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Century changes in Connecticut, U.S.A., lakes as inferred from siliceous algal remains and their relationships to land-use change

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Abstract

Scaled chrysophytes and planktonic diatoms are used to infer changes in lake water pH, specific conductivity, trophic score, and total nitrogen in 23 Connecticut waterbodies over the last 100 yr, and the changes are correlated with quantified changes in land use in the surrounding watersheds. In general, there was good agreement between the changes inferred from both organismal groups in this suite of lakes. Significant correlations were observed between chemical conditions inferred from organisms in surface sediments and present-day land uses, especially the percentages of the watersheds that are forest or residential land cover types. Approximately 20% of the waterbodies have significantly increased in pH since 1890, and none of the lakes have significantly declined in pH despite the fact that this region receives significant amounts of acidic deposition. These findings support previous work, indicating that the pH of Connecticut lakes has not declined over the recent past. One fourth of the lakes have significantly increased in specific conductivity, especially those situated in watersheds that have become highly residential in nature. Inferred specific conductivity has more than doubled in six of the lakes during the last century. Six of the lakes have become significantly more eutrophic, while only one lake has become more oligotrophic since 1890. The majority of the lakes situated in watersheds that have remained over ~80% forested have not significantly changed, whereas those that have become over ~25% residential have experienced the greatest amount of change. The potential influences of watershed-based alkalinity generation, winter road salt use, and implications of these findings in lake management are discussed.

One of the primary reasons that the effects of environmental stresses on aquatic ecosystems are difficult to assess is the fact that historical lake water data are often lacking (Brenner et al. 1993; Siver et al. 1996). As a result of the paucity of background data, it is often impossible to estimate the degree and rate of change in the chemical and biological structure of waterbodies and to distinguish between natural changes and those caused by anthropogenic stresses. However, recent advances in paleolimnological techniques, especially formation of biological-based inference models, have resulted in the ability to reconstruct historical lake water conditions with a high degree of resolution (Bennion et al. 1996).

Most inference models are based on organisms that are differentially distributed over the environmental gradient of interest. The point along a given gradient where a species is most abundant and the degree of spread of the taxon along the gradient are referred to as the optimum and tolerance, respectively (Birks et al. 1990). The optima and tolerances of all taxa along a specific gradient are often estimated using weighted averaging where the abundances of each organism in surface sediments of a suite of lakes are correlated with contemporary lake water chemical conditions (Birks et al. 1990). The analyses result in relationships referred to as inference models (Birks et al. 1990). Once formed, the inference models are then applied to older sections of cores in order to estimate the historical chemical conditions. Such a paleolimnological method has been successfully used to construct inference models for pH (e.g., Cumming et al. 1992*a*; Davis et al. 1994), specific conductivity (Siver 1993), salinity (Wilson et al. 1994), overall trophic status (Siver and Marsicano 1996), total phosphorus (Hall and Smol 1996; Bennion et al. 1996), and total nitrogen of lake water (Siver 1998).

Most paleolimnological studies have employed a single organismal group to infer past conditions of lakes in specific regions (e.g., Hall and Smol 1996). Commonly, diatoms are used to construct inference models; however, chrysophyte scales (e.g., Siver 1993) and cysts (e.g., Zeeb and Smol 1995) have also yielded highly significant and ecologically useful models. Charles and Smol (1988) formed models that simultaneously incorporated both diatoms and chrysophyte scales for pH inference work in the Adirondacks (New York). Models that have independently incorporated diatoms or scaled chrysophytes have also been constructed and applied to lakes in the Adirondacks (Cumming et al. 1992*a,b*). Except for a few cases, such as the work by Cumming et al. (1992*a,b*), studies that use multiple algal groups to reconstruct lake water conditions independently for specific geographic regions are rare.

Likewise, with a few exceptions, studies that link paleolimnological inferences over known time periods to actual changes in the associated watersheds are rare. Brenner et al. (1993) used diatom remains to compare inferred changes in total phosphorus with land-use shifts in a small Florida lake. Lott et al. (1994) related 19th and 20th century changes in the specific conductivity of a small lake in the Pocono Mountains (Pennsylvania) to logging events in the watershed. Other studies (e.g., Hall and Smol 1996) make reference to broad regional changes in land use but do not link inferred chemical changes for individual lakes to detailed land-use changes in their surrounding watersheds.

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A number of paleolimnological studies have employed the use of comparing top and bottom sections of undated cores in order to estimate changes in a large number of lakes over a broad geographic region (e.g., Cumming et al. 1992*b*; Hall and Smol 1996). The method has most often been used to compare present-day lake-water conditions (tops) to preindustrial or pre-European settlement conditions (bottoms) (Sullivan et al. 1990). The assumption, based on analysis of other cores from an area of interest, is that the bottom core sections do indeed represent preindustrial or pre-European conditions. Although the top and bottom comparison method is clearly a useful technique, a primary drawback is the fact that the bottom sections do indeed represent different time periods, and as a result, the rates and timing of changes for individual lakes may be over- or underestimated. If dates for cores from a suite of lakes were available, it would be more precise to utilize sections from the cores that represent the same time period in order to make comparisons between lakes.

A primary goal of our work has been to estimate the degree to which lakes in Connecticut have changed during the last century and ultimately to compare the changes to alterations in the surrounding watersheds. The project was composed of three components. First, changes in the chemical conditions of 42 lakes over the last 55 yr were estimated using actual chemical measurements (Siver et al. 1996). Second, high-resolution aerial photographs were used in conjunction with a geographic information system in order to assess changes in land use of 30 lake watersheds since 1934 (Field et al. 1996). Models that relate land uses to lake-water chemical conditions were then used to estimate changes in total phosphorus and total nitrogen concentrations as a result of the land-use alterations (Field et al. 1996). In the third component of the project, reported on in this paper, scaled chrysophytes and planktonic diatom remains were used to infer changes in pH, specific conductivity, trophic status (Siver and Marsicano 1996), and total nitrogen since 1890 in 23 of the lakes that were dated with ^{210}Pb. The inferred chemical changes were then correlated with the land-use changes reported by Field et al. (1996).

Methods

A total of 23 lakes that were reported on in previous studies (Canavan and Siver 1994; Siver et al. 1996) and from which ^{210}Pb dates were estimated are included in this study (Table 1). Twenty-one of the 23 lakes are situated in, and representative of, waterbodies in the Eastern Uplands, Western Uplands, and Coastal Slope regions of Connecticut (Canavan and Siver 1994); these geological regions are underlain primarily with schists, gneiss, some granites, and other relatively resistant rocks. The watersheds surrounding the study lakes range from being undeveloped (e.g., over 90% forested) to being highly developed (over 25% residential land cover). Much additional information on each lake and its watershed, including complete lake-water chemistry, morphological characteristics, watershed features, and geographical data are also given in previous papers (Canavan and Siver 1994; Field et al. 1996; Siver et al. 1996).

Table 1. A listing of the Connecticut lakes used in this study, including estimates of the percentage of each watershed that was covered with forests in 1990 and estimates of the percent increase in residential land use between 1934 and 1990. Land use data were from Field et al. (1996).

Lake No.	Lake	% forest (1990)	% change residential land cover‡
1	Alexander	71	23
2	Amos	71	10
3	Ball	48	29
4	Bashan	78	15
5	Beach	NA	NA
6	Billings	97	3
7	BlackW*	88	6
8	Coventry	60	29
9	CrystalE†	83	11
10	Gardner	74	14
11	Hayward	81	11
12	Kenosia	58	30
13	Long	83	11
14	Mashapaug	92	6
15	Mt Tom	70	7
16	Mohawk	97	3
17	Norwich	98	NA
18	Pattagansett	73	20
19	Rogers	91	5
20	Terramuggus	57	35
21	Uncas	99	1
22	Waramaug	NA	NA
23	Westhill	79	18

* Located in the town of Woodstock, Connecticut.
† Located in the town of Ellington, Connecticut.
‡ Value estimated from 1990 aerial photographs after work by Field et al. (1996).

Cores were retrieved from the deep basin of each lake using a gravity corer with a diameter of 10 cm, a top retainer valve, and fitted with a 0.5-m plastic tube (Glew 1989). Each core was cut on site with an extruder. The top 30 cm of each core were cut into 1-cm sections, and sections below 30 cm were sliced into 2-cm intervals. The cores were dated with ^{210}Pb by Jack Cornett and Bert Risto (AECL, Chalk River, Ontario, Canada) according to methods outlined in Cornett et al. (1984). Although both the constant initial concentration (CIC) and the constant rate of supply (CRS) models were used to generate dates for the cores (Appleby and Oldfield 1978), because the sedimentation rates have changed in many of the lakes only the CRS dates were used to select the section of each core corresponding to 1890.

Lake-water chemical data used to construct the inference models and the procedures used to obtain the data are discussed in detail in Canavan and Siver (1994) and Siver et al. (1996). Values for specific conductivity and pH represent means from collections ($n \geq 6$) made throughout the year. Values for the trophic-related variables, chlorophyll *a*, Secchi disk depth, total phosphorus, and total nitrogen, represent means from six collections taken over three summer periods.

Procedures for the preparation of samples, identification, and quantification of scaled chrysophytes and planktonic diatoms are as described in Siver and Marsicano (1996) and

Table 2. Summary statistics for weighted averaging (WA) inference models based on scaled chrysophytes and planktonic diatoms for specific conductivity, pH, trophic score, and total nitrogen concentrations. Inverse deshrinking methods were utilized in each case. RMSE estimates for specific conductivity and total nitrogen have the units μS and μg L^{-1}, respectively.

Algal group	Variable	Model	RMSE	r^2
Scaled chrysophytes	pH	WA_{boot}	0.41	0.77
	Trophic score	$WA_{tol, boot}$	45	0.72
	Specific conductivity	$WA_{tol, boot}$	23	0.89
Diatoms	pH	WA_{boot}	0.40	0.80
	Total nitrogen	WA_{boot}	78	0.44
	Specific conductivity	WA_{boot}	39	0.73

Siver (1998). Although all counts of scales and diatom valves were completed using light microscopy (LM), each sample was thoroughly examined with a Zeiss DSM 982 field emission or a Leo 435VP scanning electron microscope (SEM) in order to make identifications that would otherwise be difficult to do with LM and to establish ratios of the organisms that would be difficult to separate with LM (Siver and Marsicano 1996; Siver 1998). The ratios were subsequently used to separate counts of taxa that otherwise could not be positively identified with LM.

Weighted averaging with (WA_{tol}) and without (WA) tolerance downweighting, with bootstrap resampling, and using either classical or inverse deshrinking methods were used in the development of the inference models as discussed by Siver (1998), but only the most significant models were used in this study. The strength of each inference model was evaluated using the correlation between observed and inferred values, and the root mean square error (RMSE) associated with the bootstrap analysis ($RMSE_{boot}$). The resultant inference models used in this study for pH, specific conductivity, and total nitrogen based on planktonic diatoms are those reported by Siver (1998). The construction of inference models for pH, specific conductivity, and trophic score based on scaled chrysophytes are similar to those given previously (Siver and Hamer 1990; Siver 1993; Siver and Marsicano 1996) but modified to include the full set of lakes reported in Siver (1998) and for estimating bootstrap-derived RMSE values (Birks et al. 1990). Summary statistics for each resultant inference model used in this study are given in Table 2. Differences in inferred chemical values that are greater than the $RMSE_{boot}$ are considered significantly different (Birks et al. 1990). All WA analyses were done with WACALIB version 3.3 (Line et al. 1994).

Land-use changes since 1934 in the surrounding watersheds were estimated by Field et al. (1996) and are available for 20 of the lakes. Estimates of the percentage of forests in the surrounding watershed of one additional lake were made subsequent to the Field et al. (1996) study. Details of the determination of land-use types can be found in Field et al. (1996). Briefly, high-resolution aerial photographs with a scale of ~1 cm = 120 m were used to quantify land-use types for 1934 and 1990. Coverages were digitized and analyzed using PC ArcInfo (ESRI). Land use was categorized as forest, agricultural/open field, urban/residential, marsh, and open water. The marsh category included all types of wetlands, and for most of the watersheds the urban/residential component is composed primarily of residential areas. As discussed in Field et al. (1996), all subsequent analyses using land uses include the lake and other open waterbodies as well as all wetland areas in the percentage forest category.

As reported and discussed in detail by Field et al. (1996) and Siver and Marsicano (1996), principal components analysis (PCA) was used to derive a variable referred to in this paper as the trophic score. Essentially, the trophic score of each lake is represented by the score along the first axis of a PCA that incorporates four measured trophic-related variables: chlorophyll *a*, Secchi disc depth, total phosphorus, and total nitrogen. For simplicity, values for the trophic scores in the current study were multiplied by 100 compared to those reported in Field et al. (1996).

Results

Changes in inferred chemical conditions—Collectively, 5 of the 23 study lakes have significantly increased in inferred pH during the last century based on at least one of the organismal groups, with inferred increases ranging between 0.4 and 1.1 pH units (Fig. 1B). A significant increase in pH is inferred in 3 of the 5 lakes by both organismal groups, and none of the 23 study lakes have significantly declined in pH over the last 100 yr. Additional increases in the inferred pH were noted in Alexander (lake no. 1) and Kenosia (lake no. 12) by only the chrysophytes or the diatoms, respectively. Several of the waterbodies, including Ball (lake no. 3) and Kenosia (lake no. 12), that have significantly increased in pH during the last century already had relatively high inferred pH values in 1890. Despite the fact that none of the lakes have significantly declined in pH, the chrysophyte, but not diatom, inferred pH values may indicate a slight declining trend in a few lakes (e.g., Beach Lake, lake no. 5 in Fig. 1B).

Six of the 23 study lakes significantly increased in inferred specific conductivity during the last century (Fig. 1A). Both organismal groups signaled a significant increase in four of the six waterbodies, and none of the study lakes have significantly declined in specific conductivity. The specific conductivity has more than doubled in five of the lakes, with inferred changes ranging over 100 μS (e.g., Kenosia, lake no. 12).

The chrysophyte-inferred trophic scores significantly increased in 6 of the 23 waterbodies between 1890 and 1990 and were close to being significantly larger in four additional lakes (Fig. 1C). All three of the lakes that significantly increased in inferred total nitrogen concentrations based on diatoms also significantly increased in trophic score (Fig. 1C). Two additional lakes, Kenosia (lake no. 12) and Norwich (lake no. 17), were close to being higher significantly in total nitrogen. The chrysophyte-inferred trophic score significantly declined in only one study lake, Lake Hayward (lake no. 11).

Correlation with land-use changes—Significant correlations were observed between contemporary inferred chemical conditions and land-use patterns for 1990 (Fig. 2). Significant relationships were found between pH, specific

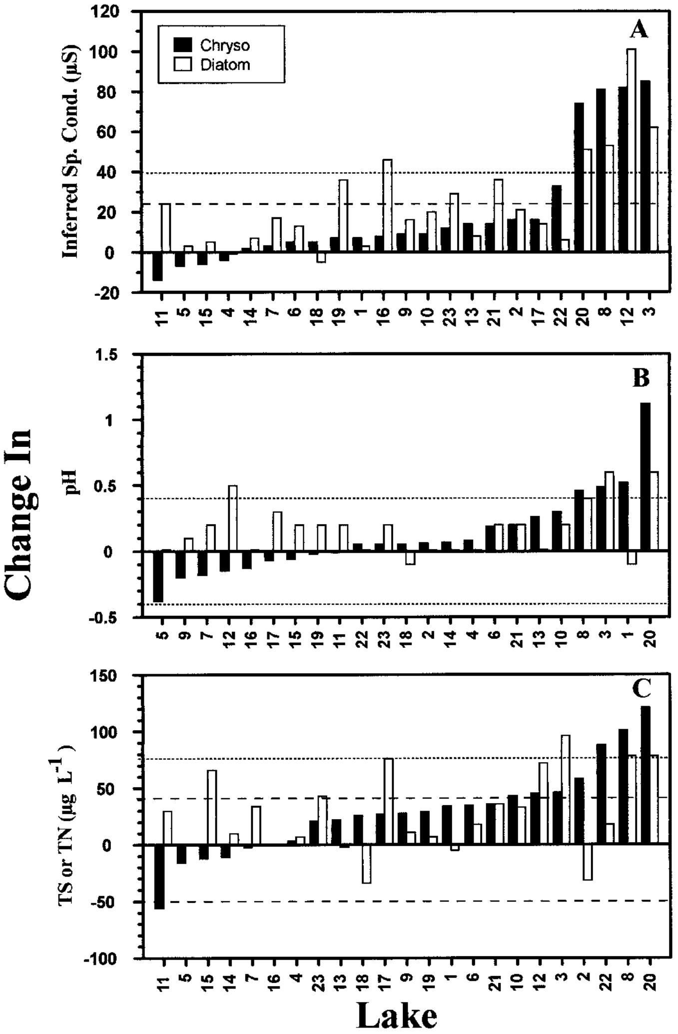

Fig. 1. A comparison of 100-yr changes in inferred specific conductivity (A), pH (B), trophic score (C), and total nitrogen (C) of 23 Connecticut lakes based on scaled chrysophyte (solid bars) and planktonic diatom (open bars) remains. Both organismal groups were used to infer specific conductivity and pH; however, only scaled chrysophytes or planktonic diatoms were used to infer trophic score and total nitrogen, respectively. In each panel, lakes are arranged in ascending order based on inferences made with scaled chrysophytes. Lake numbers refer to those listed in Table 1. Small or large dashed horizontal lines represent changes equal in magnitude to the $\mathrm{RMSE_{boot}}$, for the diatom or scaled chrysophyte models, respectively. For models with similar $\mathrm{RMSE_{boot}}$ values only a small dashed line is shown. Note that for some lakes a given change in the inferred value of a parameter may be zero. TS = trophic score and TN = total nitrogen.

conductivity, and lake trophic condition, and either the % forests or % residential land use in the surrounding watersheds for both chrysophytes and diatoms. As a result of the similarities in the results between the forest and residential land-use types, the forest cover will be used here to illustrate the correlations with contemporary chemical conditions and the residential land-use values used to examine trends during the last century. Significant relationships were also observed for agricultural land use and inferred lake-water chemistry. However, because the relationships were weaker and because agricultural land use is no longer a dominant feature of most of the watersheds, they will not be discussed further (*see* Field et al. [1996] for more discussion).

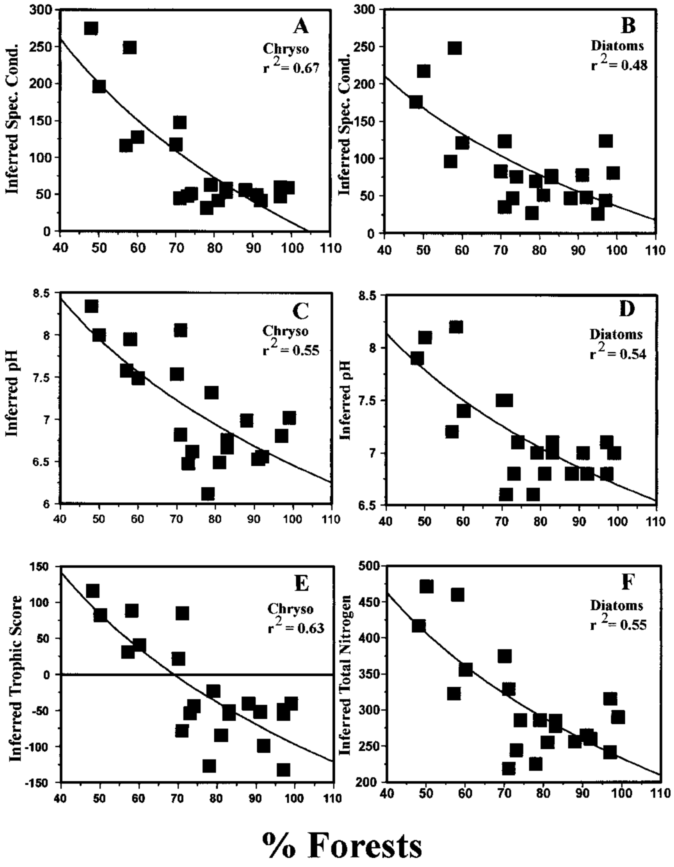

Fig. 2. Specific conductivity (A and B), pH (C and D), trophic score (E), and total nitrogen (F) inferred from the remains of scaled chrysophytes or diatoms in the surface sediments of 20 Connecticut lakes relative to the percentages of forests in the surrounding watersheds. Panels A, C, and E represent inferences made from scaled chrysophytes and panels B, D, and F those from diatoms. Best-fit logarithmic curves and related r^2 values are shown.

In general, the contemporary (1990) lake-water pH, specific conductivity, trophic score, and total nitrogen concentrations decline as the % forest cover increases in the surrounding watersheds (Fig. 2). For both organismal groups, a logarithmic model provided a slightly better fit to the data than did a linear model, and in each case the relationships were also slightly stronger for the chrysophytes (Table 3). The strongest relationship was for specific conductivity using chrysophytes. Many of the waterbodies have similar inferred lake-water chemistries provided that they are situated in a watershed with ~80% or more forest cover. As the forest cover declines below ~80%, the receiving waterbodies tend to increase in pH, specific conductivity, and become more eutrophic in nature.

Clear relationships between the amounts of change in inferred chemistries over the last 100 yr and the increase in residential land use since 1934 were observed for all chemical parameters examined (Fig. 3). With two exceptions, all

Table 3. Summary of r^2 values for linear and logarithmic models of inferred chemical conditions versus the percentage of forests in the surrounding watersheds of Connecticut lakes. Results of models for pH, specific conductivity, trophic score, and total nitrogen using scaled chrysophytes or planktonic diatoms are given. Inferred chemical conditions are based on organismal remains in surface sediments (*see text for details*).

Variable	Organismal group	Linear model	Logarithmic model
pH	Chrysophytes	0.50	0.55
	Diatoms	0.49	0.54
Specific conductivity	Chrysophytes	0.61	0.67
	Diatoms	0.42	0.48
Trophic score	Chrysophytes	0.59	0.63
Total nitrogen	Diatoms	0.49	0.55

waterbodies situated in watersheds that have experienced an increase of greater than 25% residential land use have significantly increased in specific conductivity and pH and have become more eutrophic in nature. On the other hand, most lakes situated in watersheds with less than a 20% increase in residential land use have not significantly changed in their chemical conditions. Although there are exceptions, the results were similar for both the chrysophyte and diatom inferences.

Two exceptions are worth noting. According to the diatom but not chrysophyte reconstructions, Mohawk Lake (lake no. 16), a lake situated in a primarily forested watershed with only a 3% increase in residential land cover, has increased in specific conductivity. Two other lakes, Amos Lake (lake no. 2) and Lake Hayward (lake no. 11), with similar increases in residential land use (11% and 12%), experienced a significant increase and decrease in their trophic scores, respectively, based on chrysophyte remains.

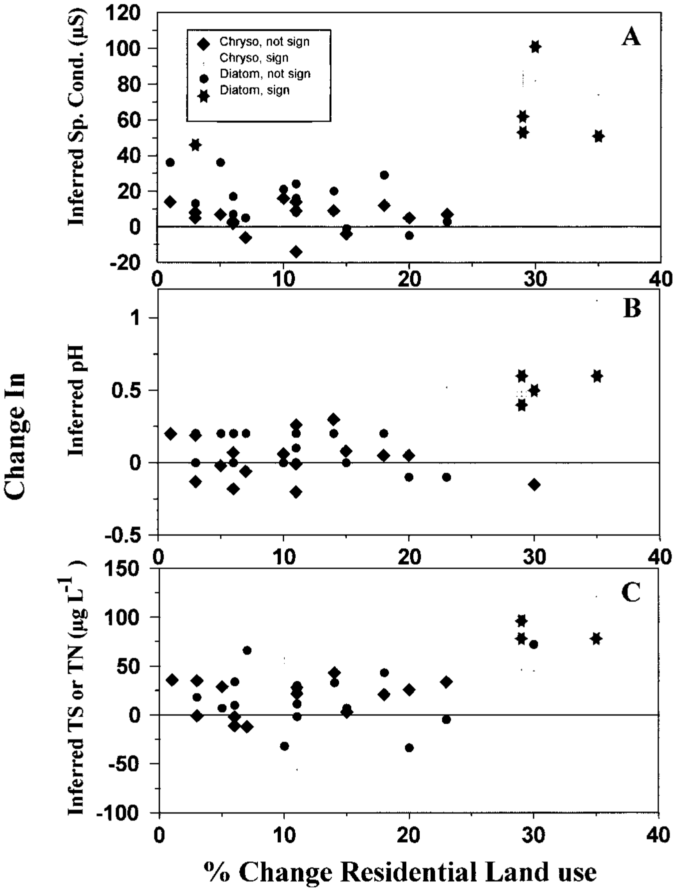

Fig. 3. Changes in inferred specific conductivity (A), pH (B), trophic score (C), and total nitrogen (C) based on scaled chrysophyte (diamonds or asterisk) and diatom (circles or stars) remains relative to the change in residential land use in the watersheds of 20 Connecticut lakes. Asterisk and star symbols reflect significant differences based on the $\mathrm{RMSE}_{\mathrm{boot}}$ for that specific inference model.

Discussion

Based on the scaled chrysophyte and diatom inferences made in this study, approximately 20–25% of the lakes have significantly increased in specific conductivity, pH, and nutrient content during the last century. Most of the lakes that have experienced significant changes are situated in watersheds that have increased substantially in residential land cover. The findings in this study are in remarkedly close agreement with those reported by Siver et al. (1996) and Field et al. (1996) for Connecticut waterbodies, many of which were included in the current study. By direct comparison of actual chemical measurements, Siver et al. (1996) found that, on average, Connecticut lakes had doubled in total phosphorus concentrations and decreased in Secchi disc depth by 1.2 m between the 1930s and 1990s. In addition, Siver et al. (1996) reported that 21% of the 42 lakes included in that survey had increased in base cation concentration by more than 20% between 1970 and 1990 and 20% of the lakes had increased in alkalinity by more than 30% since the 1930s. As was observed in the current study, the lakes reported by Siver et al. (1996) to have undergone the most extensive chemical changes were those situated in the watersheds that have also undergone the largest increases in residential land cover. Thus, it is concluded that the paleolimnological method utilized in the current study has provided an accurate and independent means of reconstructing past lake-water conditions.

The fact that some of the study lakes associated with large increases in residential land use, e.g., Ball (lake no. 3), Coventry (lake no. 8), and Terramuggus (lake no. 20), have had significant increases in inferred pH, specific conductivity, and nutrient concentrations is not surprising. Alterations that are associated with the development of residential areas can simultaneously and effectively result in changes to each of these three chemical conditions. Urban and residential land uses are known to yield a higher export of phosphorus and nitrogen per unit area to waterbodies than forested or agricultural cover types (Downing and McCauley 1992). For example, the nutrient export models used in the Field et al. (1996) study that were developed in Connecticut assumed that urban and agricultural land use contributed 17 and 5.4 times more phosphorus and 5.6 and 3.2 times more nitrogen than forests, respectively. Because of the increased concentrations of nutrients, waterbodies associated with highly residential landscapes are often more eutrophic in nature. In addition, increased algal growth resulting from elevated nutrient input can cause the pH to increase through photosynthetic activity.

In addition to resulting in an increase in nutrients that can directly stimulate algal growth, runoff from urbanized or residential areas also contains higher concentrations of dissolved salts than runoff from forested areas and will therefore result in elevated specific conductivity values in receiving waterbodies (Prowse 1987). Specific conductivity of runoff can also be significantly increased through road-deicing salts used in winter. Mattson and Godfrey (1994) demonstrated a strong correlation between concentrations of sodium and chloride in waterbodies and waterways and the use of winter road-deicing salts. Because road-deicing salts are also heavily used in Connecticut, and because there is a positive correlation between the linear distances of roads and the amounts of residential land cover in the study watersheds (King 1997), this activity has most likely contributed to the increased specific conductivities of Connecticut lakes (Siver et al. 1996).

Activities associated with increased residential land use can also result in a subsequent increase in watershed-based alkalinity generation. Disturbances such as the building of homes and roads result in the removal of low pH, organic-rich forest humic layers and subsequent exposure of base cation-rich subsoils (Prowse 1987). As a result, more of the strong acids in surface runoff would be balanced with base cations instead of hydrogen or aluminum ions, thereby increasing the alkalinity. Other activities, such as the liming of grass lawns and gardens and the application of fertilizers can increase the alkalinity of surface runoff and ultimately receiving waterbodies. In-lake alkalinity generation, through the reduction of sulfate by phytoplankton in the water column and bacterial-mediated processes in anaerobic sediments, is known to occur in some Eastern Upland Connecticut lakes (Murray 1994) as well as in other New England lakes (Giblin et al. 1990). If the reduced sulfur becomes permanently buried in the lake sediments, the gain in alkalinity becomes permanent (Giblin et al. 1990). Such in-lake alkalinity generation through the burial of sulfides may be enhanced by elevated sulfate concentrations, changes in hypolimnetic anoxia, or increased delivery of organic matter to the sediments (Mitchell et al. 1988; Murray 1994).

Paleolimnological studies have confirmed that lakes in the northeastern part of North America, especially ones in the Adirondacks (Sullivan et al. 1990; Cumming et al. 1992*a*), northern New England (Davis et al. 1994), and regions of Ontario (Dixit et al. 1992; Hall and Smol 1996) have acidified over the last ~50–150 yr, presumably as a result of anthropogenic acidic deposition. Despite the fact that areas of Connecticut are particularly susceptible to acidic deposition due to the crystalline nature of the bedrock and thin acidic soils (Rogers et al. 1959) and receive acidic deposition (Husar et al. 1991), paleolimnological studies have not revealed widespread declines in lake-water acidity since the mid-1800s (Marsicano and Siver 1993). In fact, a number of lakes have significantly increased in alkalinity (Siver et al. 1996) and pH (this study) over the last 100 yr. Marsicano and Siver (1993) and Siver et al. (1996) suggested that land-use changes, especially the development of residential areas, may have effectively buffered potential declines in pH due to acidic deposition through watershed-based, and possibly in-lake, alkalinity generation as discussed above.

It is clear in other paleolimnological studies that land-use changes have also most likely resulted in increased lake-water pH and alkalinity. Sullivan et al. (1990) found that 7 of 48 lakes in the Adirondacks had significantly increased in alkalinity since pre-1850; five of the seven waterbodies had alterations within their watersheds. Renberg et al. (1993) illustrated that forest clearing and resultant agricultural practices in the Iron Age period resulted in increased lake-water alkalinity. Davis et al. (1994) reported increases in inferred pH and alkalinity of up to 0.60 pH units and 40 μeq/L, respectively, that correlated well with logging of the surrounding catchments. Hall and Smol (1996) found that although 13% of their study lakes in south-central Ontario had declined in pH since preindustrial times, 24% had significantly increased in pH presumably due to the development of cottages. Thus, it appears that land-use activities can effectively increase the pH of poorly buffered lakes situated in regions receiving acidic deposition.

Unlike the paleolimnological works referred to above, our study links changes in water chemistry to more precise estimates of land-use change. We found significant relationships between present-day inferred pH, specific conductivity and trophic condition, and the present-day land uses, especially the percentages of forests and residential lands, in the watersheds. Thus, we feel confident that scaled chrysophyte and diatom inferences can indeed track chemical changes that are at least, in part, related to alterations in the watershed. An interesting result of our study was that the majority of the significant changes in water chemistry, especially in pH and specific conductivity, were noted in lakes where over 20–25% of the surrounding watersheds had been converted to residential land since the turn of the century. Similarly, the lakes with watersheds that maintained greater than approximately 80% forests since ca. 1890 did not generally undergo significant chemical changes. Although there were two exceptions, the same basic relationship observed between pH or specific conductivity and land use was also noted for trophic condition. The relationships observed in this study between inferred chemical changes and land use could most likely be improved on if more detailed data, such as soil types, age of homes, types and conditions of septic systems, and distances of homes to the lake or strategic water courses could be included in the analyses.

Several recent changes in the trophic condition of a few lakes were observed that do not appear to be related to land-use changes. Two lakes, Norwich (lake no. 17) and Uncas (lake no. 21), are situated in state forests and have watersheds that have remained ~98% forested since 1934. Neither lake has significantly changed in inferred trophic score or total nitrogen concentrations since 1890. However, a more detailed analysis of both lakes (unpubl. data) indicates that even though the inferred lake-water chemistry has remained relatively constant between 1890 and ca. 1980, shifts in the biological remains indicate a trend (although not significant) toward increasing eutrophy since 1980. Even though other lakes show similar trends toward becoming more eutrophic they differ from Norwich (lake no. 17) and Uncas (lake no. 21) in that they are situated in watersheds that are also experiencing increases in residential land use. We can only conclude that factors other than those related to land-use changes, such as in-lake loading of nutrients or a shift in the food-web structure, are responsible for the recent changes in scaled chrysophyte and diatom remains. It will be interesting to see if the trend toward becoming more eutrophic continues in Norwich (lake no. 17) and Uncas (lake no. 21), and to examine recent changes in nonsiliceous algal and geochemical remains in the sediments.

A paleolimnological study can be a useful and effective tool in the successful management of aquatic ecosystems (Brenner et al. 1993). Brenner et al. (1993) used such a method to estimate predisturbance chemical conditions in order to establish realistic lake restoration goals. In some instances it may be determined that restoration efforts may not benefit a given waterbody because the predisturbance conditions are found to be similar or worse than present-day conditions (e.g., Reavie et al. 1995). The paleolimnological method utilized in this study is an effective means to indicate the amounts and rates of changes in individual lakes or suites of lakes, especially if background chemical data are lacking (Brenner et al. 1993; Marsicano et al. 1995). The method can be used to examine shifts in water quality related to known alterations in the surrounding watershed (Lott et al. 1994) or atmospheric inputs (Sullivan et al. 1990), as well as to establish baseline conditions that in turn can be used to set realistic lake restoration goals or prioritize lake restoration efforts.

It is possible that the findings in this study could serve as a general benchmark for lake management and watershed development purposes for Connecticut lakes, especially for lakes situated in the geological zones referred to as the Eastern or Western Upland areas (Canavan and Siver 1994). Perhaps a goal of maintaining watersheds with greater than 80% forests or with less than 20% residential development could be used as a general target for planning purposes, especially if funding will limit more detailed analysis for a given waterbody. Regardless of such a broad generalization, it is paramount that other factors, including the water residence time, watershed to lake area ratio, soil types, degree of wetland development, the age structure and proximity of the residential areas to the receiving waterbody, and the potential for in-lake loading be integrated into the management of individual waterbodies (Field et al. 1996).

Despite the overall close agreement between the inferences made using scaled chrysophytes and those based on planktonic diatoms, there were differences in some of the lakes. Dixit et al. (1996) also noted differences in pH inferences made using the same two organismal groups working on a lake in Sudbury, Ontario. A number of reasons may explain why both scaled chrysophytes and diatoms do not always yield the same inferred results. First, although much effort was made to separate planktonic and periphytic taxa in the construction of the diatom inference models (Siver 1998), some of the counts inevitably have valves that originated from both habitats. Because the chemical conditions may differ widely between the planktonic and periphytic habitats, this could result in some variance in inferences made between the two organismal groups. Second, the complement of taxa in each organismal group may dominate at different times of the year and therefore reflect seasonal differences in the chemistry of individual lakes. Third, in any given lake, the complement of taxa representing each organismal group may respond moreso to different variables and thus yield more informative inferences for specific variables (Siver 1995). Fourth, due to significant differences in flushing rates between the lakes, the biological remains recovered from the lake sediments can represent organisms that grew during different times of the year (Siver and Hamer 1992). In lakes with low residence times a greater percentage of the remains found in the sediments most likely represent organisms that grew during periods of low flow (e.g., the autumn period). Therefore, inferences based on these remains should reflect chemical conditions corresponding to the periods of low flow. As the water residence time increases, the sediment remains should represent more of a yearly integration of the planktonic community.

In conclusion, significant changes in the chemical structure of Connecticut lakes, as inferred from biological remains, has occurred during the last century, and the changes are highly correlated with development of the surrounding watersheds. The lakes that have experienced the largest shifts are those situated in watersheds that have had the greatest amount of residential development, and those situated in watersheds that have remained largely forested remain primarily unaltered. In general, results based on scaled chrysophyte or planktonic diatom remains were similar. None of the lakes, even those situated in watersheds that have remained largely forested, significantly declined in pH, whereas others have significantly increased in pH. Because the region does receive very acidic precipitation, it is concluded that watershed-based and perhaps in-lake alkalinity generation must be aiding in the neutralization of the acidic deposition. Such an hypothesis will be the subject of future investigations.

References

Appleby, P. G., and F. Oldfield. 1978. The calibration of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena **5:** 1–8.

Bennion, H., S. Juggins, and N. J. Anderson. 1996. Predicting epilimnetic phosphorus concentrations using an improved diatom-based transfer function and its application to lake eutrophication management. Environ. Sci. Technol. **30:** 2004–2007.

Birks, H. J. B., J. M. Line, S. Juggins, A. C. Stevenson, and C. J. F. ter Braak. l990. Diatoms and pH reconstruction. Phil. Trans. R. Soc. Lond. Ser. B **327:** 263–278.

Brenner, M., T. J. Whitmore, M. S. Flannery, and M. W. Binford. 1993. Paleolimnological methods for defining target conditions in lake restoration: Florida case studies. Lake Reserv. Manage. **7:** 209–217.

Canavan, R. W., IV, and P. A. Siver. 1994. Chemical and physical properties of Connecticut lakes with emphasis on regional geology. Lake Reserv. Manage. **10:** 175–188.

Charles, D. F., and J. P. Smol. 1988. New methods for using diatoms and chrysophytes to infer past pH of low-alkalinity lakes. Limnol. Oceanogr. **33:** 1451–1462.

Cornett, R. J., L. Chant, and D. Link. 1984. Sedimentation of

Pb-210 in Laurentian shield lakes. Water Pollut. Res. J. Can. **19:** 97–107.

CUMMING, B. F., J. P. SMOL, AND H. B. J. BIRKS. 1992*a*. Scaled chrysophytes (Chrysophyceae and Synurophyceae) from Adirondack drainage lakes and their relationship to environmental variables. J. Phycol. **28:** 162–178.

———, ———, J. C. KINGSTON, D. F. CHARLES, H. J. B. BIRKS, K. E. CAMBURN, S. S. DIXIT, A. J. UUTALA, AND A. R. SELLE. 1992B. How much acidification has occurred in Adirondack region lakes (New York, USA) since preindustrial times? Can. J. Fish Aquat. Sci. **49:** 128–141.

DAVIS, R. B., D. S. ANDERSON, S. A. NORTON, AND M. C. WHITING. 1994. Acidity of twelve northern New England (U.S.A.) lakes in recent centuries. J. Paleolimnol. **12:** 103–154.

DIXIT, A. S., S. S. DIXIT, AND J. P. SMOL. 1996. Setting restoration goals for an acid and metal-contaminated lake: A paleolimnological study of Daisy Lake (Sudbury, Canada). Lake Reserv. Manage. **12:** 323–330.

DIXIT, S. S., A. S. DIXIT, AND J. P. SMOL. 1992. Long-term trends in lake water pH and metal concentrations inferred from diatoms and chrysophytes in three lakes near Sudbury, Ontario. Can. J. Fish. Aquat. Sci. **49:** 17–24.

DOWNING, J. A., AND E. MCCAULEY. 1992. The nitrogen : phosphorus relationship in lakes. Limnol. Oceanogr. **37:** 936–945.

FIELD, C. K., P. A. SIVER, AND A. M. LOTT. 1996. Estimating the effects of changing land use patterns on Connecticut lakes. J. Environ. Qual. **25:** 325–333.

GIBLIN, A. E., G. E. LIKENS, D. WHITE, AND R. W. HOWARTH. 1990. Sulfur storage and alkalinity generation in New England lake sediments. Limnol. Oceanogr. **35:** 852–869.

GLEW, J. R. 1989. A portable extruding device for close interval sectioning of unconsolidated core samples. J. Paleolimnol. **1:** 235–239.

HALL, R. I., AND J. P. SMOL. 1996. Paleolimnological assessment of long-term water-quality changes in south-central Ontario lakes affected by cottage development and acidification. Can. J. Fish. Aquat. Sci. **53:** 1–17.

HUSAR, R. B., T. J. SULLIVAN, AND D. F. CHARLES. 1991. Methods in assessing long-term trends in atmospheric deposition and surface water chemistry, p. 65–82. *In* D. F. Charles [ed.], Acid deposition and aquatic ecosystems: Regional case studies. Springer-Verlag.

KING, K. 1997. The effects of road and home development on sodium levels in Connecticut lakes. Honor's Thesis, Connecticut College.

LINE, J. M., C. J. F. TER BRAAK, AND H. J. B. BIRKS. 1994. WACALIB version 3.3—a computer program to reconstruct environmental variables from fossil assemblages by weighted averaging and to derive sample-specific errors of prediction. J. Paleolimnol. **10:** 147–152.

LOTT, A. M., P. A. SIVER, L. J. MARSICANO, K. P. KODAMA, AND R. E. MOELLER. 1994. The paleolimnology of a small waterbody in the Pocono Mountains of Pennsylvania, USA: Reconstructing 19th-20th century specific conductivity trends in relation to changing land use. J. Paleolimnol. **12:** 75–86.

MARSICANO, L. J., J. L. HARTRANFT, P. A. SIVER, AND J. S. HAMER. 1995. An historical account of water quality changes in Candlewood Lake, Connecticut, over a sixty year period using paleolimnology and ten years of monitoring data. Lake Reserv. Manage. **11:** 15–28.

———, AND P. A. SIVER. 1993. A paleolimnological assessment of lake acidification in five Connecticut lakes. J. Paleolimnol. **9:** 209–221.

MATTSON, M. D., AND P. J. GODFREY. 1994. Identification of road salt contamination using multiple regression and GIS. Environ. Manage. **18:** 767–773.

MITCHELL, M. J., S. C. SCHINDLER, J. S. OWEN, AND S. A. NORTON. 1988. Comparison of sulfur concentrations within lake sediment profiles. Hydrobiologia **157:** 219–229.

MURRAY, T. E. 1994. Iron, sulfur and phosphorus interactions in a softwater lake. Ph.D. thesis, Univ. of Connecticut.

PROWSE, C. W. 1987. The impact of urbanization on major ion flux through catchments: A case study in southern England. Water Air Soil Pollut. **32:** 277–292.

REAVIE, E. D., R. I. HALL, AND J. P. SMOL. 1995. An expanded weighted-averaging model for inferring past total phosphorus concentrations from diatom assemblages in eutrophic British Columbia (Canada) lakes. J. Paleolimnol. **14:** 49–67.

RENBERG, I., T. KORSMAN, AND H. J. B. BIRKS. 1993. Prehistoric increases in the pH of acid-sensitive Swedish lakes caused by land-use changes. Nature **362:** 824–826.

ROGERS, J. R., M. GATES, AND J. L. ROSENFELD. 1959. Explanatory text for the preliminary geologic map of Connecticut, 1956. State Geological and Natural History Survey of Connecticut. Hartford.

SIVER, P. A. 1993. Inferring the specific conductivity of lake water with scaled chrysophytes. Limnol. Oceanogr. **38:** 1480–1492.

———. 1995. The distribution of chrysophytes along environmental gradients: Their use as biological indicators, p. 214–232. *In* C. D. Sandgren, J. P. Smol, and J. Kristiansen [eds.], Chrysophyte algae: Ecology, phylogeny and development. Cambridge Univ. Press.

———. 1998. Development of paleolimnological inference models for pH, total nitrogen and specific conductivity based on planktonic diatoms. J. Paleolimnol. **21:** 45–59.

———, R. W. CANAVAN, IV, C. K. FIELD, L. J. MARSICANO, AND A. M. LOTT. 1996. Historical changes in Connecticut lakes over a 55-year period. J. Environ. Qual. **25:** 334–345.

———, AND J. S. HAMER. 1990. Use of extant populations of scaled chrysophytes for the inference of lakewater pH. Can. J. Fish. Aquat. Sci. **47:** 1339–1347.

———, AND ———. 1992. Seasonal periodicity of Chrysophyceae and Synurophyceae in a small New England lake: Implications for paleolimnological research. J. Phycol. **28:** 186–198.

———, AND L. J. MARSICANO. 1996. Inferring lake trophic status using scaled chrysophytes. Beih. Nova Hedwigia **114:** 233–246.

SULLIVAN, T. J., AND OTHERS. 1990. Quantification of changes in lakewater chemistry in response to acidic deposition. Nature (London) **345:** 54–58.

WILSON, S. E., B. F. CUMMING, AND J. P. SMOL. 1994. Diatom–salinity relationships in 111 lakes from the Interior Plateau of British Columbia, Canada: The development of diatom-based models for paleosalinity and paleoclimatic reconstructions. J. Paleolimnol. **12:** 197–221.

ZEEB, B. A., AND J. P. SMOL. 1995. A weighted-averaging and calibration model for inferring lake water salinity using chrysophycean stomatocysts from lakes in western Canada. Int. J. Salt Lake Res. **4:** 1–23.

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