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Cooling lakes while the world warms: Effects of forest regrowth and increased dissolved organic matter on the thermal regime of a temperate, urban lake

Abstract—Depending on the magnitudes and directions of changes in air temperatures, winds, and underwater light attenuation, lakes may either warm or cool. Here we report a 28-yr decrease in the whole-lake average temperature of Clearwater Lake, Canada, despite regional signatures of climate warming. Using a one-dimensional lake mixing model, we demonstrate that this pattern was attributable to a 35% reduction in surface wind speeds, itself explained by forest regrowth following local SO_2 emission reductions and tree planting, and a 10-fold increase in dissolved organic carbon concentrations causing a substantial increase in vertical light attenuation following deacidification of the lake. Long-term trends in lake temperatures do not necessarily follow those of air temperatures. The Clearwater Lake data demonstrate that any factors that influence local wind speeds and underwater light attenuation should be considered as modifiers of the effects of climate warming on lake thermal regimes.

Limnologists commonly predict that lakes will warm with a warming climate (Magnuson et al. 1997) because water temperatures of lakes can reflect local air temperatures (Edinger et al. 1968). As such, some North American lakes have warmed over the past 25 yr in synchrony with rising air temperatures (Schindler et al. 1990) and in agreement with simulations by hydrodynamic models (Hondzo and Stefan 1993; DeStasio et al. 1996). Rising or falling wind speeds, resulting from changes in surface roughness lengths associated, respectively, with deforestation or afforestation (Tanentzap et al. 2007), also influence lake heating (France 1997; Steedman and Kushneriuk 2000). Further, the heat budget of small- to medium-sized lakes may be strongly affected by changes in vertical light attenuation, linked to variations in plankton or dissolved organic carbon (DOC) concentrations (Pérez-Fuentetaja et al. 1999). Since air temperature, wind, and water clarity are also influenced by multiple anthropogenic drivers such as land use (Steedman and Kushneriuk 2000; Tanentzap et al. 2007) and climate change (Fee et al. 1996; Schindler et al. 1996; Snucins and Gunn 2000), the contemporary heat budget of lakes can be difficult to predict. Here we report a 28-yr record of whole-lake cooling of a north-temperate lake, Clearwater Lake, despite regional signatures of climate warming, such as lengthening of ice-free seasons (Futter 2003).

Clearwater Lake is a relatively small (area, 0.77 km^2; mean depth, 8.4 m; maximum depth, 21.5 m), single-basin lake located on the outskirts of Sudbury, Ontario, Canada (46°22′N, 81°03′W). The Sudbury metal smelters were among the world's largest point source emitters of SO_2 in the early 1960s, and contributed to deforestation of much of the surrounding landscape (Winterhalder 1996) and acidification of thousands of lakes in the region (Keller et al. 1999). Clearwater Lake was one such lake, with pH levels approaching 4 in the early 1970s (Yan and Miller 1984). Monitoring of lake water chemistry, thermal regimes, and biota began on a regular basis in 1973, with weekly lake visits during the 1970s and monthly visits during the ice-free season thereafter (Yan and Miller 1984). Water temperatures were recorded at the site of maximum depth at 1-m intervals through all depths using a YSI model 432D telethermometer from 1973 to 1976, a Montedoro–Whitney TC-5C thermistor from 1976 to 1981, a Flett Research Limited Mark II Telethermometer from 1982 to 1998, and either a YSI model 52 or 54 dissolved oxygen/temperature meter since 1998. Thermistors were routinely calibrated with a NBS-certified 0.1°C sensitivity thermometer. The volume-averaged temperature of the lake was estimated by weighting the temperatures at the position of maximum depth by the volume in the corresponding depth interval (which we term whole-lake temperatures hereafter). Thermocline depths were subsequently identified as the depth over which temperature began to decline most rapidly with descent through the water column.

In 1973, the thermal regime of Clearwater Lake was very unusual in comparison with nonacidic lakes of similar morphometry. The bottom waters (17-m depth) reached 15°C in late summer (Fig. 1A), about 10°C warmer than expected for lakes of this depth (Yan and Miller 1984). The lake stratified at 10–12 m on the date of maximum summer heat content, far deeper than would be expected for most lakes with a similar fetch (Ragotzkie 1978). Since the 1970s, the thermal regime of the lake at the time of maximum heat content has changed dramatically. While daytime lake surface temperatures have changed little (Fig. 1A), bottom temperatures have dropped by 7°C, from 15°C to 8°C, and thermocline depths have risen by 4 m (Fig. 1B). With this pattern of larger volumes of cooler profundal water but relatively stable surface temperatures, whole-lake temperatures at maximum heat content have fallen steadily, from 21–22°C in the early 1970s, to 19°C in recent years (Fig. 1C).

There were both meteorological and limnological correlates of Clearwater Lake's decreased whole-lake temperature. Over the March to August lake heating season, there were no long-term trends, between 1973 and 2001, in air temperature (Mann–Kendall trend test, $Z = 0.36$, $p = 0.72$; Fig. 2A), hours of bright sunshine ($Z = -0.69$, $p = 0.49$), and average monthly precipitation ($Z = -0.43$, $p = 0.67$) at the Sudbury Airport (~40 km from the lake). However, the trend of increased winter (Dec–Feb) and fall (Sep–Nov) air temperature approached statistical significance (for both periods $Z = 1.56$, $p = 0.12$; Fig. 2A). At a larger scale across Central Ontario, regional signals of climate warming (i.e., lengthening of ice-free seasons) indicate increasing late winter and early spring temperatures, possibly as part of a prolonged warming trend (Futter 2003). In contrast, wind speeds in Sudbury declined markedly ($Z = -4.13$, $p < 0.001$), by approximately 35%, from an average of 5.5 m s^{-1} in the early 1970s to 3.6 m s^{-1} of late (Fig. 2B), and data from the Airport reflect measurements from the lake (Taylor unpubl. data). In response to reductions in local and regional SO_2 emissions, there were also significant increases in mean annual lake pH ($Z = 6.35$, $p < 0.001$), DOC concentrations ($Z = 6.26$, $p < 0.001$), and vertical light attenuation (K_d) ($Z = 6.26$, $p < 0.001$; Fig. 2C–E). Since a rise in thermocline depth and reduction in bottom water temperature will result from either or both of reduced wind speeds and reduced vertical light penetration depths, the mechanism of the decrease in whole-lake average temperatures could not be reliably inferred from the correlations. A heat budget model, incorporating mixing and transport processes, was used to distinguish which of these changes in wind speeds and water clarity caused the observed whole-lake cooling pattern.

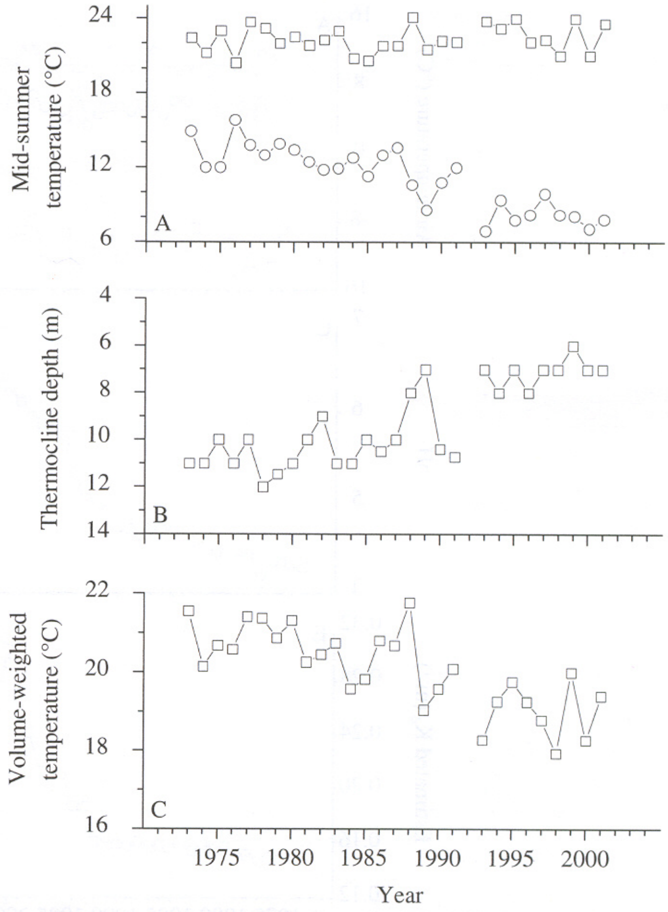

Fig. 1. Trends in Clearwater Lake heat content on dates of maximum heat content, 1973–2001. (A) Surface (0.5-m depth, open squares, Mann–Kendall trend test, $Z = 0.65$, $p = 0.51$) and bottom water temperatures (17-m depth, open circles, $Z = -4.79$, $p < 0.001$). (B) Thermocline depth ($Z = -4.47$, $p < 0.001$). (C) Whole-lake volume weighted temperatures ($Z = -4.01$, $p < 0.001$). Sampling in 1992 occurred only twice, missing the date of maximum heat content.

Methods—The dynamic reservoir simulation model (DYRESM) was parameterized to model and simulate Clearwater Lake's thermal regime from 1973 to 2001. DYRESM is a numerical one-dimensional vertical heat transfer model used to simulate changes in lake thermal structure produced by inflows, outflows, and mixing (Imberger et al. 1978). We configured the model to simulate daily temperature during the ice-free season for each year

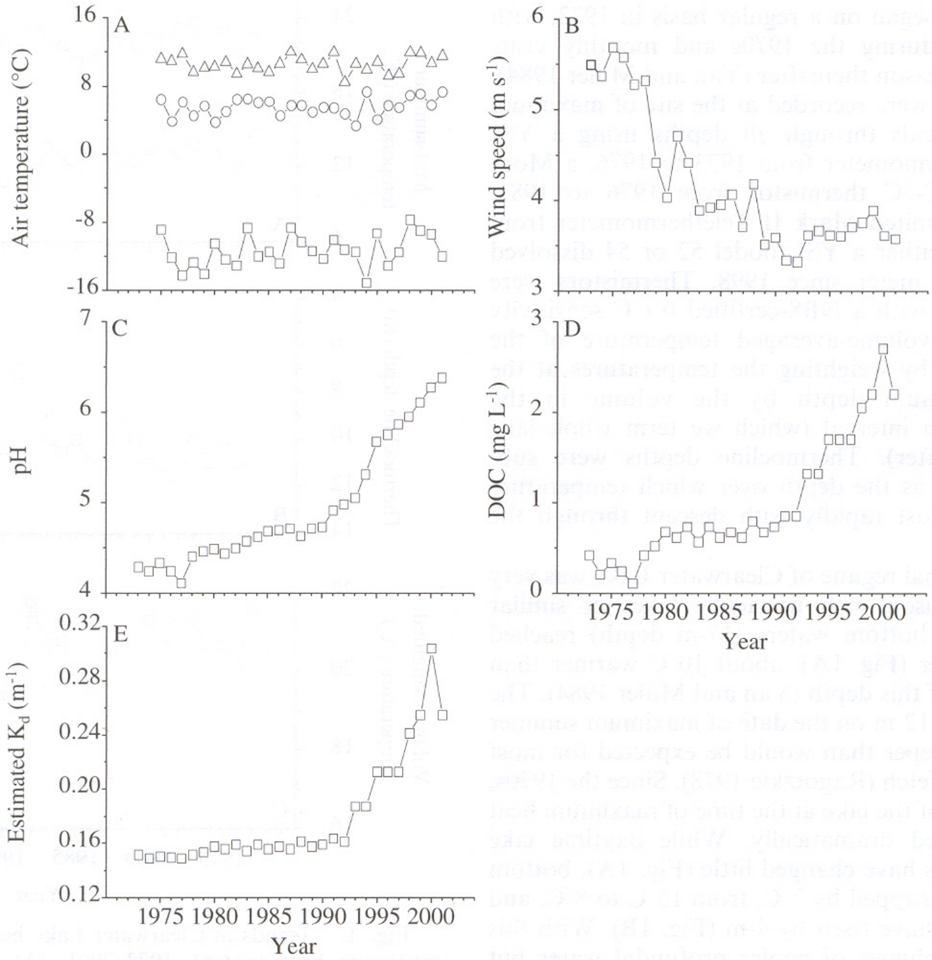

Fig. 2. Long-term changes in air temperature, wind speed, acidity, and water clarity of Clearwater Lake, 1973–2001. (A) Mean daily air temperature at Sudbury Airport, December to February (open squares), March to August (open triangles), September to November (open circles). (B) Mean annual lake heating period wind speed at Sudbury Airport (March to August). (C) Mean annual pH. (D) Mean annual July epilimnetic dissolved organic carbon (DOC) concentrations. (E) Estimated mean annual vertical light attenuation (K_d).

starting after spring turnover. Daily inflow, outflow, and meteorological data were input into the model, as were the morphometry of the lake and parameters that determined mixing and heating processes. However, this required annual values of K_d, which were never recorded at Clearwater Lake. We created a model to predict K_d, defined as the negative slope of the linear regression between the natural logarithm of downwelling irradiance and depth, from July epilimnion DOC concentrations and hydraulic retention time using 14 lakes situated in Killarney Provincial Park, Ontario, Canada, 40–60 km southwest of Sudbury ($R^2 = 0.952$, root mean square error = 0.06 m^{-1}, $p < 0.001$). Although Secchi depths were also measured in the lake, DOC is a much better predictor of K_d in Canadian Shield lakes (Pérez-Fuentetaja et al. 1999). Given that the routine sampling protocol of Clearwater Lake employed whole-lake measurements prior to 1995, we had to predict pre-1995 epilimnetic DOC concentrations from whole-lake measurements ($R^2 = 0.875$, $p < 0.001$). Lastly, our predictions of pre-1995 epilimnion DOC could only extend back to 1981 since Clearwater Lake was not sampled for DOC between 1973 and 1980, and the method of DOC analysis used throughout the record was only developed in 1978 (Crowder and Evans 1978). Given correlations between DOC concentration and pH for Canadian Shield lakes (Yan et al. 1996), including Clearwater (Dixit et al. 2001), we predicted July epilimnetic DOC concentration from pH prior to 1981 in Clearwater Lake ($R^2 = 0.927$, $p < 0.001$).

DYRESM is a suite of linked models describing physical processes in such a way that local calibration needs are avoided, or at least reduced. However, the complexities of lake applications, where benthic boundary layer and three-dimensional mixing processes weaken the predictions of a one-dimensional model, mean that some degree of calibration can be expected to improve model fit to observed data. Since several mixing and heating parameters had never been tested for a Canadian Shield lake, we performed a calibration for these parameters. Following calibration of DYRESM (Table 1), the mean prediction error ±1 standard deviation (thermocline depth, 1.09 m ± 0.89 m; bottom water temperature, 1.98°C ± 1.58°C) was comparable to other studies (e.g., DeStasio et al. 1996) and much less than the observed changes in thermocline depth and bottom water temperature. Furthermore, a regression of modeled on observed values produced high coefficients of determination, intercepts indistinguishable from zero, and slopes that differed from zero, approaching unity (Table 2; model verification). Despite the good fit of predicted on observed thermocline depths (intercept = 0.17, slope = 0.97), a large portion of the variance was unexplained ($R^2 = 0.42$). We attribute this mainly to the difference in resolution between field data (>1 m) and simulated temperature profiles (0.20–0.22 m) and simply the difficulty in defining the thermocline depth.

To determine the relative importance of reductions in wind speed versus light penetration in the cooling pattern, we performed three simulations with the calibrated model. Each simulation fixed two of air temperature, K_d, or wind speed at the 28-yr mean (28-yr monthly means for air temperature) while employing actual values of the third variable. In each case we compared model predictions with observations and with the simulation in which the actual temperatures, K_d, and wind speed data were employed. We repeated the simulations for the periods during which the largest reductions in wind speed (1976–1989) and increases in K_d (1991–2000) occurred to determine whether there was temporal separation in the effects of wind and water clarity on lake cooling.

Table 1. Values of DYRESM parameters and model simulation specifications. Values were determined either through a series of calibrations (C) or sensitivity analyses (S). Calibrations were performed at three separate periods in the modeling record, (1) early, 1978 and 1980; (2) middle, 1986, 1987, 1988; and (3) late, 1996, 1998. All input data were maintained constant, allowing only the parameter of interest to vary. The mean absolute difference between predicted and actual water temperature, thermocline depth, and bottom water temperature (17-m depth), and standard deviation of each mean, were calculated for the calibration period. Calibrations that resulted in the least amount of deviation between predicted and actual values were employed. A total of 63 simulations were performed to identify optimal layer thickness settings, 28 simulations were performed for wind stirring efficiency and albedo, and 21 for potential energy mixing efficiency. Sensitivity analyses employed the years 1978, 1988, and 1998, while using 6 to 12 simulations for each parameter. The bulk aerodynamic momentum transport coefficient was set according to Fischer et al. (1979).

Parameter	Set value
Albedo	0.08 (C)
Benthic boundary layer thickness (m)	0 (S)
Bulk aerodynamic momentum transport coefficient	0.00139
Critical wind speed (m s^{-1})	4.3 (S)
Effective surface area coefficient	1.0×10^7 (S)
Maximum layer thickness (m)	0.6 (C)
Minimum layer thickness (m)	0.25 (C)
Nonneutral atmospheric stability correction switch	False (S)
Potential energy mixing efficiency	0.2 (C)
Shear production efficiency	0.06 (S)
Vertical mixing coefficient	200 (S)
Wind stirring efficiency	0.06 (C)

Results and discussion—Both wind speeds and K_d were important in the long-term cooling pattern of Clearwater Lake. The simulation in which only air temperature was allowed to vary provided the poorest fit, with low coefficients of determination, intercepts differing from zero, and slopes substantially departing from one (Table 2). Simulations in which K_d or wind speeds were allowed to vary, while air temperature was fixed, were most similar to field data and to the simulation in which all parameters varied. Increases in K_d and reductions in wind speed provided equally good explanations for the rising thermo-

Table 2. Comparisons of DYRESM-predicted thermocline depths and temperatures at 17-m (depth) versus measured values on dates of maximum heat content, 1973–2001. DYRESM values were predicted from observed field data or fixed long-term means, 1973–2001, and compared against actual thermocline depths and bottom water temperatures with linear regressions ($n = 28$). Simulations were performed with air temperature, K_d, and wind speed variable, or with one of the three inputs variable while the remaining two were fixed. p values for slopes are same as for R^2. Bold values are significant at $\alpha = 0.05$.

Simulation inputs	R^2	p	Intercept	p (intercept)	Slope
Thermocline depths					
Air temperature, K_d, and wind speed variable (model verification)	0.42	**<0.001**	0.17	0.937	0.97
Air temperature variable	0.23	**0.01**	5.32	**0.001**	0.41
K_d variable	0.48	**<0.001**	2.66	0.058	0.69
Wind speed variable	0.37	**0.001**	2.17	0.213	0.71
Bottom water temperatures (17-m depth)					
Air temperature, K_d, and wind speed variable (model verification)	0.78	**<0.001**	1.07	0.432	1.13
Air temperature variable	0.37	**0.001**	8.02	**<0.001**	0.44
K_d variable	0.78	**<0.001**	1.27	0.348	1.11
Wind speed variable	0.37	**0.001**	7.99	**<0.001**	0.44

Table 3. Comparisons of DYRESM-predicted thermocline depths and temperatures at 17-m (depth) versus measured values on dates of maximum heat content during period of greatest change in wind speed (1976–1989). DYRESM values were predicted from observed field data or fixed long-term means, 1976–1989, and compared against actual thermocline depths and bottom water temperatures with linear regressions ($n = 14$). Simulations were performed with air temperature, K_d, and wind speed variable, or with one of the three inputs variable while the remaining two were fixed. p values for slopes are same as for R^2. Bold values are significant at $\alpha = 0.05$.

Simulation inputs	R^2	p	Intercept	p (intercept)	Slope
Thermocline depths					
Air temperature, K_d, and wind speed variable (model verification)	0.15	0.172	1.56	0.794	0.83
Air temperature variable	0.21	0.104	3.30	0.339	0.57
K_d variable	0.14	0.196	5.07	0.147	0.44
Wind speed variable	0.24	0.079	1.40	0.736	0.76
Bottom water temperatures (17-m depth)					
Air temperature, K_d, and wind speed variable (model verification)	0.41	**0.013**	5.56	0.112	0.76
Air temperature variable	0.24	0.76	7.41	**0.030**	0.46
K_d variable	0.40	**0.015**	6.18	0.074	0.71
Wind speed variable	0.24	0.78	7.41	**0.031**	0.46

cline in the lake. For bottom water temperature, the varying K_d simulation performed as well as the simulation in which all parameters varied ($R^2 = 0.78$; Table 2), while changes in wind speed could not explain the hypolimnetic cooling (intercept > 0, slope < 1; Table 2). However, the largest wind speed reductions predated the largest DOC increases (Fig. 2). Regressions of thermocline depth and bottom water temperature for these periods indicated temporal separation in the relative roles of wind speed and water clarity as regulators of lake heat content. Wind speed was more important than K_d in regulating thermocline depth during the period of greatest change in wind speed (Table 3), while K_d provided the best explanation during the period of water clarity reductions (Table 4). The varying K_d simulation was always a better predictor of bottom water temperatures, particularly during the period of greatest change in vertical light attenuation (Table 4) and bottom water temperatures (Fig. 1A). Since simulated bottom water temperatures at the onset of stratification did not show any significant cooling pattern over time for any of our three simulation periods (1973–2001, $Z = -1.00$, $p = 0.32$; 1976–1989, $Z = -0.22$, $p = 0.83$; 1991–2000, $Z = -0.53$, $p = 0.60$), which would indicate different model setup temperatures, differences in hypolimnetic temperatures from 1973 to 2001 were due to decreased warming over the summer stratification period. The weak and nonsignificant trends in decreasing modeled hypolimnetic temperatures at the onset of stratification were a result of less heat energy in the lake prior to stratification.

These simulations demonstrate that (1) reductions in wind speed and increases in DOC both contributed to the rising thermocline in Clearwater Lake over the 28-yr record; (2) reductions in K_d, arising from dramatic increases in DOC associated with deacidification (Dixit et al. 2001), explain the bottom water cooling; and (3) long-term changes in air temperature were not an important regulator of changes in thermal properties in Clearwater Lake. Sensible heat transfer through the thermocline was not the principal determinant of profundal cooling of the lake; however, decreased wind speeds did contribute to

Table 4. Comparisons of DYRESM-predicted thermocline depths and temperatures at 17-m (depth) versus measured values on dates of maximum heat content during period of greatest change in K_d (1991–2000). DYRESM values were predicted from observed field data or fixed long-term means, 1991–2000, and compared against actual thermocline depths and bottom water temperatures with linear regressions ($n = 9$). Simulations were performed with air temperature, K_d, and wind speed variable, or with one of the three inputs variable while the remaining two were fixed. p values for slopes are same as for R^2. Bold values are significant at $\alpha = 0.05$.

Simulation inputs	R^2	p	Intercept	p (intercept)	Slope
Thermocline depths					
Air temperature, K_d, and wind speed variable (model verification)	0.22	0.202	4.28	0.054	0.34
Air temperature variable	0.11	0.386	6.48	**0.018**	0.25
K_d variable	0.48	**0.039**	3.06	0.131	0.59
Wind speed variable	0.03	0.667	5.96	0.059	0.16
Bottom water temperatures (17-m depth)					
Air temperature, K_d, and wind speed variable (model verification)	0.95	<**0.001**	2.28	**0.012**	0.90
Air temperature variable	0.21	**0**.218	8.34	**0.010**	0.37
K_d variable	0.95	<**0.001**	2.15	**0.019**	0.92
Wind speed variable	0.19	0.242	8.45	**0.010**	0.35

reduced mixing and energy transfer through the water column, leading to the rising summer thermocline. In contrast, the key mechanism of hypolimnetic cooling was the reduction in direct profundal heat absorption due to increased vertical light attenuation. Small increases in the lake's heat content, arising from decreased wind speeds that lessened the extent of surface cooling and evaporation, were overwhelmed by larger reductions in heat attributable to reduced vertical light penetration and greater quantities of heat transferred from surface layers to the atmosphere.

It is clearly possible for the whole-lake volume weighted temperatures of some lakes to cool dramatically during periods of climate warming. Although air temperatures themselves have not increased significantly at Sudbury Airport, regional signatures of climate warming, such as lengthening of ice-free seasons (Futter 2003), have been observed. In our case, changes in local wind speeds and reductions in vertical light penetration, attributable to deacidification, have both affected the thermal properties, especially the thermocline depth and hypolimnetic heating rates, of Clearwater Lake. The dramatic decline in surface wind speeds at Sudbury from the mid-1970s to the mid-1980s is a regional phenomenon that can be attributed to the planting of eight million trees and the regrowth of the urban forest (Tanentzap et al. 2007). However, any land management practice with similar effects on catchment surface roughness as afforestation would have produced the same effect on lake thermal regimes. Those wishing to predict the thermal properties of lakes should give careful consideration not just to air temperatures but also to all factors that affect surface wind speeds and water clarity. Modifiers of the effects of climate warming on lake thermal regimes will include forest management practices (France 1997; Steedman and Kushneriuk 2000; Tanentzap et al. 2007), urbanization (Oke 2004), biological invasions (MacIsaac 1996), reduced precipitation and cloud cover associated with climate change (Fee et al. 1996; Schindler et al. 1996), and water, DOC, and nutrient loading rates (Schindler et al. 1996; Snucins and Gunn 2000) to lakes from their catchments.

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