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Response of the cladoceran community to trophic state change in Lake Apopka, Florida

Byron C. Shumate[1], Claire L. Schelske[2], Thomas L. Crisman[1] & William F. Kenney[2]
[1]*Center for Wetlands, Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611-6350, USA (E-mail: shumate@grove.ufl.edu)*
[2]*Department of Fisheries and Aquatic Sciences, University of Florida, 7922 NW 71st Street Gainesville, FL 32653, USA*

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Abstract

A paleolimnological evaluation of cladoceran microfossils was initiated to study limnological changes in Lake Apopka, a large (125 km^2), shallow (mean depth = 1.6 m), warm, polymictic lake in central Florida. The lake switched from macrophyte to algal dominance in the late 1940s, creating a Sediment Discontinuity Layer (SDL) that can be visually used to separate sediments derived from macrophytes and phytoplankton. Cladoceran microfossils were enumerated as a means of corroborating extant eutrophication data from the sediment record. Inferences about the timing and trajectory of eutrophication were made using the cladoceran-based paleo-reconstruction. The cladoceran community of Lake Apopka began to change abruptly in both total abundance and relative percent abundance just before the lake shifted from macrophyte to algal dominance. *Alona affinis*, a mud-vegetation associated cladoceran, disappeared before the SDL was formed. Planktonic and benthic species also began to increase below the SDL, indicating an increase in production of both planktonic and benthic species. *Chydorus* cf. *sphaericus*, an indicator of nutrient loading, increased relative to all other cladocerans beginning in the layer below the SDL and continuing upcore. Changes in the transitional sediment layer formed before the lake switched to phytoplankton dominance, including an increase in total phosphorus concentration, suggest a more gradual eutrophication process than previously reported. Data from this study supported conclusions from other paleolimnological studies that suggested anthropogenic phosphorus loading was the key factor in the hypereutrophication of Lake Apopka.

Introduction

Historical impacts

Lake Apopka (Figure 1) is a large (125 km^2), shallow (mean depth = 1.6 m), warm, polymictic lake in central Florida located approximately 20 km northwest of Orlando, Florida. The lake switched from macrophyte to phytoplankton domination in the late 1940s and became highly nutrient enriched (mean TP = 203 μg/L) through the 1990s (Schelske et al., 2000). When Lake Apopka was macrophyte dominated, it was celebrated for being one of the premier sports fisheries in Florida and was known for its clear water.

Significant anthropogenic impacts on Lake Apopka began in the late 19th century (Schelske, 2000). In 1887 the Apopka-Beauclair canal was completed, effectively lowering the lake level from 2.4–2.7 m depth to its present average depth of 1.6 m. Diffuse-source nutrient loading accelerated in the early 1920s with the increase of citrus agriculture along portions of the well-drained southern shoreline. This also marked the period when the town of Winter Garden began to discharge primary-treated sewage directly into the south-

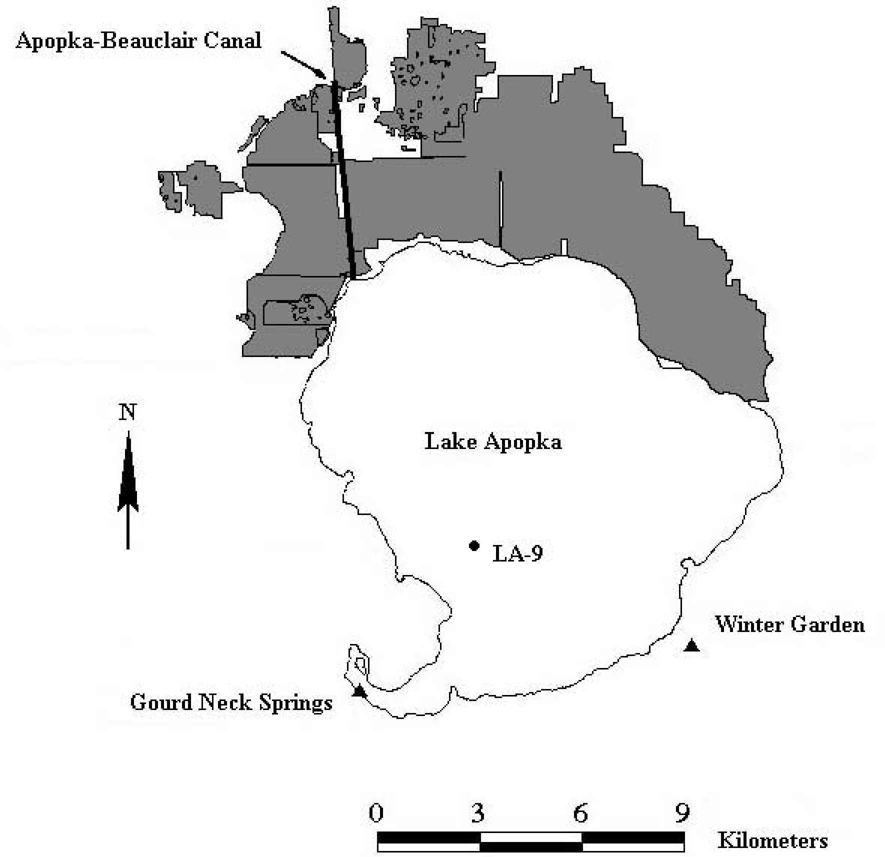

Figure 1. Map of Lake Apopka with location of core station LA-9 (28°36′06.5″N and 81°38′19.6″W). The shaded area along the northern shore approximates the wetland area that was diked and drained in the early 1940s so rich, muck soil could be used for agricultural purposes.

eastern shore of Lake Apopka. From 1942–1947, approximately 80 km^2 sawgrass (*Cladium jamaicense*) marsh was diked and drained along the northern and eastern shores for agricultural development. These 'muck farms' discharged fertilizer-enriched drainage water into Lake Apopka until their purchase by the St. Johns River Water Management District in the 1990s. In 1948, a citrus processing plant began discharging effluent into the lake. A control structure was placed in the Apopka-Beauclair canal in 1956, stabilizing the outflow.

There are two main hypotheses for the development of hypereutrophy in Lake Apopka. One is based on anecdotal accounts of a hurricane in 1947 (Bachmann et al., 1999), whereby the storm uprooted a substantial biomass of macrophytes and stirred up the bottom sediments. This action initiated a process that left the lake algal dominated and devoid of aquatic vegetation by 1950. Successive algal blooms were attributed to increased availability of phosphorus from wind-driven resuspension of macrophyte-derived sediments. Recent evidence, however, documents that the Category 4 hurricane passed well to the south of Lake Apopka on its east to west trajectory, but hurricane force winds were recorded at Cape Canaveral about 100 km to the east (Lowe et al., 1999).

The second hypothesis attributes historical anthropogenic phosphorus loading as the key factor for Lake Apopka's shift to hypereutrophy after the late 1940s (Schelske et al., 2000). Agricultural nutrient inputs, mainly from the muck farms, are presumed responsible for increased growth of epiphytic and planktonic algae in this scenario. The competitive advantage for planktonic algae in progressively enriched waters with low transparency would have led to the extinction of submerged vegetation and associated epiphytes in the lake. The present study and other evidence (Battoe et al., 1999; Lowe et al., 1999) suggest that the changes in Lake Apopka were more gradual than the abrupt transformation suggested by the hurricane hypothesis.

Paleolimnological investigation

Few studies on Lake Apopka were conducted until the late-1970s, when a multi-year survey of water quality in the Harris Chain of Lakes collected detailed data on biotic components of Lake Apopka as well as physical and chemical parameters (Brezonik et al., 1977, 1980, 1981; Tuschall et al., 1979). An extensive 80-station sediment study in 1991 characterized the sediment stratigraphy in Lake Apopka as phosphorus-poor, consolidated, flocculent sediment overlain by a less dense, phosphorus-rich, unconsolidated, flocculent sediment layer (Reddy & Graetz, 1991).

Paleolimnological analyses were initiated to infer historic changes in phosphorus loading in Lake Apopka, because of the limited historical limnological data. Schelske (1997) analyzed 57 sediment cores for several trophic state proxies, including sediment bulk density (rho), percent organic matter (%OM), total carbon to total nitrogen ratios (TC/TN), total phosphorus (TP), non-apatite inorganic phosphorus (NAIP), diatom microfossils, and biogenic silica (BSi). Additional related studies used sedimentary polyphosphate (Kenney, 1997), sedimentary chlorophyll derivatives (Waters, 2000), cyanobacterial pigments (Waters, 2000), and diatom microfossils (Schelske et al., 1999). Data interpretations were consistent with loss of macrophyte dominance and a shift to increased algal productivity associated with increased phosphorus loading. These investigations clearly demonstrated that the deeper consolidated sediments were derived from macrophytes, while the surficial flocculent sediments were of algal origin.

None of the previous paleolimnological analyses examined faunal subfossil assemblages. This study was initiated to examine stratigraphic changes in cladoceran microfossil assemblages in Lake Apopka, and to determine whether such changes were consistent with either gradual cultural eutrophication or a rapid change resulting from the 1947 hurricane. Cladocerans have been used often in paleoecological reconstructions of environmental change. Their chitinous exoskeletal components (shell, head shield, postabdomen, postabdominal claws, antennal segments, and mandibles) are usually well preserved after death. Furthermore, most are identifiable to species. Ecological information exists for most species, and they are sensitive to changes in environmental variables such as trophic state, conductivity, and predation intensity (Crisman, 1978).

Materials and methods

Sediment cores were collected from Lake Apopka in 1995 (Schelske, 1997), 1997 (Kenney, 1997), and 1999 (Waters, 2000) at site LA-9 (Figure 1) using a simple piston corer (Fisher et al., 1992). All cores were extruded vertically in the field at 4 cm (Waters, 2000) or 5 cm (Kenney, 1997; Schelske, 1997) intervals. The deepest algal-derived interval, the Sediment Discontinuity Layer (SDL), was visually identified for each core.

Wet subsamples were collected (Kenney, 1997) from core LA-9-97 and stored under refrigeration in sealed test tubes. These were prepared for cladoceran analysis in June 1999 by a slightly modified version of the Frey (1986) method, whereby a heated shaker bath was used instead of a hot plate with a magnetic stirrer to break sediment aggregates. Although Frey (1986) recommended use of hot, dilute HCl to dissolve carbonates, molluscan shell matter, present in deeper sediments, did not interfere with slide preparation. Quantitative slides were prepared according to Crisman (1980). Microfossils were counted under a stereomicroscope at 400 × magnification. Head capsules and shells for each species were enumerated, and at least 200 chydorid remains were counted in each sample. Numbers of individuals per taxon in a sample were based on the most numerous body part identified for each species (Frey, 1986).

Results and discussion

Correlation of cores

When standardized to the SDL, our core from 1997 was stratigraphically consistent with the other cores with respect to the analyzed sediment parameters. The sample below the SDL showed the beginnings of an increase in bulk density (Figure 2a) and an increase in TP (Figure 2b). A shift in the diatom microfossil community from LA-9-95 (Schelske et al., 1999) also occurred below the SDL. The data clearly indicated a transitional interval below the phytoplankton sediments, deeper than the SDL.

Cladoceran analyses

Concentrations of the three most common cladoceran taxa (*E. tubicen*, *C.* cf. *sphaericus*, and *Alona circum-*

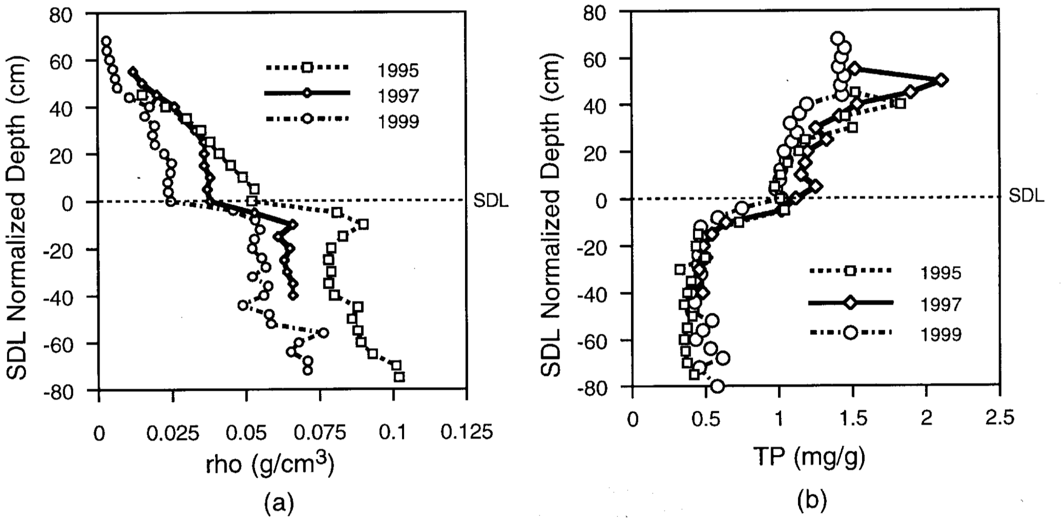

Figure 2. Lake Apopka sediment parameters from cores LA-9-95 (Schelske, 1997), LA-9-97 (Kenney, 1997), and LA-9-99 (Waters, 2000). Sediment bulk density (rho) and total phosphorus (TP) are graphed in 2a and 2b respectively. The depth of the SDL was set to zero for each core. Sample depths are labeled as the maximum depth of the measured sediment interval.

fimbriata) increased upcore beginning just below the SDL (Figure 3). This corroborated diatom (Schelske et al., 1999), polyphosphate (Kenney, 1997), and pigment (Waters, 2000) data, in that three of four dominant cladoceran taxa displayed total abundance increases beginning at this sample interval. This increase probably reflected a response to increased nutrient input to the system. *Alona affinis* was absent from the interval below the SDL and above (Figure 3). This species is associated with mud-vegetation habitats (Chengalath, 1982), and its absence in the flocculent sediments of algal origin reflected the loss of littoral habitat in Lake Apopka.

Stratigraphic changes in the relative abundances of cladocerans in core LA-9-97 were also evaluated (Figure 4). *C.* cf. *sphaericus*, whose temperate analogue is a well-known indicator of eutrophication (Crisman, 1978; Frey, 1980), has been associated with increased nutrient loading in Florida lakes (Crisman, 1980; Crisman et al., 1992). It displayed the greatest relative increase, starting from the interval below the SDL and continuing upcore. The relative abundance of *A. circumfimbriata* also began to increase at this level. Predominantly benthic, its increased abundance probably reflected the loss of macrophytes. Relative abundance changes also corresponded with other environmental proxies in the core (Figure 2). Most striking was the proliferation of *C.* cf. *sphaericus* relative to all other species and the loss of *A. affinis* with the onset of increased phosphorus loading (Figure 2b). This was consistent with increased eutrophication and drastic reduction of macrophyte cover. The cladoceran results also corroborated interpretations of the recent history of Lake Apopka based on physical (Figure 2a), chemical (Figure 2b), and diatom species composition for LA-9-95 (Schelske et al., 1999). However, diatoms were evaluated at alternate 5-cm interval in that study, and the SDL was not examined (Schelske et al., 1999). Nevertheless, a transition in the diatom assemblage was evident between the intervals immediately above and below the SDL. A more diverse community gave rise to a transitional community dominated by meroplanktonic (*Aulacoseira italica*) and sessile epipelic benthic (*Pseudostaurosira brevistriata*, *Staurosirella pinnata*, and *Staurosira construens*) species. Relative diatom abundances and total concentrations displayed stratigraphic shifts coincident with cladoceran community changes detected in core LA-9-97.

Appreciable numbers of planktonic and facultatively planktonic cladocerans and diatoms were enumerated in the older, macrophyte sediments. Anecdotal accounts maintained that Lake Apopka was completely dominated by macrophytes prior to the onset of algal dominance (Bachmann et al., 1999; Schelske, 2000). However, the planktonic *E. tubicen*, the facultatively planktonic *C.* cf. *sphaericus*, and the meroplanktonic diatom, *Aulacoseira italica* (Schelske et al., 1999), were found in consolidated, macrophyte sediments at LA-9, below the SDL. These biological proxies indicate that planktonic refugia existed in Lake Apopka during the period of macrophyte dominance.

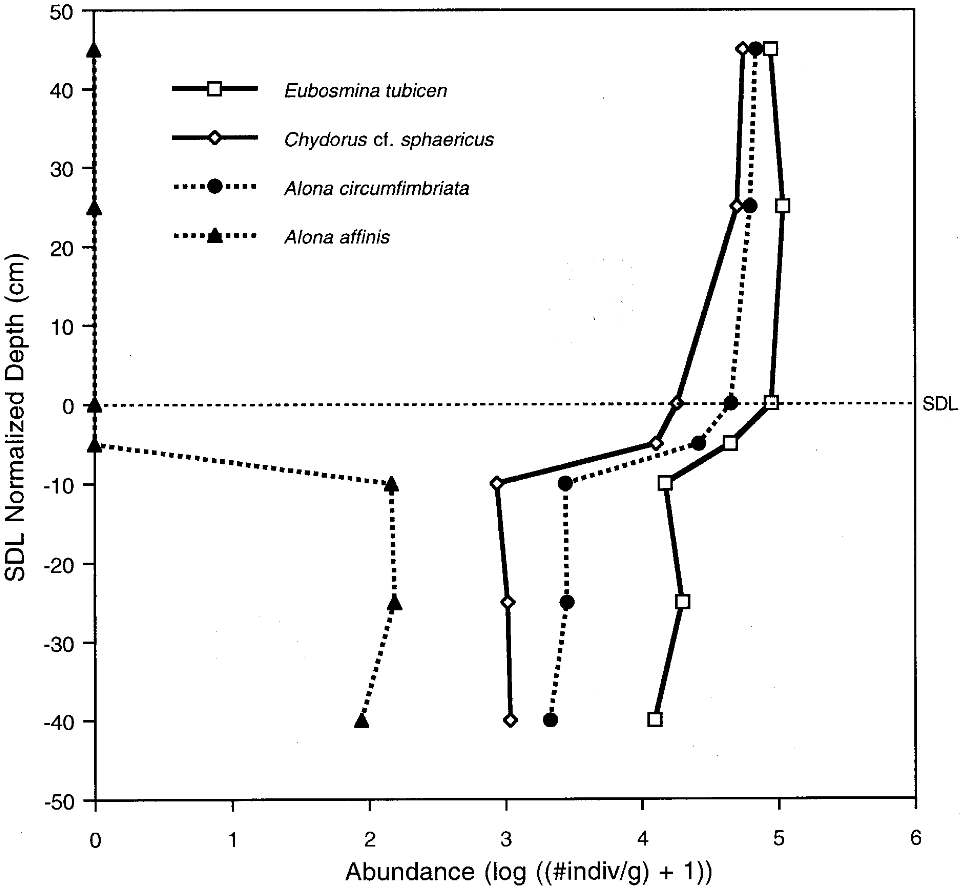

Figure 3. Cladoceran abundance for LA-9-97. The depth of the SDL was set to zero. Sample depths are labeled as the maximum depth of the measured sediment interval.

Timing of shift in community structure

Lake Apopka sediment cores (Schelske, 1997) were ^{210}Pb dated using a modified version of the CRS model (Appleby & Oldfield, 1983), which assumes a constant rate of supply of excess ^{210}Pb to the lake sediments. The diking and draining of the fringing wetlands in the 1940s, which altered lake hydrology and may have changed the supply rate of ^{210}Pb to the sediments, confounded application of the model to Lake Apopka. Schelske (1997) concluded that only sediments deposited after diking and draining could be dated reliably using the model, making it impossible to assign an age to the sediments below the SDL.

Calculation of sediment accumulation rates for the topmost macrophyte sediments in Lake Apopka has remained problematic. Although no age has been assigned, it can be assumed that the transitional interval (just below the SDL) was deposited before the switch from macrophytes to phytoplankton. Changes in the microfossil assemblage in this interval reflected a faunal response to increased phosphorus loading to the lake before the 1940s. This is expected, because phosphorus loading from the city of Winter Garden and citrus processing were significant in the 1920s (Battoe et al., 1999; Schelske et al., 2000). Furthermore, if these layers were chronologically deposited, there had to be some time lapse between their sedimentation.

Sediment mixing

The cladoceran sediment record did not support the notion that surficial, flocculent, algal-derived sediments were merely older, consolidated, macrophyte-derived sediments resuspended by catastrophic or periodic wind events (Bachmann et al., 1999). The two layers should

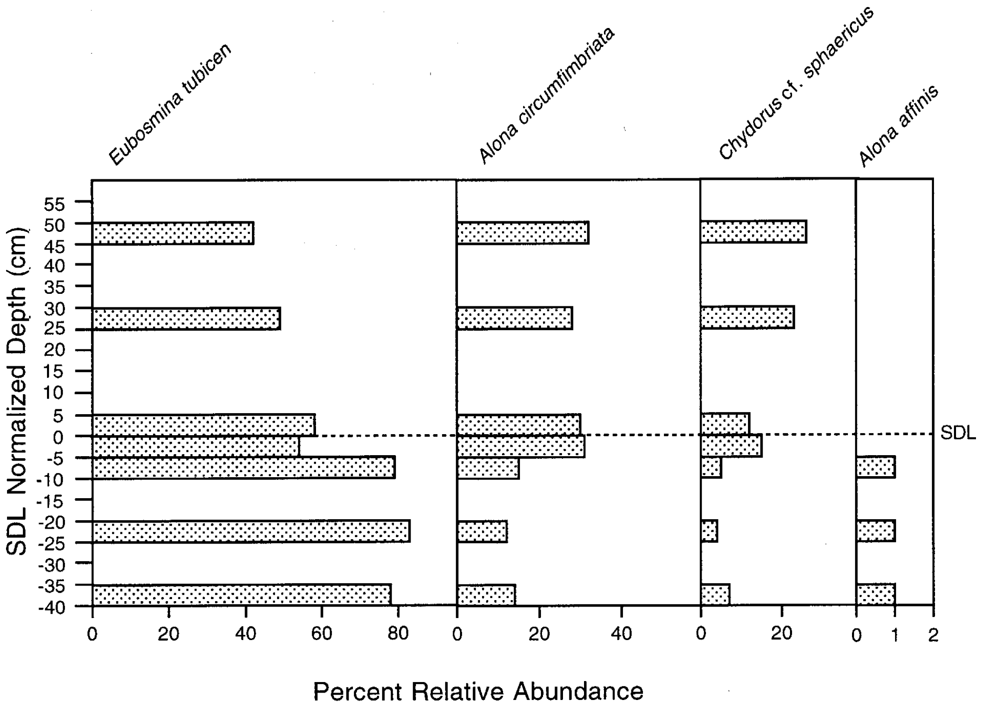

Figure 4. Cladoceran percent relative abundance for LA-9-97. The depth of the SDL was set to zero. Sample depths are labeled as the maximum depth of the measured sediment interval.

have had some similarities, but cladoceran abundances (Figure 3) and relative percent abundances (Figure 4) differed. Poor preservation of consolidated sediments combined with constant integration of recently deceased cladocerans in the flocculent sediments could have explained this. *A. affinis*, however, was absent in the flocculent, but well documented in the consolidated sediments. These differences were corroborated by changes in diatom community structure (Schelske et al., 1999).

Summary

The cladoceran sediment record (Figures 3 & 4) independently supported other paleolimnological evidence (Figure 2) from Lake Apopka, a large (125 km^2), shallow (mean depth = 1.6 m), warm, polymictic lake in central Florida, which became hypereutrophic as a result of anthropogenic phosphorus loading (Battoe et al., 1999; Lowe et al., 1999; Schelske et al., 2000). This study demonstrated that an abrupt change in the cladoceran microfossil assemblage began below the SDL, the stratigraphic interval dividing the older, consolidated, macrophyte sediments from younger, flocculent, phytoplankton sediments. Cladoceran microfossil abundances increased dramatically in recent sediments suggesting enhanced lacustrine productivity. The loss of *A. affinis*, a cladoceran associated with mud-vegetation, in recent sediments probably coincided with the loss of littoral habitat. The relative abundance of *C.* cf. *sphaericus* increased upcore, providing additional evidence of eutrophication in Lake Apopka. Changes in the sediment cladoceran assemblage occurred below the zone of phytoplankton sediments and coincided stratigraphically with other paleolimnological evidence suggestive of increasing eutrophication in Lake Apopka before the shift to phytoplankton dominance.

Some anecdotal accounts suggested that the eutrophication process in Lake Apopka was a sudden event that resulted from a hurricane, which uprooted macrophytes and left the lake phytoplankton dominated within a few weeks. However, information from lake sediment cores, including data on cladocerans, TP, polyphosphate, bulk density, pigments, and diatoms, suggests that there was a transitional sediment layer between the baseline, macrophyte-dominated sediments and the SDL. The absence of *A. affinis* from the interval below the SDL and above indicated that the interval below the SDL was indeed a transitional sediment interval, and not the product of sediment mixing from a large-scale wind event or other physical process. The cladoceran record confirms that eutrophication of Lake Apopka began before the lake was phytoplankton dominated.

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References

Appleby, P. G. & F. Oldfield, 1983. The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103: 29–35.

Bachmann, R. W., M. V. Hoyer & D. E. Canfield Jr., 1999. The restoration of Lake Apopka in relation to alternative stable states. Hydrobiologia 394: 219–232.

Battoe, L. E., M. F. Coveney, E. F. Lowe & D. L. Stites, 1999. The role of phosphorus reduction and export in the restoration of Lake Apopka, Florida. In Reddy, K. R., G. A. O'Connor & C. L. Schelske (eds.), Phosphorus Biogeochemistry in Subtropical Ecosystems. Lewis Publishers, Boca Raton, 511–526.

Brezonik, P. L., C. D. Pollman, T. L. Crisman, J. N. Allinson & J. L. Fox, 1977. Limnological studies on Lake Apopka and the Oklawaha chain of lakes 1. Water Quality in 1977. Report to Florida Department of Environmental Regulation, Tallahassee. Report No. ENV-07-78-01, Department of Environmental Engineering Sciences, University of Florida, 283 pp.

Brezonik, P. L., T. L. Crisman, C. D. Pollman & P. D. Sacco, 1980. Limnological studies on Lake Apopka and the Oklawaha chain of lakes. 3. Water quality in 1979. Report No. ENV-07-80-02, Department of Environmental Engineering Sciences, University of Florida, 109 pp.

Brezonik, P. A., S. D. Preston & T. L. Crisman, 1981. Limnological studies on Lake Apopka and the Oklawaha chain of lakes. 4. Water quality in 1980 and a summary of the four-year database. Report No. ENV-07-81-02. Department of Environmental Engineering Sciences, University of Florida, 140 pp.

Chengalath, R., 1982. A faunistic and ecological survey of the littoral Cladocera of Canada. Can. J. Zool. 60: 2668–2682.

Crisman, T. L., 1980. Chydorid cladoceran assemblages from subtropical Florida. In Kerfoot, W. C. (ed.), Evolution and Ecology of Zooplankton Communities Special Symposium Volume 3. University Press of New England. Hanover, New Hampshire, 657–668.

Crisman, T. L., 1978. Interpretations of past environments from lacustrine animal remains. In Walter, D. (ed.), Biology and Quaternary Environments. Australian Academy of Sciences, Canberra, 69–101.

Crisman, T. L., J. R. Beaver, J. K. Jones, A. E. Keller, A. G. Neugaard & V. Nilakantan, 1992. Historical Assessment of Cultural Eutrophication in Lake Weir, Florida. Department of Environmental Engineering Sciences, University of Florida, Gainesville and St. John's River Water Management District, Palatka, FL, 442 pp.

Fisher, M. M., M. Brenner & K. R. Reddy, 1992. A simple, inexpensive piston corer for collecting undisturbed sediment/water interface profiles. J. Paleolim. 7: 157–161.

Frey, D. G., 1980. On the plurality of *Chydorus sphaericus* (O. F. Müller) (Cladocera, Chydoridae), and designation of a neotype from Sjaelsø, Denmark. Hydrobiologia 69: 83–123.

Frey, D. G., 1986. Cladocera Analysis. In Berglund, B. E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons Ltd., 667–692.

Kenney, W. F. III, 1997. A comparison of chemical assays for the estimation of bioavailable phosphorous in Lake Apopka sediments. M. S. Thesis, University of Florida, 67 pp.

Lowe, E. F., L. E. Battoe, M. F. Coveney & D. L. Stites, 1999. Setting water quality goals for restoration of Lake Apopka: Inferring past conditions. Lake Reserv. Manage. 15: 103–120.

Osborne, J. A., 1974. Unpublished zooplankton data for Lake Apopka, Florida. Florida Technological University, Orlando, FL.

Reddy, K. R. & D. A. Graetz, 1991. Internal nutrient budget for Lake Apopka. Final Report, Project No. 15-150-1 SWIM 1987-90. Special Publication SJ 91-SP6. St. Johns River Water Management District, Palatka, FL, 371 pp.

Schelske, C. L., 1997. Sediment and phosphorus deposition in Lake Apopka. Final Report, Contract No. 96W213. Special Publication SJ97-SP21. St. Johns River Water Management District, Palatka, FL, 97 pp.

Schelske, C. L., 2000. Wind or nutrients: Historic development of hypereutrophy in Lake Apopka, Florida. Arch. Hydrobiol. Spec. Issues Advanc. Limnol. 55: 543–563.

Schelske, C. L., C. M. Donar & E. F. Stoermer, 1999. A test of paleolimnological proxies for the planktonic/benthic ratio of microfossil diatoms in Lake Apopka. In Mayama, S., M. Idei & I. Koizumi (eds.), 14th Diatom Symposium. Koeltz Scientific Books, Koenigstein, 367–382.

Tuschall, J. R., T. L. Crisman, P. L. Brezonik & J. N. Allinson, 1979. Limnological Studies on Lake Apopka and the Oklawaha Chain of Lakes 2. Water Quality in 1978. Report to Florida Department of Environmental Regulation, Tallahassee. Report No. ENV-07-79-02, Department of Environmental Engineering Sciences, University of Florida, 114 pp.

Waters, M. N., 2000. The use of sedimentary algal pigments to infer historic algal communities in Lake Apopka, Florida. M. S. Thesis, University of Florida, 56 pp.