Long-term Scientific Benefits from Preserving Old-growth Hemlock Stands at Clear Lake Near Minden, Ontario, Canada

R. A. Reid[1,4], *K. M. Somers*[1,2], *J. E. Nighswander*[3], *and A. M. Zobel*[3]

Abstract

Clear Lake is located in the centre of the 1300 ha Clear Lake Conservation Reserve in Haliburton County, Ontario, Canada. In 1988, the reserve was designated as a protected area representing undisturbed, old-growth ecosystems. The reserve includes several headwater lakes and their associated catchments which support old-growth hemlock stands that are estimated to be up to 400 years old. In addition to scientific studies, the reserve is a popular, year-round recreation area. The reserve is visited by organized field trips involving local naturalist groups, outdoor education programs, and the general public interested in ecotourism. Scientifically, Clear Lake has been studied as a relatively unimpacted reference ecosystem since 1967. We present time-trend data for water chemistry since 1980, historical fish-stocking records, and post-1987 data on littoral-zone benthic macroinvertebrates and crayfish. Because of recent observations that lakes in south-central Ontario are affected by long-term regional weather patterns, the long-term trends in water chemistry, the benthic macroinvertebrate community, and crayfish relative abundances are also compared to a summary El Nino - Southern Oscillation (ENSO) index. Our data reveal several different patterns of long-term change in water chemistry, benthos and crayfish relative abundances. Gradual changes in some water-chemistry parameters are attributed to recovery from the long-range transport and deposition of airborne acids. Strong relationships with the ENSO index were rare, but data from the last few years may be affected by unauthorized, fish-species introductions in 1994. The reserve, and specifically Clear Lake, represents a good example of how scientific studies, government agencies, and the public can work together to preserve and monitor undisturbed ecosystems for future generations. Unfortunately, gradual changes in reference ecosystems are inevitable given the broad geographic scale of anthropogenic activities.

Introduction

In 1988 the provincial government recognised the Clear Lake Conservation Reserve as a protected area supporting old-growth hemlock stands in Haliburton County, in south-central Ontario, Canada. The 1300 ha reserve includes a series of small headwater lakes, their catchments, and unique stands of hemlock that are estimated to be up to 400 years old. The reserve has been protected to ensure that this type of ecosystem is available for public education and recreational use, and scientific study. Traditional activities such as fishing, hunting, and fur trapping are permitted, but logging, mining, hydro-electric development, and other industrial uses are not allowed.

Clear Lake, the largest lake near the center of the reserve, is a 88.4 ha lake with a catchment of approximately 125 ha. This lake has been the focus of scientific studies since 1967 (Schindler and Nighswander 1970). Originally this small, softwater lake was selected as a relatively unimpacted reference lake for monitoring eutrophication impacts that often follow shoreline development associated with building recreational cottages (e.g., see Dillon and Rigler 1975, Dillon et al. 1986, 1994). Despite a modest increase in the number of cottages on Clear Lake, gradual changes in the water chemistry have been observed. Some of these historical changes can be attributed to the long-range transport of airborne acids originating far beyond the reserve boundaries (e.g., LaZerte and Dillon 1984). Recently, climate change has been implicated as a factor contributing to changes in the water chemistry of inland lakes (Dillon et al. 1997, Schindler 1998).

In addition to the scientific studies, Clear Lake is used throughout the year by organized field trips involving naturalist groups, outdoor education programs, and members of the general public interested in ecotourism. The old-growth hemlock stands and the relatively undisturbed lakes and wetlands provide a unique recreational experience. However, there are growing concerns that the ecosystem embodied by the Clear Lake Conservation Reserve is gradually changing. This paper examines: (1) time-trend data on the water chemistry of Clear Lake; and (2), bioassessment data using nearshore benthic macroinvertebrates and crayfish, to search for evidence of long-term changes in this reference ecosystem. Our analyses suggest that broad-scale, regional stressors such as acid deposition and climate change, as well as local stressors associated with the unplanned introduction of predatory fish are contributing to the observed changes in Clear Lake.

Methods

Clear Lake is a small headwater lake located in Sherborne Township, in the County of Haliburton (latitude 45° 11' N, longitude 78° 43' W), roughly 250 km northeast of Toronto, Ontario (Figure 1). The lake is on the Precambrian Shield which is characterized by noncalcareous bedrock, thin soils, numerous lakes and wetlands (Jeffries and Snyder 1983). The annual precipitation averages 900 mm/yr with snow representing approximately 200 mm of this total (Schindler and Nighswander 1970). The July mean temperature is 18 C, whereas the January mean temperature is -10 C.

[1]Ontario Ministry of the Environment, Dorset, ON, CAN, P0A 1E0

[2]Dept. of Zoology, University of Toronto, Toronto, ON, CAN, M5S 3G5

[3]Dept.of Chemistry, Trent University, Peterborough, ON, CAN, K9J 7B8

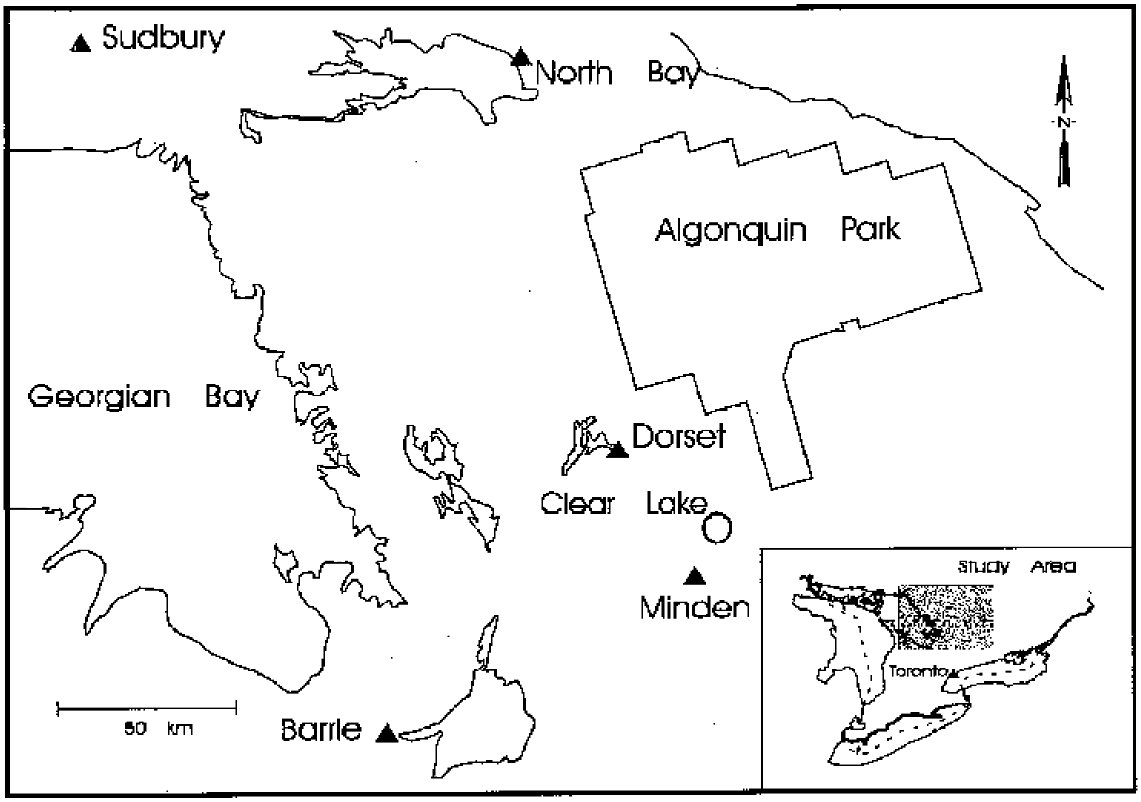

Figure 1.—Location of the Clear Lake Conservation Reserve in south-central Ontario.

Clear Lake is 88.4 ha in surface area, with a maximum depth of 33 m and a mean depth of 12.4 m (Girard and Reid 1990). The lake lies at an elevation of 369 m ASL. Gunn et al. (1988) found the following fish species in the lake during a mid-1980s inventory: lake trout (*Salvelinus namaycush*), white sucker (*Catostomus commersoni*), northern redbelly dace (*Phoxinus eos*), lake chub (*Couesius plumbeus*), common shiner (*Notropis cornutus*), bluntnose minnow (*Pimephales notatus*), fathead minnow (*P. promelas*), blacknose dace (*Rhinichthys atratulus*), creek chub (*Semotilus atromaculatus*), pearl dace (*S. margarita*), pumpkinseed sunfish (*Lepomis gibbosus*), and yellow perch (*Perca flavescens*). The fish community represented by this set of species is characteristic of softwater lakes in this part of south-central Ontario (Gunn et al. 1988, Jackson 1988). The large number of minnow species suggests minimal human disturbance and an absence of introduced predators that is consistent with the results of a regional-scale survey of lakes in the northeastern United States (Whittier et al. 1997).

Water Chemistry - Interest in the water chemistry of Clear Lake began in 1967 (Schindler and Nighswander 1970). The data reported in this study were collected using a standard sampling protocol from 1980 through 1998 (Girard and Reid 1990). However, no samples were collected in 1995, 1996 or 1997. The frequency of sampling over the ice-free period varied over the years, but water samples were always collected at a station located over the deepest spot in the lake. Once the water samples were collected they were kept in a cooler in the field, and then they were refrigerated at the analytical lab. Nineteen water-chemistry parameters were determined using standard analytical methods (Anonymous 1983) in a chemistry laboratory. These parameters included: total inflection-point alkalinity (ALK), pH, dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), conductivity (COND), calcium, sodium, potassium, magnesium, chloride, sulphate, ammonium, nitrate, total Kjeldahl nitrogen (TKN), total phosphorus (TP), aluminum, iron, manganese, and silica. Nine of these parameters were measured in mg/L. pH was measured in standard units and COND was measured in µS/cm at 25^{o} C. The remaining parameters were measured in µg/L.

Benthic Macroinvertebrates - Regional surveys of benthic macroinvertebrate communities in lakes in Ontario have revealed that differences in the benthic communities are correlated with differences in lake water chemistry (Harvey and McArdle 1986, Stephenson et al. 1994). Many of the small lakes in south-central Ontario have been historically impacted by acid deposition (LaZerte and Dillon 1984, Dillon et al. 1997). The littoral areas of these lakes often experience lower pH values relative to mid-lake regions in the early spring (Gunn and Keller 1985). Because water-quality data alone do not adequately characterize the health of aquatic ecosystems (Karr 1993), we initiated a monitoring program to collect littoral-zone benthic macroinvertebrates from a series of acid-sensitive, headwater lakes in 1988 (Reid et al. 1997). Clear Lake was one of these lakes.

Samples of shallow-water sediments (<1 m) were collected at 5 sites around the lake in late September, October, or early November (see Reid et al. [1997] for a complete description of the field and laboratory protocols). The 5 sites were randomly selected in a stratified design based on the predominant nearshore substrates (Reid et al. 1995). If 60% of the nearshore substrates were sandy with macrophytes, then 3 of the 5 sites were randomly selected from areas with predominantly sandy sediments and macrophytes.

Each of the 5 sites was sampled for a period of 10 minutes. An individual with a D-frame, 250 µm-mesh, long-handled net walked out to a depth of approximtely 1 m, turned towards shore and slowly walked towards the shore, kicking the bottom to dislodge the sediments and associated invertebrates. While the sediments were in the water column, the net was swept back and forth in order to collect the disturbed material. Periodically the sediments in the net were shaken into a large pail to prevent the net from clogging with debris. After 10 minutes the pail was sealed and labelled. Once all 5 samples were collected, the pails were returned to the laboratory and refrigerated. Within 36 hours of the field collection, all samples were rinsed over a 1000 µm sieve, sorted and the macroinvertebrates were removed.

Over the 5 years from 1988 to 1992, each sample was sorted in its entirety and the resultant animals were identified to the lowest practical taxonomic level (e.g., some immature insects cannot be identified to the species level unless the adult form is available; Reid et al. 1997). Benthic macroinvertebrates in Clear Lake were not sampled in 1993 or 1994. However, Clear Lake was re-sampled in 1995 and again in 1998. In these last two years, the same field sampling protocol was used and the same 5 sites were sampled, but a rapid bioassessment protocol was used to sort and enumerate the samples (David et al. 1998). Instead of picking all of the animals from a given sample, each sample was randomly subsampled and only 100 animals were removed (Somers et al. 1998). These animals were identified to a relatively coarse taxonomic level such as order or family.

To provide comparable data over the period of this study, the total counts of the various taxa at the 5 sites were summarized into a single, whole-lake total for a given year using the following 14 taxonomic groups: Amphipoda, Coleoptera, Diptera - Ceratopogonidae, Diptera - Chironomidae, Ephemeroptera, Gastropoda, Hirudinea, Lepidoptera, Megaloptera, Odonata - Anisoptera, Odonata - Zygoptera, Oligochaeta, Pelecypoda, and Trichoptera. The individual totals for a given taxonomic group were converted to simple proportions of the total count for a given year. Four additional taxonomic groups were included in the lake total, but were excluded from subsequent data analysis because they were only found in three-or-fewer years (i.e., Decapoda, Hemiptera, Hydracarina, and Plecoptera).

Crayfish - In addition to the monitoring program for littoral benthic macroinvertebrates, we also initiated a program in 1988 to monitor crayfish populations in a series of south-central Ontario lakes under the assumption that changes in crayfish relative abundances would reflect anticipated improvements in water quality (David et al. 1994). A related study using the same sampling protocols collected crayfish from 100 lakes in south-central Ontario between 1989 and 1994 (David et al. 1997). That study concluded that an unusually large proportion of the lakes in the vicinity of Dorset (i.e., within 15 km of Clear Lake, see Figure 1) did not support crayfish populations. Although there are no historical data on crayfish populations in most of these lakes, France and Collins (1993) present data from Plastic Lake (which is less than 8 km directly west of Clear Lake) documenting the disappearance of crayfish during a period in the 1980s when Plastic Lake gradually acidified (Dillon et al. 1987). Although the water chemistry of many of the Dorset-area lakes has improved (Dillon et al. 1997), recovery of the crayfish populations has not been observed (David et al. 1994).

Crayfish were captured with baited, wire-mesh, minnow traps with the funnel entrances enlarged to 3.5 cm to accommodate large crayfish (Collins et al. 1983). Three sites representing (1) rocky or cobble areas, (2) silt and sand with macrophytes, and (3) detritus-covered sediments with woody debris were selected to span the range of habitats commonly used by the different crayfish species in Ontario (Crocker and Barr 1968). At each site a series of traplines consisting of six traps were set perpendicular to shore. The traps were at least three m apart along a given trapline, and the traplines were set at least three m apart within a site. Traps were only set for a single night in July or August of a given year. In 1988, the first year of the study, 180 traps were set. This number was reduced to 60 in 1989, and to 18 in 1990. Thereafter, a total of 54 traps was used each year. Because of this variation in trapping effort over the first three years, all crayfish catches are expressed as the total number of crayfish caught per trap per night (i.e., as catch per unit effort, or CPUE).

Each trap was baited with fish-flavoured, canned cat food that was placed in a perforated plastic film (35 mm) canister. A single canister was placed in each trap. Similar baits were used each year because different baits attract different species and different sizes of crayfish (Somers and Stechey 1986). Traps were set at depths ranging from <1 m to > 6m and left in place from the afternoon of one day to the morning of the next. Crayfish were sampled during their midsummer intermoult period which is the best time of the year to estimate crayfish relative abundance (Capelli and Magnuson 1983). Trap catches exhibit minimal seasonal variation at this time of the year (Somers and Green 1993).

Statistical Analysis - The 3 sampling programs produced single numbers for a given parameter in a given year. Time trends in the water-chemistry data were assessed with simple, least-squares regressions between a given concentration and the year of collection. Those variables with significant, non-zero slopes were flagged as an indication that the Clear Lake ecosystem was changing over time ($P<0.05$). Time trends in the 12 benthic invertebrate indices and the crayfish CPUEs were evaluated in a similar

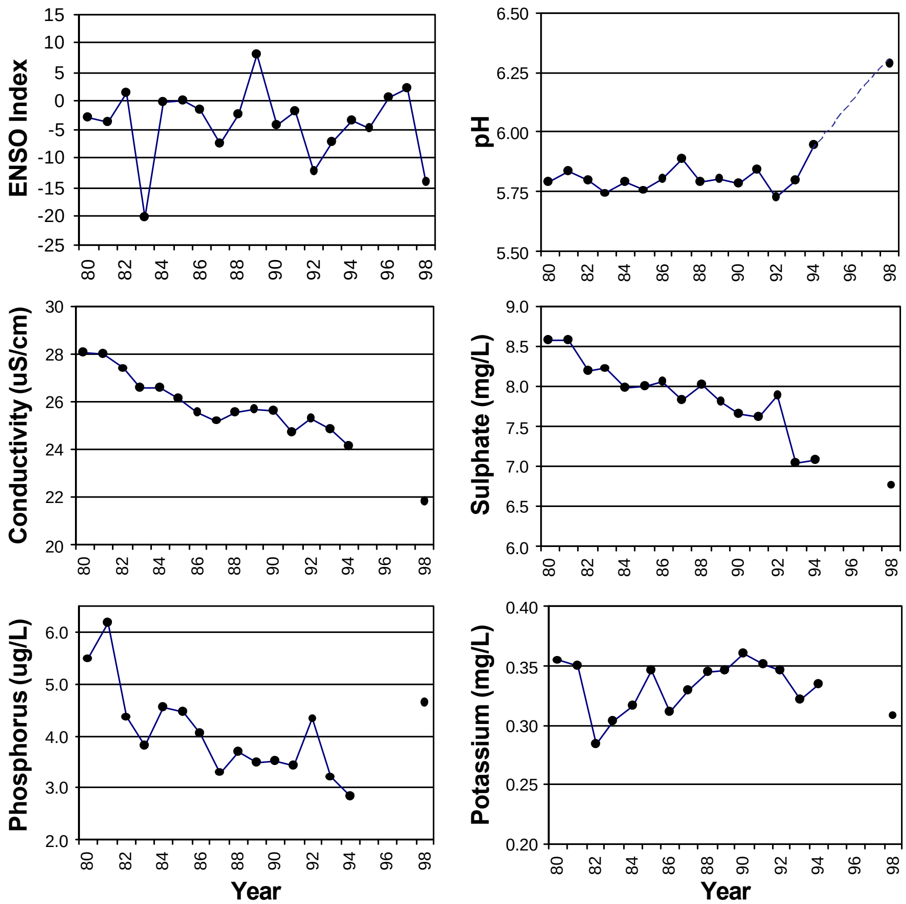

Figure 2.—Temporal trends in the ENSO index and 5 water-chemistry parameters from 1980 through 1998.

manner for the period 1988-98. Simple Pearson product-moment correlations between the benthos and crayfish data, and the water chemistry were assessed for those years where matching data were available. Significant correlations between biological and chemical parameters may reveal interactions that are not linearly related to the year of sampling. Because of the relatively small number of data points, nonparametric Spearman rank correlations (r_s) were also calculated and assessed for significance. In addition, Pearson and Spearman coefficients were compared to determine if outliers (i.e., $r>r_s$) or curvilinear relationships (i.e., $r<r_s$) affected the Pearson correlations.

Because of growing interest in the impacts of climate change on inland lakes (Dillon et al. 1997, Schindler 1998), we also correlated the various water chemistry and biological parameters with an El Nino - Southern Oscillation (ENSO) index which presumably reflects yearly changes in global weather patterns. This index was proposed by Rusak et al. (1999) as the sum of the standardized monthly sea-level air pressure differences between Darwin, Australia and Tahiti spanning the six-month period from October to March. Because a climate-change signal may require some period of time to cascade through the various trophic levels of a lake, we also evaluated correlations between the ENSO index and the various chemical and biological parameters with lags of one and two years. To obtain the lag-one correlation, the observed ENSO index for a given year was paired with the Clear Lake data for the following year. The lag-two correlation was calculated by shifting the Clear Lake data by two years.

Results and Discussion

Water Chemistry - Time trends in midlake water chemistry varied considerably (Figure 2), although only the gradual increase in pH produced a positive Pearson correlation that was statistically significant (r=0.584, P<0.05). By contrast, 7 of the 19 chemical parameters produced strong negative time-trend correlations that were significant (i.e., COND, Ca, SO_4, TP, Fe, Mn, and Si). Our comparison of Pearson and Spearman correlations indicated that both coefficients generally provided similar results. Only pH and ALK produced Pearson correlations that were noticeably different (larger) than the Spearman correlations suggesting that the data for 1998 might represent an influential outlier (see Figure 2). The remaining chemical parameters varied over time (e.g., see K in Figure 2), but no long-term trends were evident. The ENSO index revealed a similar degree of variation over time.

Of the Pearson correlations between all-possible pairs of the 19 water-chemistry parameters, 22.8% were statistically significant (P<0.05). Almost 80% of these significant

Table 1. —Pearson correlations between the benthic taxa and sampling year, the ENSO index, and ENSO lags of 1 and 2 years.

Taxonomic group	Sampling year	ENSO index	ENSO lag 1	ENSO lag 2
Amphipoda	-0.082	0.306	0.397	-0.907
Coleoptera	0.087	-0.527	-0.156	-0.093
Diptera - Ceratopogonidae	-0.186	-0.035	-0.561	0.721
Diptera - Chironomidae	-0.654	0.306	-0.199	0.571
Ephemeroptera	-0.045	0.262	-0.481	0.453
Gastropoda	-0.051	-0.069	0.849	0.364
Hirudinea	0.344	-0.120	-0.225	-0.447
Lepidoptera	-0.338	0.801	-0.409	-0.617
Megaloptera	-0.389	0.160	-0.652	-0.379
Odonata - Anisoptera	0.800	-0.305	-0.042	-0.275
Odonata - Zygoptera	0.482	-0.488	0.226	0.152
Oligochaeta	0.255	-0.549	-0.354	0.038
Pelecypoda	0.487	-0.823	0.556	0.176
Trichoptera	0.813	-0.275	0.089	-0.310
Cambarus bartoni	-0.353	0.438	0.438	-0.239
Orconectes propinquus	-0.674	0.258	-0.081	0.357

correlations were positive indicating strong temporal coherence (or synchrony, see Rusak et al. 1999) among many of the parameters. In all cases, the significant negative correlations involved pH, ALK or NH_4 indicating that the positive temporal trends in these 3 parameters differed markedly from the long-term declines in the other parameters. In several instances, significant positive correlations were obtained between parameters that showed no long-term temporal trends. These parameters included K, Na, Cl, NO_3, TKN, and Al.

The Spearman rank correlation analysis confirmed our findings, with 19% of all-possible rank correlations being significant ($P<0.05$). Apparently one-or-more outliers may have undue influence on the Pearson correlations because we found fewer significant rank correlations compared to the Pearson analyses. From the time-trend plots (Figure 2), the data for 1998 are suspect, but additional data are required because water-chemistry samples were not collected between 1995-7. Almost 91% of the significant Spearman correlations were positive, emphasizing strong concordance among many of the parameters. The significant negative rank correlations involved pH or NH_4, but not ALK, suggesting that the rank-order trend for ALK was weaker than the trend observed in the raw data.

Only one of the Pearson correlations between the 19 water-chemistry parameters and the ENSO index was significant (Mg, $r=0.576$, $P<0.05$), and none of the rank correlations was significant. When the water chemistry was shifted by lags of one and two years, none of the Pearson or Spearman correlations with the ENSO index was significant. These results suggest that annual weather-related events embodied by the ENSO index did not significantly influence the observed variation in Clear Lake water chemistry.

Benthic Macroinvertebrates - Because the biological data were collected over a shorter time frame than the water-chemistry data, we required larger correlations for statistical significance (i.e., 7 versus 16 years). Of the 12 benthic macroinvertebrate indices, only two revealed significant changes over time (Table 1). Both dragonflies (Odonata, Anisoptera) and caddisflies (Trichoptera) increased in relative abundance between 1988 and 1998 (Figure 3). Clams (Pelecypoda), damselflies (Odonata, Zygoptera), and leeches (Hirudinea) also increased in relative abundance, whereas chironomids (Diptera, Chironomidae) declined over the same time period (Figure 3), but not significantly. The corresponding Spearman rank correlations were generally lower than the Pearson correlations (and not significant) suggesting that one-or-more outliers affected the Pearson results. From the time-trend plots, the data for 1995 and 1998 are potential outliers underscoring the possibility of recent changes in the littoral benthic community.

Only 5 Pearson correlations between all-possible pairs of the 12 benthic indices were significant ($P<0.05$). Negative correlations between the chironomids versus the dragonflies

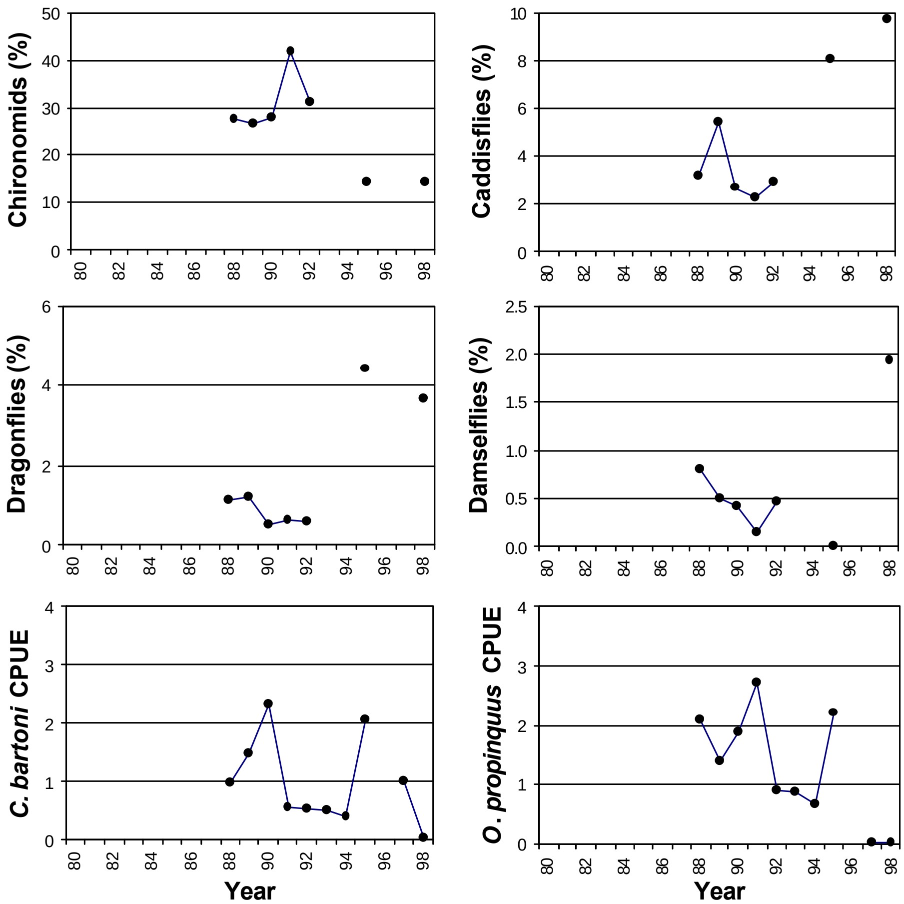

Figure 3.—Temporal trends in 4 benthic macroinvertebrate groups and the trap catches of two crayfish species from 1988 to 1998. Marked changes are apparent after the unauthorized introduction of bass predators (*Micropterus* spp.) in 1994.

and caddisflies, and a positive correlation between the dragonflies and caddisflies simply reflected the significant time trends in these 3 taxonomic groups (Figure 3). Significant negative correlations between the relative abundances of beetles and amphipods (Coleoptera versus Amphipoda), and clams (Pelecypoda) and aquatic Lepidopterans may simply be chance relationships, given the large number of correlations that were calculated. These same relationships were also statistically significant when Spearman rank correlations were used, suggesting that outlying values did not have undue influence on these estimates. By contrast, a significant negative rank correlation between the relative abundances of snails (Gastropoda) and alderflies (Megaloptera) revealed a curvilinear relationship because the Pearson correlation was not significant (i.e., r_s>r).

Lepidopteran relative abundance exhibited a significant positive correlation with the ENSO index (r=0.801, Table 1), whereas clam relative abundance was negatively correlated with the index (r=-0.823, P<0.05). These opposing trends undoubtedly contributed to the significant negative correlation observed between these two taxa (r=-0.789), and suggests that this significant correlation may not simply be an artifact of examining a large number of correlations. The corresponding rank correlations with the ENSO index were both weaker (r_s=0.744 and -0.639, respectively) and not significant indicating that the Pearson correlations were influenced by one-or-more unusual years (i.e., 1995, and to a lesser degree 1998). Only the relative abundance of snails (r=0.849) was significantly correlated with the lag-one ENSO index (Table 1), whereas the amphipods were significantly correlated with the lag-two index (r=-0.907). The rank lag-one correlation for the snails was not significant (r_s=0.598), but the rank correlation for the lag-two index and amphipod relative abundance was significant (r_s=-0.805).

Most of the correlations between the 12 benthic macroinvertebrate groups and the 19 water-chemistry variables were not significant (Table 2). Only the dragonflies, damselflies and caddisflies produced more significant correlations with the water-chemistry parameters than might be expected by chance. Surprisingly, most of the significant correlations were negative, suggesting that the increases in the relative abundances of these 3 taxa over time (Figure 3) coincided with decreases in the concentrations of parameters like SO_4 or COND (Figure 2). The significant positive correlations involved ALK and pH, but some of the highest negative correlations involved K, Cl (but not Na), and Mn despite the fact that K and Cl were not correlated with sampling year or the ENSO index and its lags.

Crayfish - The trapping data spanned 1988 through 1998 with the exception of 1996 when crayfish were not sampled.

Table 2. —Summary of the Pearson correlations between the benthic taxa and the 19 water-chemistry parameters.

Taxonomic group	Positive Values (P<0.05)		Negative Values (P<0.05)	
	Number	%	Number	%
Amphipoda	0	0.00	0	0.00
Coleoptera	1	0.05	0	0.00
Diptera - Ceratopogonidae	0	0.00	0	0.00
Diptera - Chironomidae	0	0.00	0	0.00
Ephemeroptera	0	0.00	0	0.00
Gastropoda	1	0.05	0	0.00
Hirudinea	1	0.05	0	0.00
Lepidoptera	1	0.05	0	0.00
Megaloptera	0	0.00	1	0.05
Odonata - Anisoptera	2	0.11	5	0.26
Odonata - Zygoptera	2	0.11	4	0.21
Oligochaeta	0	0.00	0	0.00
Pelecypoda	1	0.05	2	0.11
Trichoptera	2	0.11	6	0.32
Cambarus bartoni	4	0.21	0	0.00
Orconectes propinquus	3	0.16	0	0.00

Two crayfish species were captured in the traps, *Cambarus bartoni* and *Orconectes propinquus*. Both of these species are common in lakes in south-central Ontario (David et al. 1997), although *C. bartoni* was reported to have disappeared from nearby Plastic Lake in the 1980s (France and Collins 1993).

Trap catches of both crayfish species declined over the 11 years (Figure 3). The Pearson correlation between *C. bartoni* CPUE and sampling year was not significant (Table 1). The Spearman correlation provided a similar value (r_s=-0.402) suggesting that outliers or curvilinear trends were not present. By contrast, the CPUE of *O. propinquus* was significantly correlated with sampling year (Table 1). As with *C. bartoni*, outliers or a curvilinear trend were not indicated by the Spearman correlation (r_s=-0.671, r=-0.675). Despite similar downward trends (Figure 3), the catches of the two species were not significantly correlated. Closer examination of the time-trend plots indicates that the catch of *C. bartoni* increased over the first 3 years, then precipitously dropped in 1991, and gradually declined through 1994. The catch of *O. propinquus* dropped from 1988 to 1989 and then increased through 1991, only to drop suddenly in 1992, a year after the drop in *C. bartoni* CPUE. After the gradual decline in the CPUE of both species through 1994, the catches were unusually high in 1995, only to drop to their lowest values in 1998. Although there was a weak correlation between *C. bartoni* CPUE and the ENSO index (r=0.438, r_s=0.433), all of the correlations between crayfish CPUEs and the ENSO or ENSO lag values were not significant (Table 1).

The *C. bartoni* CPUE was not significantly correlated with any of the 12 benthic macroinvertebrate indices (P>0.05). By contrast, the catch of *O. propinquus* was significantly negatively correlated with both damselfly (r=-0.811) and clam (r=-0.781) relative abundances. The Spearman rank correlations for these two relationships were somewhat lower than the Pearson correlations (both were r_s=-0.748) and they were not significant suggesting that an outlier contributed to the significant Pearson correlations. Surprisingly the rank correlation between *C. bartoni* CPUE and aquatic beetle (Coleoptera) relative abundance was significant (r_s=-0.788), but this is probably just a chance result given the large number of correlations that were calculated.

Crayfish catches were significantly correlated with several of the 19 water-chemistry parameters (Table 2). The CPUE of *C. bartoni* was positively correlated with DIC (r=0.772), Na (r=0.940), K (r=0.754), and TKN (r=0.712), whereas the CPUE of *O. propinquus* was correlated with K (r=0.785), Fe (r=0.718), and Mn (r=0.747). The rank correlations between the catch of *C. bartoni* and DIC and TKN were not significant, suggesting that outliers contributed to the significant Pearson correlations. However, rank correlations with COND (r_s=0.894) and Mn (r_s=0.757) were significant suggesting a curvilinear relationship between these parameters and *C. bartoni* CPUE. Only the rank correlation of the catch of *O. propinquus* and K (r_s=0.797) was significant, indicating that outliers probably affected the other significant Pearson correlations.

The significant correlations between crayfish CPUE and K are interesting. In a study of crayfish populations in 14 lakes, including Clear Lake, David et al. (1994) observed a decline in crayfish CPUEs between 1988 and 1992 that coincided with a gradual increase in Al concentrations in many of those lakes. However, we found no such correlation with our longer time series (r=-0.122 and -0.091 for *C. bartoni* and *O. propinquus*, respectively). Our results suggest that changes in crayfish relative abundances in Clear Lake are not correlated with Al, but the strong correlations with K suggest that processes within the catchment may be affecting the crayfish. Perhaps the changes in water chemistry require some time to influence crayfish relative abundances. Thus, lag correlations like those used for the ENSO index may provide interesting insights into the role of water chemistry in crayfish population dynamics.

Fish Stocking - Historically, Clear Lake has been stocked with salmonids in order to supplement the sport fishery. From 1932 through 1962, brook trout (*Salvelinus fontinalis*) were stocked in the lake although natural recruitment was never documented. From 1964 to 1970, rainbow trout (*Oncorhynchus mykiss*) were stocked, but again no natural recruitment was observed. As a result, the native population of lake trout was supplemented with stocked fish from 1974 through 1979, although stocking has not continued during the period of this study. However, smallmouth bass (*Micropterus dolomieui*) and largemouth bass (*M. salmoides*) have been found in the lake in the last several years. Apparently these two species were introduced by anglers in approximately 1994 in an attempt to supplement the fishery. Both of these species are predators that impact crayfish populations (Stein 1977, Collins et al. 1983, Somers and Green 1993), as well as minnow assemblages (Whittier et al. 1997). As a result, the pronounced changes in several benthic macroinvertebrate groups and the crayfish populations after 1994 (Figure 3) may simply reflect the introduction and establishment of these two bass species. A follow-up survey of the fish community in Clear Lake would probably reveal changes from the mid-1980s survey, especially among the minnow assemblage. This introduction may also impact lake water chemistry given the well established top-down, cascading effects of predators on food webs and lake productivity (Carpenter et al. 1985).

Summary

Although Clear Lake has been protected as a conservation reserve, time-trend data on water chemistry, benthic macroinvertebrates, and crayfish populations revealed gradual changes in a number of parameters. Some of these changes may be attributed to reductions in acid deposition, and subsequent recovery from the historical effects of acidification (Yan et al. 1996). Climate change, as indicated by an ENSO index, did not correlate with these long-term trends, although climate-change impacts are expected (Dillon et al. 1997, Schindler 1998). The recent introduction of two predatory fish species coincided with marked changes in the benthos and crayfish over the last few years of this study. In combination, the relatively short data record and the recent predator introduction limit our ability to unequivocally distinguish long-term recovery from acidification, from signals associated with climate change.

Despite Clear Lake being a protected reference ecosystem, long-term changes are inevitable (Underwood 1992, Hughes 1995). Continued study will document these changes and provide a better understanding of the consequences of seemingly simple actions like the introduction of sportfish by anglers. Data from long-term monitoring studies of multiple reference ecosystems are required to disentangle the impacts of multiple stressors from natural variation in relatively undisturbed ecosystems (Underwood 1991, White and Walker 1997).

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