ± 0.4^b	0.4 ± 0.3^a
NTC3 to NTC4 (590–1,690 m downstream)	0.1 ± 0.1^a	0.1 ± 0.1^a	0.1 ± 0.1^a
Reference Sites			
WTC1 to WTC2 (0–1,400 m downstream)	0.2 ± 0.2^a	0.3 ± 0.2^a	0.3 ± 0.2^a
WTC2 to WTC3 (1,400–1,900 m downstream)	0.3 ± 0.1^a	0.2 ± 0.1^a	0.2 ± 0.1^a
WTC3 to WTC4 (1,900–2,300 m downstream)	0.1 ± 0.1^a	0.1 ± 0.1^a	0.1 ± 0.1^a

Cooling rates were calculated as the difference in daily maximum temperature between the upstream and downstream sites on each segment divided by the distance between sites. Error bars are standard deviations about the mean. Values in the same row followed by a different superscript lowercase letter are significantly different at $\alpha=0.05$ using one-way ANOVA for comparison of means.

a different heat budget than nearby naturally vegetated zones (St-Hilaire et al. 2000). Hence, stream heating in impacted reaches is most likely due to both increased direct solar irradiation and warmer groundwater inputs, with cooling in shaded reaches resulting from both less direct solar insolation of the stream channel and cooler groundwater inputs (Mellina et al. 2002; Johnson 2003, 2004), assuming all other factors (e.g., slope, aspect, channel morphology, substrate type and hyporheic flow regime, etc.) are equal between treatment and control reaches.

The increased cooling rate after the NTC treatment reach reflects the increase in stream temperature following riparian harvesting, leading to an increase in distance from the surrogate equilibrium temperature as exemplified by the watershed trend line for each year. However, when all available cooling rate data from both the treatment and control watersheds in 1999, 2000, and 2001 is plotted against the difference between the observed $T_{max,\ 7\text{-}day\ avg}$ value and the $T_{max,\ 7\text{-}day\ avg}$ value "expected" from the D_{WD} versus $T_{max,\ 7\text{-}day\ avg}$ relationship at each particular location/year combination, only a modest relationship is

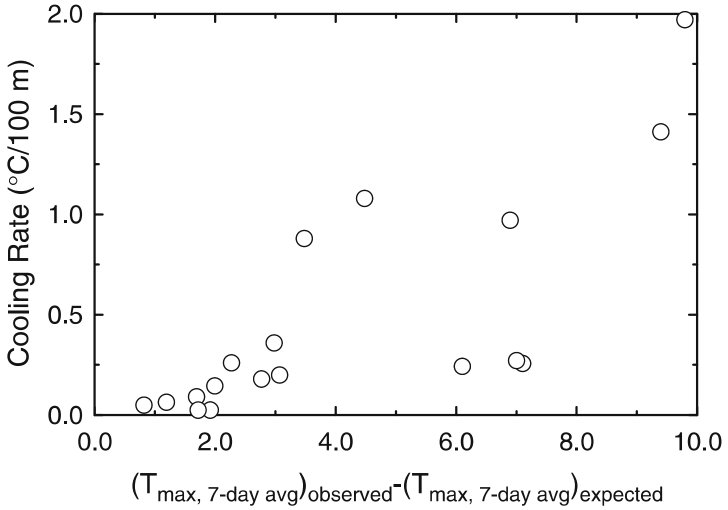


Fig. 4 Rate of stream cooling in relation to the observed $T_{max,\ 7\text{-}day\ avg}$ value and the $T_{max,\ 7\text{-}day\ avg}$ value "expected" from the D_{WD} versus $T_{max,\ 7\text{-}day\ avg}$ relationship at each particular location/year combination

observed (Fig. 4). Among the heat exchange mechanisms affecting stream temperature (direct and indirect solar irradiation, air convection, evaporation/condensation, groundwater flux, streambed conduction, and hyporheic flux), there are considerable spatial heterogeneities in the relative magnitudes of each exchange mechanism within and between stream reaches (Story et al. 2003). For example, hyporheic fluxes cause a buffering of stream temperatures, whereas groundwater fluxes generally cause a depression in stream temperatures (Loheide and Gorelick 2006; although Curry et al. 2002, report groundwater driven net increases in stream temperature). Both fluxes are highly dependent on the nature of the stream substrate, and the magnitude and direction of groundwater communication with surface streamflow (Johnson 2004). As well, small headwater streams may have variable shading from riparian groundcover (e.g., grass, sedge, and rush) or due to deep incising and shading by the streambank (Quinn et al. 1997), both factors that change over the course of several meters down a streamcourse. Furthermore, temporal patterns in downstream cooling from riparian harvesting have been reported, with some reaching moving from “no cooling” to “slight cooling” to “substantial cooling” on daily timescales (Story et al. 2003). Together, the spatial and temporal variations in the scalar and vector components of these factors greatly complicate generalized descriptions of cooling rates in streams, as is evident in our dataset and throughout the literature (see e.g., Mellina et al. 2002; Rutherford et al. 2004).

5 Conclusions

Reducing riparian shade by harvesting activities alongside a wetland-sourced headwater stream in a treatment watershed increased maximum stream temperatures by up to 1–2°C relative to the control watershed. Because of the general downstream cooling trends in lentic-sourced headwater streams, riparian harvesting activities in these regions have a reduced thermal impact relative to similar harvesting alongside lentic-sourced headwater streams, whose maximum stream temperatures may warm by up to 8°C following harvesting. The downstream influence of elevated maximum stream temperatures from riparian harvesting of lentic-sourced headwater streams appears to be localized, but persists for at least 2 years following harvesting. Both lentic-sourced treatment and control streams in the current study relaxed towards baseline equilibrium temperature estimated by the lotic-sourced watershed trend within several hundred meters of downstream travel distance, with cooling rates proportional to the distance from expected thermal equilibrium. Due to the heating in wetland-sourced stream reaches adjacent to riparian harvesting, the regions downstream of treatment areas cool more rapidly than similar regions in control watersheds as the stream attempts to achieve thermal equilibrium.

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