Effects of riparian deforestation on littoral water temperatures in small Boreal forest lakes

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In a four-month comparison of hourly littoral water temperatures in four small boreal lakes, recent shoreline deforestation was associated with an altered temperature regime at only one lake, on a southern shoreline. There, daytime hourly median water temperatures were increased by 0.3 °C, with frequent increases of 0.5 °C and occasional increases of up to 1.2 °C, relative to a nearby forested shoreline; nighttime temperatures were reduced by about 0.2 °C. Over about three months, the littoral zone of the deforested southern shoreline accumulated only about one-half of a degree day more than the forested shoreline. Time-series analyses of hourly climate data and water temperature patterns from two nearby undisturbed lakes suggest that hourly littoral water temperature patterns were primarily associated with hourly patterns of solar energy, while day-to-day water temperature patterns were associated only with air temperature. Where riparian deforestation significantly reduces littoral shading, the main effect on littoral water temperatures is likely to be an increase in diurnal temperature fluctuation. Daily average water temperatures are strongly associated with regional air temperature, and are not likely to be affected significantly by localized riparian deforestation.

Introduction

Because littoral habitats in lakes offer a relative abundance of light, nutrients, and clean substrate compared with offshore waters, they are relatively important to primary and secondary production in lake ecosystems (e.g., Wetzel 1983, France and Steedman 1996). Aside from catchment-scale hydrologic and geomorphic effects, removal by logging, fire or blowdown of shoreline or riparian

forest around Boreal lakes is known to directly affect a variety of littoral and lentic ecological phenomena. These include increased wind energy and thermocline deepening (France 1997), increased autumn mixing depth, increased phytoplankton biomass and production (Rask *et al.* 1993) and reduced inputs of terrestrial plant material (France 1996). Effects that have not yet been documented for Boreal lakes, but can be inferred from stream and river studies, include reduced littoral habitat complexity, increased insolation, altered nutrient and energy flows, and altered temperature regimes (e.g. recent reviews by Steedman and Morash 1998, Meehan 1991).

Water temperature is a key regulator of the physiology and ecology of littoral biota (Precht *et al.* 1973, Shuter *et al.* 1983, Cossins and Bowler 1987, Regier *et al.* 1990), and is frequently a limiting factor affecting distribution, behaviour and survival. In streams, riparian deforestation is unequivocally associated with changes (usually increases) in water temperature and temperature variability. These changes are usually attributed to decreased shading, although other factors including wind, stream discharge, channel form, and groundwater inputs have all been used in predictive models (Brown and Krygier 1967, Holtby 1989, Griffith and Perry 1991, Davies and Nelson 1994). Unlike streams, lakes have relatively high thermal mass and small edge:area ratio. In all but the smallest lakes, only a portion of the lake surface is shaded by riparian forest. Removal of littoral shading through riparian deforestation should therefore have relatively minor effects on whole-lake heat budgets. However, there is considerable evidence that solar heating is important to the temperature dynamics of shallow waters such as those found in the littoral margins of lakes (Haufe and Burgess 1956, Kahn *et al.* 1970, Schindler 1971, Nilsson and Svensson 1995).

The objectives of this paper were to: (1) present the first empirical evidence regarding the effects of riparian deforestation and increased insolation on littoral water temperatures of small Boreal forest lakes; and (2) use high-resolution time series of littoral water temperature and climate data to infer the generality of these relationships.

Study area and methods

The six lakes used in this study (none are formally named) are located in Boreal/Great Lakes transition forest on the Canadian shield approximately 200 km northwest of Thunder Bay, Ontario, Canada and 150 km southeast of the Experimental Lakes Area (Fig. 1). The area has shallow soils with abundant bedrock outcrops, and relief generally not more than about 60 m in the catchments of the study lakes. The two undisturbed lakes, L26 and L42, are part of the Ontario Ministry of Natural Resources Coldwater Lakes Experimental Watersheds study area; the four other lakes (SEDgewick, SANdbar, SNAke, and WAPegesi) are located around the periphery of the Coldwater Lakes area, and had shorelines that were partially (nominally 50%) deforested on different aspects during commercial timber harvest 6 to 11 years before this study (Table 1). Mature trees in the shoreline riparian forests around the undisturbed lakes (> 75-year-old black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and eastern white cedar (*Thuja occidentalis*)) ranged from about 8 to 31 m in height. In contrast, the secondary regrowth on the logged shorelines (9- to 11-year-old trembling aspen (*Populus tremuloides*) and white birch (*Betula papyrifera*)) ranged from 0 to 8 m in height (France 1997). These four lakes did not provide an ideal comparison of deforestation effects, due to differences in cutover age, shoreline slope, and lake characteristics, but represented a practical compromise of site characteristics, timber management history, and accessibility. WAP, which had dense coniferous forest adjacent to a poorly regenerating cutover on a southern shore, provided the most dramatic contrast in riparian shade. Late-summer thermocline depths in the study lakes range from about 5–8 m (France 1997).

From May to September, 1995, on undisturbed L26 and L42, mid-lake surface water temperatures (0.5 m depth) and meteorological data (air temperature, solar radiation, and wind speed) were collected at 5 s intervals by a Campbell Scientific data logger and sensors mounted on rafts in the middle of each lakes. Littoral water temperature
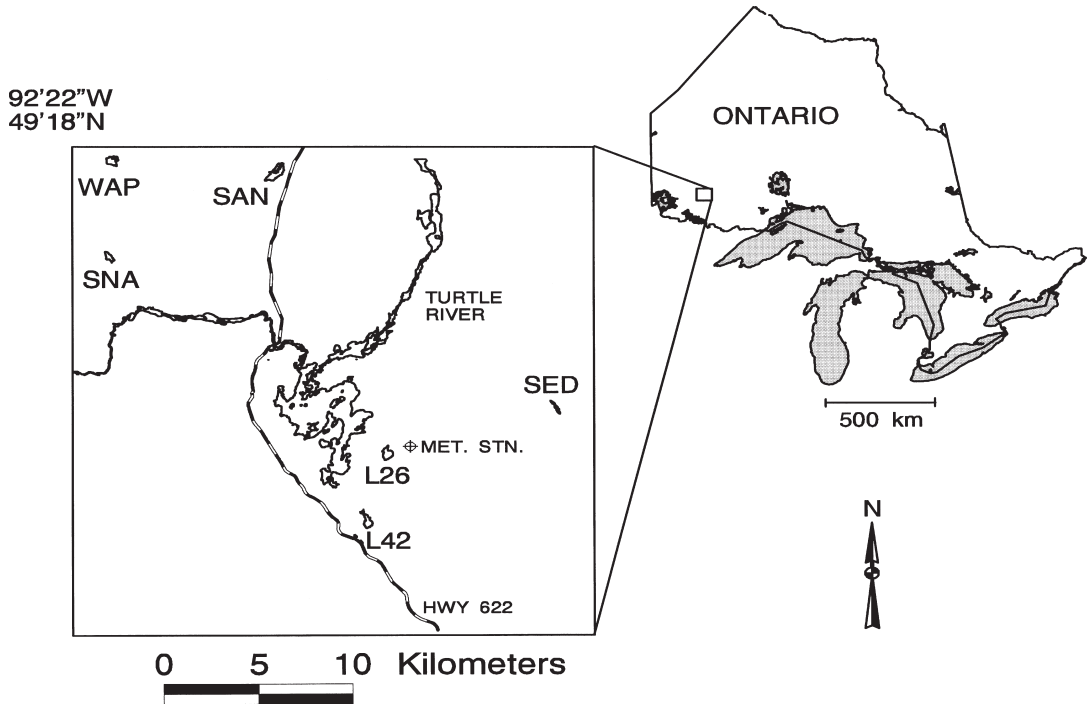
Fig. 1. Map of study area, showing location of lakes in relation to upland meteorological station.

and light intensity were recorded at 0.5 m depth, 1–3 m from the water's edge, in 0.7 m of water, at 15 and 48 min intervals, respectively, by Onset Stowaway data loggers placed at cardinal compass points around the shorelines of L26 and L42, and on each side of a riparian clearcut boundary, 50–100 m from the boundary, on the other four lakes. None of the loggers were placed near macrophytes. It was not possible to select moni-

toring locations that standardized small-scale littoral features such as substrate size amongst the six lakes. The north logger on L26 failed early in the monitoring period. The length of the data series at WAP was reduced because a road washout delayed access and the loggers could not be reset. Upland meteorological data were collected at 5 s intervals by Campbell Scientific weather station 1 km NE of L26, at an elevation of 470 m. All

Table 1. Map coordinates and selected characteristics of study lakes. Where indicated as "na", maximum depth is probably < 15m.

Lake	Latitude	Longitude	Elev. (m)	Area (ha)	Max. depth (m)	DOC (mg l⁻¹)	Total P (µg l⁻¹)	Riparian deforestation	
								Cut date	Cut location
L42	49°04′50′′	92°09′20′′	440	26	19	2	5	uncut	–
L26	49°07′20′′	92°08′40′′	418	29	37	5	3	uncut	–
SED	49°09′00′′	92°01′05′′	445	8	na	9	6	1989	West
SAN	49°16′45′′	92°13′25′′	415	46	na	8	4	1984	East
SNA	49°14′20′′	92°20′40′′	405	14	na	17	8	1984	North-west
WAP	49°17′40′′	92°20′30′′	430	28	na	11	10	1986	South

temperature and weather data were aggregated to hourly or daily averages for comparison. A small number of observations were interpolated or repeated to complete gaps (less than 1 day in length) in the various hourly time series. Campbell temperature sensors are certified to be accurate to 0.2 °C; the Onset temperature sensors used in this study were accurate to within 0.2 °C in a 5-day enclosure comparison trial. All statistical analyses were conducted on SPSS version 6.0 for Windows.

We used Box-Jenkins or AutoRegressive Integrated Moving Average (ARIMA) models (Box and Jenkins 1976, SPSS 1993) to remove autocorrelation and related self-predicting properties from L26 and L42 mid-lake and littoral water temperature time series, before partitioning the remaining variance among the three predictor variables of interest: solar energy (kW m^{-2}), wind (m s^{-1}), and air temperature (°C), in a conventional multiple regression. Hourly data were differenced (transformed by subtracting each observation from the previous one) at both daily and hourly intervals to stabilize the time series before fitting to a seasonal ARIMA (1,1,1) (1,1,1) 24 model. This model estimated coefficients for autoregression-1 and moving-average-1 processes, for hourly and daily intervals. For the time series of daily averages, an ARIMA (0,1,1) model was used, with daily differencing and a moving average-1 component. The autoregressive and moving-average coefficients estimated with these models therefore relate to once-differenced (daily data) or twice-differenced (hourly data) data. For example, model coefficients for hourly data relate to the "hourly change in daily difference" of surface water temperature, somewhat analogous to the "acceleration" of the water temperature. All ARIMA models reported here produced random residuals, a key diagnostic criterion for successful partitioning of variance in autocorrelated time series data.

Results

Comparison of deforested and forested shorelines on four lakes

Riparian deforestation was not necessarily associated with increased littoral light exposure in the four partially deforested study lakes (Table 2). Only WAP, partially deforested on the southern shore, experienced increased light exposure on the

Table 2. Total light exposure at 0.5 m depth, at forested and deforested littoral locations (lumen hours m^{-2} × 10^6).

Lake	Forested	Deforested	Aspect	No. hours
SED	1.01	0.97	East	2 952
SAN	1.68	1.98	West	2 952
SNA	0.61	0.48	South-east	2 928
WAP	0.38	0.90	North	1 752

Table 3. Effect of cloud cover on diurnal littoral water temperature range (°C). Each entry is the increase in diurnal temperature fluctuation associated with an approximate doubling of solar energy from one day to the next (*see* text).

Location	July 19–July 20 36 (63–29)[*]	July 21–July 22 36 (68–32)[*]
L26 main basin (mean of 3 locations)	0.8	0.7
L42 main basin (mean of 4 locations)	0.3	0.6
L42 embayment	0.3	1.1
SAN cut	0.1	1.2
SED cut	0.2	0.3
SNA cut	0.8	0.4
WAP cut	1.0	0.6
Daily average change (SD)	0.5 (0.4)	0.7 (0.3)
Overall average, both days (SD)		0.6 (0.3)

[*] Change in daily total solar energy (MJ m^{-2})

deforested shoreline. The other three lakes showed little difference (SED, SAN), or a slightly higher light exposure on the forested shoreline (SNA).

This pattern was also apparent in the littoral water temperature records (Fig. 2). Only WAP clearly showed evidence of daytime warming at the deforested site, with median differences of about 0.3 °C, frequent differences of 0.5 °C, and maximum differences of about 1.2 °C. The mean temperature on the deforested WAP shoreline was only 0.01 °C or about one-half of a degree-day warmer than the forested shoreline, over 81 days of observation. All four lakes showed some evidence of increased nighttime cooling on the deforested shoreline, but these differences were close to the 0.2 °C resolution of the temperature sensors, and were most evident at WAP and SNA. All four lakes showed increased variability in the difference between deforested and forested shorelines during daylight hours. Deforested sites were occasionally cooler than forested sites during the day; this was common and more pronounced at SAN, and very rare at WAP.

Littoral temperature patterns on cloudy and sunny days

We examined the meteorological data to identify days when air temperature was unusually stable, and the effect of solar energy on water temperature could be examined in relative isolation from warming or cooling trends in air temperature. This analysis provided some additional broad-scale information about the magnitude of water temperature change that might be associated with loss of riparian shade.

The most stable air temperatures in the record occurred July 19–22, 1995, when the three-day running average of hourly air temperature at the upland meteorological station varied by less than 0.5 °C. Two overcast and two clear days alternated in this four-day sequence. Solar radiation on the cloudy days was about one-half of that on the sunny days, roughly analogous to the contrast in light intensity observed between the forested and deforested WAP sites.

As a group the six study lakes showed an average change in diurnal temperature range of
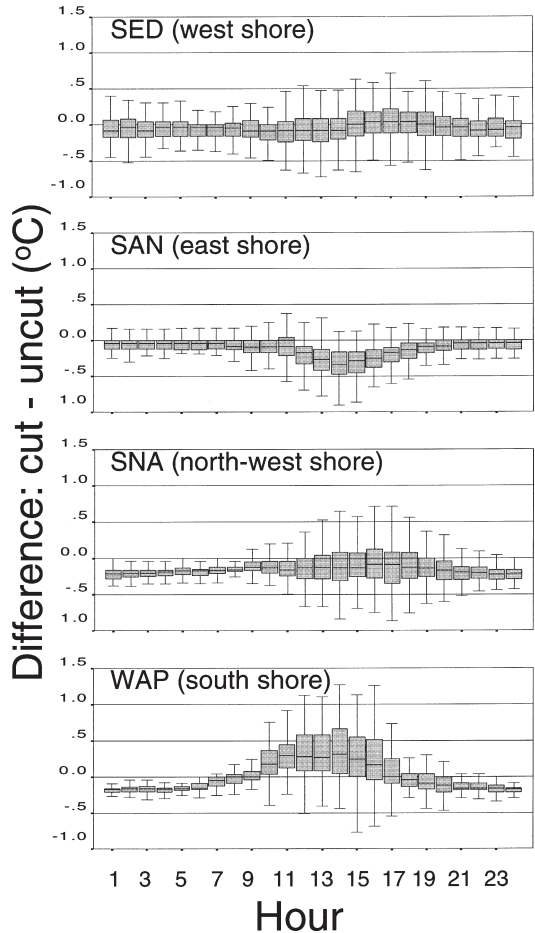

Fig. 2. Boxplots showing hourly distributions of the difference in littoral water temperatures between adjacent deforested (cut) and forested (uncut) shorelines on four study lakes. The bottom, middle, and top of each box represent the 25th, 50th, and 75th percentiles of each set of observations. The vertical lines at the top and bottom of each box extend to the maximum and minimum observations (excluding observations more than 1.5 box-lengths from the 25th or 75th percentile). There were 123 observations for each box at SED and SAN; 122 at SNA, and 81 at WAP.

0.6 °C (range 0.1–1.2 °C) associated with an approximate doubling of solar energy from one day to the next during this period (Table 3). Because these observations were based on changes in regional cloud cover, rather than changes in riparian shading, they could be expected to over-estimate the effect of local shade loss from riparian tree cutting.

Statistical associations of lake water temperature with solar energy, wind, and air temperature

Predictor-variable coefficients in the ARIMA models (Table 4) describe the relative importance of solar energy, air temperature, and wind velocity in accounting for water temperature variation not associated with autocorrelative processes in the time series. Because so much of the pattern in these time series was self-predicting (i.e. a combination of integrative, autoregressive, and moving-average processes), the additional explanatory power contributed by the predictor variables was generally small. However, interpretation of the relative importance of the predictor variables is reliable, because their pattern of influence is statistically significant over the entire time series. The various regression coefficients in Table 4 were relatively insensitive to the time span of the analysis, over a range of about 500–3000 hourly observations.

In hourly models of water temperature, light energy was consistently more important than air temperature or wind velocity, particularly at littoral as compared with mid-lake sites. The importance of air temperature was low in all of the hourly models, although there is some suggestion that air temperature was slightly more important at the littoral sites. There was a small negative effect of wind velocity at mid-lake locations only, suggesting that surface water temperatures may be slightly moderated by evaporative cooling or mixing with deeper water on windy days.

In the models based on daily averages of all measures, air temperature was the only signifi-

cant independent variable. As in the hourly models, the relative importance of air temperature was greater at littoral sites than at mid-lake sites.

Discussion

Our observations of small Boreal lakes suggest that increases of up to 0.5–1 °C in daily maximum water temperature, and decreases of about 0.2 °C in daily minimum temperatures, can be expected following riparian deforestation, in locations where complete loss of littoral shade occurs. As riparian vegetation re-grows, this effect should be reduced, and eventually eliminated. Re-establishment of a mature forest canopy takes a minimum of 20–30 years in northwestern Ontario (Alban 1982, Morris *et al.* 1997). The observed patterns of daytime heating and nighttime cooling were mostly compensatory, and did not lead to significant changes to average temperature or heat accumulation in these habitats. These inferences regarding the magnitude and generality of littoral temperature response to riparian deforestation were drawn from three types of evidence: (1) comparison of littoral water temperatures along adjacent forested and deforested shorelines in four lakes of different aspects, over a period of about four months; (2) comparison of diurnal temperature patterns in a variety of littoral locations on six lakes, on cloudy and sunny days; and (3) time-series analysis of climate and water temperature linkages in two undisturbed lakes.

The temperature effects observed in this study were relatively small compared with those re-

Table 4. Regression coefficients of time-series models. ar1 and dar1 refer to hourly autoregression-1 and daily autoregression-1 coefficients; ma1 and dma1 refer to hourly moving average-1 and daily moving average-1 coefficients (*see* text). All coefficients shown are statistically significant, P(coefficient = 0) < 0.01.

Lake	Location	Hourly Models (n = 2 951)							Daily Models (n = 123)	
		ar1	ma1	dar1	dma1	Solar energy (kW m^{-2})	Air temp. (°C)	Wind speed (m s^{-1})	ma1	Air temp. (°C)
L42	mid-lake raft	0.33	–	0.09	0.96	0.07	0.03	–0.01	–0.70	0.06
	main basin littoral (mean of 4 stations)	0.60	0.31	0.06	0.95	0.23	0.03	0.01	–0.62	0.07
	shallow enclosed bay	0.70	0.55	0.07	0.95	0.41	0.04	–	–0.51	0.10
L26	mid-lake raft	0.12	–0.28	–	0.96	0.03	0.02	–0.01	–0.75	0.05
	main basin littoral (mean of 3 stations)	0.65	0.41	0.08	0.96	0.28	0.02	–	–0.67	0.05

ported for streams with deforested shorelines. An increase of 5 °C in summer average temperature was associated with removal of riparian forest along Boreal forest streams in the Experimental Lakes Area of northwestern Ontario (Nicolson 1975). In other regions of North America, increases in maximum stream temperatures of up to 10 °C were observed relative to forested controls, although increases of 5 °C or less were most common (Lee and Samuel 1976, Krause 1982, Lynch *et al*. 1984).

The spatial extent of littoral warming following riparian deforestation is likely to be limited to littoral areas that actually lose shade. The location of these areas is a function of aspect, pre-deforestation riparian vegetation, shoreline slope, shoreline complexity, and cutover age. This study examined the effect of aspect, but because of the difficulty in finding lakes with partially-cut shorelines, did not effectively control these other factors. The inter-site variation evident in Table 2 and Fig. 2 reflects this. In locations where riparian forest is sparse, set back from the water's edge, or on a northern shoreline (in the Boreal forest), littoral water temperatures are not likely to show a measurable response to littoral deforestation. This study did not measure the effects of riparian deforestation on small-scale (i.e. tenths of meters) vertical or horizontal patterns of littoral water temperature. Although the littoral waters of small lakes can generally be assumed to be well-mixed on a scale of meters, this may not be the case at smaller spatial scales. Localized benthic heating of several hundredths of a °C was observed in Boreal lakes, in shallow water under full sunshine and calm air (Schindler 1971). Local shoreline bathymetry and substrate may also influence mixing of littoral and offshore waters, and increase the local warming effects of solar energy (e.g. the shallow enclosed bay on L42, Table 4). To the extent that riparian deforestation may affect both insolation and wind energy, and their interactions, undetected small-scale changes in littoral water temperature patterns may have occurred at our study sites.

Stream warming can generally be prevented by shoreline buffer strips of relatively undisturbed riparian forest (Brown and Krygier 1970, Clinnick 1985). Shoreline buffer strips, particularly on southern shores, should also be effective in preventing littoral temperature changes in lakes. If regional deforestation is extensive enough to increase daily average air temperature, daily average littoral water temperatures could be expected to track a lagged running average of those increases. There is some evidence that such changes have occurred as a result of deforestation by fire and logging in this part of the Boreal forest (Schindler *et al*. 1990).

Little is known about the ecological effects of small (i.e. < 2 °C) temperature changes in thermally dynamic habitats such as lake littoral zones, but changes as small as 2–4 °C were shown to affect lake thermal structure and physical properties (Schindler *et al*. 1990), fish behaviour and production (Bardach and Bjorklund 1957, Meisner *et al*. 1987), and invertebrate growth, primary production, and detrital decomposition (Webster and Waide 1982, Rempel and Carter 1986, 1987). Our study suggests that littoral heat accumulation (i.e. degree-days) in these lakes was not altered by riparian deforestation. However, small temperature effects such as those observed in this study may be important in situations where natural variability puts water temperature close to behavioral or physiological thresholds for littoral biota, or where littoral biota actively seek subtle temperature optima. Changes in littoral shading and water temperature may also exacerbate biological effects of climate warming (e.g. France 1991, Firth and Fisher 1992, Carpenter *et al*. 1992, Sweeny 1993) and increased UV-b flux (Schindler *et al*. 1996).

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