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Whole-basin, mass-balance approach for identifying critical phosphorus-loading thresholds in shallow lakes

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Abstract Lake Lochloosa, Florida (USA) recently underwent a shift from macrophyte to phytoplankton dominance, offering us the opportunity to use a whole-basin, mass-balance approach to investigate the influence of phosphorus loading on ecosystem change in a shallow, sub-tropical lake. We analyzed total phosphorus (TP) sedimentation in the basin to improve our understanding of the forcing factor responsible for the recent shift to phytoplankton dominance. We measured ^{210}Pb activity, organic matter (OM), organic carbon (OC) and TP in short sediment cores from 20 locations to develop a comprehensive, whole-basin estimate of recent mass sedimentation rates (MSR) for bulk sediment, OM, OC and TP. The whole-basin sedimentation models provided insights into historic lake processes that were not evident from the limited, historic water quality data. We used Akaike's Information Criteria to differentiate statistically between constant MSR and exponentially increasing MSR. An eightfold, exponential increase in TP accumulation over the past century provided evidence for the critical role of increased P loading as a forcing factor in the recent shift to phytoplankton dominance. Model results show increased TP retention and decreased TP residence time were in-lake responses to increased TP loading and the shift from macrophyte to phytoplankton dominance in Lake Lochloosa. Comparison of TP loading with TP retention and historic, diatom-inferred limnetic TP concentrations identified the TP loading threshold that was exceeded to trigger the shift to phytoplankton dominance.

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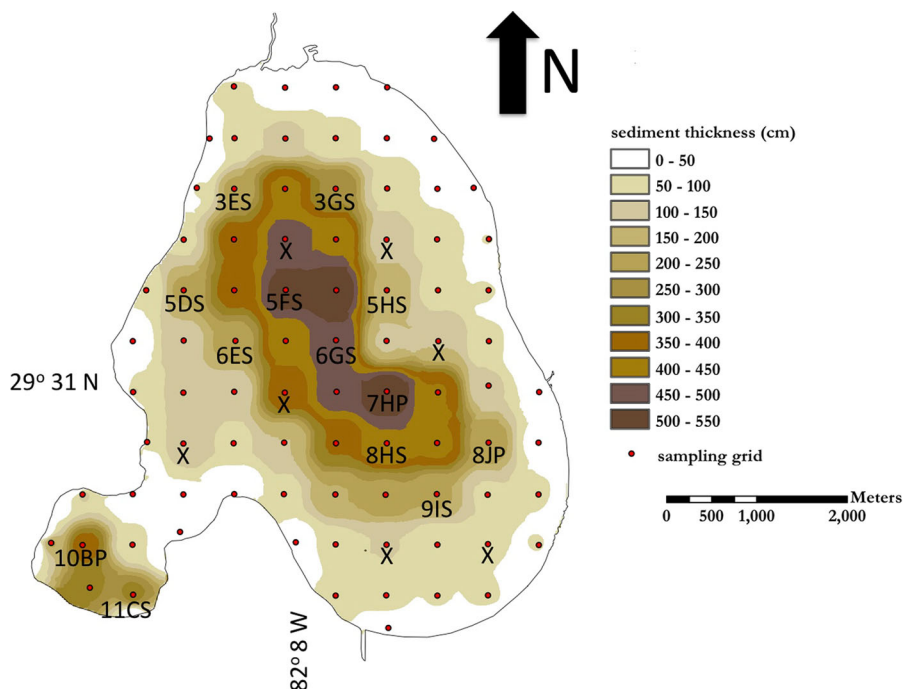
Introduction

In the past 20 years, numerous limnological and paleolimnological studies have focused on the structure, function and environmental history of shallow lakes. Shallow lakes represent a majority of lakes globally (Downing et al. 2006) and predominate in Florida, USA. The alternative stable states model (Scheffer et al. 1993) describes the functioning of shallow lakes as a contrast between periods of lesser external phosphorus (P) loading when macrophytes dominate and periods of increased external P loading that result in a shift to phytoplankton dominance. Numerous modern examples of phytoplankton-dominated (Jeppesen et al. 2003) and macrophyte-dominated shallow lakes (Zimmer et al. 2009) exist, and historic shifts between these stable states are evident from sediment core data (Kenney et al. 2002; Sayer et al. 2010).

We collected multiple sediment cores and applied a whole-basin, mass-balance approach (Engstrom and Rose 2013) to shallow, sub-tropical Lake Lochloosa, Florida, USA (Fig. 1) to gain insights into factors that drove a recent increase in phytoplankton abundance and a decrease in macrophyte coverage in the lake. From 1980 to 2009, Chl *a* concentrations increased from 25 to 92 μg L^{-1} (Huber et al. 1982; Florida Lakewatch 2009). At the same time, areal and volumetric macrophyte coverage decreased dramatically (Lakewatch 2004). A recent study showed surface sediments (0–4 cm) in Lake Lochloosa had 1.5 mg g^{-1} total P (TP), roughly double the concentrations found in deeper sediments (Brenner et al. 2009). We suspected that comprehensive analysis of TP sedimentation rates in the lake could improve our understanding about the forcing factor(s) responsible for the recent change in the primary producer community in this shallow lake.

Because of the potential for wind-induced mixing of deposits in shallow lakes, the ability of sediments in such water bodies to preserve an accurate record of past environmental conditions has been questioned (Schottler and Engstrom 2006; Engstrom et al. 2006). In a recent study of shallow lakes in Florida, ^{210}Pb-dated cores revealed orderly deposition of sediments over the past 100 years (Kenney et al. 2010). Heggen et al. (2012) suggested that study of a single core might be sufficient to evaluate microfossil sedimentation in small lakes, whereas Rippey et al. (2008) concluded that five to ten cores are needed to estimate whole-basin sediment accumulation. Because wind-stressed

Fig. 1 Map of Lake Lochloosa. Contours of soft sediment thickness (ST) are in cm. Sampling sites for ST are represented by red circles. Names of coring locations are presented below the sampling site. "X" below a sampling site indicates that a core was collected, but could not be ^{210}Pb-dated successfully

sediment thickness (cm)

0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 500
500 - 550

• sampling grid

Meters
0   500   1,000   2,000

29° 31 N

82° 8 W

shallow lakes of Florida can display highly variable sediment distribution (Whitmore et al. 1996a), we attempted to ^{210}Pb-date sediment cores from 20 locations in Lake Lochloosa, with the goal of estimating recent, whole-basin accumulation for bulk sediment, organic matter (OM), organic carbon (OC) and TP. We hypothesized that P loading and the TP sedimentation rate (TP-MSR) increased over the past century, and that a whole-basin mass-balance assessment would reveal the TP loading threshold was exceeded, which triggered the shift to phytoplankton dominance.

Site description

Lake Lochloosa is a relatively large (~ 22.9 km^2), shallow ($z_{max} = \sim 3$ m) water body in north central Florida, USA (29°31′38″N, 82°8′26″W, Fig. 1) (Florida Lakewatch 1996). The water body has no significant overland inflows, but water leaves the lake via Cross Creek and flows southwest into Orange Lake. European settlement in the area began after 1880, following completion of a railroad that connected the Florida cities of Jacksonville and Tampa (Glisson 1993). Early reports indicated that macrophyte coverage limited seine-haul fishing to 10 small areas (<2 ha) of the lake (Glisson 1993). Recent limnological data show that the lake is eutrophic. For samples collected between 1993 and 2009, mean values for measured water quality variables were: total phosphorus = 68 µg L^{-1}, total nitrogen = 2,234 µg L^{-1}, Chl a = 92 µg L^{-1}, and Secchi disk depth = 55 cm) (Florida Lakewatch 2009). In the early 1980s, Huber et al. (1982) reported mean nutrient concentrations in Lake Lochloosa (TP = 53.8 µg L^{-1}, TN = 1,902 µg L^{-1}) that were similar to current concentrations, but a lower mean Chl a value (24.5 µg L^{-1}) and greater Secchi disk depth (82 cm) (Florida Lakewatch 2009). Currently the lake is phytoplankton-dominated. Between 1991 and 2003, the area covered by aquatic vegetation decreased from 70 to 6 %, with a corresponding decrease in percent volume filled with macrophytes, from 22 to 0.7 % (Lakewatch 2004). These observations are consistent with sediment core data that showed recent sediments had lower OC to total nitrogen ratios than deeper sediments (Brenner et al. 2009). These data indicate increased phytoplankton productivity relative to macrophytes in the last 30 years.

Materials and methods

We measured water depth and soft sediment thickness (ST) at 85 locations that were evenly spaced throughout the lake to approximate equal-area representation. We measured water depth by lowering a submersible camera to the sediment/water interface and recording the length of cable deployed. We forced rigid, marked metal rods into the sediment to an impenetrable contact and recorded the depth from the water surface. Soft ST was estimated as the difference between the depth to the impenetrable contact and the water depth. We used the ST data to identify 20 coring locations where there had been sufficient sediment accumulation to likely yield reliable ^{210}Pb chronologies (Fig. 1).

Twenty sediment/water interface cores were collected with a piston corer (Fisher et al. 1992). Cores were extruded vertically and sectioned at 4-cm intervals in the field. Samples were stored in low-density polyethylene cups in ice chests for transport to the laboratory. Sediment sections were frozen, freeze-dried and ground to a fine powder in the laboratory before analyses. OM content was determined by weight loss on ignition (LOI) after combustion at 550 °C for 2 h. Organic C was measured with a Carlo Erba NA1500 CNS elemental analyzer (Verardo et al. 1990). TP was measured according to Schelske et al. (1986). Sediment bulk density (g dry cm^{-3} wet) was determined from the proportion of dry matter in wet sediment and proportions of inorganic and OM in dry sediment, using the equation of Binford (1990).

Because they are used in the estimation of past P export from the lake, historic limnetic TP concentrations are a critical component to the whole-basin, mass-balance approach (Engstrom and Rose 2013). We assessed historic limnetic TP concentrations with a diatom-based transfer function. To obtain diatom-based, historic limnetic total P inferences (DI-TP), we used a previously compiled calibration data set (Riedinger-Whitmore et al. 2005). Exploratory analyses were performed using CANOCO version 4.5 (ter Braak and Smilauer 2002). Analyses were performed on 144 species that represented at least 3 % of the assemblage in one sample. Using square-root-transformed species percentages, DCA showed a first-axis gradient length of 4.4, justifying modal methods for the transfer function. Past DI-TP values for core LOO-8JP were obtained by weighted averaging with classical de-shrinking in C2 (Juggins 2007),

($r^2 = 0.89$, RMSE $= 0.173$ for $\log_{10}$TP, $n = 73$ P-limited lakes).

Sediment cores were dated by [210]Pb. Radiometric measurements (^{210}Pb and [226]Ra) were made using low-background gamma counting with well-type intrinsic germanium detectors (Appleby et al. 1986; Schelske et al. 1994). Sediment ages were calculated using the constant rate of supply (CRS) model (Appleby and Oldfield 1983; Oldfield and Appleby 1984). Age errors were propagated using first-order approximations and calculated according to Binford (1990).

To obtain continuous output from age-depth chronologies, we modeled Bulk-MSR, OM-MSR, OC-MSR and TP-MSR using ^{210}Pb dates from cores with reliable chronologies and a calculated date of 1900 or older. The benefit of modeling MSR as a function of sediment age was that it provided continuous data that could be summed across cores, each year, to estimate whole-basin sedimentation from 1900 to 2006. For each core, we compared an exponential model (MSR $= e^{(a\text{Date} + b)}$, $k = 2$) to a constant-sedimentation-rate model (MSR $= C$, $k = 1$) using a log-likelihood approach and Akaike's Information Criteria (AIC) analysis (Brett and Benjamin 2008; Akaike 1974). Parameters (k) for the exponential model and the constant-sedimentation-rate model were determined by optimizing the sum of the log-likelihood (LL) for each model with the Solver function of Microsoft Excel. We used the metric ΔAIC that combines the cumulative likelihood and number of parameters to evaluate the competing models, where $\Delta\text{AIC} = (2k_{\text{Constant}}\text{-}2\text{LL}_{\text{Constant}}) - (2k_{\text{Exponential}}\text{-}2\text{LL}_{\text{Exponential}})$. To be conservative, we accepted the constant-sedimentation-rate model for cores with $\Delta\text{AIC} \leq 14$. If $\Delta\text{AIC} > 14$, we accepted the exponential model. Whole-basin sedimentation models were constructed by summation of model year output for each ^{210}Pb-dated core ($n = 13$) and the error terms for each year of the lake-wide models were calculated as

$$\sigma_{\text{year,whole-basin}} = \sqrt{(n - 1)(\sigma_{\text{year,13 cores}})^2}$$

Results

We established reliable chronologies, with dates of 1900 or older, for 13 of the 20 cores we attempted to date using [210]Pb (Fig. 2). All 13 cores with reliable chronologies were collected at locations with at least 1.85 m of ST, but two cores collected at locations with $\geq$1.85 m of ST could not be dated reliably. Thus, we established reliable ^{210}Pb chronologies for 86.7 % of the 15 cores collected from locations with at least 1.85 m of ST. In the lake-wide study of ST, 28 of 84 locations (33.3 %) had ST > 1.85 m. From these data we deduced that the 13 cores with reliable chronologies represented 28.9 % or 6.62 km^2 of the lake bottom. This area contains $\sim$55 % of the soft sediment volume. Because we did not determine complete density profiles for every location, we could not calculate the proportion of sediment mass represented by these ^{210}Pb-datable locations. Given the expected sediment compaction in deeper deposits from locations with greater ST, however, we assume this area represents much more than 55 % of the total soft sediment mass.

For Lake Lochloosa, the whole-basin models indicate that Bulk-MSR, OM-MSR, OC-MSR and TP-MSR increased exponentially from 1900 to 2006 (Fig. 3). Estimates for modern (2006) sedimentation rates were at least four times greater than estimates for historic sedimentation rates *ca.* 1900. MSR and OC-MSR increased $\sim$fourfold from 1900 to 2006, OM-MSR increased $\sim$fivefold over the same period and TP-MSR increased $\sim$eightfold over the ^{210}Pb-datable portion of the cores.

Scaling the whole-basin sedimentation models to the area represented by the datable cores (6.62 km^2) yielded annual whole-basin sedimentation estimates with 95 % confidence intervals for each year from 1900 to 2006. Bulk sedimentation increased exponentially from 610 ± 190 MT a^{-1} in 1900 to $2{,}400 \pm 765$ MT a^{-1} in 2006. OM sedimentation increased exponentially from 280 ± 124 MT a^{-1} in 1900 to $1{,}500 \pm 516$ MT a^{-1} in 2006. OC sedimentation increased exponentially from 170 ± 57 MT a^{-1} in 1900 to 720 ± 263 MT a^{-1}. Total phosphorus sedimentation increased exponentially from 0.50 ± 0.20 MT a^{-1} in 1900 to 4.1 ± 1.3 MT a^{-1} in 2006.

Of the 52 location-specific MSR models (i.e. 13 locations $\times$ 4 variables), the constant MSR model was most parsimonious (i.e. $\Delta\text{AIC} \leq 14$) for only eight models at four locations. Somewhat random observed sedimentation resulted in the constant MSR models being the most parsimonious at these locations (e.g. 8JP, Fig. 4). At location 8JP, constant sedimentation over time was most parsimonious for all four
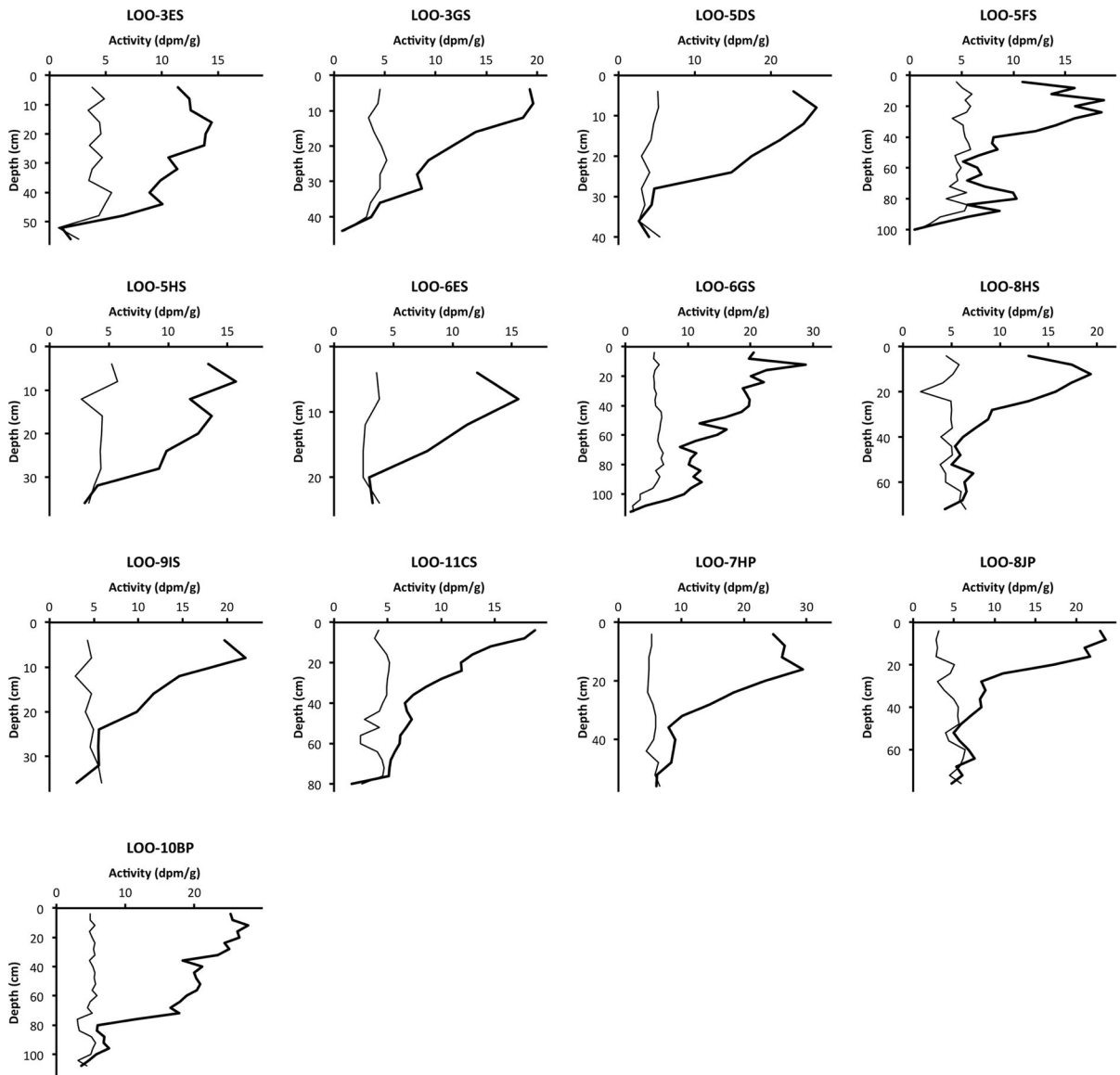
Fig. 2 ^{210}Pb (*thick line*) and ^{226}Ra (*thin line*) activities (dpm g^{-1}) plotted against depth (cm) for the 13 study cores. Samples represent 4-cm core intervals

variables (Bulk-MSR, OM-MSR, OC-MSR and TP-MSR). At location 9IS, constant sedimentation over time was most parsimonious for Bulk-MSR and OC-MSR. At location 8HS, the constant-sedimentation-rate model was most parsimonious for OC-MSR. At location 11CS, the constant-sedimentation-rate model was most parsimonious for OM-MSR. In all other location-specific MSR models, the exponential models were most parsimonious (e.g. 3ES, Fig. 5). The location-specific TP-MSR models for only two cores, 5FS and 7HP, closely resemble the 13-core average,

but even these cores fall outside the 95 % confidence interval of the 13-core average (Fig. 6). More often, individual location-specific models (e.g. 6GS and 9IS) fall far outside the 95 % confidence interval of the 13-core average.

For the whole-basin models (Bulk, OM, OC, TP), observed and predicted MSR were significantly correlated (Figs. 7, $p < 0.0001$, n = 182). A few outlier samples in each model have strong influence on whole-basin model performance as measured by R^2 ($R^2 = 0.25$–0.36). Removing only nine outliers

Fig. 3 Whole-basin sedimentation models for bulk mass sedimentation rate (Bulk-MSR), organic matter, organic carbon and total phosphorus. The mean (*dark line*) and 95 % confidence intervals (*thin lines*) are plotted against ^{210}Pb-modeled dates
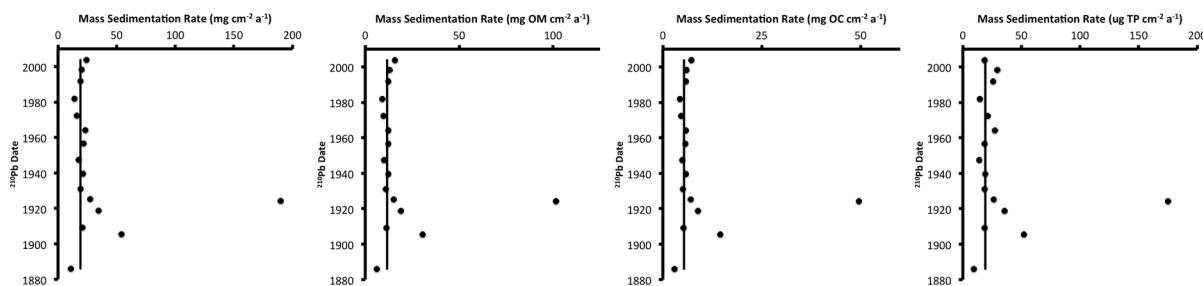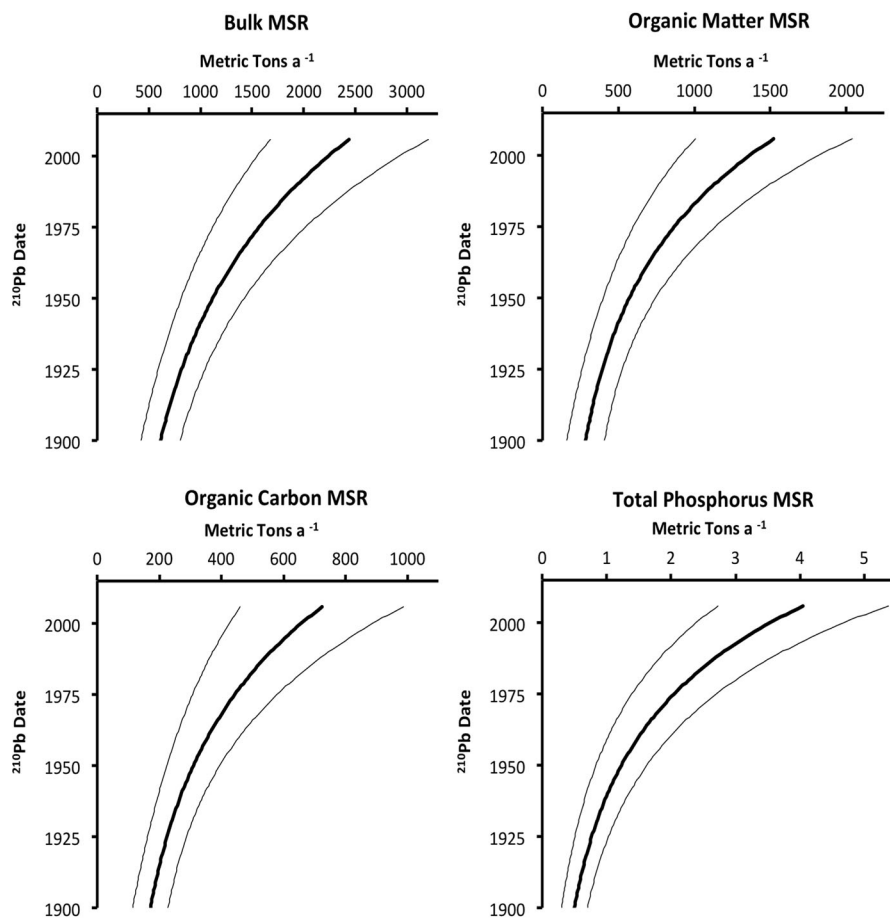
Fig. 4 Bulk sediment, organic matter (OM), organic carbon (OC) and total phosphorus (TP) mass sedimentation models for site 8JP. Measured data (*closed circles*) and modeled data (*dark line*) are plotted against ^{210}Pb-modeled dates

(<5 %) from each model improved model performance, as measured by R^2, substantially (n = 173, R^2 = 0.7–0.8). This comparison demonstrates the influence of outliers on R^2, identifies a shortcoming of the use of R^2 for parameter optimization or model selection, and reinforces the superiority of the LL approach for parameter optimization and AIC analysis for model selection.

Diatom-based limnetic total P inferences

RDA with forward selection showed three significant environmental variables, and these had significant correlation with the first ordination axis: $\log_{10}$TP (r = 0.85), pH (r = 0.61), and specific conductance (r = 0.51). The ratio of the eigenvalue of the first axis (λ_1) of an RDA constrained only by
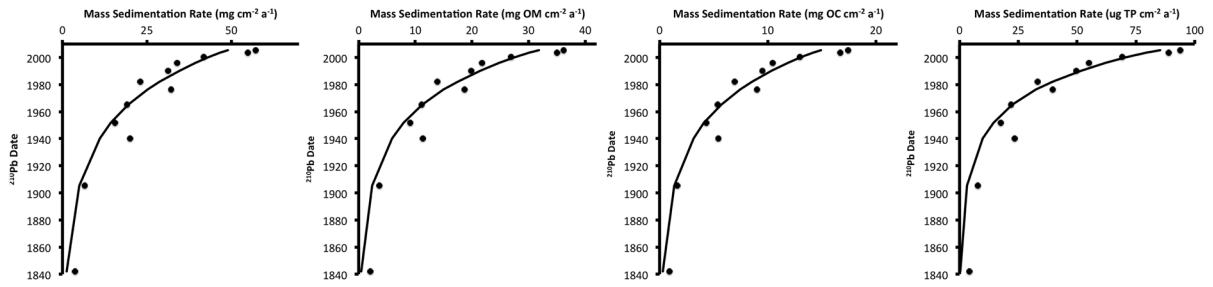
Fig. 5 Bulk sediment, organic matter (OM), organic carbon (OC) and total phosphorus (TP) mass sedimentation models for site 3ES. Measured data (*closed circles*) and modeled data (*dark line*) are plotted against ^{210}Pb-modeled dates
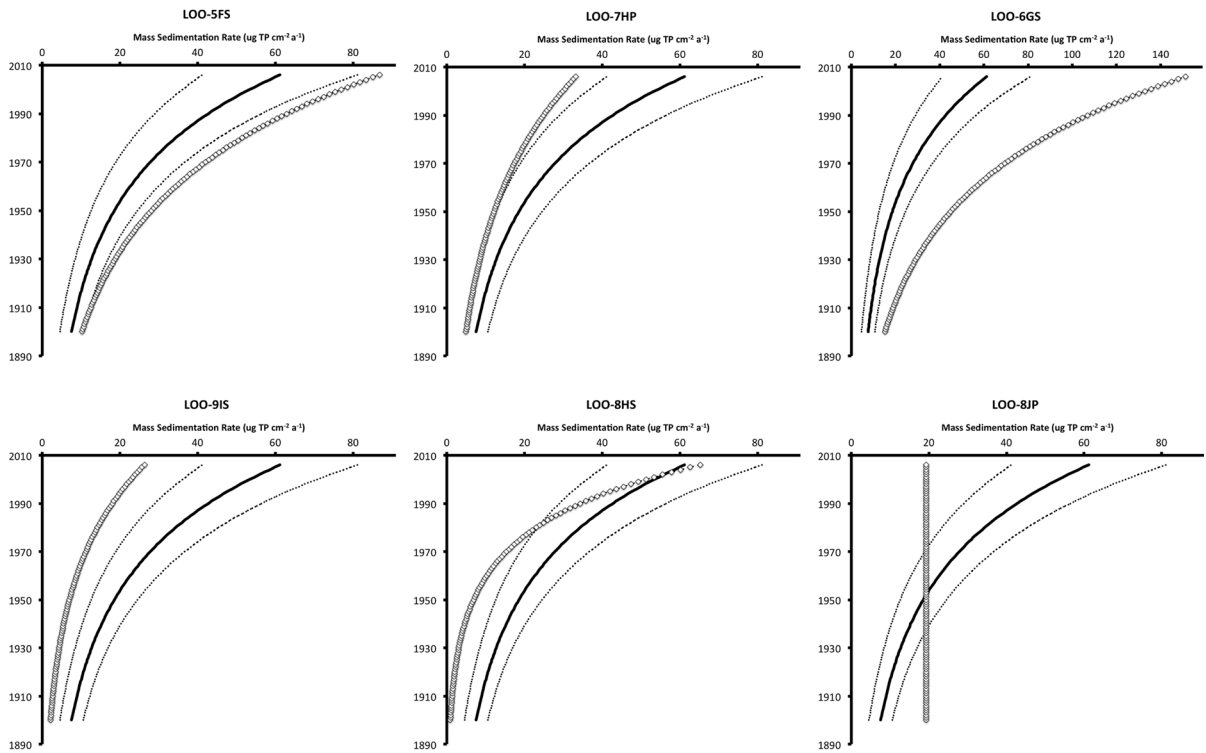

Fig. 6 Location-specific TP-MSR models plotted against the 13-core average TP-MSR model. The 13-core average TP-MSR model (*thick line*), 95 % confidence intervals (*dotted lines*) and location-specific TP-MSR models (*open diamonds*) are plotted against ^{210}Pb-modeled dates

$\log_{10}$TP to the eigenvalue of the first unconstrained axis (λ_2) was 0.70, indicating that factors other than $\log_{10}$TP can strongly influence diatom variation across this training set. λ_2/λ_2 with pH as the only constraining variable was 0.42, demonstrating weaker influence.

We were conscious of the need to avoid applying a DI-TP model with undue influence from secondary variables (Juggins 2013; Juggins et al. 2013). Despite apparent potential for pH and specific conductance to

influence TP reconstructions using this calibration set, we believe that DI-TP inferences for Lake Lochloosa are reasonably reliable for the following reasons. Water quality varies widely in the calibration set because of diverse geological conditions, but water-quality variation in Lake Lochloosa is substantially narrower. Summary autecological data for diatom assemblages in the LOO-8JP core showed that pH and salinity were largely unchanged over time, but hypereutrophic diatoms increased (Fig. 8a–c), which
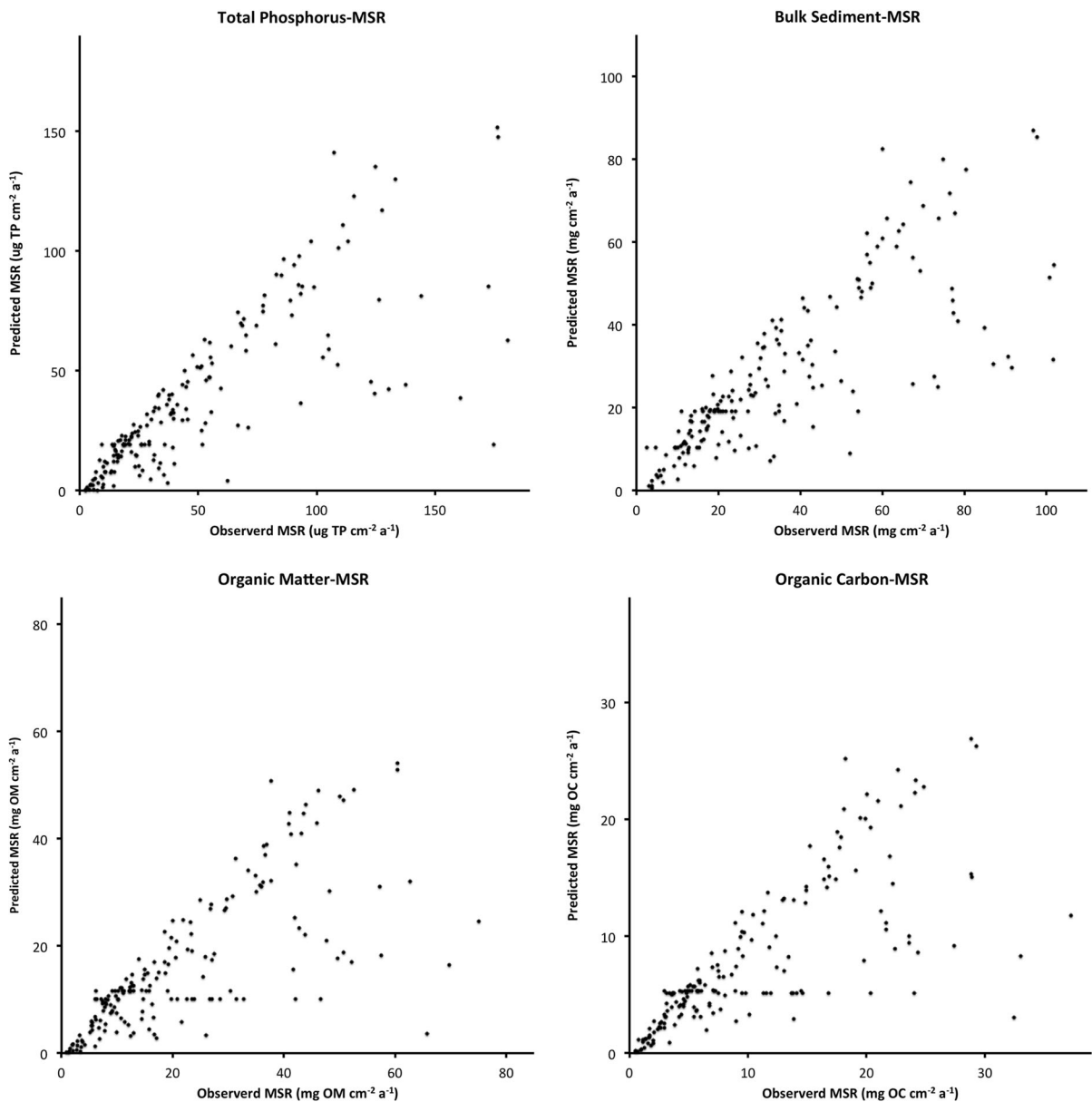
Total Phosphorus-MSR

Bulk Sediment-MSR

Organic Matter-MSR

Organic Carbon-MSR

Fig. 7 Comparisons of observed and predicted mass sedimentation rates (MSR) for the four whole-basin models. Observed and predicted total phosphorus (TP)-MSR were significantly correlated ($p < 0.0001$, $R^2 = 0.36$, n = 182). When only 9 outliers were removed, R^2 for observed and predicted TP-MSR improved considerably ($R^2 = 0.81$, n = 173). Observed and predicted bulk sediment-MSR were significantly correlated ($p < 0.0001$, $R^2 = 0.25$, n = 182). When 9 outliers were removed, R^2 for observed and predicted bulk sediment-MSR improved considerably ($R^2 = 0.70$, n = 173). Observed and predicted organic matter (OM)-MSR were significantly correlated ($p < 0.0001$, $R^2 = 0.28$, n = 182). When 9 outliers were removed, R^2 for observed and predicted OM-MSR improved considerably ($R^2 = 0.71$, n = 173). Observed and predicted organic carbon (OC)-MSR were significantly correlated ($p < 0.0001$, $R^2 = 0.30$, n = 182). When 9 outliers were removed, R^2 for observed and predicted OC-MSR improved considerably ($R^2 = 0.72$, n = 173)

supports increased DI-TP inferences. Baseline inferences of ~40 µg L^{-1} TP are consistent with modern conditions in relatively undisturbed lakes in the vicinity (median = 40 µg L^{-1}; Griffith et al. 1997), and with the mean baseline value of 42.9 µg L^{-1} obtained from our paleolimnological studies of seven
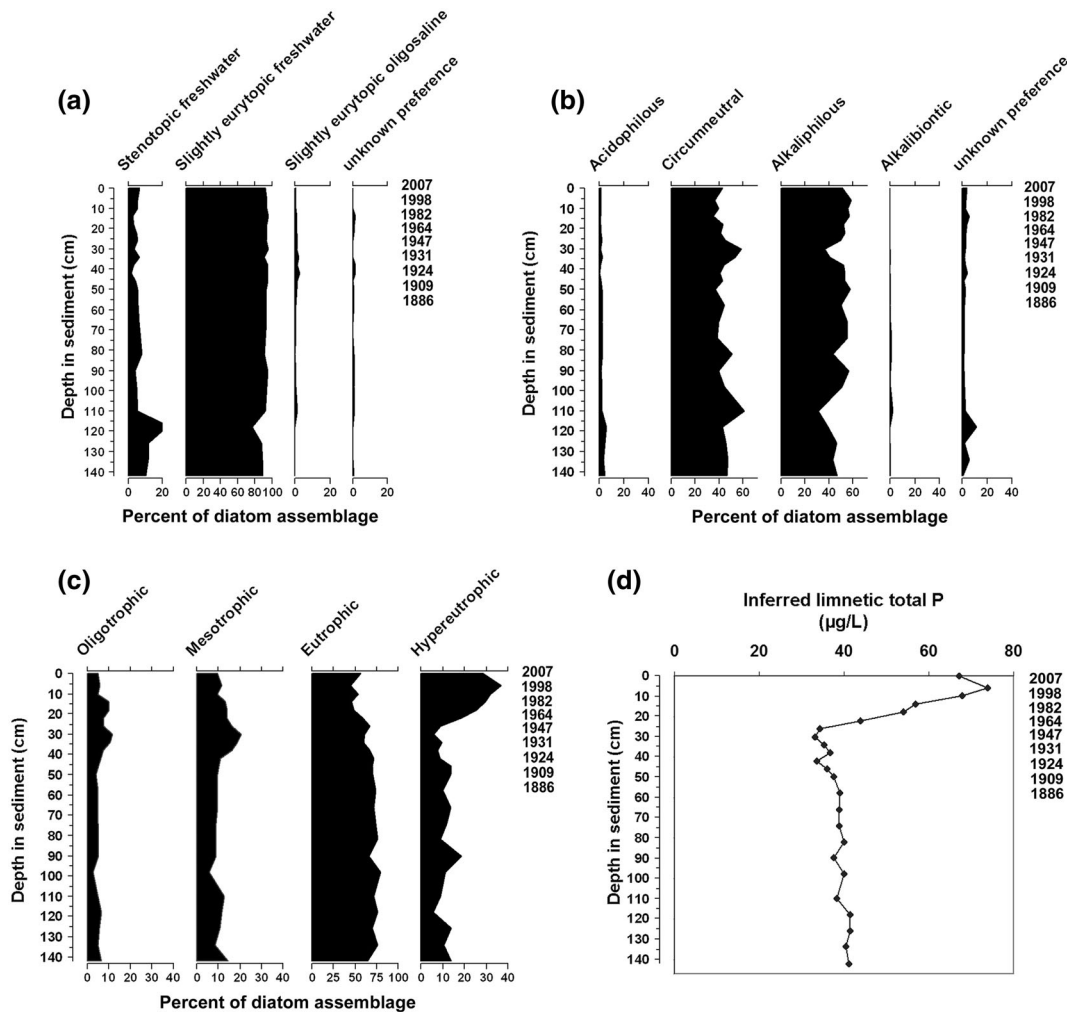
Fig. 8 Summary autecological data and limnetic total P inferences for diatom assemblages in core LOO-8JP. Auteco-logical preference percentages were calculated following methods presented in Whitmore et al. (1996b). **a** Salinity preferences of diatoms. **b** pH preferences. **c** Trophic-state preferences. **d** Diatom-inferred limnetic total p values

other nearby lakes (unpublished data). The modern inference of 67.2 μg L^{-1} is consistent with the mean measured limnetic TP value of 67.4 μg L^{-1} reported near the time of our study, and with the overall mean of 67.6 μg L^{-1} for the period from 1993 to 2011 (Florida Lakewatch 2013).

Diatom-based limnetic TP inferences for core LOO-8JP (Fig. 8d) indicated recent P enrichment of the water column. Baseline, diatom-inferred TP values in Lake Lochloosa were in the low range of eutrophic conditions ($\sim$40 μg L^{-1}). Limnetic TP inferences were stable until the mid-twentieth century, but increased after the 1950s, up to $\sim$70 μg L^{-1} at the time of our study.

Discussion

The whole-basin sedimentation model provided insights into historic lake functioning that were not evident from limited, archived water quality data. This is clear in the comparison of historic limnetic TP and TP-MSR. Although water-column TP shows little change over the past 35 years, TP-MSR increased eightfold from 1900 to 2006. This eightfold, exponential increase in TP-MSR over the past century provides evidence for the role of increased P loading in the recent shift to phytoplankton dominance in Lake Lochloosa. The exponential increases in OM-MSR and OC-MSR are also indicative of increased primary

production associated with the recent shift to phytoplankton dominance.

A trend of exponentially increasing TP-MSR was evident in 12 of the 13 cores in this study. Comparing TP-MSR from individual cores to the 13-core average TP-MSR, it is apparent that analysis of only one or a few cores in Lake Lochloosa would yield misleading results for whole-basin MSR (Fig. 6). This study thus validates the additional effort necessary to carry out an investigation of multiple cores for whole-basin sedimentation analysis (Rippey et al. 2008). Only two cores, 5FS and 7HP, closely resemble the 13-core average, but even these cores fall outside the 95 % confidence interval of the 13-core average. More often, individual cores (e.g. 6GS and 9IS) fall far outside the 95 % confidence interval of the 13-core average. For instance, core 8HS accurately estimated modern sedimentation, but yielded an over-estimate of the relative increase in TP-MSR over time.

Data from core 8JP showed constant TP-MSR over time, and had our study focused on core 8JP alone, the TP-MSR data would not have corroborated the diatom-based historic limnetic TP inferences. These limited TP-MSR data suggest no change in TP sedimentation coincident with the shift from macrophyte to phytoplankton dominance. Thus, insufficient data can lead to erroneous explanations for what triggered the observed shift to phytoplankton dominance.

We used whole-basin MSR models to identify the cause for a shift between stable states. The AIC approach allowed us to statistically differentiate between constant MSR and exponentially increasing MSR. Thus, we objectively verified the exponential increases in TP loading using historic estimates of TP-MSR. Using a LL approach to optimize parameters and AIC to evaluate model performance minimized the influence of outlier samples common in environmental data. In this case, it prevented overestimation of MSR, resulting from short-term episodes of rapid sedimentation. The MSR models were useful in providing continuous data for past sedimentation rates, but they should not be used to predict future sedimentation in the lake.

If TP loading continues to increase, future whole-basin sedimentation is probably best described by a sigmoid function, with an earlier period of exponential increase over time, followed by a later period when MSR approaches a maximum value asymptotically.

Our exponential function represents the earlier component of the sigmoid curve. Because we did not observe the maximum sedimentation rates possible, we cannot model our data to fit a sigmoid function. To assume that whole-basin MSR will continue to increase exponentially is incorrect.

A recent hydrologic study of Lake Lochloosa (Lin 2011) provided data that allowed comparisons of TP loading, TP retention and TP residence time between 1905 and 2006 (Table 1). Because the Lochloosa basin is currently 84 % forests and wetlands and there is no evidence for recent hydrologic modifications, we assumed that the lake's hydrologic budget remained relatively stable over the past century. Given these assumptions, we can deduce from our data that TP retention in the system increased over twofold from 1905 to 2006. Current TP loading is ~ 6.2 MT a^{-1} and recent TP sedimentation is ~ 4 MT a^{-1}, indicating a 0.65 TP retention coefficient in the lake. If historic TP loading were ~ 1.8 MT a^{-1} and historic TP sedimentation were ~ 0.6 MT a^{-1}, then historic TP retention coefficient for the lake was only ~ 0.30. Our modern estimate for TP retention (0.65) is similar to values for other shallow Florida lakes (Fig. 9a) determined by an alternative, watershed-modeling approach (Fulton et al. 2004; Fulton and Smith 2008).

In a time during which TP storage in the water column and TP sedimentation increased, a simple mass balance calculation for Lake Lochloosa shows decreased TP residence time in the water column. Currently, the residence time for TP in the water column is ~ 0.5 a. Historically, the residence time for TP in the water column might have been 1 a or longer, especially if TP in macrophytes is considered part of the water-column storage (Canfield et al. 1983). Longer residence times for TP in the water column of macrophyte-dominated systems may result from the greater role that macrophytes and associated epiphytes play in P burial in Florida lakes (Brenner et al. 2006).

Although it is apparent from our study that the shift from macrophyte dominance to phytoplankton dominance resulted in an increase in TP retention and a decrease in TP residence time for Lake Lochloosa, one remaining question is "what was the contribution of senescing macrophytes to TP sedimentation?" Canfield et al. (1983) estimated the TP content of macrophytes in Lake Lochloosa to be equivalent to 93 µg L^{-1}. If, historically, 25 % of the volume of Lake Lochloosa were inhabited by macrophytes, then

Table 1 Limnological characteristics in terms of total phosphorus (TP) for Lake Lochloosa calculated for years 1905–2006 (Lin 2011 and this study)

Pb-210 Date	Sedimentation TP (MT/a)	Diatom inferred TP (ug/L)	Water column TP (MT)	Export TP (MT/a)	Loading TP (MT/a)	Retention TP	TP Residence Time a
2006	4.1	67	3.2	2.2	6.2	0.65	0.5
2004	3.9	74	3.6	2.4	6.3	0.62	0.6
1998	3.4	68	3.3	2.2	5.6	0.61	0.6
1992	3.0	57	2.7	1.9	4.8	0.61	0.6
1982	2.4	54	2.6	1.8	4.1	0.57	0.6
1972	1.9	44	2.1	1.4	3.3	0.57	0.6
1964	1.6	34	1.7	1.1	2.7	0.59	0.6
1957	1.4	33	1.6	1.1	2.5	0.57	0.6
1947	1.2	35	1.7	1.1	2.3	0.50	0.7
1940	1.0	37	1.8	1.2	2.2	0.46	0.8
1931	0.9	34	1.6	1.1	2.0	0.44	0.8
1925	0.8	36	1.7	1.2	1.9	0.40	0.9
1924	0.8	38	1.8	1.2	2.0	0.38	0.9
1919	0.7	39	1.9	1.3	2.0	0.35	1.0
1909	0.6	39	1.9	1.3	1.8	0.32	1.0
1905	0.6	39	1.9	1.3	1.8	0.30	1.0

For these calculations, lake surface area (22.9 km^2, mean depth (2.1 m) and water export (1.4 m a^{-1}) were assumed to be constant

the total inventory of TP in macrophytes would be 1.1 MT or 0.34 modern water-column equivalents. If the lake were 100 % occupied by macrophytes, then the total inventory of TP in macrophytes would be 4.4 MT or 1.4 modern water-column equivalents. Our study estimates that ^{210}Pb-datable sediments (1900–2006) contain 175 MT of TP or $\sim$55 modern water-column equivalents. These data indicate that total senescence of macrophytes in Lake Lochloosa and complete sedimentation of the TP contained in those macrophytes could only account for 1–3 % of the TP stored in ^{210}Pb-datable sediments.

In this study, the absence of a "step-wise" increase in TP-MSR or TP loading complicated the identification of a P threshold (Scheffer et al. 1993) associated with the shift to phytoplankton dominance. In a study of 72 shallow lakes in Minnesota, USA, Zimmer et al. (2009) found upper thresholds for the clear-water state of 22 µg L^{-1} Chl a, and 62 µg L^{-1} TP. Despite their identification of water-quality thresholds, Zimmer et al. (2009) recommended that lake managers focus on improving resilience of clear regimes in shallow lakes by reducing nutrient loading.

Our study helps to identify the TP loading threshold that can trigger a shift from a macrophyte-dominated

state to a phytoplankton-dominated state. Because TP:Chl a ratios vary both across lakes and within lakes over time (e.g. in Lake Lochloosa TP:Chl a ranged from 0.5 to 2.0), determination of a loading threshold rather than a water-quality threshold could help avoid possible errors associated with the natural variability between TP and Chl a. Quantification of a water-quality threshold for alternative stable states in shallow lakes is further complicated by the role of dissolved OM in light attenuation. Schelske et al. (2010) showed that dissolved color attenuates light at roughly one-third the rate of Chl a when comparing the effects of color, in Pt units, to Chl a in µg L^{-1}. This relationship between color and light attenuation helped quantify the influence of dissolved color on the development of phytoplankton dominance in Lake Apopka, FL, USA (Schelske et al. 2010). Applying this relationship to Lake Lochloosa, the modern color value (90 Pt units) attenuates light comparable to a Chl a concentration of 30 µg L^{-1}.

Because of limited modern data for water quality and macrophyte coverage, Lake Lochloosa represents a challenge for identifying the exact timing of the shift to phytoplankton dominance. Furthermore, using environmental response variables such as macrophyte
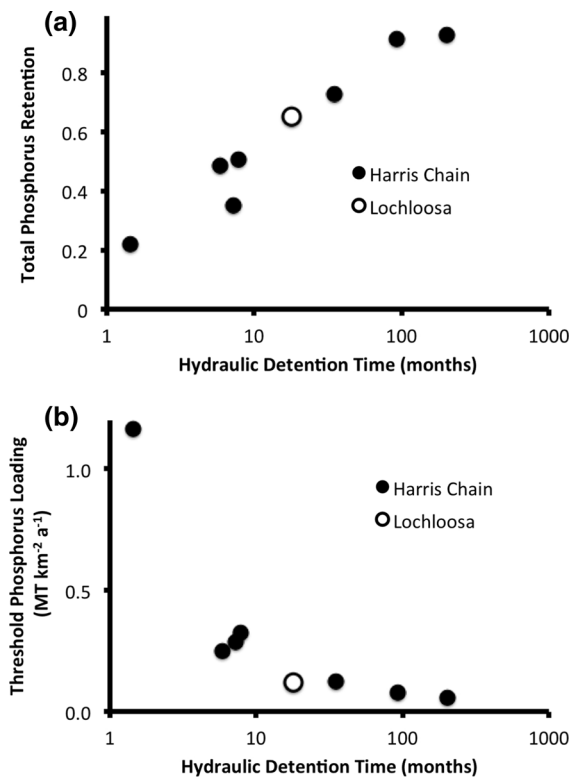
Fig. 9 a Hydraulic detention time (excludes evaporation) versus phosphorus retention coefficient for seven lakes in the upper Ocklawaha River Basin and Lake Lochloosa. **b** Hydraulic detention time (excludes evaporation) versus phosphorus-loading threshold for seven lakes in the upper Ocklawaha River Basin and Lake Lochloosa. Ocklawaha River Basin data from Fulton et al. (2004) and Fulton and Smith (2008). Lake Lochloosa hydrologic data from Lin (2011)

Fig. 10 Using a whole-basin, mass-balance approach to identify the phosphorus-loading threshold in shallow, subtropical Lake Lochloosa, Florida. A time-sequence (1900–2006) of diatom-inferred limnetic total phosphorus (DI-TP) and phosphorus retention (sedimentation/loading) are plotted against phosphorus loading (MT a^{-1}) for the lake. Selected ^{210}Pb-dates (1905, 1964, 1981, 2006) are presented. The phosphorus-loading threshold that triggered the shift to phytoplankton dominance was 2.7 MT a^{-1} and that threshold was exceeded after *ca.* 1964

coverage or Chl *a* might identify loading rates long after the triggering threshold was crossed, especially in Lake Lochloosa, where loading increased throughout the recent sediment record. A plot of TP retention and historic DI-TP versus TP loading (Fig. 10), however, identifies the TP-loading threshold that was crossed to trigger the shift to phytoplankton dominance in Lake Lochloosa.

In Lake Lochloosa, initial increases in TP loading resulted in increased TP retention in the system, but did not increase the limnetic TP concentration until the maximum observed TP retention ($\sim$0.65) was asymptotically approached *ca.* 1964. After 1964, increased TP loading resulted in increased limnetic TP concentrations. From this comparison, we deduce that the critical TP loading threshold was crossed *ca.* 1964. The whole-basin, mass-balance analysis for Lake
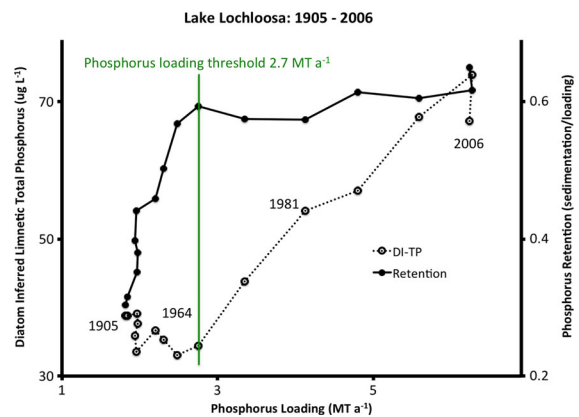
Lochloosa shows that estimated TP loading was 2.7 MT a^{-1} in 1964, or about 1.5-fold greater than TP loading in 1905. This threshold is equivalent to 44 % of modern TP loading (6.2 MT a^{-1}). Our modern estimate for the TP-loading threshold (2.7 MT a^{-1} or 0.12 MT km^{-2} a^{-1}) in Lake Lochloosa is similar to values for other shallow Florida lakes (Fig. 9b), determined by an alternative, watershed-modeling approach (Fulton and Smith 2008).

If the goal of lake managers is to re-establish the macrophyte-dominated state in Lake Lochloosa, it would be advisable to target a TP loading rate below the threshold rate of 2.7 MT a^{-1}. This is because of increased storage of TP in recent sediments, which may cause internal P loading to be greater now (Søndergaard et al. 2001) than it was when the triggering threshold was first exceeded in 1964. Secondly, maintaining the stable state of the lake at the "threshold TP-loading rate" would be subject to the unpredictable nature of stochastic, biotic or physical triggers (Scheffer and Carpenter 2003).

Using a 1983 estimate for total atmospheric TP deposition in Gainesville, Florida (Brezonik et al. 1983) near Lake Lochloosa, we calculated that roughly half of the threshold TP loading rate (2.7 MT a^{-1}) is supplied directly to the lake via

atmospheric deposition. Furthermore, atmospheric deposition to the 228-km^2 drainage basin is 13 MT a^{-1}, about five-fold greater than the threshold rate. Atmospheric TP deposition may be even greater now than it was 30 years ago. Given the inherent difficulty of managing atmospheric deposition and light attenuation by dissolved OM, re-establishment of the macrophyte-dominated state in Lake Lochloosa might prove to be difficult.

Conclusions

Our whole-basin sedimentation analysis of Lake Lochloosa, provided insights into historic lake processes that were not evident from the limited archive of water quality data. Because of variable sedimentation among coring sites in the lake, analysis of only one or a few cores from Lake Lochloosa might have led to misleading conclusions, so the additional effort necessary to develop a whole-basin sedimentation model was justified. The whole-basin mass balance approach provided an effective means to identify the trigger for ecosystem change. We calculated a greater than three-fold increase in TP loading over the past century from an eight-fold increase in TP sedimentation and a two-fold increase in water column TP and TP export. The TP-loading increase triggered a shift from macrophyte to phytoplankton dominance, causing an increase in TP retention and a decrease in TP residence time in the lake. Comparison of TP loading with TP retention and historic, diatom-inferred limnetic TP concentrations identified the TP loading threshold that was exceeded, which triggered the shift from macrophyte to phytoplankton dominance.

References

Akaike H (1974) A look at the statistical model identification. IEEE Trans Autom Control 19:716–723

Appleby PG, Oldield F (1983) The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103:29–35

Appleby PG, Nolan PJ, Gifford DW, Godfrey MJ, Oldfield F, Anderson NJ, Battarbee RW (1986) ^{210}Pb dating by low background gamma counting. Hydrobiol 143:21–27

Binford MW (1990) Calculation and uncertainty of ^{210}Pb dates for PIRLA project sediment cores. J Paleolimnol 3:253–267

Brenner M, Hodell DA, Leyden BW, Curtis JH, Kenney WF, Gu B, Newman JM (2006) Mechanisms for organic matter and phosphorus burial in sediments of a shallow, subtropical, macrophyte-dominated lake. J Paleolimnol 35:129–148

Brenner M, Curtis JH, Whitmore TJ, Zimmerman A, Kenney WF, Reidinger-Whitmore M (2009) Sediment accumulation rate and past water quality in Lochloosa Lake. Final report for the St. Johns River Water Management District 278 p

Brett MT, Benjamin MM (2008) A review and reassessment of the lake phosphorus retention and nutrient loading concept. Freshw Biol 53:194–211

Brezonik PL, Hendry CD, Edgerton ES, Schulze R, Crisman TL (1983) Acidity, nutrients and minerals in atmospheric precipitation over Florida: deposition patterns, mechanisms and ecological effects. EPA-600/S3-83-004 U.S. EPA Corvallis, OR. NTIS document PB 83-165 837

Canfield DE, Langeland KA, Maceina MJ, Haller WT, Shireman JV, Jones JR (1983) Trophic state classification of lakes with aquatic macrophytes. Can J Fish Aquat Sci 40:1713–1718

Downing JA, Prairie YT, Cole JJ, Duarte CM, Tranvik LJ, Striegel RG, McDowell WH, Kortelainen P, Caraco NF, Melack JM, Middelburg JJ (2006) The global abundance and size distribution of lakes, ponds and impoundments. Limnol Oceanogr 51:2388–2397

Engstrom DR, Schottler SP, Leavitt PR, Havens KE (2006) A reevaluation of the cultural eutrophication of Lake Okeechobee using multiproxy sediment records. Ecol Appl 16:1194–1206

Engstrom DR, Rose NL (2013) A whole-basin, mass-balance approach to paleolimnology. J Paleolimnol 49:333–347

Fisher MM, Brenner M, Reddy KR (1992) A simple, inexpensive piston corer for collecting undisturbed sediment/water interface profiles. J Paleolimnol 7:157–161

Fulton RS III, Schulter C, Kelelr TA, Nagid S, Godwin W, Smith D, Clapp D, Karama A, Richmond J (2004) Pollutant load reduction goals for seven major lakes in the upper Ocklawaha river basin. St Johns River Water Management District 125 p. http://www.sjrwmd.com/technicalreports/pdfs/TP/SJ2004-5.pdf

Fulton RS III, Smith D (2008) Development of phosphorus load reduction goals for seven lakes in the upper Ocklawaha river basin, Florida. Lake Res Manage 24:139–154

Glisson JT (1993) The Creek. University of Florida Press, Gainesville 283 p

Griffith G, Canfield D, Horsburgh C, Omernik J (1997) Lake regions of Florida. U.S. Environmental Protection Agency EPA/R-97-127, Corvallis, OR. 88 p

Heggen MP, Birks HH, Heiri O, Grytnes J-A, Birks HJB (2012) Are fossil assemblages in a single core from a small lake

representative of total deposition of mite, chironomid, and plant macrofossil remains? J Paleolimnol 48:669–691

Huber WC, Brezonik PL, Heany JP, Dickinson RE, Preston SD, Dwornik DS, DeMaio MA (1982) A classification of Florida lakes. Final report to the Florida Department of Environmental Regulation, Report ENV-05-82-1, Tallahassee, Florida. v. 1–2 547 p

Jeppesen E, Jensen JP, Søndergaard M, Hansen KJ, Møller PH, Rasmussen HU, Norby V, Larsen SE (2003) Does resuspension prevent a shift to a clear state in shallow lakes during reoligotrophication? Limnol Oceanogr 48:1913–1919

Juggins S (2007) C2 Version 1.5 User Guide. Software for ecological and palaeoecological data analysis and visualisation. Newcastle University, Newcastle Upon Tyne, UK. 73 p

Juggins S (2013) Quantitative reconstructions in paleolimnology: new paradigm or sick science? Quat Sci Rev 64:20–32

Juggins S, Anderson NJ, Hobbs JMR, Heathcote AJ (2013) Reconstructing epilimnetic total phosphorus using diatoms: statistical and ecological constraints. J Paleolimnol 49:373–390

Kenney WF, Schelske CL, Waters MN, Brenner M (2002) Sediment records of phosphorus driven shifts to phytoplankton dominance in shallow Florida Lakes. J Paleolimnol 27:367–377

Kenney WF, Brenner M, Curtis JH, Schelske CL (2010) Identifying sources of organic matter in sediments of shallow lakes using multiple geochemical variables. J Paleolimnol 44:1039–1052

Lakewatch Florida (1996) Florida Lakewatch Data (1986-1996) Department of Fisheries and Aquatic Sciences. University of Florida, Gainesville

Lakewatch F (2004). http://lakewatch.ifas.ufl.edu/data2004.htm

Lakewatch F (2009). http://lakewatch.ifas.ufl.edu/data2005.htm

Lakewatch F (2013). http://lakewatch.ifas.ufl.edu/Lakewatch_County_Data.HTM

Lin Z (2011) Estimating water budgets and vertical leakages for karst lakes in North-central Florida (United States) via hydrological modeling. JAWRA 1–16. doi: 10.1111/j.1752-1688.2010.00513.x

Oldfield F, Appleby PG (1984) Empirical testing of ^{210}Pb-dating models for lake sediments. In: Haworth EY, Lund WG (eds) Lake sediments and environmental history. University of Minnesota Press, Minneapolis, pp 93–124

Riedinger-Whitmore MA, Whitmore TJ, Brenner M, Moore A, Smoak JM, Curtis JH, Schelske CL (2005) Cyanobacterial proliferation is a recent response to eutrophication in many Florida lakes: a paleolimnological assessment. Lake Res Manage 21:423–435

Rippey B, Anderson NJ, Renberg I, Korsman T (2008) The accuracy of methods used to estimate the whole-lake accumulation rate of organic carbon, major cations, phosphorus and heavy metals in sediment. J Paleolimnol 39:83–99

Sayer CD, Burgess A, Kari K, Davidson TA, Peglar S, Handong Y, Rose N (2010) Long-term dynamics of submerged macrophytes and algae in a small and shallow, eutrophic lake: implications for the stability of macrophyte dominance. Freshw Biol 55:565–583

Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. Tree 18:648–656

Scheffer M, Hosper SH, Meijer M-L, Moss B, Jeppesen E (1993) Alternative equilibria in shallow lakes. Tree 8:275–279

Schelske CL, Conley DJ, Stoermer EF, Newberry TL, Campbell CD (1986) Biogenic silica and phosphorus accumulation in sediments as indices of eutrophication in the Laurentian Great Lakes. Hydrobiologia 143:79–86

Schelske CL, Peplow A, Brenner M, Spencer CN (1994) Low-background gamma counting: applications for ^{210}Pb dating of sediments. J Paleolimnol 10:115–128

Schelske CL, Lowe EF, Kenney WF, Battoe LE, Brenner M, Coveney MF (2010) How anthropogenic darkening of Lake Apopka induced benthic light limitation and forced the shift from macrophyte to phytoplankton dominance. Limnol Oceanogr 55:1201–1212

Schottler SP, Engstrom DR (2006) A chronological assessment of Lake Okeechobee (Florida) sediments using multiple dating markers. J Paleolimnol 36:19–36

Søndergaard M, Jensen JP, Jeppesen E (2001) Retention and internal loading of phosphorus in shallow, eutrophic lakes. Sci World 1:427–442

ter Braak CJF, Smilauer P (2002) CANOCO reference manual and CanoDraw for Windows user's guide. Software for canonical community ordination (version 4.5), Microcomputer Power, Ithica, NY, USA. 500 p

Verardo DJ, Froelich PN, McIntyre A (1990) Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 Analyzer. Deep Sea Res 37:157–165

Whitmore TJ, Brenner M, Schelske CL (1996a) Highly variable sediment distribution in shallow, wind-stressed lakes: a case for sediment mapping surveys in paleolimnological studies. J Paleolimnol 15:207–221

Whitmore TJ, Brenner M, Curtis JH, Dahlin BH, Leyden B (1996b) Holocene climatic and human influences on lakes of the Yucatan Peninsula, Mexico: an interdisciplinary, palaeolimnological approach. Holocene 6:273–287

Zimmer KD, Hanson MA, Herwig BR, Konsti ML (2009) Thresholds and stability of alternative regimes in shallow Prairie-Parkland lakes of central North America. Ecosyst 12:843–852