

Land–water linkages: influences of riparian deforestation on lake thermocline depth and possible consequences for cold stenotherms

Robert France

Abstract: The purpose of the present study was to determine if riparian deforestation would expose lake surfaces to stronger winds and therefore bring about deepening of thermoclines and resulting habitat losses for cold stenotherms such as lake trout (*Salvelinus namaycush*). Removal of protective riparian trees through wind blowdown and two wildfires was found to triple the overwater windspeeds and produce thermocline deepening in two lakes at the Experimental Lakes Area. A survey of thermal stratification patterns in 63 northwestern Ontario lakes showed that lakes around which riparian trees had been removed a decade before through either clearcutting or by a wildfire were found to have thermocline depths over 2 m deeper per unit fetch length compared with lakes surrounded by mature forests. Riparian tree removal will therefore exacerbate hypolimnion habitat losses for cold stenotherms that have already been documented to be occurring as a result of lake acidification, eutrophication, and climate warming.

Résumé : La présente étude avait pour but de déterminer si le déboisement riverain expose les surfaces des lacs à des vents plus forts qui ont pour effet de déplacer les thermoclines à une plus grande profondeur, entraînant ainsi la perte d'habitat pour les sténothermes d'eaux froides comme le touladi (*Salvelinus namaycush*). On a constaté que l'élimination des arbres protecteurs sur la rive par l'action du vent (chablis) et deux feux naturels triplait la vitesse du vent au-dessus de l'eau et déplaçait les thermoclines à une plus grande profondeur dans deux lacs de la Région des lacs expérimentaux. Un relevé des conditions de stratification thermique dans 63 lacs du nord-ouest de l'Ontario a révélé que les lacs dont les rives ont été dégagées des arbres 10 ans plus tôt, soit par coupe à blanc soit par suite d'un feu de forêt, avaient des thermoclines qui étaient plus profondes (plus de 2 m par unité de longueur de course) que celles des lacs entourés d'une forêt mûre. Ainsi, l'enlèvement des arbres riverains aura pour effet d'exacerber la perte d'habitat pour les sténothermes d'eaux froides dans l'hypolimnion, perte que l'on observe déjà par suite de l'acidification des lacs, de l'eutrophisation et du réchauffement de la planète.

[Traduit par la Rédaction]

“Wind over lake: the image of inner truth”
- the *I Ching* quoted in Backas (1992)

Temperature is a fundamental biological determinant (e.g., Tracy and Christian 1986; France 1991 and references therein) that regulates microhabitat selection (e.g., Spotila et al. 1989). As a result, patterns of temperature stratification in lakes segregate species into thermal habitats that best suit their metabolic requirements (e.g., Magnuson et al. 1979; Christie and Regier 1988). Because the thermocline separates hypolimnetic waters from surface heat sources, cold stenotherms occupy deeper regions during the summer (e.g., Brandt et al. 1980; Crowder and Magnuson 1982). For such species, individual health and population size may be determined by habitat limitations in late summer when the volume of cold water is at a minimum (e.g., Evans et al. 1990; Schofield et al. 1993). Therefore, if any additional anthropogenic stresses reduce the already diminished volume of this essential habitat for cold stenotherms, population reductions and extirpations may result (Coutant 1987).

The purpose of the present study was to investigate the role played by surrounding riparian forests in modifying patterns

of wind-induced mixing in Canadian Shield lakes. My hypothesis was that riparian deforestation would expose lake surfaces to stronger winds whose effect could be measured by a deepening of thermocline depths, and thus by inference, cause losses of cold stenothermal habitats. Evidence supporting such a supposition is limited to two studies. Logging of the catchment around a small boreal lake in Finland was thought to increase the mixing depth in 1 year through increased wind action caused by removal of large protecting trees (Rask et al. 1993). A wildfire that burned the catchment of a lake was believed by Schindler et al. (1990) to have contributed to a deepening of the thermocline in a small lake in northwestern Ontario, Canada. My objective in this study was to determine if such results, rather than being particular to these two lakes, instead represent a general response of lakes exposed to riparian deforestation.

Methods

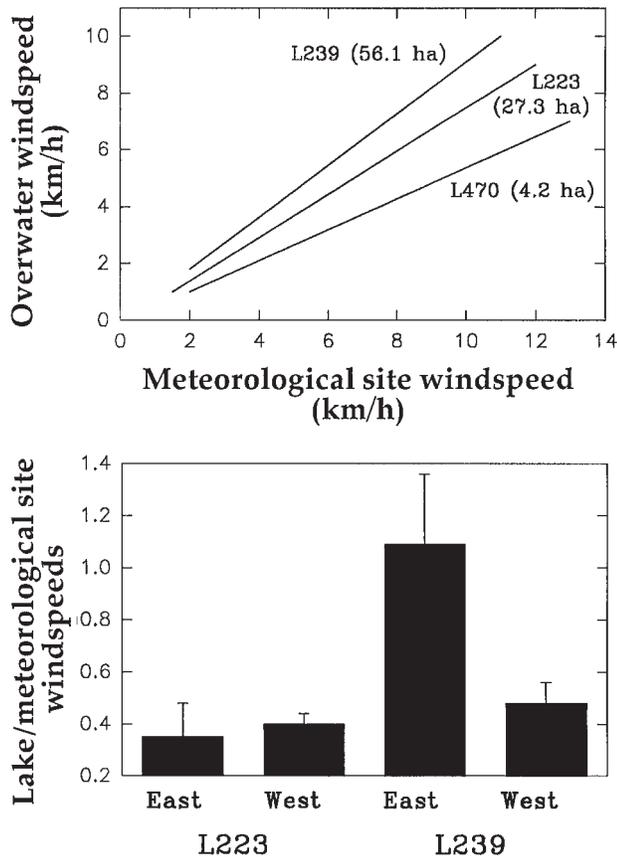
Reanalysis of data from the Experimental Lakes Area

Data on overwater windspeeds were obtained from an unpublished undergraduate thesis (Solinske 1982) conducted on three lakes in the Experimental Lakes Area (ELA) of northwestern Ontario. These measurements are some of the few that exist (see also Schindler 1971) for small Canadian Shield lakes. Three anemometers, one for each of Lakes 470 (L470), L223, and L239, were situated on floating rafts placed in the middle of each lake so windruns from all compass directions

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R. France. Harvard University, Graduate School of Design,
48 Quincy St., Cambridge, MA 02138, U.S.A.

Fig. 1. Upper panel: comparisons between overwater windspeed measured on three boreal lakes of different size and at the meteorological site at the ELA during summer 1981 (reanalyzed data from unpublished thesis of Solinske 1982). Lower panel: mean ratios (\pm SD) of easterly or westerly windspeeds measured over two ELA lakes during a 2-week period in 1981 to windspeeds at the meteorological site measured at the same time (reanalyzed data from Solinske 1982, see text). L223 is completely surrounded by an intact riparian forest whereas L239 is exposed to winds from the east as a result of a blowdown and forest fire along its eastern riparian shore.



could be recorded. The instruments were situated with wind cups 1.3 m above the water surface so that winds could be monitored without major disturbances created by surface roughness. Data were collected between July 6 and August 24, 1981, and compared with similar measurements made at a meteorological site located 366 m west of L239 at an elevation of 43 m above the lake level (Beaty 1990). Also, for a 2-week period, windspeeds were measured for different directions over L223 and L239. Such land-to-water comparisons are the established procedure (Richards et al. 1966; Phillips and Irbe 1978) and have the effect of lumping all the various influences that cause the winds over water to vary from winds overland (Solinske 1982), i.e., the difference in frictional effect between land and water, differences in atmospheric stability created by air-water temperature differences, and lengths of overwater fetch.

Data on temperature profiles for 1984 and 1985 (Lyng and Cruikshank 1985; Cruikshank 1986) were added to previous information extending back to 1969 (Cruikshank 1984) to examine the relationship between the length of fetch (i.e., the distance in which wind can blow across a water surface) and the average interannual late-summer (July 25 – August 25) thermocline depth for an empirical synthesis of data from 26 ELA lakes. Data for L239 and L240, half of whose

riparian shorelines had been denuded due to a blowdown and two wildfires (Schindler et al. 1980, 1990), were not included in this synthesis.

New synoptic survey

Between July 25 and August 25, 1994, I measured temperature profiles in an additional 63 lakes situated within 50–150 km of ELA in northwestern Ontario. As in the previous ELA studies, planar thermocline depth was later calculated as the point of the maximum rate of temperature change (Hutchinson 1957). These data were logarithmically transformed as in Cruikshank (1984). From topographic maps, fetch was measured as the longest straight axis of the lake where winds can blow uninterrupted by landforms. These data were logarithmically transformed as in Hanna (1990). The riparian forests around 10 of the surveyed lakes had been completely clearcut to the water's edge 9–11 years previously (France et al. 1996). For 23 of the surveyed lakes, riparian forests had been completely destroyed in 1980 as part of a massive forest fire (>100 000 ha in extent) that burnt all the way to L239 in ELA. The remaining 30 lakes were surrounded by undisturbed riparian forests and were sampled to establish 1994 references to compare with the more extensive data existing for the 26 different lakes sampled from 1969 to 1985 at ELA.

Mature trees in the shoreline riparian forests around the undisturbed reference lakes (>75-year-old black spruce (*Picea marina*), jack pine (*Pinus banksiana*), and eastern white cedar (*Thuja occidentalis*)) ranged in size from about 8 to 31 m in height depending on surface topography and inshore distance. 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. Shoreline trees around lakes located in the massive forest burn area were unmeasured, but as the fire was 13 years old, they were judged to be only slightly larger in size than those present on the clearcut shorelines.

Results and discussion

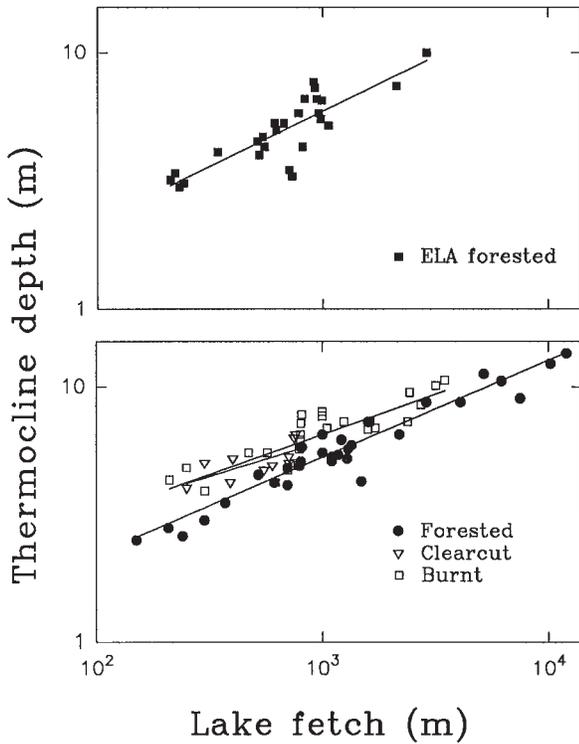
Influence of fetch on thermocline depth

Overwater windspeeds in relation to data from the nearby meteorological site increased with surface area for three ELA lakes (Fig. 1, upper panel, data from Solinske 1982). Spiegel and Imberger (1980) outlined two processes by which the epilimnion is thickened by wind action: (i) wind moving across lake surfaces creates a stirring action resulting in a downward forced turbulence and (ii) in larger lakes, the turbulence created at the base of the metalimnion results from velocity shearing associated with movement of seiches between warm, less dense metalimnetic and cold, denser hypolimnetic waters. Therefore, because surface wind waves are strongly fetch dependent for most lakes, wind-induced mixing will be greater in larger lakes. Consequently, thermocline depth can be empirically related to fetch length for lakes at ELA in northwestern Ontario (Schindler 1971; Cruikshank 1984; Fig. 2, upper panel), as has been found for lakes located elsewhere (Arai 1981; Shuter et al. 1983; Patalas 1984; Gorham and Boyce 1989; Hanna 1990). Among the 30 forested lakes sampled in 1994, fetch was found to be as good a predictor ($R^2 = 0.97$) of thermocline depth as in the forested ELA lakes sampled previously ($R^2 = 0.85$).

Influence of riparian forests on lake thermocline depth

Hutchinson (1957) proposed that “in theory the degree of exposure or shelteredness should be expected to play a part in determining the thickness of the epilimnion.” Data from Solinske

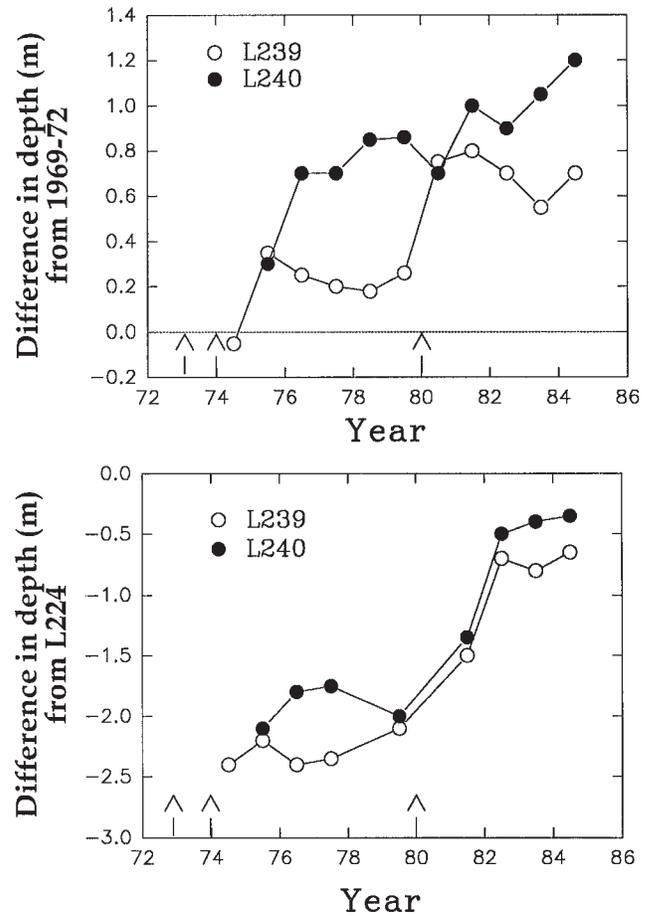
Fig. 2. Relationship between length of lake fetch and late-summer thermocline depth for (upper panel) 26 ELA lakes sampled during 1969–1985 with forested riparian shores ($y = -0.50 + 0.42x$, $R^2 = 0.85$) and for (lower panel) 63 different northwestern Ontario lakes sampled in 1994 with forested ($y = -0.41 + 0.38x$, $R^2 = 0.97$), clearcut ($y = -0.03 + 0.27x$, $R^2 = 0.72$), and burnt ($y = -0.13 + 0.31x$, $R^2 = 0.86$) riparian shores.



(1982) show that forest cover can indeed have an influence on wind velocities measured over ELA lake surfaces. For L223, which is completely surrounded by an undisturbed riparian forest, originating wind direction had no influence on overwater windspeeds expressed as ratios to meteorological site windspeeds (Fig. 1, lower panel). In such a situation, the forested riparian terrain reduces the velocity of horizontally moving air masses. A major blowdown in 1973 and severe forest fires in 1974 and again in 1980 demolished the forest along the eastern side of L239, leaving barren hills (Schindler et al. 1980, 1990). The highest wind velocities over this lake originated from the east (Fig. 1, lower panel), presumably due to reduced wind resistances (Solinske 1982). Riparian tree removal therefore had the effect of increasing the exposure of L239 to wind energy, a result that, considering the demonstrated importance of fetch to thermocline depth (Fig. 2, upper panel), might be expected to have altered the pattern of thermal stratification.

The average late-summer (i.e., July 25 – August 25) thermocline depths in L239 and adjacent L240 (which had also lost a major portion of its insulating riparian forest due to the same blowdown and fires) were found to increase in the years following forest disturbance (Schindler et al. 1990; Fig. 3, upper panel). To account for long-term trends due to factors other than deforestation, results from L239 and L240 can be compared with data from L224, which escaped the effects of the blowdown and fires. Thermocline depths for L239 and L240 were originally about 2 m less than that in L224 in the mid-

Fig. 3. Changes in late-summer thermocline depths in L239 and L240 in the ELA following blowdown (1973) and burning (1974 and 1980) of riparian forests along their eastern shorelines (arrows) compared with (upper panel) predisturbance (1969–1972) values and (lower panel) values in nearby and completely forested L224.

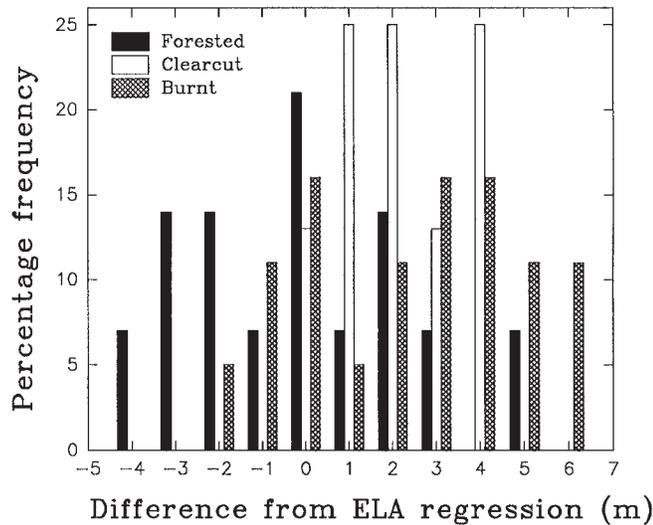


1970s, but deepened over time toward that in L224, becoming only a 0.5 m less than that of the reference lake by the mid-1980s (Fig. 3, lower panel).

Temporal studies of thermal stratification data for these two ELA lakes (see also independent and different analysis in Schindler et al. 1990 for L239) that had lost their fringing riparian forests due to blowdown and wildfires therefore support similar observations of Rask et al. (1993) for a single Swedish lake whose watershed had been logged. The next step was to see if these findings were particular to just these few individual basins or were representative of a more general response of small boreal lakes to riparian forest clearance.

Residual differences between the lakes sampled in 1994 and the general interannual regression equation for forested ELA lakes ranged from -4 (shallower) to 5 m (deeper), centered about a mode of 0 (Fig. 4). Residual differences in relation to the general interannual ELA regression averaged 2.4 m deeper in thermocline depth for burnt and clearcut lakes (Fig. 4). Regression equations for burnt and clearcut lakes were similar and significantly different (paired ANCOVA tests, p 's < 0.05) from that for lakes with forested shorelines. Only two burnt lakes had thermoclines as shallow as predicted from the regression line developed for the forested lakes

Fig. 4. Frequency distribution of residual differences between thermocline depths measured in forested, burnt, and clearcut northwestern Ontario lakes sampled in 1994 (from Fig. 2, lower panel) and those predicted from the interannual ELA regression equation (from Fig. 2, upper panel).



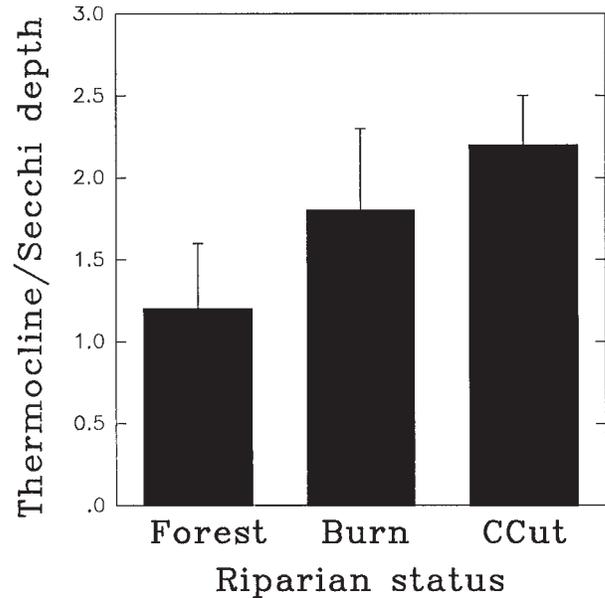
(Fig. 2, lower panel). Also, as expected, regression lines for the three groups of lakes converged with increasing lake size (Fig. 2, lower panel), suggesting that the insulating role of riparian trees in impeding wind movement may be one of diminishing importance for progressively larger lakes.

In small lakes, water clarity, through controlling the depth of light penetration and extent of solar radiative heating, may also have a modifying role on thermocline depths set by fetch-related wind mixing (Mazumder and Taylor 1994) and therefore thickness of hypolimnia (Teleki and Herskowitz 1986). Although in some situations, these influences of water clarity may be related to algal biomass (Mazumder 1990; Mazumder et al. 1990), in Canadian Shield lakes, colour is often the primary determinant (e.g., Schindler 1971; Dillon et al. 1986; R. France, unpublished data). Clearcut and burnt lakes in this study region of northwestern Ontario have significantly higher colour values, measured as dissolved organic carbon concentrations, and therefore significantly lower water clarities, measured by Secchi depths, than those of forested lakes (R. France, unpublished data). One would therefore expect such lakes to exhibit shallower thermocline depths due to a more rapid heat absorbance closer to the water surface. The fact that the opposite occurred (Fig. 5) indicates the overwhelming dominance of the surrounding riparian forests in modifying the patterns of wind-induced mixing in these small boreal lakes.

Consequences of habitat loss for cold stenotherms

Habitat loss of cold, well-oxygenated hypolimnetic water is widely suspected among fishery biologists to be the major cause of declining lake trout (*Salvelinus namaycush*) stocks in Ontario (Evans et al. 1990; Olver et al. 1991). For example, MacLean et al. (1990) determined that reproduction of lake trout was positively correlated with the depth range and volume of the late summer hypolimnion. Therefore, the demonstration here that thermoclines deepen as a result of riparian deforestation is a further stress on lake trout populations, additional to

Fig. 5. Comparisons of ratios (\pm SD) between thermocline and Secchi depths for northwestern Ontario lakes surrounded by intact (Forest), burnt (Burn), and clearcut (CCut) riparian forests.



other habitat compressions by anthropogenic agents such as acidification, eutrophication, and climate warming, as briefly discussed below.

Varied physical-chemical processes occurring within the epilimnion as a result of anthropogenic lake acidification enhance water clarity (e.g., Yan 1983; Shearer et al. 1987), which in turn increases thermocline depth (Effler and Owens 1985) and reduces potential trout habitats (Schofield et al. 1993). Such a development may have contributed to the extirpation of lake trout that has been estimated (Beggs et al. 1985) to have occurred in about 3% of all Ontario lakes.

As a result of nutrient additions from cottage development (Hutchinson et al. 1991), lake productivities have increased, promoting elevated rates of hypolimnetic metabolism and consequently decreased oxygen concentrations (Cornett and Rigler 1980). This shrinkage of hypolimnetic habitat was thought to be a major factor in causing reproductive failures in one quarter of the lake trout populations surveyed in eastern and central Ontario (MacLean et al. 1990).

The predominance of small lake basins of limited depth in northwestern Ontario means that 22% of the lake trout populations located there can be categorized as highly susceptible to extirpation on the basis of lake thermal and oxygen regimes (Ryan and Marshall 1994). The possibility of thermocline deepening in lakes in this region as a result of climate warming (Schindler et al. 1990) may also have detrimentally affected these lake trout populations by reducing the extent of cold, oxygenated habitats (Ryan and Marshall 1994). These problems are further exacerbated because, coincident to rising regional atmospheric and lake temperatures, the incidence of major storm events has increased markedly since the 1950s across Canada (Jardine 1994) as reflected by a doubling of windspeeds measured at the ELA meteorological station between 1970 and 1988 (Schindler et al. 1990).

Cannibalism is an important determinant of lake trout

recruitment, segregating juveniles from adults to deeper parts of the hypolimnion (Evans et al. 1990). Compression of the thermally available habitat, as through riparian deforestation, for example, therefore concentrates lake trout, increasing interaction and competition as well as the potential for cannibalism.

Empirical estimates suggest that in half of Ontario lakes, less than 6% of the total lake volume is suitable for juvenile lake trout, and in one fifth of the lakes, only 1% of the lake volume is available for such nursery development (Evans et al. 1990). Because most of the lakes containing lake trout in northwestern Ontario are already near the minimum depth necessary for sustaining viable populations (about 28 m), any changes in hypolimnion volume may exacerbate the potential for regional extinctions (Ryan and Marshall 1994). As a result, thermocline deepening produced by riparian deforestation, although of a magnitude of only several metres in extent, might still impair lake trout recruitment and population survival. If hypolimnia are compressed in thickness to less than 3 m, both oxygen concentrations and trout carrying capacities decline markedly (Teleki and Herskowitz 1986).

Habitat compression is not only a concern for lake trout. Other cold stenotherms such as deepwater sculpin (*Myoxocephalis quadricornis*), amphipods (*Diporeia hoyi*), and opossum shrimp (*Mysis relicta*) are also dependent on cold, deepwater refugia during the summer (Dadswell 1974).

Implications for riparian forest management

As a result of the widely recognized negative influences of siltation on salmonid egg survival, Ontario restricts riparian clearcutting around lakes known to contain trout populations (Ontario Ministry of Natural Resources 1988). Over the last two decades, however, there has been a progressive shrinkage in the recommended widths for protective buffer strips around such trout lakes (Ontario Ministry of the Environment 1994). At present, it is possible to remove trees to within 30 m of lakes on riparian shorelines of less than 30% surface slope (Ontario Ministry of Natural Resources 1988, 1991). In Quebec, where actual buffer strip “laws” exist, rather than mere “recommendations” or “guidelines” as is the case in Ontario, it is possible to cut to within 20 m of lakes regardless of either riparian slope or type of fish species present (Québec Ministère des Forêts 1992). Buffer strips are susceptible to blowdown due to being newly exposed to considerable wind energy (e.g., Alexander 1964; Steinblums et al. 1984; Stephenson 1988). Whether such buffer strips will be of sufficient width to protect pelagic zones from increased wind energy through the period of backshore forest regrowth is unknown, and worthy of future investigation.

The present study measured a doubling of thermocline depth per unit Secchi depth a decade after the complete logging of riparian forests around 10 lakes. The average height of sapling regrowth on these shorelines was 2 m, enough to substantially reduce wind energy (e.g., Moen 1967; Capel 1988; Johnson and Beck 1988). It is possible, therefore, that lake mixing depths may have been even deeper immediately following riparian deforestation. For example, the greatest increases in thermocline depth in L239 and L240 occurred during or immediately following tree blowdown and burning. Easterly windspeeds over L239 1 year after removal of the last of the riparian trees during the massive wildfire of 1980 were

almost three times greater than those originating from the forested western shore. Almost a century is required for forests to reach maturity in this region of northwestern Ontario. The protection offered by riparian trees with respect to the influences of wind-induced lake mixing will therefore undergo a gradual process of recovery to pre-disturbance levels. Whether lake trout populations and other cold stenotherms can adapt to such prolonged periods of recurring habitat compression following the initial, most severe effect is an important management issue necessitating predictive modelling along the lines of that initiated by Ryan and Marshall (1994).

Note added in proof

Two recent published analyses of ELA data give credence to the conclusions of the present study. Schindler et al. (1996) state: “It is difficult to discount entirely the role of increased wind velocities and wind exposures. Surface waves on small ELA lakes became larger after catchments were burned because less protection was afforded by denuded shorelines. The effect was noticeable enough to require that boats at the dock on Lake 239 had to be tied bow outward to prevent swamping when winds were onshore—a procedure that was not necessary in the early 1970s.” The data presented here in Fig. 1 (lower panel) provide the empirical support for Schindler et al.’s (1996) anecdote about increased wind at L239 and nearby L240 relative to other unburnt ELA lakes (this paper, Fig. 3 (lower panel), which therefore contributed toward the progressive increases observed in summer thermal capacities of L239 and L240 (Schindler et al. 1996, Fig. 9).

Schindler et al. (1996) continue, however, with the statement: “Nevertheless, the empirical analysis of Fee et al. (1996) indicated that increased wind exposure played a negligible part in thermocline deepening of small ELA lakes.” Despite this statement, Fee et al.’s (1996) data do seem to support both Schindler et al.’s (1996) anecdotal evidence as well as the present analysis. Fee et al. (1996) present a convincing case that water transparency plays a major role in regulating epilimnetic mixing depth in small ELA lakes. Further, a comparison of results shown in their Fig. 6 and Table 2 indicates that the mixing depth in L239 was 1.3 times greater per unit water transparency compared with that in L223. Although, of course, some of this difference may be attributable to the fact that L239 experiences greater wind velocities on account of its greater size (this paper, Fig. 1 (upper panel), Fee et al.’s (1996) findings support my regional analysis shown in Fig. 5 whereby lakes exposed to winds through riparian deforestation do have greater ratios of thermocline to Secchi depth.

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