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Cyanobacterial Proliferation is a Recent Response to Eutrophication in Many Florida Lakes: A Paleolimnological Assessment

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Abstract

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Cyanobacteria dominate many highly productive Florida lakes. Algal proliferation often is attributed to eutrophication during the last century, but it is poorly documented because Florida's water-quality monitoring programs became common only after 1980. We interpret paleolimnological data from the sediment cores of 6 productive lakes to determine when cyanobacterial proliferation first occurred, and whether it resulted from natural edaphic influence or from eutrophication caused by human activities. Major algal-pigment groups in sediments were analyzed using pigment-extraction and spectrophotometric techniques. Pigment profiles are compared with WACALIB-derived inferences for limnetic total-P, limnetic chlorophyll *a*, and trophic-state index values based on sedimented diatoms, and with stable isotope ($\delta^{13}C$ & $\delta^{15}N$) signatures of organic matter. Cyanobacterial and algal proliferation increased during recent decades in 5 of the 6 study lakes in response to eutrophication. Two lakes demonstrated some evidence of recovery following nutrient-mitigation programs that reduced sewage and other point-source inputs. Five lakes showed intermittent to moderate cyanobacteria presence in the bottom portion of their cores because of edaphic nutrient supply or early watershed disturbance. One highly productive lake showed no evidence of eutrophication and demonstrated that dense cyanobacterial populations can occur naturally. Relationships were particularly strong among sedimented pigment profiles and diatom-inferred limnetic water-quality profiles. Although cyanobacteria have long-standing presence in some naturally productive Florida lakes, our studies suggest that algal proliferation in many lakes is both recent and abrupt in response to eutrophication. Paleolimnological methods are informative about the timing and causes of cyanobacterial appearance in regions where long-term water-quality data are lacking.

Key Words: cyanobacteria, pigments, diatoms, paleoelimnology, Florida, eutrophication

Cyanobacteria are common in highly productive Florida lakes where they reduce water clarity, limit recreational uses, and affect the utility of lakes as potable water supplies. Florida has approximately 7800 lakes (Brenner *et al.* 1990), but little is known about algal populations and water quality conditions prior to 25-30 years ago. Several early studies characterized water quality in Florida's lakes (*e.g.*, Shannon and Brezonik 1972, Canfield 1981, Huber *et al.* 1982), but consistent monitoring by state agencies and by citizens groups became well-established only since the 1980s.

Some Florida lakes have demonstrated cultural eutrophication in response to urbanization, agriculture, phosphate mining, or point-source nutrient inputs (*e.g.*, Brenner *et al.* 1995, 1996, 1999b). Such eutrophication becomes apparent when lakes are examined over >100 years by paleolimnological methods. Geological setting exerts a strong influence on water quality within the state (Canfield 1981, Griffith *et al.* 1997), however, and the majority of Florida's productive lakes are situated in areas where they are predisposed to higher trophic state by edaphic influence, such as phosphatic deposits. Information about long-term water quality and algal abundance is helpful for evaluating the likelihood of improving water quality through lake-management efforts. When nutrients and algal abundance are high because of natural factors rather than human influence, attempts to reduce algal populations and limnetic nutrient concentrations are less likely to prove effective (Brenner *et al.* 1993).

Some Florida lakes appear to have sustained cyanobacterial populations over long periods of time (*e.g.*, Carr 1934). For the majority of Florida's productive lakes, it generally is unknown when cyanobacteria first appeared, or whether cyanobacterial presence results naturally from edaphic influence or from eutrophication caused by human activities.

Carotenoid and chlorophyll pigments are found in algae and macrophytes in freshwater ecosystems. Cyanobacteria are present in greatest numbers in eutrophic conditions, and they contain a larger percentage of carotenoid pigments than do other algal groups. Carotenoids are preserved in lake sediments, and their total sedimentary concentrations are thought to be proportional to productivity of a lake at the time of deposition (Swain 1985, Sanger 1988). Carotenoids and chlorophyll pigments in sediment cores have been used to document historic changes in algal and cyanobacterial abundance (Leavitt and Carpenter 1990, Hickman and Schweger 1991, Leavitt 1993). Waters *et. al* (2005) show that chlorophyll derivatives and carotenoid pigments are highly correlated with total phosphorus content in a sediment core from Lake Apopka, Florida, and they interpret changes in chlorophyll and carotenoid pigments as being indicative of past algal productivity.

Oscillaxanthin and myxoxanthophyll are two principal carotenoid pigments that increase in lake sediments during eutrophication. Oscillaxanthin is found only in the Oscillatoriaceae, a cyanobacterial group that is often first to dominate when eutrophic conditions develop (Swain 1985, Feuillade *et al.* 1995). *Oscillatoria* are numerically abundant cyanobacteria in many productive Florida lakes (E. Phlips, University of Florida, unpublished data). Myxoxanthophyll is found in the majority of cyanobacterial species, and its presence in sediments is a good general indicator of cyanobacterial presence in the past (Swain 1985, Sanger 1988). Myxoxanthophyll and oscillaxanthin sediment concentrations have been used, for example, to document historic trophic-state changes in Lake Wabamun, Alberta (Hickman and Schweger 1991) and in Lake Windermere (Sabater and Haworth 1995). Myxoxanthophyll is a general indicator of filamentous and colonial cyanobacterial presence (Leavitt 1993), and was found to be present in 25 out of 28 species in six families of cyanobacteria that were examined by Hertzberg *et al.* (1971).

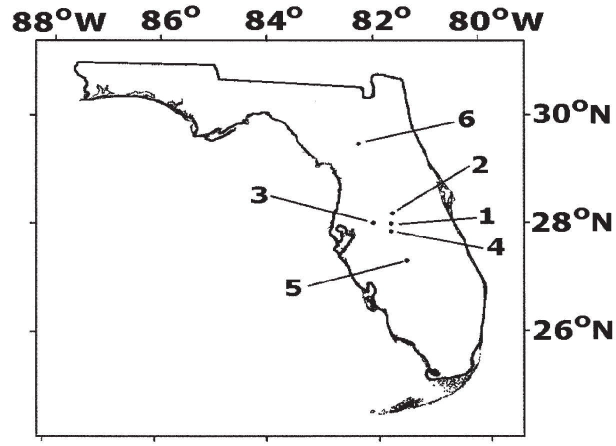

Figure 1.-Map showing location of study lakes: 1. Lake Conine, 2. Lake Haines, 3. Lake Hollingsworth, 4. Lake May, 5. Lake Persimmon, 6. Lake Wauberg.

Our approach focuses on general trends in cyanobacterial response to eutrophication as assessed by total carotenoids, oscillanxanthin, and myxoxanthophyll as opposed to identification of cyanobacterial pigments by HPLC (Leavitt and Hodgson 2001). We chose these indicators of cyanobacterial presence for the present study because of their long-standing utility as overall cyanobacterial standing crop indicators and because of their simplicity of assessment.

Sedimented algal pigments are subject to degradation in lake sediments, so changes in pigment concentrations throughout a sediment core can result from differential preservation. Principal degradation products of sedimented chlorophyll are pheopigments, which can be assayed by acidification and spectrophotometric analysis (Lorenzen 1967). Swain (1985) defined the term percent native chlorophyll to describe the portion of undegraded chlorophyll pigments in sediment samples. Percent native chlorophyll provides a measure of preservation quality for chlorophyll pigments in a sediment core, and by the same principle Swain proposed their use as a probable indicator of cyanobacterial pigment preservation in the same samples.

Water quality information for Florida lakes rarely extends back more than a few decades, so information about cyanobacterial presence prior to the state's exponential population growth and development in the mid 1900s generally is lacking. The extent of human influence on cyanobacterial populations in Florida is documented poorly. The present study examines algal pigment abundance in six productive Florida lakes using paleolimnological methods. Sedimented pigments are compared with quantitative estimates of past

Table 1.-Study lakes with means of measured values for limnetic total P, limnetic chlorophyll *a*, and limnetic total N concentrations. Florida 305(b) (averaged) TSI values were calculated from the data shown.

Lake	County	Mean Limnetic total P (μg/L)	Mean Limnetic chlorophyll *a* (μg/L)	Mean Limnetic total N (μg/L)	Florida 305(b) averaged TSI
Conine[1]	Polk	322	80	1700	75
Haines[1]	Polk	115	82	1620	74
Hollingsworth[2]	Polk	382	115	3652	86
Hollingsworth[3]	Polk	113	135	2517	80
Hollingsworth[4]	Polk	106	83	1754	74
May[1]	Polk	63	49	1340	67
Persimmon[5]	Highlands	35	85	3425	70
Wauberg[1]	Alachua	113	79	1640	73

[1]Lakewatch (2000): Conine 1991-1995 data, Haines and May 1991-2000 data, Wauberg 1990-2000 data.
[2]Florida Lakes Data Base, Huber *et al.* (1982), 1968-1970 data.
[3]Canfield and Hoyer (1992), 1987-1988 data.
[4]Lakewatch (2003).
[5]Lakewatch (1997), 1995 data.

water quality based on sedimented diatoms, and with stable isotope ($\delta^{13}C$ & $\delta^{15}N$) signatures of organic matter in ^{210}Pb-dated sediment cores. Our objective is to determine whether cyanobacterial and algal abundance in productive lakes results primarily from edaphic influence or from eutrophication that occurred prior to the establishment of water quality monitoring programs.

Study Sites

Lakes Conine, Haines, and May (Figure 1) are located in Polk County on a chain of 19 interconnected lakes called the Winter Haven Chain of Lakes. Lakes Conine and Haines are among 5 lakes located on the portion referred to as the Northern Chain, and Lake May is among 14 lakes that are located on the Southern Chain. Lakes on the Winter Haven Chain are connected by a series of canals that were constructed beginning in the 1920s to facilitate shipment of citrus and for recreational use of the lakes. Historically, Chain Lakes have been used as a place to dump waste materials, although some efforts were made to improve water quality by 1970 (FDAWPC 1970). Pollution sources that introduced nutrients to the Winter Haven Chain of Lakes by 1949 included chemical fertilizer plants, citrus packing, citrus and vegetable canning, soft drink and milk bottling waste, laundry waste, and untreated municipal sewage effluent. Water flow through the canal system tended to distribute introduced materials throughout the chain. Spence and Hammer (1983) documented nearly 6000 homes on the Southern Chain that used septic waste systems in areas where soils were considered poor for this usage. As of the late 1980s, the City of Lake Alfred discharged treated sewage effluent into Lake Haines at the rate of 0.3 million gallons/day, and the City of Winter Haven discharged treated sewage effluent into Lake Conine at the rate of 1.7 million gallons/day. Both of these sewage effluent inputs were discontinued in 1992.

Lakes Conine, Haines, and May overlie deeply weathered clays and sands of the phosphatic Hawthorn Formation in the Winter Haven karst division of the Central Lake District (Brooks 1981). Lake Conine has a surface area of 96 ha, and Lake Haines has a surface area of 295 ha. Lake May, the smallest of these three lakes, has a surface area of 17.4 ha and is located between Lakes Howard and Shipp within the city of Winter Haven. Lake Conine received whole-lake alum application in 1995, which significantly reduced limnetic phosphorus, nitrogen, and chlorophyll *a* values.

Lake Hollingsworth is located in the City of Lakeland in Polk County. Local geology is dominated by phosphatic sands and clays of the Bone Valley Formation (Brooks 1981). Nearly all of the lake's 6673 km^2 watershed consists of residential and urban development. Citrus and other agriculture began in the watershed by 1880, and the city of Lakeland incorporated the watershed by 1885. Residential development expanded to the west shore by the 1930s. The lake received inputs from septic systems prior to installation of municipal sewage treatment systems. Secchi depth averaged 0.30 m in 1968-1970 (Chew 1974). There are 57 stormwater outfall pipes that discharge into the lake, and the lake experiences high bacterial counts that reduce recreational use during the winter. Lake Hollingsworth was the subject of a previous paleolimnological study that documented the influence of increased nutrient loading on eutrophication (Brenner *et al.* 1995). Water quality has shown directional improvement during the last 35 years (Table 1). The lake was subject to partial dredging and whole-lake alum treatment since the time of our study.

Lake Persimmon, in Highlands County, has a surface area of approximately 44 ha and a watershed area of approximately 270 ha. The lake is hypereutrophic (Table 1), and cyanobacterial densities in Lake Persimmon are highest among 76 Highlands County lakes studied in Southwest Florida Water Management District's (SWFWMD) Ambient Monitoring Program (K. Kolasa, SWFWMD, pers. comm.). Rutter (1999) found numerous cyanobacterial taxa in Lake Persimmon including *Anabaena*, *Aphanocapsa*, *Dactylococcopsis*, *Merismopedia*, and *Oscillatoria* in the winter, and *Dactylococcopsis* and *Microcystis* in the summer. *Lyngbya* sp., however, appears to be dominant among the algae in Lake Persimmon (K. Kolasa, pers. comm.). Forty-one percent of the watershed is used for citrus agriculture and 27% is residential. Citrus agriculture was established in Lake Persimmon's watershed between 1944 and 1957 (C. Ford, Highlands County Soil and Water Conservation District, pers. comm.). Aerial photographs show that a portion of the northeastern shoreline, which was a wet area in 1944, had been channelized by 1957. Portions of low-lying areas and wetlands to the west and southwest of the lake appear to have been filled during construction of a subdivision and airport, which might have altered drainage patterns to the lake (C. Ford, pers. comm.). A canal was constructed on the east side of Lake Persimmon between 1962 and 1966 for lake access. Groundwater collected by SWFWMD from wells adjacent to Lake Persimmon shows excessively high nitrate concentrations (up to 30 mg L^{-1}), and water in a canal on the eastern side of the lake exhibits nitrate concentrations on the order of 4.5 mg L^{-1} (SWFWMD, unpublished data). An aeration system was installed on the lake in 2002, subsequent to our study, and has led to temporary improvements in water clarity.

Lake Wauberg borders Paynes Prairie State Preserve in Alachua County, Florida. The lake is hypereutrophic (Table 1) and is considered to be nutrient impaired (Wu *et al.* 2003). Lake Wauberg lies within the Central Valley lake region (Griffith *et al.* 1997), and local geology is dominated by limestone and clayey sands (Brooks 1981). Most of the surrounding watershed consists of forests and wetlands. The University of Florida has maintained recreational facilities along the north shore of the lake since 1918, and along the south shore since 1985. Lake Wauberg has sustained cyanobacterial populations since at least the 1930s (Carr 1934). Recent averaged Secchi depth is 0.62 m (Florida Lakewatch 2003). Water quality is subject to considerable fluctuation, possibly because of natural variation in groundwater inputs from local phosphate-bearing geological deposits (Brooks 1981).

Methods

Sediment cores were recovered using a 1.83-m-long, 7-cm diameter piston corer (Fisher *et al.* 1992) or with a 4-cm diameter, 1.83-m long cellulose acetate butyrate piston corer. Cores were sectioned in the field in 4 or 5 cm intervals. Subsamples for pigment analyses were refrigerated and stored in the dark prior to analyses.

Myxoxanthophyll, oscillaxanthin, total carotenoids, and total chlorophyll pigments were extracted from 7-10 g of wet sediment sample using acetone following the procedures outlined in Swain (1985) and Waters *et al.* (2005). Extracts for total chlorophyll were measured at 665 nm using an Hitachi 2000 spectrophotometer. Percent native chlorophyll (measured at 665 nm before and after acidification with HCl) was used to assess pigment preservation within each sediment core. Subsamples for total carotenoids were saponified using a 20% KOH/methanol mixture, extracted into petroleum ether, and measured at 448 nm. Aliquots for myxoxanthophyll and oscillaxanthin were extracted into petroleum ether, dried, and dissolved in ethanol. Pigment concentrations were determined using the trichromatic method, which quantifies the pigments based on absorbance at 412, 504, and 529 nm (Swain 1985). Organic matter content of samples was assessed by loss on ignition (Håkanson and Jansson 1983). Total carotenoid, total chlorophyll, oscillaxanthin, and myxoxanthophyll values were expressed per unit organic matter to avoid changes in pigment concentration estimates caused by changes in allochthonous sediment supply.

Diatom samples were digested in H_2O_2 and $K_2Cr_2O_7$ (Van der Werff 1955). A minimum of 500 valves was counted in each sample. Past limnetic total P concentrations were inferred from diatom data by weighted-averaging calibration (WACALIB: Line *et al.* 1994) using log-transformed limnetic total P values for a calibration set of 69 P-limited Florida lakes (r^2 adj. = 0.88, s.e. pred. = 0.387). Past limnetic chlorophyll *a* concentrations were inferred by WACALIB using log-transformed limnetic chlorophyll *a* values for a calibration set of 75 Florida lakes (r^2 adj. = 0.79, s.e. pred. = 0.273). Predicted values from these models were de-transformed to yield past limnetic total P and limnetic chlorophyll *a* inferences. Past Florida 305(b) TSI (Paulic *et al.* 1996) values, which are calculated as an average of TSI values based on limnetic total P, total N, and chlorophyll *a*, also were inferred for two N-limited lakes (Lakes Hollingsworth and Wauberg) by WACALIB using a calibration set of 72 Florida lakes (r^2 adj. = 0.86, s.e. pred. = 8.163).

Stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analyses of organic matter were obtained by combusting samples in a Carlo Erba NA 1500 C/N/S analyzer. Combustion gases (CO_2 and N_2) were analyzed with a VG PRISM II series mass spectrometer. CO_2 values were standardized to CM-UF REF (Carrara Marble-University of Florida Reference Gas) and N_2 values were standardized to UF- N_2 REF, both in-house reference standards. $\delta^{13}C$ is expressed as per mil (‰) deviation from the Vienna PeeDee Belemnite (VPDB) limestone standard,

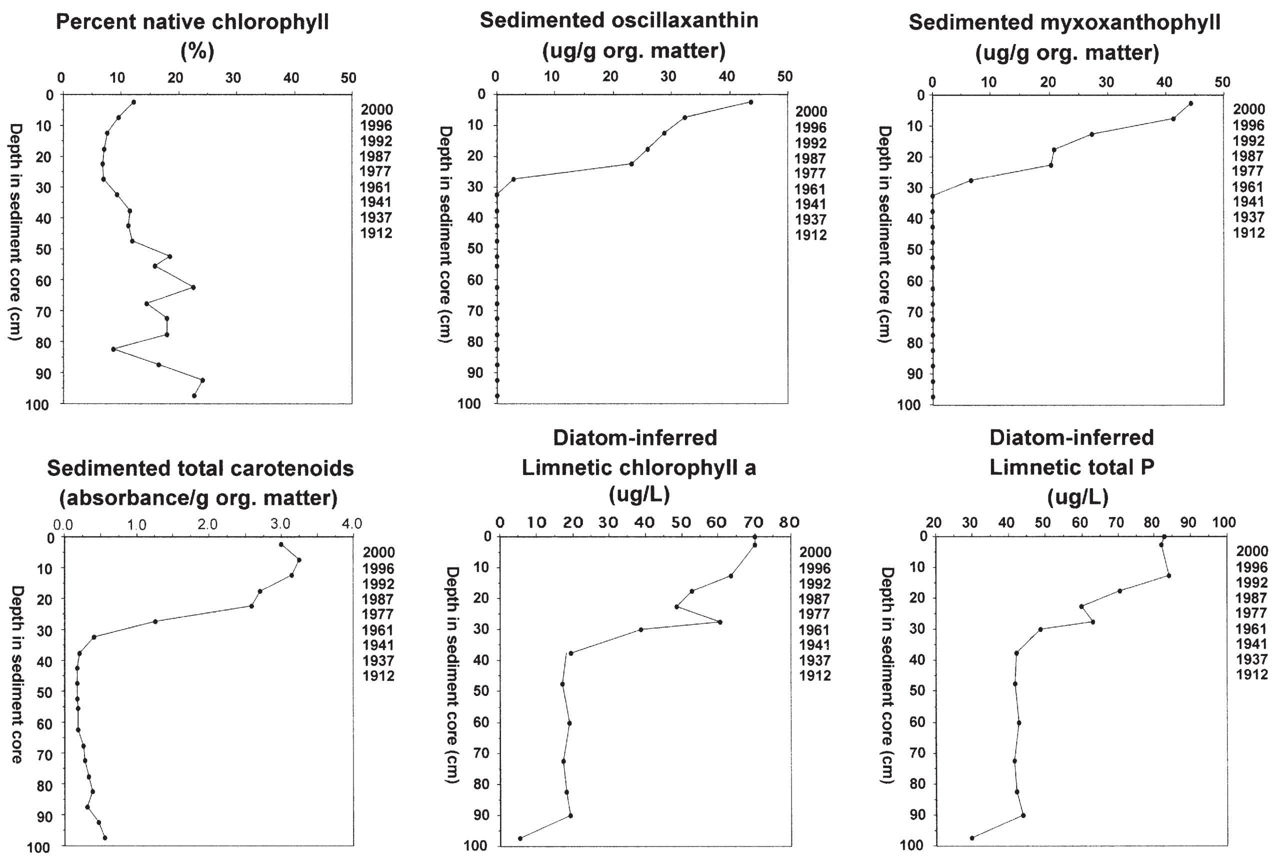

Figure 2.-Percent native chlorophyll, pigment concentrations, and water quality inferences for sediment core from Lake Haines, Polk. Co.

and $\delta^{15}N$ is expressed as per mil (‰) deviation from the atmosphere.

We used gamma spectrometry in order to ^{210}Pb date sediment samples (Appleby *et al.* 1986, Schelske *et al.* 1994). Total ^{210}Pb activity was determined from the 46.5 kev gamma peak. Unsupported ^{210}Pb activity was calculated by subtracting ^{226}Ra, as estimated from ^{214}Pb and ^{214}Bi activities, from the total ^{210}Pb activity. Sediment age/depth relationships were calculated using the constant rate of supply model (Appleby and Oldfield 1983).

Sediment cores from Lakes Conine, Haines, May, and Wauberg were obtained in 2000, and all analyses shown are from the same core in each of these lakes. Lake Persimmon was cored in 1998, and all analyses were performed on one core, with the exception of pigment analyses, which were performed on a core removed in parallel at the same time and location. Direct stratigraphic correlations are possible for the Lake Persimmon profiles, although ^{210}Pb dates are labelled only on profiles from the ^{210}Pb dated core. Lake Hollingsworth was cored initially in 1992 for paleolimnological analyses, and the sediment core used for pigment analyses was retrieved at the same location using g.p.s. coordinates in 1999. Additional sedimentation in the 1999 core makes direct stratigraphic correlation with the 1992 core less accurate, though overall historic trends within these cores still are comparable.

Results

Five out of 6 study lakes showed abrupt cyanobacterial proliferation and evidence of eutrophication during the last century. Cyanobacterial pigments were absent at the base of the core in one lake, were present intermittently at the base of cores from 3 lakes, were present at moderate levels at the base of the core from one lake, and were present at continuously high levels throughout the core from one lake. Two study lakes showed some evidence of improved water quality and cyanobacterial decrease at the tops of their sediment cores.

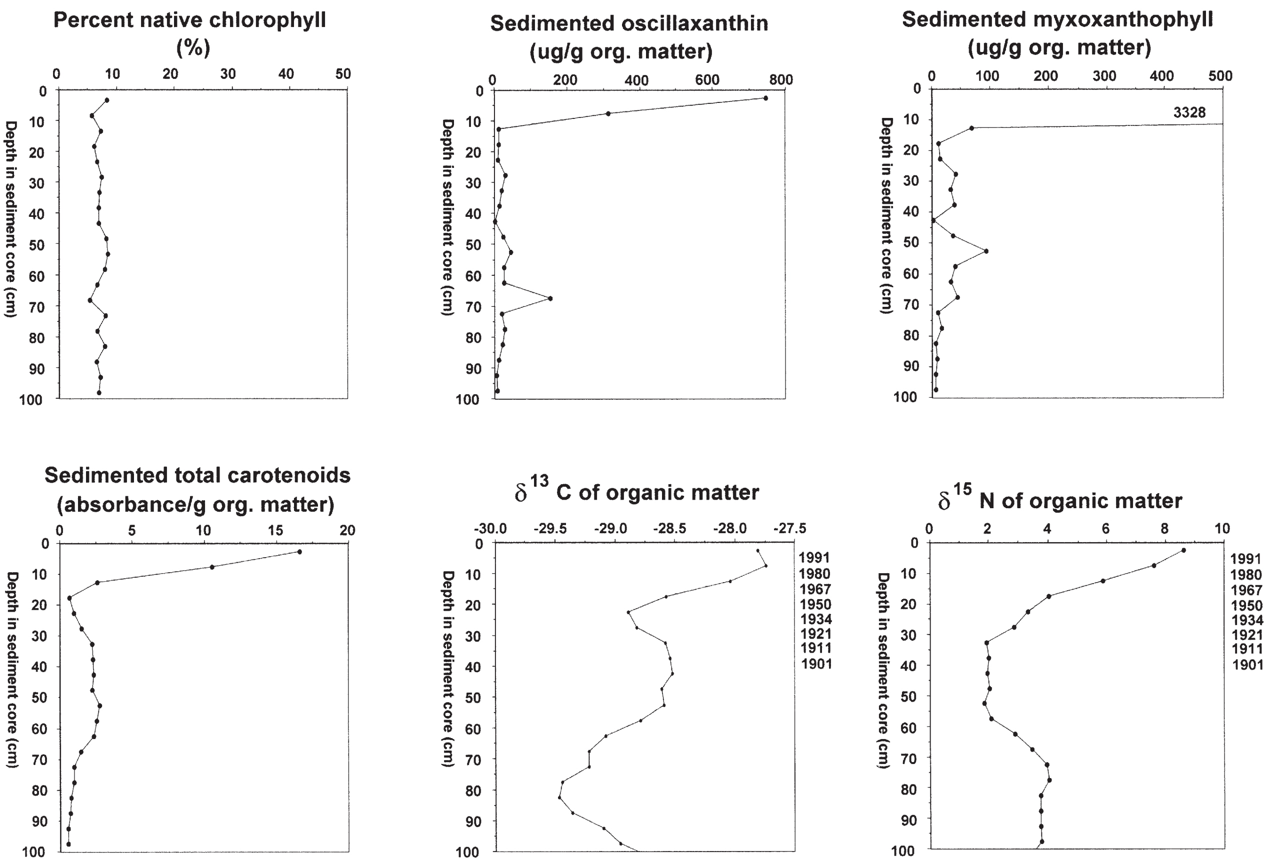

Figure 3.-Percent native chlorophyll, pigment concentrations, and stable isotope values of organic matter for sediment cores from Lake Persimmon, Highlands Co.

Lakes that show cyanobacterial increase and evidence of eutrophication

Lake Haines shows evidence of distinct recent cyanobacterial increase. Oscillaxanthin and myxoxanthophyll are absent in the sediment core below the 25-30-cm interval (c. 1961), but they increase rapidly in the top 30 cm of the sediment core (Figure 2). Sedimented total carotenoid concentrations increase abruptly above the 35-40-cm interval (c. 1941). Percent native chlorophyll varies somewhat in the lower portion of the core, but ranges from 10-20% and indicates that pigment preservation generally is constant above the 50-cm level. Diatom-inferred limnetic chlorophyll *a* inferences between the 90 and 37-cm levels average 18 µg/L, then values increase above the 37-cm level to a maximum value of 70 µg/L in the topmost sample. Inferred limnetic total P values show a long period of constancy (mean 37 µg/L) from the base of the sediment core to the 37-cm level, then increase above this level to ~83 µg/L at the top of the sediment core.

Lake Persimmon shows extremely abrupt cyanobacterial proliferation (Figure 3) in recent sediments. Oscillaxanthin, myxoxanthophyll, and total carotenoid concentrations are present at low levels from the base of the core to the 17-cm level, but they increase dramatically above the 15-cm level (c. 1967). Oscillaxanthin concentrations increase from 11 µg/g organic matter at the 12-cm level (c. 1973) to 744 µg/g organic matter at the top of the core. Myxoxanthophyll concentrations increase from 12 µg/g organic matter at the 17-cm level (c. 1958) to 3329 µg/g organic matter at the top of the core. Sedimented total carotenoid values range less than 2.5 absorbance units/g organic matter below the 17-cm level, then increase abruptly to 17 absorbance units/g organic matter at the top of the core. Percent native chlorophyll values show very constant pigment preservation throughout the core. $\delta^{13}C$ values indicate that primary productivity increased in the lake since the time of the 70-cm level. $\delta^{15}N$ values decline somewhat between the 70-cm and 30-cm levels, possibly because nitrogen fixation by cyanobacteria influenced $\delta^{15}N$ values closer to atmospheric values (0 ‰: Gu *et al.* 1996, Brenner *et al.* 1999a). Above the 30-cm level (c. 1921), however, $\delta^{15}N$ values increase steadily to a peak of ~8.5 ‰

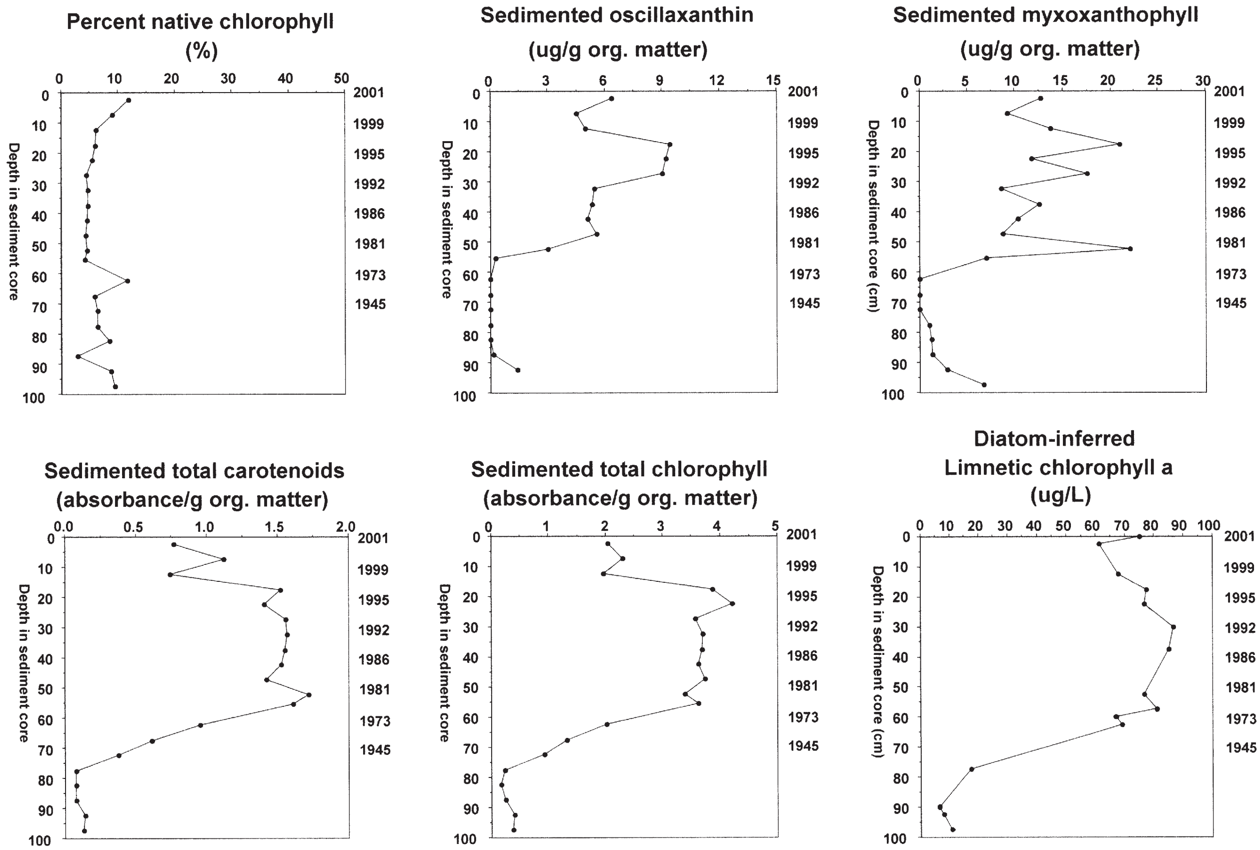

Figure 4.-Percent native chlorophyll, pigment concentrations, and water quality inferences for sediment core from Lake Conine, Polk Co.

at the top of the core. High $\delta^{15}N$ values in recent sediments suggest a changing source of nitrates entering the lake, with septic and commercial fertilizers as likely sources.

In the Lake Conine core (Figure 4), sedimented total carotenoid and total chlorophyll concentrations increase above the 80-cm level. Oscillaxanthin and myxoxanthophyll concentrations are low below the 60-cm level (c. 1973), but they increase abruptly above the 60-cm level. Percent native chlorophyll values vary somewhat below the 55-cm level, but generally are very constant above the 55-cm level, indicating that increased pigment concentrations are not an artifact of differential preservation. Limnetic chlorophyll *a* inferences are approximately 11 µg/L at the base of the core, they increase to ~70-85 µg/L between the 65 and 30-cm levels (1992), then they decline to an average of 72 µg/L above the 30-cm level. Pigment profiles decline above the 20-cm level (c. 1995) and provide some evidence of water quality improvement.

Lake Hollingsworth (Figure 5) sustained comparatively higher cyanobacterial pigment concentrations throughout the bottom portion of its sediment core than did the 3 previously discussed lakes. Oscillaxanthin and myxoxanthophyll concentrations are moderately high from the bottom of the core to the 40-cm level. Oscillaxanthin concentration increases to a peak at the 25-cm level, and myxoxanthophyll increases to a peak around the 10-cm level. Percent native chlorophyll values increase by about 50% between the 50 and 20-cm levels, but sedimented pigments in this portion of the core increase at a more rapid rate than would be accounted for simply by differential preservation. Percent native chlorophyll values continue to increase in the uppermost samples of the core suggesting better preservation, but algal pigment concentrations decrease in this portion of the sediment core. Diatom-inferred Florida 305(b) averaged TSI values are approximately 57 at the base of the core, increase to ~76 at the 30-cm level (1963), then decline to approximately 72 at the top of the core. $\delta^{13}C$ values increase from about -21 ‰ at the 50-cm level (1916) to about -16 ‰ at the 33-cm level (1959), then decline slightly to the top of the core. All cyanobacterial and water quality indicators suggest some water quality improvement towards the top of the sediment core.

In Lake May (Figure 6), oscillaxanthin and myxoxanthophyll concentrations are present intermittently below the 62-cm

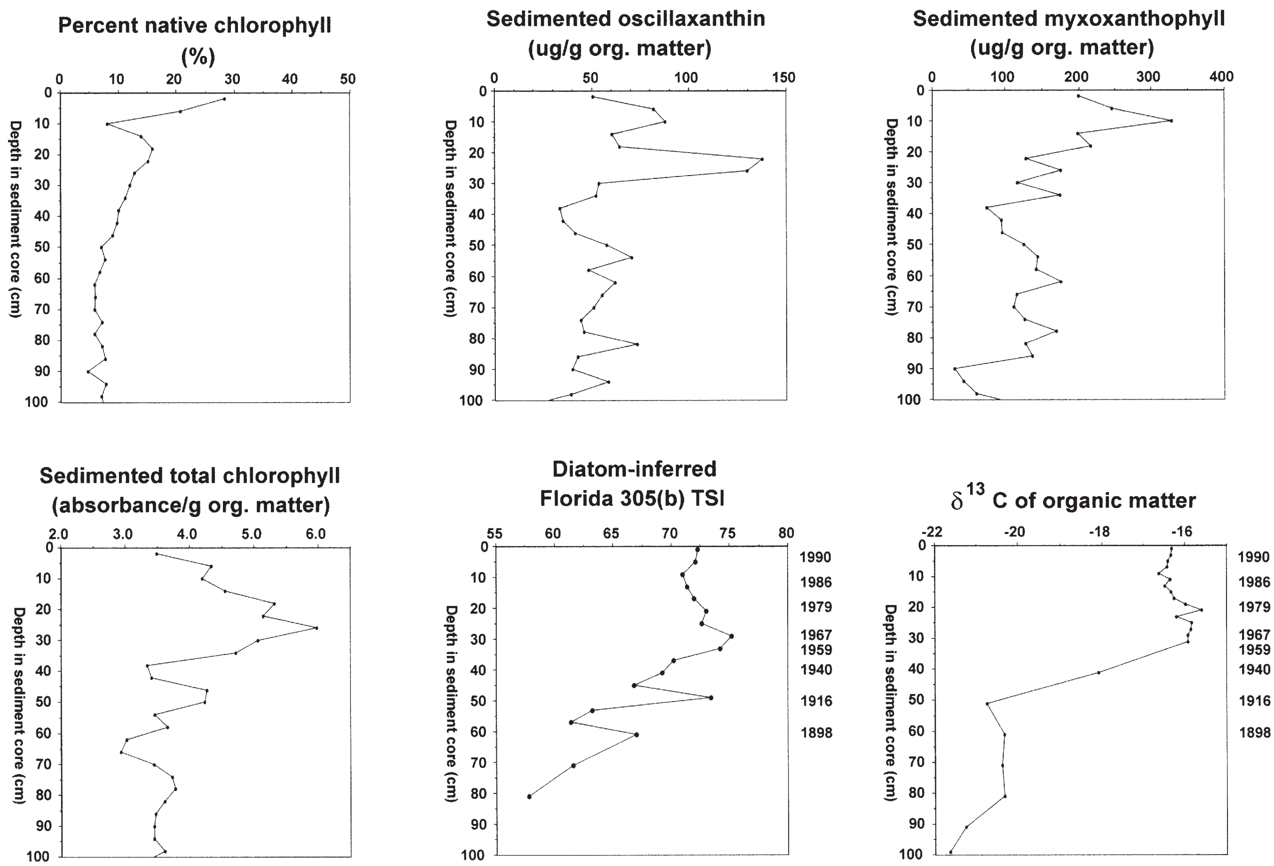

Figure 5.-Percent native chlorophyll, pigment concentrations, water quality inferences, and carbon stable isotope values for sediment cores from Lake Hollingsworth, Polk Co.

level (c. 1925) in the core. Oscillaxanthin and myxoxanthophyll concentrations essentially are 0 µg/g organic matter between the 62-cm level (c. 1925) and the 37-cm level (c. 1961), then they increase abruptly to 174 µg/g organic matter for oscillaxanthin and 430 µg/g organic matter for myxoxanthophyll at the top of the sediment core. Sedimented total carotenoids show a more general pattern of increase between the 70-cm level (c. 1882) and the 30-cm level (1970). Percent native chlorophyll values are very constant throughout the sediment core and indicate that changes in pigment concentrations are not caused by differential preservation. At the base of the sediment core, diatom-inferred limnetic total P concentration is approximately 42 µg/L and inferred limnetic chlorophyll *a* is approximately 16 µg/L. Diatom-inferred limnetic total P increases from 47 µg/L above the 40-cm level (1958) to 78 µg/L at the 30-cm level (1970), then declines to 62 µg/L at the top of the core. Limnetic chlorophyll *a* values follow a similar pattern: they are approximately 16 µg/L at the base of the core, increase abruptly above the 40-cm level to a peak of 70 µg/L at the 30-cm level, then decline to 48 µg/L at the top of the core.

A lake that shows persistent cyanobacterial presence

In Lake Wauberg, sedimented total chlorophyll, oscillaxanthin, and myxoxanthophyll concentrations are high throughout the core, which represents a period of time since prior to 1894 (Figure 7). Myxoxanthophyll values decline from approximately 95 µg/g organic matter at the 85-cm level (c. 1894) to 27 µg/g at the top of the sediment core. In contrast, oscillaxanthin and sedimented total chlorophyll values increase from the base of the core to a peak at the 50-55 cm level (1959-1966), remain high until the 25-cm level (1988), then decline to the top of the core. Percent native chlorophyll values decline from about 10% at the base of the sediment core to 5 % at the top of the core, and suggest that some of the pigment concentration decline at the top of the core might be caused by decreased preservation. Diatom-inferred Florida 305(b) TSI values decrease slightly from a value of 67 at the 85-cm level (c. 1894) to a value of 63 at the top of the sediment core.

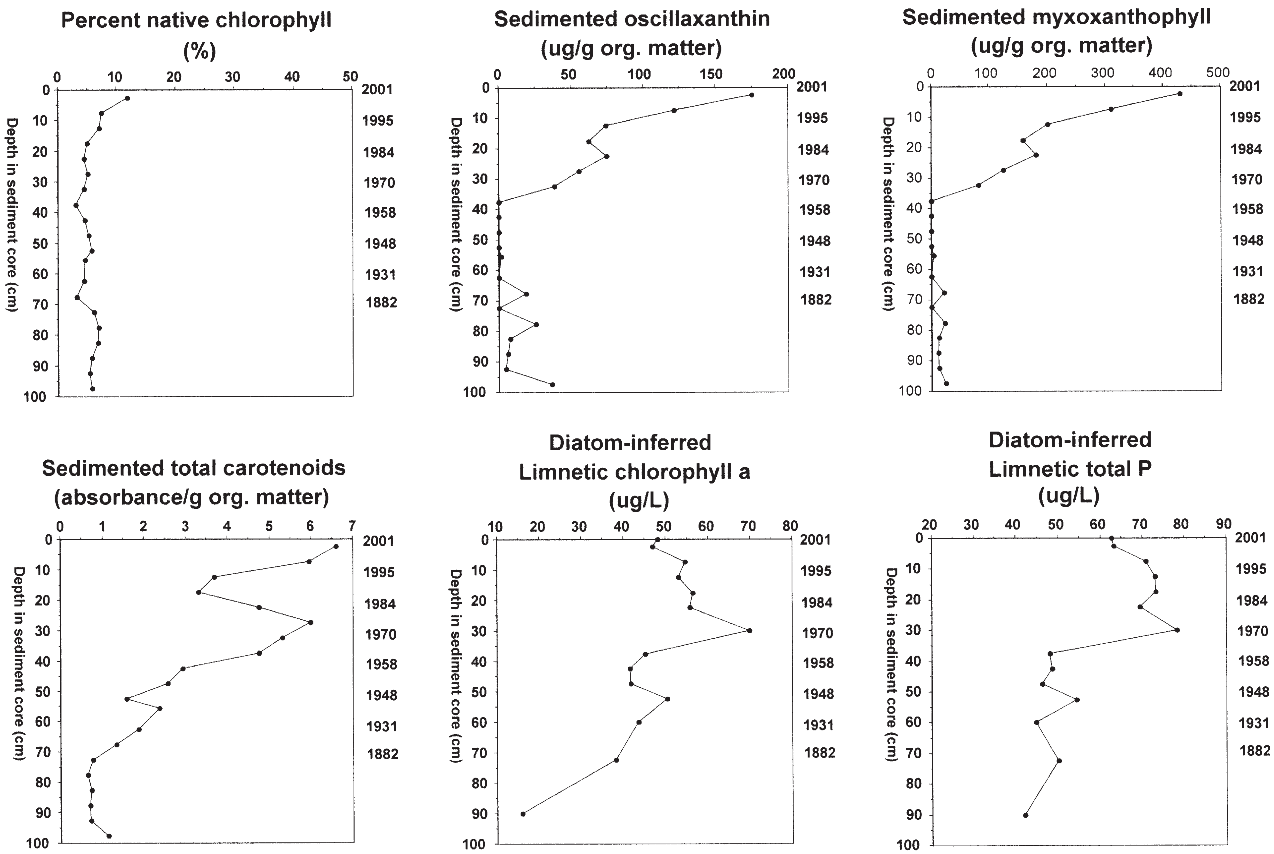

Figure 6.-Percent native chlorophyll, pigment concentrations, and water quality inferences for sediment core from Lake May, Polk. Co.

Discussion

Cyanobacterial proliferation occurred during recent decades in the majority of our study lakes, and patterns of cyanobacterial pigment change show strong concurrence with changes in inferred limnetic nutrient concentrations. The timing of cyanobacterial and nutrient increases in affected lakes was consistent with the expansion of agriculture, residential development, and point-source nutrient inputs, including sewage effluent and food-processing wastes. Human influence on cyanobacterial populations in productive Florida lakes appears to have been considerable in a number of instances.

In Lake Persimmon, for example, cyanobacterial pigment concentrations in sediments increased dramatically in the 1960-1970s, indicating that recent influences were responsible for unusually dense cyanobacterial concentrations in this lake. Commercial fertilizers from citrus agriculture appear to have contributed to cyanobacterial increase, as suggested by extremely high nitrate concentrations in subsurface waters and surface inflow to the lake, and by recent high $\delta^{15}N$ values in lake sediments. $\delta^{15}N$ values vary depending upon the source of nitrates. $\delta^{15}N$ values of commercial fertilizers, for instance, range between -2 ‰ and +4 ‰, and can become further enriched by up to +6 ‰ by ammonia volatilization, particularly in the presence of calcareous soil material. Nitrate from nitrification of organic soils ranges from +3 ‰ to +8 ‰, and nitrate from fecal wastes, including septic systems, ranges from +10 ‰ to +20 ‰ (Aravena *et al.* 1993).

Several factors might have led to $\delta^{15}N$ enrichment in recent Lake Persimmon sediments, such as leaching from residential septic systems around the perimeter of the lake. The effects of septic systems on $\delta^{15}N$ enrichment of groundwater have been demonstrated by Aravena *et al.* (1993). Although organic soil influx can increase $\delta^{15}N$ values in lake sediments, this is improbable in Lake Persimmon because our study disclosed that inorganic sediment accumulation rates decreased during recent decades. Fellows and Brezonik (1980) showed that subsurface seepage is an important component of the water budget in Florida lakes, and that nitrate content of seepage flows can be increased by the agricultural fertilization of citrus groves (Fellows and Brezonik 1981). Fertilizer applications to Florida citrus groves typically are in the range of 225-280 kg N ha^{-1} yr^{-1} (Reitz *et al.* 1972; J. Ferguson, University of Florida, pers. comm.). Synthesized fertilizers are a likely

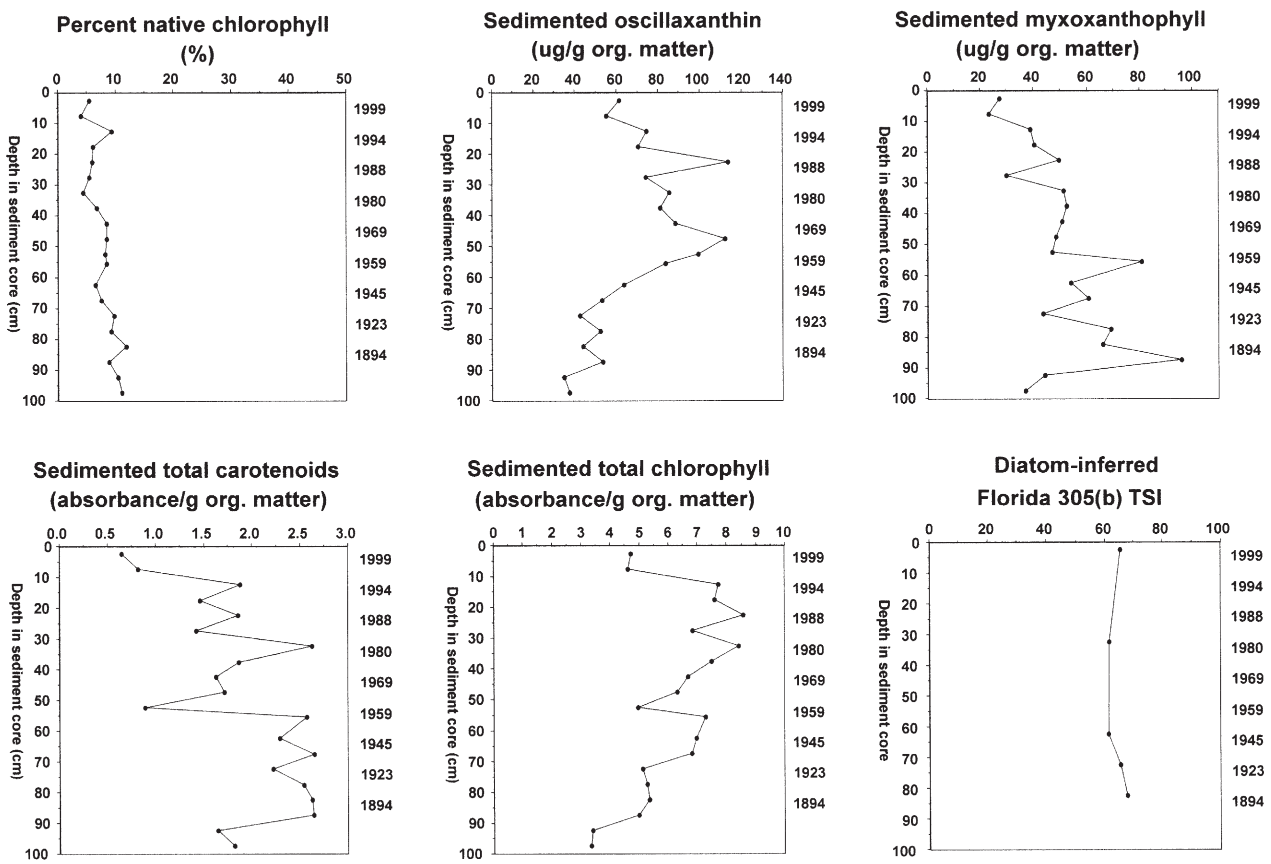

Figure 7.-Percent native chlorophyll, pigment concentrations, and water quality inferences for sediment core from Lake Wauberg, Alachua Co.

source, therefore, of subsurface N input and $\delta^{15}N$ enrichment in Lake Persimmon's sediments, particularly because 41% of the watershed is in citrus agriculture. Waters in a residential well on the south side of Lake Persimmon yielded $\delta^{15}N$ values of +2.5 ‰ (SWFWMD, unpublished data), which are within the range associated with commercial fertilizers (Aravena *et al.* 1993). Sandy soils, such as the Pleistocene sands in the Lake Persimmon watershed, typically require annual lime applications on the order of a few tons per acre to maintain optimal pH for citrus agriculture (J. Ferguson, University of Florida, pers. comm.), and this liming of citrus groves near Lake Persimmon could have facilitated $\delta^{15}N$ enrichment by ammonia volatilization (Aravena *et al.* 1993).

Sedimented cyanobacterial concentrations changed in a way that is highly consistent with the history of watershed nutrient influence on Lake Conine. Total carotenoids, total chlorophylls, and diatom-inferred limnetic chlorophyll *a* concentrations began to increase prior to the 1940s, and their patterns of change show strong concurrence (Figure 4). Oscillaxanthin and myxoxanthophyll concentrations were low prior to the 1970s, then they increased and remained high until the mid 1990s. Diatom-inferred limnetic chlorophyll *a* concentrations began to decline in 1992 at the time when municipal wastewater inputs were discontinued to Lake Conine. Cyanobacterial pigment concentrations declined slightly later, in 1995, at the time when Lake Conine was subject to whole-lake alum treatment.

Lake Haines, which also is on the Northern Winter Haven Chain and has received sewage effluent inputs like Lake Conine, shows a pattern of water quality change that is similar in timing to that of Lake Conine. Profiles for sedimented total carotenoids, diatom-inferred limnetic chlorophyll *a*, and diatom-inferred limnetic total P show constant water quality until the early 1940s (Figure 2), followed by a rapid increase in all 3 variables. Oscillaxanthin and myxoxanthophyll pigments were absent in the core prior to the early 1960s, then they appeared and showed a rapid increase until the present time. Diatom-inferred limnetic total P showed a slight decline at the top of the core beginning with the 1992 sample, which was the time when wastewater discharge to the lake was discontinued. Oscillaxanthin and myxoxanthophyll did not decline at the top of the Lake Haines core as they did in

Lake Conine, but Lake Haines, unlike Lake Conine, did not receive alum treatment prior to our study.

Water quality in Lake May began to change by about 1900. Lake May is located in Winter Haven, and it is the smallest and possibly most susceptible lake in our study. Sedimented total carotenoid pigments and diatom-inferred limnetic chlorophyll *a* inferences increased from c. 1900 to a peak in 1970, when diatom-inferred limnetic total P values also reached their highest point (Figure 6). Oscillaxanthin and myxoxanthophyll pigments essentially were absent in the core between 1931 and 1958, then they increased abruptly to the present time. Diatom indicators of water quality, and to some extent carotenoid pigments, suggest that some water quality improvement occurred since 1970, but there was no evidence of decline in oscillaxanthin and myxoxanthophyll pigment deposition in the lake.

Lake Hollingsworth showed significant cyanbacterial presence by c. 1900, which might be attributable in part to its location on phosphatic sands and clays of the Bone Valley Formation, as well as to establishment of citrus agriculture on adjacent slopes of its watershed by 1880. Diatom-inferred Florida 305(b) averaged TSI values showed progressive increase from the base of the core, and $\delta^{13}C$ values showed rapid increase after 1916. Both of these patterns are consistent with the timing of residential and urban development in the watershed (Brenner *et al.* 1995). Diatom-inferred Florida 305(b) TSI and $\delta^{13}C$ values decreased in sediments after the 1960s, probably in response to implementation of municipal sewage treatment for homes in the watershed. Sedimented total chlorophyll, oscillaxanthin, and myxoxanthophyll concentrations show a similar decline in the top portion of the core in the present study, despite increased pigment preservation that might obscure such declines. The precise timing of these pigment declines can not be determined in the present study, however, except that approximate stratigraphic correlation suggests that they occurred in recent decades. Water quality data from monitoring programs supports the conclusion of limnetic nutrient reductions since 1970, as shown by the 3 sets of data for Lake Hollingsworth in Table 1. Presently, mean limnetic total P values in the lake are less than 1/3, and mean limnetic total N values are less than 1/2 of what they were in 1968-1970.

Lake Wauberg is naturally eutrophic, and cyanobacteria were present throughout the 100-cm sediment record. Lake Wauberg's history shows that Florida lakes can be naturally productive and sustain cyanobacterial populations that are not directly attributable to eutrophication caused by human activities. The lake lies above phosphatic deposits of the Hawthorn Formation (Brooks 1981) and probably receives nutrient-rich groundwater inputs. Groundwater inputs to Florida lakes frequently are intermittent or variable (Deevey 1988), and they can influence water-level and trophic-state fluctuations over decadal periods of time. Lake Wauberg's variation in water quality, therefore, might result from natural variation in groundwater hydrology.

Wu *et al.* (2003) propose total maximum daily load goals for Lake Wauberg that are appropriate for target water quality conditions of 56 µg/L limnetic total P and a Florida 305(b) TSI value of 60. They arrived at these objectives after calculating natural background water quality by subtracting estimated watershed land-use loadings obtained with EUTROMOD from current nutrient and chlorophyll *a* concentrations in the lake. These restoration objectives, however, appear unattainable in light of empirical data from our paleolimnological study. Although the greatest part of watershed development occurred since 1980, cyanobacteria have been abundant in Lake Wauberg since prior to 1894, and Florida 305(b) TSI values have remained at > 60 during this period. The conclusion of sustained eutrophic conditions is consistent with limnological observations that document well-established cyanobacterial populations in Lake Wauberg as early as the 1930s (Carr 1934). The persistent presence of cyanobacteria alone suggests a long-term Florida 305(b) TSI value > 60 (Paulic *et al.* 1996), which is inconsistent with the natural background Florida 305(b) TSI estimate of 46.5 by Wu *et al.* (2003). Attempts to manage naturally productive lakes at limnetic nutrient concentrations that are less than natural background conditions are likely to prove costly and ineffective because such efforts endeavor to reduce nutrients below the levels at which they are being supplied from edaphic sources.

Cyanobacteria were present intermittently or at low levels in the early sedimentary records of 5 of the 6 lakes that we examined. Myxoxanthophyll and oscillaxanthin profiles in Lakes Conine, May, Hollingsworth, and Persimmon indicate that cyanobacterial populations in the early part of the last century were substantially less dense than they are today. Cyanobacteria appear to have been absent entirely in Lake Haines based upon the absence of myxoxanthophyll and oscillaxanthin pigments in sediments prior to the 1960s. Cyanobacterial increases in these lakes show strong relationships to past increases in limnetic nutrient concentrations and to watershed influences, particularly point-source nutrient inputs. Similar patterns of cyanobacterial response to water quality change have been observed in six additional Florida lakes in Seminole, Hillsborough, and Lake Counties (Riedinger -Whitmore, unpublished data). Cyanobacteria currently pose management problems in many Florida lakes, particularly within densely populated regions of central and southern Florida. Decisions about appropriate lake restoration goals can be difficult in such geologically heterogeneous regions when baseline water quality information is lacking. Because of the lack of long-term (>30 years) monitoring data for most Florida lakes, paleolimnological methods complement water quality monitoring programs by providing missing information about water quality change and subsequent cyanobacterial response during the past.

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