USE OF WATER CLARITY TO MONITOR THE EFFECTS OF CLIMATE CHANGE AND OTHER STRESSORS ON OLIGOTROPHIC LAKES

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Abstract. We present evidence from studies of lakes in Killarney Park, Ontario, Canada that water clarity is a key variable for monitoring the effects of climate change, high UV exposure and acidification. In small oligotrophic lakes, these stressors affect water clarity primarily by altering the concentration of DOC in lake water. Clear lakes (<2 mg L^{-1} DOC) proved to be highly sensitive indicators of stressors, exhibiting large thermal and optical responses to small changes in DOC. Extremely clear (<0.5 mg L^{-1} DOC) acidic lakes showed the effects of climate change and solar bleaching in recent decades. These lakes became much clearer even though they were slowly recovering from acidification.

Keywords: acidification, core variable, solar bleaching, thermal and optical responses, water clarity

1. Introduction

Water clarity is an important environmental variable for assessing both natural and anthropogenic factors that affect aquatic ecosystems, and is one of the core variables being recommended for the detection and monitoring of ecosystem change in Canada (Tegler *et al*., 2001). In oligotrophic lakes, water clarity is primarily controlled by the concentration of coloured organic matter (dissolved organic carbon DOC) (Smith *et al*., 1973; Morris *et al*., 1995; Fee *et al*., 1996; Williamson *et al*., 1996), which, in turn, affects a wide range of chemical, physical and biological processes. These include thermal structure, light transmission for photosynthesis, attenuation of damaging levels of ultraviolet light, vertical distribution of plants and animals, as well as the form and availability of toxic metals (Welsh *et al*., 1993; Driscoll *et al*., 1995; Fee *et al*., 1996; Schindler *et al*., 1997; Williamson *et al*., 1999a; Pérez-Fuentetaja *et al*., 1999). The dominant effects of clarity on mixing depth and other aspects of thermal stratification are mainly confined to small lakes (<500 ha, Fee *et al*., 1996). Wind and other meteorological events become increasingly more important in larger lakes.

In the Boreal Shield ecozone of North America, many thousands of small lakes are vulnerable to the adverse effects of large scale stressors such as climate change, acidification and ozone depletion. All three have important effects on DOC. Cli-

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mate change, in particular the increased occurrence of drought events, can reduce the export of DOC from lake catchments and increase the clarity of lake waters (Schindler *et al*., 1996a,b, 1997; Curtis and Schindler, 1997). Acidification also reduces DOC in lake water (Bukaveckas and Driscoll, 1991), either through precipitation with Al or other metals, or directly through dissociation by H^+. Finally, ozone depletion allows increased levels of UV-B radiation to reach the earth (Kerr and McElroy, 1993; Madronich, 1994; Shindell *et al*., 1998). Increased exposure to UV-B (280–320 nm) can have direct effects on phytoplankton (Xenopoulos *et al*., 2000) but can also destroy the DOC in the surface layer and allow light, including UV, to penetrate to deeper layers in the water column where further photodegradation or ‘bleaching’ can occur (Dillon and Molot, 1997a; Morris and Hargreaves, 1997). The UV-driven bleaching is expected to have the greatest effects in slow flushing lakes where water has prolonged exposure to UV radiation (Curtis and Schindler, 1997). Reduced precipitation or stream flow during dry periods can further extend the water exposure period in lakes, an example of one of the many possible interactions among stressors (Schindler, 1998).

Long term ecological monitoring programs are needed to assess the effects of the complex interactions of climate change, acidification and ozone depletion. For example, in a 10 yr monitoring study, Yan *et al*. (1996) found that a lake recovering from acidification rapidly reacidified when drought initiated the oxidation and later release of stored sulphur from the lake catchment. The reacidification of the lake (from pH 5.8 to 4.5) was accompanied by increased Al concentrations, decreased DOC, increased clarity, and an increase in the depth (from 1.8 to 5.6 m) exposed to 1% of surface irradiance of UV-B. Schindler *et al*. (1996a,b) reported similar and equally unexpected changes in ‘reference lakes’ in the Experimental Lakes Area of Ontario during a 20 yr monitoring period. The sequence of changes in the ELA lakes appeared to be the result of recent climate changes as well as the effect of wildfires.

In this article, we address the hypothesis that DOC, and other measures of lake water clarity such as Secchi depth, can be used to identify the individual and combined effects of climate change, high UV exposure and acidification. For this study we use the monitoring data for lakes in Killarney Park, a Canadian EMAN (Ecological Monitoring and Assessment Network) site in Ontario. Killarney Park was one the first areas in Canada where the damaging effects of acidification were documented (Beamish and Harvey, 1972; Sprules, 1975). It also contains some of Canada’s clearest waters, where ecological effects of increasing UV-B may be significant, and is within an area where future climate changes are predicted to be severe (Environment Canada, 1994).

Figure 1. Location of the principal study lakes in Killarney Park, Ontario, Canada. The area of orthoquartzite bedrock and the DOC concentrations of sampled lakes are indicated.

2. Study Area and Principal Study Lakes

Killarney Park is a wilderness area located along the north shore of Lake Huron (Figure 1). Its surface area is 48 110 ha and it contains 514 lakes and ponds ranging in size from 0.03 to 810.0 ha (median surface area 1.46 ha) and varying in elevation from 181 to 415 m above sea level. The LaCloche Mountain Range forms an arc of orthoquartzite ridges that occupy about half of the Park area. The white orthoquartzite bedrock is highly resistant to erosion and provides almost no buffering against acid precipitation. The lakes on the orthoquartzite ridges are therefore very dilute and many of them are very acidic. Surrounding the ridges and in the valleys between are sandstone, granite, and limestone areas that provide much more buffering capability to associated lakes. The forest cover also reflects these geological characteristics. The ridge top areas have quite sparse vegetation dominated by stunted red oak (*Quercus borealis*), red maple (*Acer rubrum*) and jack pine (*Pinus banksiana*). The deeper soils of the valley slopes and bottoms support dense stands of sugar maple (*Acer saccharum*), white birch (*Betula papyrifera*), eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*) and other tree species, and also contain small but important wetland areas that have a considerable influence on the clarity of downstream lakes. Many of the wetland areas were created by beaver (*Castor canadensis*) dams.

An extensive survey was conducted between 1995–1997 to map the physical, chemical and biotic composition of the Park lakes (Snucins and Gunn, 1998). Many of the lakes are acidic (110/154 lakes with $\text{pH} < 6.0$) and have impoverished biotic communities, but have exhibited some improvements in recent decades because of reductions of SO_2 emissions in eastern North America. The evidence of chemical and biological recovery in Killarney is addressed in an associated paper by Snucins *et al*. (2001). A second striking feature of the survey results was the high proportion of the lakes that were extremely clear. Nearly 30% of the 154 surveyed lakes had DOC concentrations <2.0 mg L^{-1}. In some of these lakes, particularly the ones on the orthoquartzite ridges, Secchi depth visibility exceeded 30 m (Snucins and Gunn, 1998).

From the initial results of the extensive survey, a set of 21 lakes was selected to investigate relationships between lake and catchment characteristics and the optical and thermal properties of the lakes (Figure 1). We selected lakes that varied as widely as possible in chemical (pH 4.6–7.7, Ca 0.95–7.60 mg L^{-1}, total P 3.2–18.8 μg L^{-1}, DOC 0.1–4.6 mg L^{-1}) and morphological features (surface area 3.4–406.3 ha, max. depth 8.0–61.0 m) (Tables I and II). Most lakes have no seasonal residences or roads within their catchments. Cottages exist on the south shores of Johnnie and Carlyle Lakes and the main park campground is on George Lake. There is no mining or forestry activities within the Park.

TABLE I

Physical characteristics of the Killarney Park study lakes and the composition of their catchments

Lake	Lake surface area (ha)	Maximum depth (m)	Mean depth (m)	Catchment components (ha)								
				Productive forest	Treed muskeg	Open wetland	Brush and alder	Exposed bedrock	Upstream lakes and ponds	Streams	Other[a]	Total catchment[b]
Acid	19.6	29.0	10.9	308.5	0.0	0.8	0.6	103.5	30.0	1.6	0.0	463.8
Bell	347.4	26.8	8.1	5892.8	263.1	275.0	2.0	445.9	1353.1	26.4	0.0	8596.3
Carlyle	156.7	14.6	5.7	716.0	1.7	33.3	0.0	77.8	68.9	2.6	0.0	1058.6
Chain	10.9	10.5	2.7	462.7	59.0	29.0	0.0	62.3	51.3	3.1	0.0	677.1
Clearsilver	30.9	13.7	5.3	192.2	0.0	0.0	0.0	109.7	8.6	1.5	0.0	342.2
David	406.3	24.4	7.0	1015.0	59.6	66.3	0.0	284.5	84.7	2.1	0.0	1915.5
George	188.5	36.6	16.4	3452.1	1.3	30.5	7.4	1184.0	819.6	15.7	23.3	5716.7
Helen	82.6	41.2	20.5	580.7	5.6	18.6	6.3	151.3	36.2	3.6	0.0	883.5
Ishmael	72.8	19.8	11.3	775.6	5.6	21.1	6.3	233.5	125.9	4.0	0.0	1242.6
Johnnie	342.3	33.6	10.0	8941.6	306.0	339.5	10.2	948.5	2044.4	35.3	2.2	12952.5
Kakakise	112.6	30.5	13.5	406.4	0.0	3.2	0.0	207.8	14.4	1.2	0.0	749.4
Killarney	326.5	61.0	10.8	2012.1	1.3	4.6	1.9	647.8	229.4	6.9	0.0	3227.5
Low	33.8	28.4	14.4	663.4	5.6	18.6	6.3	151.8	118.9	3.7	0.0	1000.4
Lumsden	23.8	21.8	9.0	370.2	0.0	1.8	1.3	255.9	52.6	3.6	0.0	707.9
Nellie	260.5	54.9	19.2	1067.6	0.0	3.2	0.0	105.7	28.6	1.3	0.0	1465.0
Norway	63.3	33.6	15.1	667.5	0.0	2.7	1.9	231.2	79.7	1.5	0.0	1046.4
OSA	278.9	39.7	12.0	325.2	0.3	1.4	0.0	243.7	29.4	1.7	0.0	879.0
Partridge	11.0	16.9	6.2	36.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.9
Ruth-Roy	54.5	18.0	4.3	272.3	0.0	1.0	1.4	168.6	2.8	0.3	0.0	496.8
Teardrop	3.4	16.6	9.6	6.9	0.0	0.0	0.0	2.6	0.0	0.0	0.0	12.8
Terry	11.5	8.0	3.1	376.3	1.7	30.0	0.0	76.5	45.1	2.6	0.0	542.8

[a] Includes campgrounds and roads found within the Park; [b] The catchment total includes the surface area of the lake. The sum of the catchment components does not exactly equal the total catchment area (±1%) because of rounding and software errors.

TABLE II

Selected chemical characteristics of the Killarney Park study lakes. Lakes sampled as 5 m tube composite samples on November 2–3, 1998

Lake	pH	Cond.	ANC	Ca	Mg	SO_4	DOC[a]	Al	Cu	Ni	Total P	NO_x[b]
		(μS cm^{-1})	(mg L^{-1})					(μg L^{-1})				
Acid	5.1	20	–0.18	0.95	0.38	5.50	0.4	121.0	<0.1	3.8	5.6	80
Bell	6.1	26	1.55	1.80	0.68	7.00	3.9	23.7	1.2	3.7	17.6	30
Carlyle	6.2	25	1.89	1.60	0.64	6.50	3.0	20.8	1.1	4.0	13.2	10
Chain	4.9	25	–0.20	1.30	0.48	7.00	3.4	174.0	1.3	13.0	17.0	10
Clearsilver	4.9	22	–0.41	1.20	0.36	5.00	1.4	126.0	0.4	9.6	7.6	30
David	4.9	21	–0.07	1.10	0.40	6.00	1.4	61.5	1.1	9.1	15.6	10
George	6.2	25	1.04	1.70	0.64	7.50	1.4	10.7	<0.1	2.7	12.2	10
Helen	6.9	30	4.71	2.35	0.92	6.50	3.1	8.4	0.4	0.4	14.0	10
Ishmael	6.8	31	5.39	2.45	0.96	6.00	3.2	4.5	0.0	0.2	11.2	5
Johnnie	6.0	25	1.07	1.65	0.64	7.50	3.1	32.3	1.6	5.5	14.6	25
Kakakise	6.6	29	2.83	2.10	0.82	7.00	2.6	12.1	0.7	1.0	13.2	5
Killarney	5.2	26	–0.05	1.45	0.52	7.50	0.3	136.0	0.3	6.7	3.4	130
Low	7.7	69	20.73	7.60	1.98	8.50	2.8	6.0	0.6	2.1	4.0	5
Lumsden	5.3	20	0.07	1.05	0.44	6.00	0.4	76.2	0.1	4.8	6.0	75
Nellie	4.6	33	–0.91	1.35	0.42	9.00	0.1	438.0	1.9	9.7	4.8	180
Norway	5.3	24	0.10	1.45	0.56	7.50	0.7	103.0	0.3	7.2	4.6	75
O.S.A	4.9	31	–0.39	1.85	0.56	8.50	0.3	133.0	1.1	7.1	3.4	240
Partridge	5.8	27	0.81	1.90	0.68	9.00	1.7	28.7	0.4	4.8	18.8	15
Ruth-Roy	4.8	24	–0.56	1.00	0.38	6.50	0.2	221.0	1.2	10.2	3.2	55
Teardrop	6.8	25	3.13	1.75	0.88	6.50	0.8	3.1	<0.1	0.5	5.6	5
Terry	5.7	22	1.10	1.40	0.56	6.00	4.6	131.0	0.7	4.8	4.0	10

[a] DOC <0.3 mg L^{-1} are at or below the detection limits of the analytical method; [b] NO_x includes nitrite and nitrate.

3. Methods

A limnological study of the 21 lakes was conducted in 1998 to assess their sensitivity to climate change, high UV exposure and acidification/recovery. This spatial comparative approach focussed primarily on physical and chemical habitat features, with particular emphasis on the thermal and optical properties of the lakes that affect the vertical structure of the habitat. In addition we summarized available information on long-term changes in optical properties of 4 lakes with historic data (Nellie, OSA, George, Bell). Most of the earlier studies were water quality surveys designed to assess the effects of changing acid deposition on lake chemistry (Maki and Rozenberg, 1973; Conroy *et al.*, 1978; Keller *et al.*, 1998). There were very few historic data on DOC from these surveys. Secchi depth measurements were the only data we could use to assess long-term changes in water clarity at the Killarney Park EMAN lakes.

Lake surface area and catchment characteristics (productive forests, bedrock, wetlands, etc.) for each lake were extracted (using MapInfo) from digital OBM (Ontario Base Map) and FRI (Forest Resources Inventory for Ontario) maps and validated with aerial photographs taken in 1987. Catchment components include all upstream waters, wetlands and terrestrial areas draining into a particular lake. Lake morphometry data were available for most lakes from previous surveys. Depth sounding along transects and standard contour mapping techniques were used to create bathymetric maps for lakes that had not been previously surveyed.

During the 1998 survey temperature and oxygen levels were measured at 1 m intervals at the maximum depth station of each lake during the last week of August. This end-of-summer period is when maximum temperatures occur in these lakes. The epilimnion, metalimnion, and hypolimnion were defined graphically by the intersection of trend lines fitted to the thermal profiles (Wetzel, 1975). Surface temperature was defined as the temperature 1 m below the surface. Bottom temperature was defined as the temperature at 1 m above the lake sediments.

Solar radiation in the photosynthetically active range (PAR) of 400–700 nm was measured using a LiCor (model Li-1000 or Li-1400) Integrating Quantum Photometer equipped with cosine-corrected Li-192S flat sensors. PAR readings were usually measured monthly but were only conducted on calm days when sky conditions were relatively constant. Measurements were taken at 1 m intervals from the surface to the lake bottom. The depth at which surface downwelling light was attenuated to the 1% level was determined from the measured values or, in very clear lakes, by linear regression of measured values beyond the maximum depth of the lakes. Secchi depth readings were also recorded during the monthly surveys. We used the mean observed Secchi depth reading as well as the mean observed 1% light level from the monthly samples as measures of lake water clarity for statistical analyses.

An Optronics Laboratory Inc. scanning spectroradiometer (Model OL-754), equipped with a spherical Optronics Model OL IS-470-WP underwater sensor, was used on July 18–24, 1998 to measure full spectrum (280–800 nm) irradiance in 5 of the Killarney study lakes (George, Killarney, OSA, Ruth-Roy, Terry) that ranged widely in optical properties (max. Secchi depth 3.2–23.0 m; DOC 0.3–4.6 mg L^{-1}). The full irradiance was measured to a maximum depth of 13 m in each lake.

Water sampling occurred after the lakes had mixed (November 2–3, 1998). All lakes were sampled as 0–5 m composite samples, using a nalgene tube lowered from the surface. Analyses of pH, acid neutralizing capacity (ANC), and specific conductance were conducted at Laurentian University. Analyses of metals, major ions, nutrients and DOC were conducted by the Ontario Ministry of the Environment following methods outlined in OMOE (1983). To measure DOC, samples were acidified and flushed with nitrogen to remove DIC, then photo-oxidized to decompose DOC to DIC. The samples were then acidified with sulphuric acid and CO_2 was colorimetrically determined using an autoanalyzer with a phenolphthalein indicator.

4. Results and Discussion

4.1. LONG-TERM TRENDS IN SECCHI DEPTH IN INDIVIDUAL LAKES

The long-term monitoring data for Secchi depth transparency show that significant changes have occurred in the light environment of Killarney lakes during the past 25 yr, and that individual lakes exhibit widely different rates and directions of change (Figure 2). Extremely clear, acidic lakes, like Nellie and OSA, show the effect of climate change and solar bleaching in recent decades. These lakes, which currently have DOC values of 0.1 and 0.3 mg L^{-1}, respectively, have become much clearer (slopes significantly >0 at $P < 0.05$). For example, in 1973 Nellie had an average Secchi depth of 20.7 m. In 1998 it averaged 28.8 m. This change occurred even though the lakes were slowly beginning to recover from acidification, a change that is usually associated with a decline rather than an increase in water clarity (Yan, 1983). From paleolimnologically derived estimates, pre-industrial pH of Nellie and OSA were 6.8 and 5.9 respectively (Snucins *et al.*, 2000). The pHs of Nellie and OSA are presently 4.6 and 4.9, respectively (Table II). During the period 1980 to 1998, when significant reductions in atmospheric deposition of acid occurred in the area (Hindar and Henriksen, 1998), the measured pH of Nellie and OSA lakes increased by about 0.2–0.3 (Snucins *et al.*, 2000).

In George Lake, a lake with an intermediate concentration of DOC (1.4 mg L^{-1}), Secchi depth changes followed the expected relationship between clarity and acidity, showing a decline by approximately 0.1 m yr^{-1} (Figure 2) as the pH rose from about 4.9 in 1980 to 6.2 in 1998. However, in Bell Lake, a lake with a relatively high DOC concentration (3.9 mg L^{-1}; Table II) there was no significant ($P > 0.05$) change in water clarity during the monitoring period even though pH had risen from 5.0 to 6.1 (Figure 2).

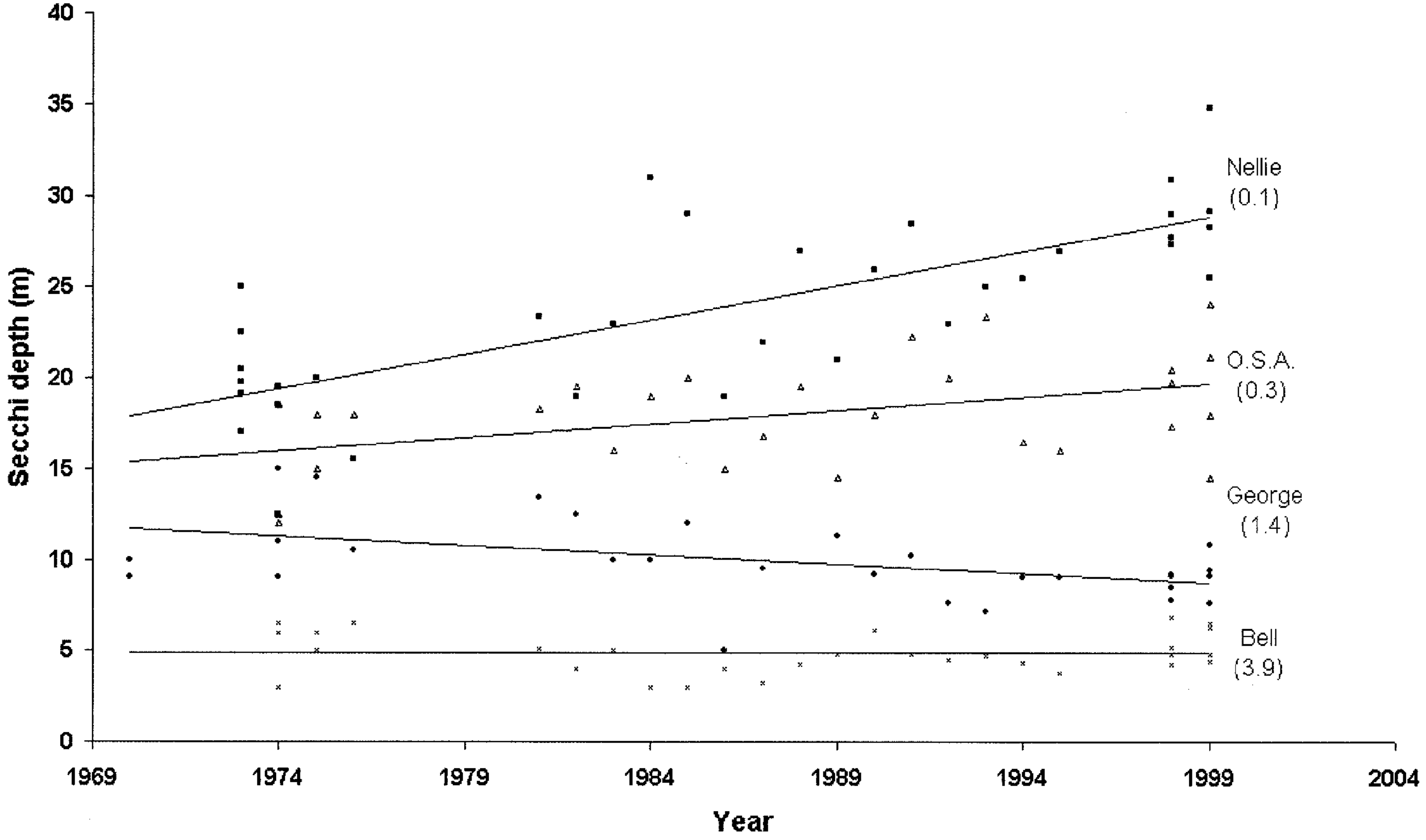

Figure 2. Changes in Secchi depth transparency of study lakes in Killarney Park Ontario. The fall 1998 DOC concentrations (mg L^{-1}) for the four study lakes are indicated in parentheses.

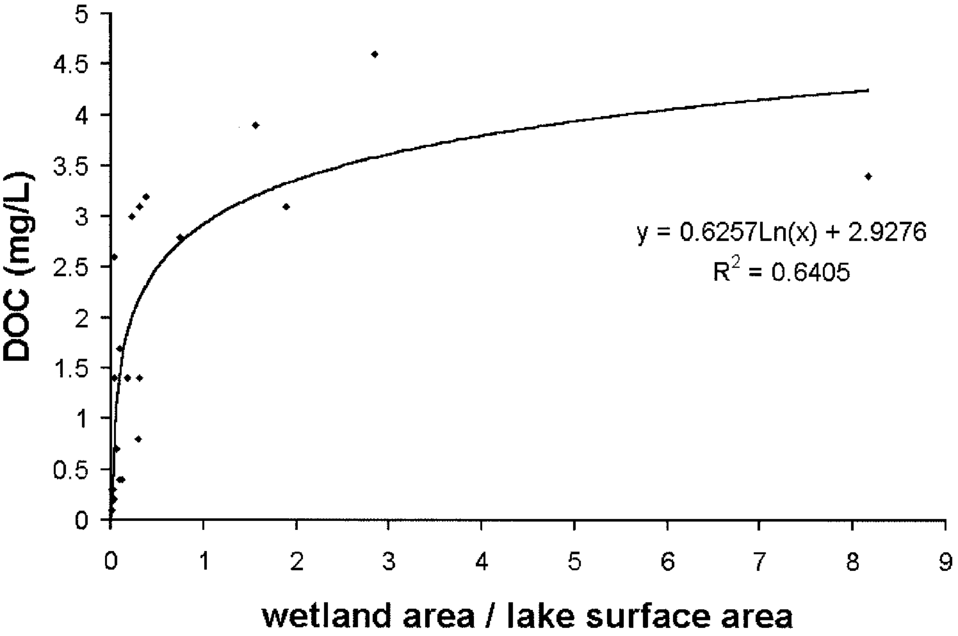

Figure 3. Increases in lake water DOC with increasing ratio of wetland area to lake area.

4.2. SOURCES OF DOC

The DOC concentration in lake water increases as the ratio of the wetland area to the lake area increases (Figure 3). This finding is consistent with other studies that indicated that wetlands are the dominant source of DOC for Shield lakes (Engstrom, 1987; Urban *et al.*, 1988; Rasmussen *et al.*, 1989; Devito *et al.*, 1989; Dillon and Molot, 1997b).

The size of the wetland areas that generate DOC may vary slightly from year to year because of changing rainfall levels or fluctuations in beaver populations that produce wetlands by damming tributary streams, but because of the geomorphology of the Killarney lake catchments, the overall supply of DOC to these lakes has presumably always been relatively low. As we will discuss later, this fact leads to the conclusion that relatively high clarity has been a permanent feature of these waters. Steep terrain, thin soil, small catchment areas, and the large extent of exposed bedrock surrounding these lakes (Table I) are some of the main catchment features that may limit the development of DOC-generating wetland areas.

Acidification does increase the clarity of these lakes, and as we have seen in the example of George Lake (Figure 2), clarity will likely decrease in many of the acidic lakes in the future when pH increases.

Teardrop Lake provides an internal check on what historic conditions may have been like in some of the headwater lakes before acidification. Teardrop Lake is a circumneutral headwater lake (pH 6.8) on the orthoquartzite ridge. Its chemistry is

TABLE III

Thermal and optical properties of the Killarney Park study lakes. Thermal structure determined during August 24–31, 1998

Lake	Secchi depth range (m)	Mixing depth (m)	Surface temp. (°C)	Bottom temp. (°C)	Depth (m) to 1% surface irradiance		
					PAR (mean)	UVA	UVB
Acid	11.20—15.25	10.0	21.5	4.9	20.5	–	–
Bell	4.23–6.80	6.0	21.8	6.1	8.3	–	–
Carlyle	3.20–5.55	5.5	23.2	7.5	8.8	–	–
Chain	3.05–5.70	3.7	22.2	5.3	5.4	–	–
Clearsilver	6.77–11.65	8.5	22.4	10.5	13.9	–	–
David	7.10–11.75	9.8	21.9	7.0	19.1	–	–
George	7.75–9.15	8.5	22.6	5.3	20.3	6.6	2.7
Helen	6.15–8.50	6.5	22.4	4.5	11.2	–	–
Ishmael	6.05–7.20	6.1	22.9	5.7	11.4	–	–
Johnnie	4.70–7.30	6.5	22.1	5.1	9.4	–	–
Kakakise	6.10–8.55	6.0	23.3	5.2	11.3	–	–
Killarney	14.60–23.00	9.0	21.8	4.6	44.6	34.2	13.7
Low	7.05–9.00	6.5	22.7	4.8	13.3	–	–
Lumsden	13.45–14.25	11.0	21.6	6.9	20.7	–	–
Nellie	27.38–30.90	10.5	20.4	10.1	69.8	–	–
Norway	9.57–15.50	7.7	21.9	4.8	26.8	–	–
O.S.A	17.30–20.50	12.5	22.3	8.6	50.3	60.7	28.1
Partridge	5.30–10.52	7.6	23.3	10.7	20.7	–	–
Ruth-Roy	13.20–>17.00[a]	–	22.1	22.0	37.0	10.3	8.9
Teardrop	11.60–12.05	7.8	20.9	13.1	19.6	–	–
Terry	2.05–2.87	2.5	23.6	5.6	4.0	0.4	0.2

[a] Bottom of lake.

unique (well buffered) because of an intrusion of a narrow dike or calcium-bearing diabase within the catchment, but this lake has no wetlands in its catchment and as a result has a DOC <1.0 mg L^{-1} and a Secchi depth transparency of approximately 12 m. The low DOC and high Secchi of this unacidified lake supports our argument that relatively high clarity is a natural feature of some of the lakes in Killarney Park.

4.3. DOC AS A CONTROLLING VARIABLE IN THERMAL AND OPTICAL PROPERTIES

The differences in DOC concentrations (0.1–4.6 mg L^{-1}) among the lakes were associated with very large differences in optical and thermal properties (Table III).

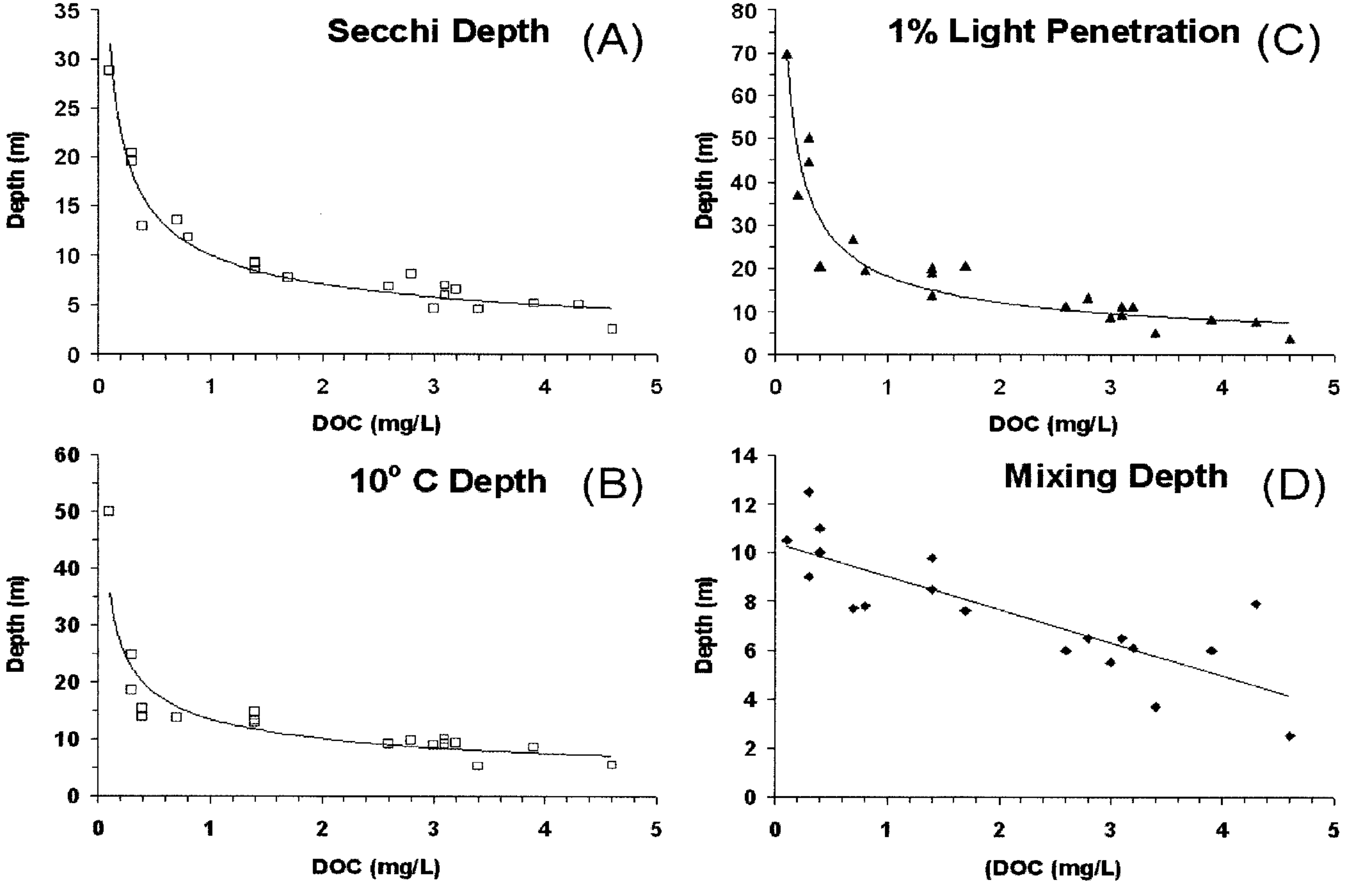

Figure 4. Effects of DOC on thermal and optical properties of Killarney Park lakes. (A) Secchi depth, (B) depth to 10 °C isopleth, (C) 1% penetration depth for PAR, (D) mixing depth.

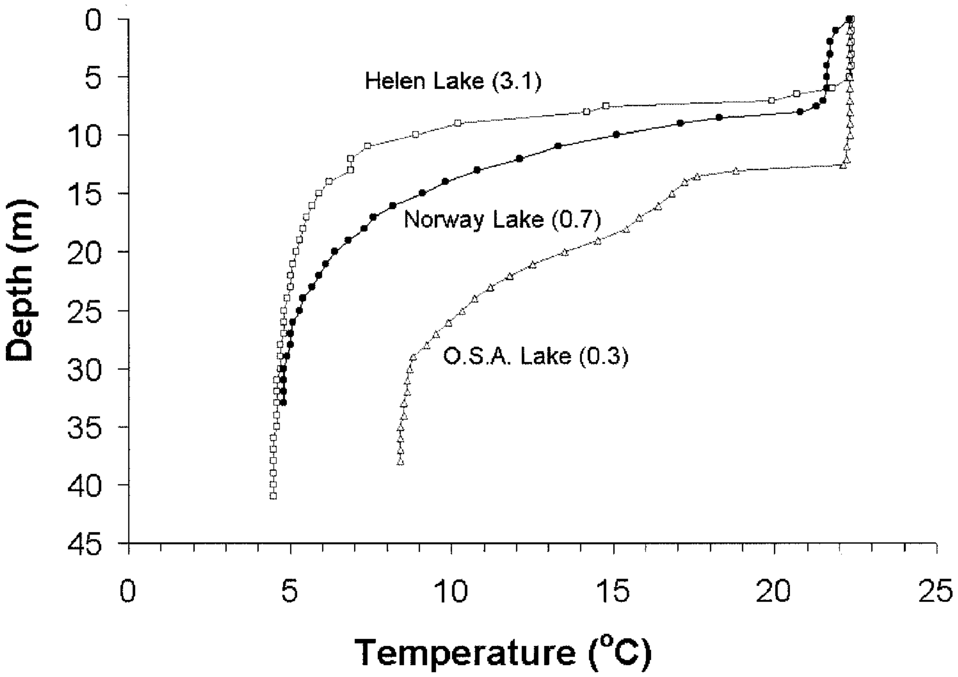

Figure 5. Temperature profiles for 3 Killarney lakes with similar basin depths (33–41 m) but differing in DOC concentrations (shown in parentheses). Lakes were sampled during August 24–29, 1998.

Most of the relationships between DOC and optical and thermal properties of the Killarney lakes are exponential with very rapid changes occurring below a DOC of approximately 1.0–2.0 mg L^{-1} (Figure 4). Secchi depth (r^2 = 0.85), depth to the 10 °C isotherm (r^2 = 0.84), and the depth of PAR light penetration (r^2 = 0.83) can be readily predicted from DOC using a power or exponential relationship (Figures 4a–c). These findings indicate that very small changes in the DOC concentration in ultraclear lakes will have dramatic effects on habitat availability and quality for many biota.

The depth of the surface mixing zone increases with declining DOC concentrations, in a linear rather than an exponential fashion (Figure 4d). However, if expressed in terms of thermal volumes instead of depth, the decrease in the volume of the cold hypolimnetic zone with declining DOC in these lakes is also likely to be an exponential relationship (we presently lack very precise bathymetry data to accurately illustrate this relationship).

In the low DOC lakes, the steep thermal and density gradient between the epilimnion and the metalimnion begins to break down and the metalimnion becomes a very broad transition zone between the surface and bottom water habitats (see examples Figure 5). This change represents an important structural change in the vertical features of the habitats of various biota. For instance, the loss of the steep density gradients in the metalimnion, where algal cells settle in typical oligo-

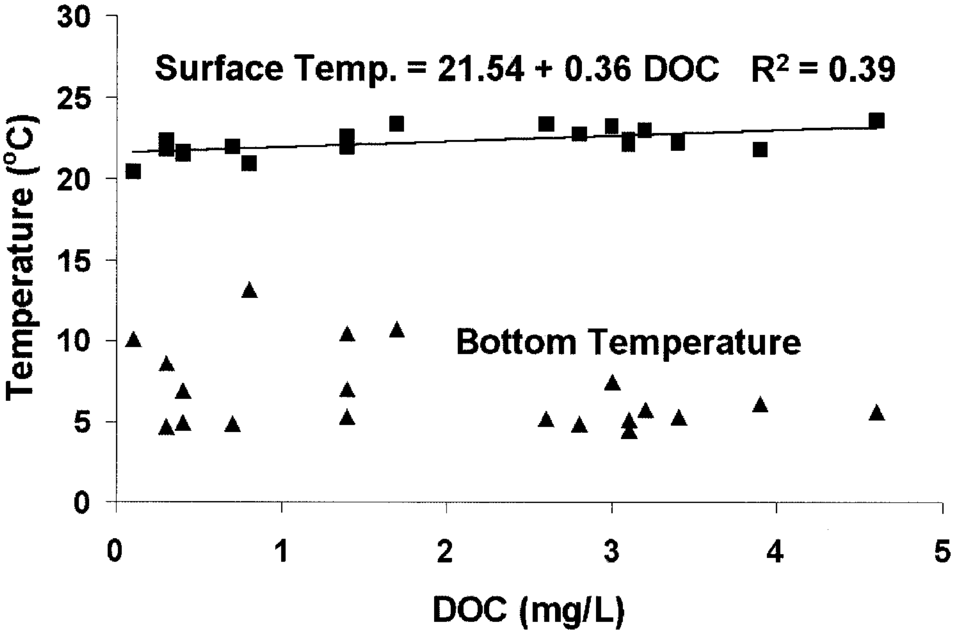

Figure 6. Differences in surface and bottom temperatures with increases in lake water DOC. Temperature profiles measured in late August 1998.

trophic lakes (Wetzel, 1975) may have adverse effects on the feeding efficiency of zooplankton in clear lakes.

The surface and bottom temperatures showed changes across the range of DOC in our study set (Figure 6). There was a small, but significant ($P < 0.05$) warming of the surface waters, presumably through greater heat absorption, in high DOC lakes. The differences in bottom temperature among lakes were related to both maximum depth and DOC. Bottom temperatures tended to increase with decreasing maximum depth, but in lakes of similar depth the bottom temperature tended to increase with decreasing DOC. For example, the bottom temperature in Helen Lake (maximum depth 41.2 m; DOC 3.1 mg L^{-1}) was 4.5 °C, but in O.S.A. Lake (maximum depth 39.7 m; DOC 0.3 mg L^{-1}) it was 8.4 °C. In some of the clearest lakes (DOC < 2 mg L^{-1}) very high temperatures occurred throughout the hypolimnion. For example, in Nellie Lake, our clearest lake (DOC 0.1 mg L^{-1}) the temperature on the bottom at 54.5 m on August 25, 1998 was 10.1 °C. In addition to the effects on bottom temperatures, Snucins and Gunn (2000) found that DOC and lake depth interacted to affect the formation of a thermocline. Some of the clear relatively shallow lakes do not stratify. For example, in late summer Ruth-Roy (max. depth 18 m, DOC 0.2 mg L^{-1}) was isothermal (22 °C) throughout the water column.

The great depth to which PAR extends in these low DOC lakes (Table III) creates growing conditions for phytoplankton and macrophytes that are unusual for small inland lakes – more typical of clear oligotrophic Great Lakes such as Lake

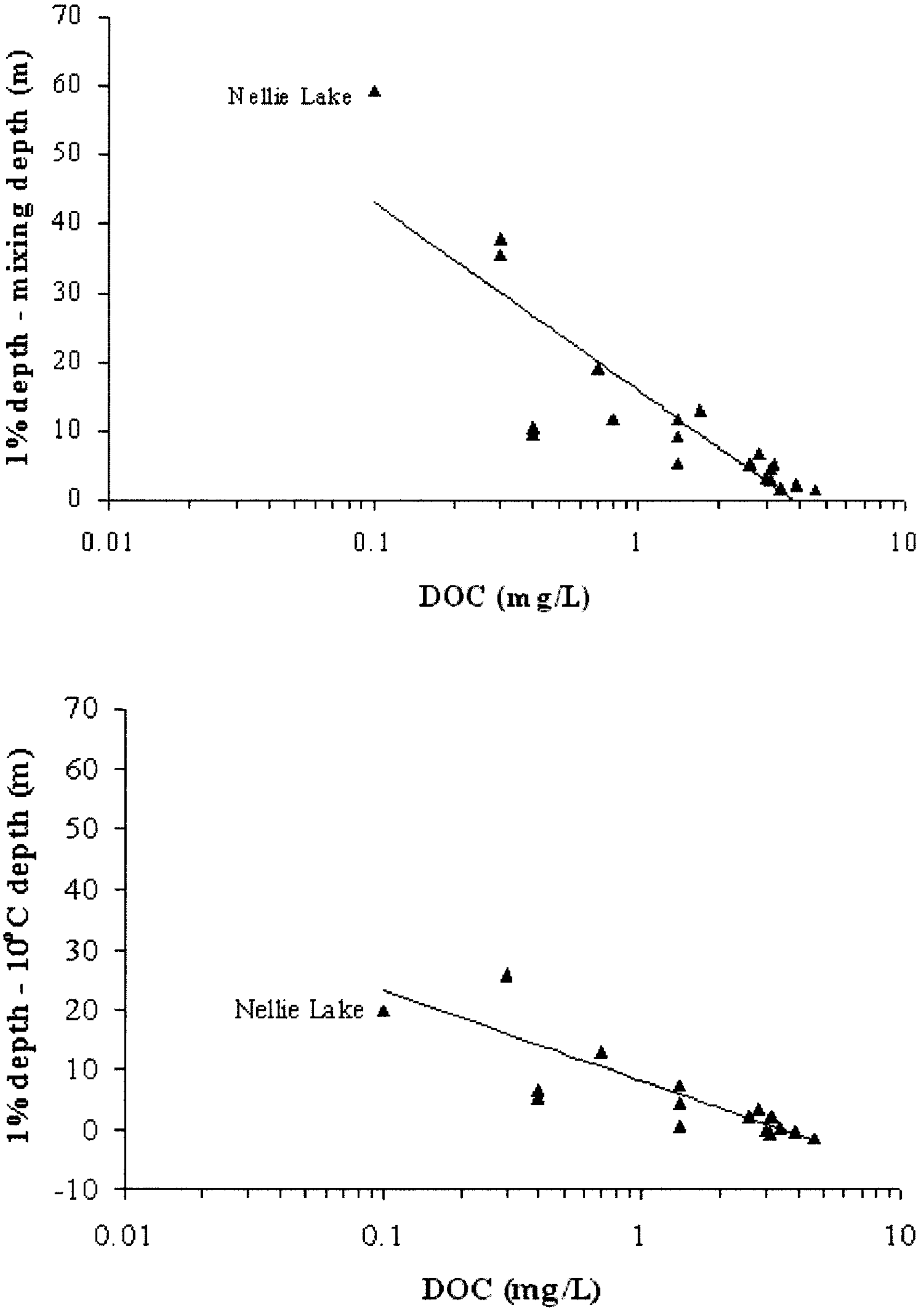

Figure 7. Illumination of the deep water habitats with declining DOC as characterized by the depth below the mixing layer exposed to >1% PAR (upper panel), and the depth below the 10 °C isopleth exposed to >1% PAR (bottom panel).

Superior (Kerfoot and Kirk, 1993). In the low DOC lakes, the euphotic zone (the illuminated portion of the water column where photosynthesis occurs – defined here as the 1% PAR depth), extends well below the mixing depth (Figure 7a). This could influence the spatial and temporal patterns of primary production. In several of the clear lakes (Clearsilver, Lumsden, Nellie, OSA, Partridge, Ruth-Roy), the potential growing zone for plants includes the entire water column and lake bottom. For example, in Nellie Lake, the euphotic zone extends right to the bottom of this 55 m deep lake and would extend to at least 70 m if the lake were deep enough. Mats of green mosses (*Drepanocladus* sp.) have been collected from depths of at least 52 m in Nellie Lake. Such depths are very rare for growth of green plants (Chambers and Kalff, 1985). Depths of approximately 120 m are the greatest depths with reported plant growth in the literature for ultraclear lakes such as Waldo Lake (Malueg *et al*., 1972), Lake Tahoe (Frantz and Cordone, 1967) and Crater Lake (Hasler, 1938).

The illuminated zone also extends well below the depth where preferred temperatures exist for deep water organisms. For instance the lake trout has a laboratory-derived, preferred temperature of about 10–12 °C (Christie and Regier, 1988). In lakes with DOC < 1.0 mg L^{-1} (Figure 7b) much of the lake trout thermal habitat would therefore be significantly illuminated with potentially important metabolic and feeding effects.

4.4. UV EXPOSURE

In situ measurements using the submersible scanning spectroradiometer demonstrated that UV-B and UV-A penetrated to great depths in the ultraclear lakes. In OSA and Killarney lakes (lakes with DOC approx. 0.3 mg L^{-1}) the depth of 1% of surface irradiance for UV-B and UV-A extended well below the mixing depth (Table III). This is very unusual for inland lakes. From extensive survey data for North American lakes, Williamson *et al*. (1996) estimated a median 1% attenuation depth of 0.39 m for UV-B and 0.93 m for UV-A. In this extensive survey the median 1% attenuation depth for UV-B was 18% of the depth to the thermocline. For UV-A it was 42% of the mixing depth.

Of the five study lakes examined during July 19–24, 1998, the maximum observed depths of 1% UV-B and UV-A were 28.1 and 60.7 m, respectively, in Killarney Lake. These depths are approaching the highest values in the literature for penetration of UV in natural waters (Smith and Baker, 1981; Smith *et al*., 1992; Kirk 1994). Morris *et al*. (1995) estimated a 1% depth for UV-B of 33 m in Lago Schmolla, a 4 m deep lake with a barren watershed high in the Argentine Andes. Smith and Baker (1981) reported a 1% depth for UV-B approaching 40 m in the Sargasso Sea.

4.5. POTENTIAL EFFECTS ON BIOTA

The survey results indicate that important habitat changes occur when the epilimnetic DOC declines below 1.0–2.0 mg L^{-1} in small dimictic lakes of the Boreal Shield. One profound effect of low DOC is the illumination of the hypolimnion. As the clarity increases, the principal sites of primary productivity may be concentrated in the cool deep waters of the hypolimnion instead of within the epi- and meta-limnion. This shift will likely have important effects on foraging efficiencies of deep-water herbivores (Kerfoot and Kirk, 1993). Predation pressures from sight-feeding predators will also be affected (O'Brien, 1987). Hypolimnetic species that require a cool, dark refuge site to avoid predation may therefore be lost from such lakes (Moore *et al.*, 1996). Similarly, certain species would have difficulty recolonizing recovering acid lakes if clarity remains high and dark, cold, hypolimnetic refuges are eliminated.

The direct and indirect effects of increased exposure to UV in clearwater lakes and streams are under intensive investigation (Bothwell *et al.*, 1994; Hader *et al.*, 1995; Karentz *et al.*, 1994; Vinebrooke and Leavitt, 1996; Williamson *et al.*, 1994, 1999a, b, and many others), but the overall effects of UV radiation on freshwater ecosystems are still poorly understood. Xenopoulos *et al.* (2000) recently showed that incident UV radiation can vary widely over a few weeks or even days, and high UV exposure had significant effects on phytoplankton biomass, especially under thermal stratification conditions that restrict vertical movement of algae. Williamson *et al.* (1999b) provide considerable evidence that UV may have had important ecological effects in clearwater lakes that have undergone acidification. Their research suggests that some of the unexplained variability in macroinvertebrate and zooplankton communities in low pH lakes, including some Killarney lakes (Yan *et al.*, 1985), may be accounted for by the additional effect of high UV exposure.

5. Implications for Monitoring

Water clarity is a simple and useful measure of water quality that has long been used to assess the effects of ecosystem disturbances that occur at a local scale. These include nutrient additions, erosion of catchment soils, resuspension of lake sediments, etc. In this study we show that water clarity can also be used to identify the effects of large-scale stressors that operate at a regional or global scale. Long-term monitoring programs for extremely clear lakes, such as those at Killarney, will be important for identifying trends, interactions and impact of both natural and anthropogenic factors that affect lake ecosystems in the Boreal Shield ecozone of Canada.

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