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Influence of fisheries and shoreline management on limnological characteristics of three Missouri reservoirs

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ABSTRACT

Landscape-level analyses based on land cover, morphology, and hydrology account for most of the cross-system variation in pelagic nutrients and suspended solids in Missouri reservoirs. They are based on geometric means, which reduce the influence of extreme temporal variation measured in individual reservoirs. This analysis of 3 conservation reservoirs, managed to benefit recreational fisheries, details how internal processes can alter nutrients, chlorophyll, mineral turbidity, and transparency in long-term (21–42 year) datasets, which contribute to temporal variation. Management practices include the addition of grass carp and herbicides to control nuisance macrophytes and shoreline stabilization with rock and water willow. Among these reservoirs, there is strong evidence that macrophyte removal can increase pelagic nutrients by >90%, resulting in a switch to plankton-dominated conditions (alternative states). In one case, eradication of aquatic vegetation increased mineral turbidity by >60%, which was reversed by reestablishing macrophytes and stabilizing the shoreline. This temporal series supports the modifications of phytoplankton–nutrient relations by mineral turbidity shown in state-wide analyses. Collectively, the long-term data show a significant increase in cyanobacteria biovolume and cyanotoxins, with maximum microcystin concentrations increasing as much as 20 times. Actively flipping lakes to plankton-dominated systems via fisheries management and shoreline stabilization practices has negative impacts on overall water quality, with implications for human and wildlife health.

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Introduction

In the agricultural Midwestern United States, the proportion of cropland in the watershed serves as a surrogate for nonpoint source nutrient input to regional impoundments (Jones et al. 2020a, 2020b). This single metric can account for over half of cross-system variation in pelagic phosphorus (P) and nitrogen (N) in reservoirs statewide; inclusion of hydraulic flushing rate and reservoir depth further refines these models (Knoll et al. 2003, Jones et al. 2008b, 2009). These metrics also explain variation in suspended solids (Jones and Knowlton 2005). Concepts underpinning this empirical approach are consistent with early findings of external loading and other key factors determining trophic state in natural lakes (Edmondson 1961, Vollenweider 1975). These predictor variables are considered relatively stable and easily measured (Knoll et al. 2015); values used to characterize nutrients in individual reservoirs are typically based on long-term geometric means, thereby limiting the effects of temporal variation (Knowlton et al. 1984, Knowlton and Jones 2006a, 2006b). Residual variation in these cross-system patterns is attributed to extreme weather, stochastic processes, or human intervention (Harris 1980, Knowlton and Jones 2006a, 2006b, Canfield et al. 2016).

This study quantifies marked fluctuation in nutrients, phytoplankton chlorophyll, and suspended solids measured from 1978 to 2020 in Little Dixie Lake, from 1999 to 2020 in Carl DiSalvo Lake, and from 1989 to 2020 in Little Prairie Lake, all in the state of Missouri, which coincided with routine management practices by Missouri state agency professionals to benefit the recreational fishery. These case studies illustrate how basin-specific measures to remove nuisance macrophytes with the addition of grass carp (*Ctenopharyngodon idella*) and herbicides, and replacement by planting desired macrophyte taxa (e.g., water willow [*Justicia americana*]) to control turbidity via shoreline stabilization, have changed the limnological characteristics of these impoundments. Statewide, numerous reservoirs are managed to optimize the recreational fishery, and the impact on nutrients and phytoplankton have been previously reported (Knowlton and Jones 2006b).

Typically, lake trophic state assessments ignore nutrients in macrophytes (Canfield et al. 1983), but pelagic

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nutrients often increase when grass carp remove vegetation and disturb sediments (Maceina et al. 1992, Dibble and Kovalenko 2009, Huser et al. 2016). Emergent and submersed vegetation have beneficial effects of reducing sediment-related water quality problems in shallow lakes (James and Barko 1994). Macrophyte stands serve as fish nursery habitats and forage refugia from predators (Savino and Stein 1982). Anglers, however, consider dense macrophyte beds a nuisance, and for several decades fishery biologists have introduced exotic grass carp to reduce or eradicate macrophyte communities (Hanlon et al. 2000, Dibble and Kovalenko 2009). This approach contrasts with fisheries management efforts in the Laurentian Great Lakes, which are aimed at preventing grass carp invasion (Cudmore et al. 2017, Whitledge et al. 2021).

Since 1998, the use of glyphosate (e.g., Roundup and Rodeo) has increased 5-fold in terrestrial and aquatic applications (Benbrook 2016); it is the most widely used herbicide in the United States, particularly in the Midwest Corn Belt (Battaglin et al. 2014, Hébert et al. 2019). Application of these herbicides to unwanted macrophyte stands is included in management efforts to benefit sport fisheries. As an organo-P compound, it can also serve as a source of P to phytoplankton communities (Pérez et al. 2007, Saxton et al. 2011, Hébert et al. 2019) and promote cyanobacteria and associated toxins (Harris and Smith 2016, Wu et al. 2016, Brêda-Alves et al. 2021).

Our objective was to determine if fish and macrophyte (or shoreline) management change internal processes sufficiently to uncouple pelagic nutrients from landscape-level models (Jones et al. 2008b, 2009, 2020b). Currently, these practices are an unquantified source of variation in the Missouri statewide cross-system pattern. Variation resulting from in-lake management would also complicate interpretation and application of regional nutrient criteria, which emphasize external loads as drivers of trophic state (Knowlton and Jones 2006a, Jones et al. 2020a). Noteworthy, temporal variation in nutrients, phytoplankton biomass, turbidity, transparency, and cyanotoxin levels in these 3 monitored impoundments (Jones et al. 2020b) are seemingly independent of changes in their respective watersheds. This observation prompted the hypothesis that in-lake management practices were contributing to the pronounced temporal variation measured in these impoundments.

Study site

Little Dixie Lake

Little Dixie Lake, impounded on Missouri Department of Conservation (MDC) land in 1958, is located in the Glacial Plains ecological section of the state (Jones et al. 2008b) where limestone and shale formations compose the geology and soils are weathered glacial till. The impoundment has a surface area of 79 ha, mean depth of 3.2 m, and a flushing rate of 0.45/yr. The 937 ha catchment is 16.5% forest, 1.5% open wood, 36% grass, 29% cropland, 3% wetland, 11% water, and 3% urban. Land cover in the watershed is reasonably stable; in the 1990s, conservation funds were used to convert ~11% of the catchment from agriculture to grassland and restored prairie. Lake management benefits the warm-water fishery, including bass (*Micropterus*), bluegill (*Lepomis macrochirus*), redear sunfish (*Lepomis microlophus*), catfish (*Siluriformes*), and crappie (*Pomoxis*). Following construction, the impoundment was turbid due to shoreline erosion. To address this problem, ~27% of the shoreline was stabilized with rock riprap in the mid-1970s. Beginning in 1981, grass carp were introduced for macrophyte control (Table 1); stocking was within the range shown to eliminate submersed vegetation (Hanlon et al. 2000). By 1989, mineral turbidity was evident and aquatic vegetation had "disappeared." A second stocking effort occurred ~15 years after the previous introduction (Table 1), which is about the lifespan of grass carp (Opuszynski and Shireman 1995). Between 2002 and 2014, the shoreline was stabilized by additional rock riprap and water willow. During this time, occasional herbicide (Rodeo [53.8% glyphosate]) treatments were applied as well as additional grass carp stockings (Table 1). Available records show gizzard shad (*Dorosoma cepedianum*) and common carp (*Cyprinus carpio*) have been present in the lake since records began in 1980.

Carl DiSalvo Lake

Carl DiSalvo Lake, constructed in 1944 as a water supply for nearby lead mining operations, was purchased in 1981 by MDC to serve as a warm-water fishery. It is located in the Ozark Highlands (Jones et al. 2008b) where geology includes igneous rock, sandstone, and dolomites; the 4179 ha catchment is 55% forest, 6.5% open wood, 30% grass, 0.5% cropland, 4% wetland, 3% water, and 1% urban. The impoundment has a surface area of 87 ha, mean depth of 1.8 m, and a flushing rate of 7.2/yr. This shallow impoundment historically supported a well-developed macrophyte community, which eventually created angler complaints. In 2004, one-third of the reservoir was treated with herbicide to reduce coontail (*Ceratophyllum*) stands, and in 2014, three-fourths of the surface area was treated to reduce American lotus (*Nelumbo lutea*). Herbicide

Table 1. Timeline narrative of fisheries management on 3 Missouri reservoirs from 1981 to present. Individual fish per hectare are indicated in parentheses.

Years	Little Dixie (79 ha surface area)	Carl DiSalvo (87 ha surface area)	Little Prairie (39 ha surface area)
1981–1987	Introduced 2200 grass carp (>300 mm, 28/ha)		
1995	Water willow transplanted for shoreline stabilization		
2000		Localized herbicide treatments confined to boat ramps and fishing jetties (2000–2012)	
2001	Eurasian watermilfoil reached nuisance conditions		Water willow transplanted for shoreline stabilization
2002	Stocked 1100 grass carp (14/ha)		
2003			Introduced vegetation cages containing water star grass (*Heteranthera dubia*) and eelgrass (*Vallisneria americana*)
2004		Introduced 420 grass carp (>200 mm, 5/ha); concurrently, 1/3 treated with herbicide to reduce coontail	
2007			Eurasian watermilfoil observed
2009			Eurasian watermilfoil covered 70% of the reservoir surface area
2010	Stocked 400 grass carp (5/ha)		Herbicide treatment of 8 ha with Sonar Q
2011			Introduced 500 grass carp (~225 mm, 13/ha); Herbicide treatment of 8 ha with Sonar Q
2012	Herbicide treatment of ~1 ha with Rodeo in an isolated cove		Stocked 1000 grass carp (~225 mm, 26/ha)
2013			Stocked 500 grass carp (~225 mm, 13/ha)
2016			Herbicide treatment with glyphosate and Navigate
2014	Stocked 100 grass carp (<2/ha)	Herbicide treatment of three-fourths surface area with Rodeo for American lotus	
2017	Stocked 200 grass carp (2.5/ha)		Stocked 500 grass carp (~225 mm, 13/ha); Herbicide treatment with glyphosate
2018	Stocked 30 grass carp (<1/ha)		Herbicide treatment with glyphosate and Navigate

treatments were confined to fishing access areas periodically during 2002–2012 (including Rodeo, Habitat [active ingredient imazapyr], Navigate [active ingredient 2,4-dichlorophenol], Aquathol [active ingredient endothall], and Sonar Q [active ingredient fluridone]; Table 1) to treat American Lotus, coontail, and Eurasian watermilfoil (*Myriophyllum spicatum*). Grass carp were introduced in 2004 along with additional herbicide spraying via crop dusters. Available records show gizzard shad and common carp have been present since fishery records began in 1981.

Little Prairie Lake

Little Prairie Lake (also known as Towell Lake), constructed in 1964 by MDC in the Little Prairie Conservation Area, is managed as a warm-water fishery. The 622 ha catchment, located in the Ozark Highlands, is 45% forest, 7% open wood, 37% grass, 7% water, and 4% urban. It has a surface area of 39 ha, mean depth of 3.5 m, and a flushing rate of 1.2/yr. Noticeable levels of mineral turbidity resulted in angler complaints. Plantings in the early 2000s to reduce mineral turbidity included water willow, water star grass (*Heteranthera dubia*), and eelgrass (*Vallisneria americana*). Eurasian watermilfoil (*Myriophyllum spicatum*) was observed in 2007 and covered 70% of the reservoir by 2009 (Table 1). Grass carp stocking rate (65 individuals/ha since initiation in 2011) in this reservoir exceeds the density of grass carp typically used in Missouri for macrophyte management (Table 1). Herbicides (Navigate, Aquathol Super K, Sonar Q, and glyphosate [52%]) were applied for vegetation control between 2010 and 2018. In 2017, Eurasian watermilfoil covered ~30% of the reservoir surface area. Available records show gizzard shad and common carp have been present in the lake since records began in 1974.

Methods

Surface samples were collected on 3 or 4 occasions during summer from near-dam locations on each impoundment; Little Dixie was sampled for 39 summers (1978–2020, excluding 1985–1988), DiSalvo 21 summers (1999–2020, excluding 2005), and Little Prairie Lake 32 summers (1989–2020). Samples were processed by standard methods (Jones et al. 2008b, Petty et al. 2020). Measurements included total phosphorus (TP, µg/L), total nitrogen (TN, µg/L), chlorophyll (Chl, µg/L; total, not pheophytin corrected), Secchi disk transparency (m), and nonvolatile suspended solids (NVSS, mg/L). Filterable suspended solids (fTSS, mg/L) is a parameter initiated to characterize fine materials in suspension defined by particles passing through the filters used in solids analysis measured nephelometrically (Knowlton and Jones 2000). To interpret Chl response to P and N, Chl:TP and Chl:TN ratios were calculated and used to characterize changes over time.

In 2003 (7–9 Jul) and 2015 (10–11 Aug), surface samples from all 3 reservoirs were preserved with glutaraldehyde for microscopic determination of phytoplankton biomass with identification to genus (by Dr. Ann St. Amand, PhycoTech, Inc., St. Joseph, MI, USA). In 2004–2006 and 2015–2020 we also collected surface samples for cyanotoxin analysis, specifically the hepatotoxin microcystin. Microcystin concentrations in 2004 were measured using enzyme-linked immunosorbent assay (ELISA) kits (EnviroGard(R), Montclair, CA, USA; detection limit 0.10 µg/L; kit is cross-reactive with microcystin-LR, -YR, and -RR and nodularin). After 2004, microcystin concentrations were measured using ELISA kits (Abraxis, LLC., Warminster, PA, USA) with a detection limit of 0.1 µg/L (Adda specific).

Data analysis

May samples were excluded because not all years were represented. This approach best represents internal processes during summer stratification by avoiding the aftermath of spring inflow and residual clear water events (Jones and Knowlton 2005, Jones et al. 2020b). Trophic-state criteria are from Jones et al. (2008b) and are summer geometric means. The trophic state index (TSI) for Secchi depth, Chl, and TP were after Carlson (1977), with graphic methods of Carlson and Havens (2005) to illustrate patterns in nutrient deficiency, turbidity, and perceived zooplankton grazing. Deviations from TSI predictions also form the basis of landscape-level predictive models described in detail in Jones et al. (2008b) and applied in Jones et al. (2009) and Jones et al. (2020b).

Statistical analysis

Nonparametric statistics

A regime shift (RS) analysis (sequential t-test STARS; Rodionov and Overland 2005) was used to investigate the possibility of abrupt shifts in the long-term datasets. The STARS test uses sequential t-tests to search for changes of a specified magnitude over a chosen number of years (cut-off length = 20 yr). The STARS test is a cumulative sum of normalized deviations from the mean of an identified new regime in which the difference between the current and new regimes is statistically significant, as assessed by a Student's t-test ($p < 0.05$). If STARS detected a shift, the geometric mean of the years before and after the shift, excluding the RS year, were reported to reflect the direction of change. If an RS was not detected, we proceeded to test for long-term monotonic trends with Mann-Kendall trend tests. We then examined trends on the segments separated by the RSs and report on the Sen's slopes to show directionality of trends. Nonparametric Mann Whitney U test was applied to the microcystin data to determine differences between 2 time periods: 2004–2006 and 2015–2020. Correlation analysis was also included (SPSS Statistics v. 27).

Results and discussion

To assess the potential impact of fish and shoreline management on limnological characteristics, we compared long-term means and pre- and post-management TP, TN, Chl, and NVSS concentrations and Secchi disk depths with previously published predictions using landscape-level models (Jones et al. 2008b, 2009, 2020b).

Little Dixie Lake

The long-term geometric means (Table 2) matched median values ($n = 199$) for reservoirs located on Missouri's Glacial Plains and are typical of regional reservoirs (TP = 48 µg/L, TN = 900 µg/L, Chl = 18 µg/L, NVSS = 3.3 mg/L, and Secchi disk depth = 0.8 m; Jones et al. 2020b). Noteworthy is the 4-fold range in TP, 3-fold range in TN, 7-fold range in Chl, 7-fold range in Secchi depth, and order of magnitude range in NVSS and fTSS between minimum and maximum summer geometric mean values in this data series (Table 2).

Variation in limnological characteristics broadly corresponded with in-lake management practices (Table 1 and 2, Fig. 1). Early data from Little Dixie (Fig. 1) both predate and coincide with initial stocking of grass carp for macrophyte control (1981); summer means for nutrients and Chl were among the lowest in the time series, concurrent with maximum Secchi transparency (Fig. 1). In Little Dixie, water quality changes between pre-grass-carp years (1978–1980) and post-grass-carp additions (1982–2020), respectively, were: TP = 29–61 µg/L, TN = 454–854 µg/L, Chl = 11.4–25.4 µg/L, NVSS = 2.8–4.2 mg/L, and Secchi depth = 1.0–0.6 m. Post-grass-carp addition nutrient levels were similar to values predicted using cropland–nutrient relationships for Missouri reservoirs, as modified by morphology and hydrology (TP = 60 µg/L and TN = 890 µg/L; Jones et al. 2009), and mean suspended solid values were similar to predictions using regional models (NVSS = 4.2 mg/L; Jones and Knowlton 2005). Post-grass-carp addition Secchi depth and Chl concentrations, however, were slightly shallower and higher,

Table 2. Long-term geometric means of limnological parameters for the 3 study reservoirs. Geometric mean (min–max), *n* (sample size) in italics. Chlorophyll (Chl), total phosphorus (TP), total nitrogen (TN), nonvolatile suspended solids (NVSS), and filterable suspended solids (fTSS).

Parameter	Units	Little Dixie	Carl DiSalvo	Little Prairie
Chl	μg/L	23.3 (8.8–58.2) *39*	25.9 (2.8–113.2) *21*	7.6 (3.9–16.6) *31*
Secchi	m	0.6 (0.2–1.4) *39*	0.9 (0.3–2.7) *21*	1.3 (0.6–2.9) *31*
TP	μg/L	56 (24–94) *39*	52 (16–182) *21*	22 (13–51) *31*
TN	μg/L	825 (450–1227) *37*	695 (336–1822) *21*	465 (316–608) *31*
Chl:TP	mass ratio	0.4 (0.1–0.9) *39*	0.5 (0.2–1.0) *21*	0.3 (0.2–0.7) *31*
Chl:TN	mass ratio	0.03 (0.01–0.05) *37*	0.04 (0.01–0.08) *21*	0.02 (0.01–0.03) *31*
ln(TN:TP)	mass ratio	2.63 (2.13–3.03) *37*	2.56 (2.01–3.18) *21*	3.04 (2.44–3.53) *31*
NVSS	mg/L	4.1 (1.5–13.4) *38*	1.3 (0.1–5.1) *21*	1.6 (0.3–5.4) *31*
fTSS	mg/L	2.2 (0.8–21.6) *26*	0.9 (0.4–3.0) *19*	1.4 (0.4–6.3) *27*

respectively, than model predictions (0.8 m for Secchi, Jones et al. 2008a; and 19.2 μg/L for Chl, Jones and Knowlton 1993).

The 1990s were clearly a period of change in this reservoir; years 1999 and 2000 were an identified regime shift in all parameters, with the exception of TN (Table 3, Fig. 1). From 1984 to 1999, aquatic vegetation was virtually eradicated from Little Dixie, and the reservoir had extreme mineral turbidity (Table 1 and 3); mean NVSS increased by 63% relative to the previous period, with a significant regime shift (RS) occurring in 1984 (Table 3, Fig. 1f). Minimum Secchi transparency coincided with maximum suspended solids, and the 2 metrics show an RS at about the same time (Table 2 and 3, Fig. 1). The fTSS measurements reached a maximum summer mean of 21.6 mg/L in 1997, when NVSS averaged 9.2 mg/L (Table 2, Fig. 1g). These summer mean values are the highest ever recorded for fTSS and within the top 5% for NVSS in long-term data (1978–2016) for reservoirs located statewide ($n = 2121$ and 2660 summer means, respectively; Jones et al. 2020b). It is unusual among Missouri reservoirs for fTSS to average ~2 times the weight of NVSS (seston measured on filters; Fig. 1f), having occurred in only 2% of summer means ($n = 2121$; Jones et al. 2020b).

There is no basis to assume this abrupt change in mineral turbidity was a response to external loading, particularly given the potentially beneficial conversion of ~11% of the watershed from agricultural to prairie grass prior to this increase. Rather, it coincides with vegetation removal by grass carp; turbulence likely increased and wind resuspension of sediments from the lake bed and shoreline altered the light climate (Carper and Bachmann 1984, Hamilton and Mitchell 1988), but benthivorous fish would also have contributed to suspended solids (Zambrano et al. 2001). The concurrent RSs and increase in TP (by 42% from 1978–1982 to 1984–1992 and an additional 38% from 1984–1992 to 1994–1998; Table 3, Fig. 1b) are consistent with nutrient release from macrophytes with grass carp feeding and fecal deposition (Dibble and Kovalenko 2009) and sediment resuspension by turbulence and fish feeding (Peters and Cattaneo 1984). Restoration of nonvegetated turbid lakes is considered difficult (Scheffer 2001), but macrophytes were reestablished in Little Dixie Lake with shoreline stabilization (using rock and water willow); these management efforts also coincided with the end of the normal lifespan of grass carp initially stocked in the reservoir, suggesting reduced feeding by these fish.

The response of Chl to TP differed with in-lake management practices. High concentrations of mineral turbidity can suppress phytoplankton in Missouri reservoirs (Hoyer and Jones 1983, Knowlton and Jones 2000, Jones et al. 2008b). Following shoreline stabilization (2002–2014), which coincided with a significant decline in suspended solids (Table 3, Fig. 1f) and the introduction of additional grass carp (2002, Table 1), Chl nearly tripled relative to previous conditions, with significant RS detections following these manipulations (Table 1 and 3, Fig. 1a). TP increased 37% between 2001–2003 and 2005–2020 (Table 3), with an increase of 25 μg/L between 2011 and 2012 (Fig. 1b). This increase is concurrent with application of the herbicide Rodeo to a reservoir cove (Table 1), which would have added P from the formulation and released macrophyte-bound P. The

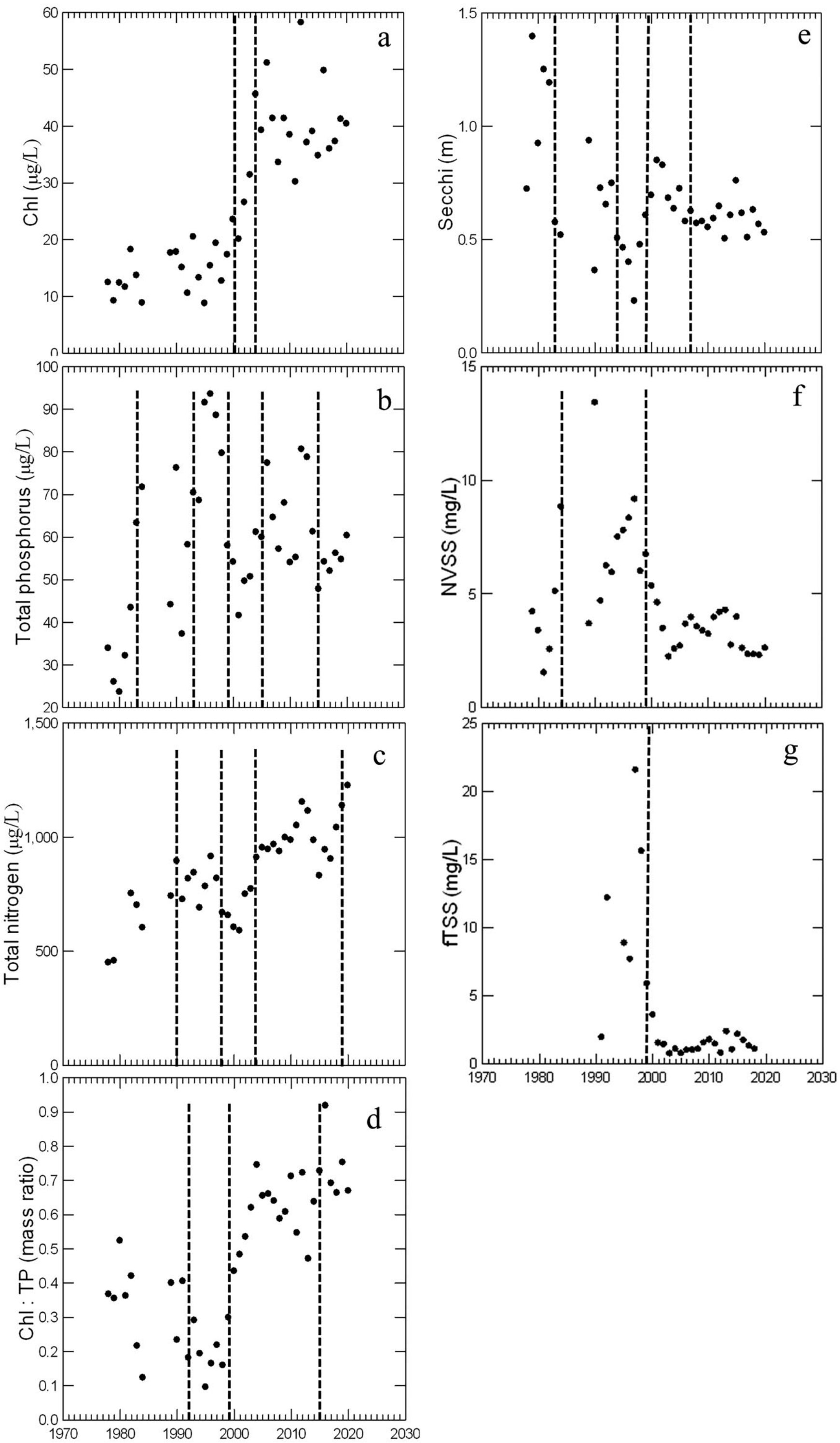

Figure 1. Long-term (1978–2020) limnological parameters for Little Dixie reservoir. Shown are geometric means (dots) of (a) chlorophyll (Chl), (b) total phosphorus (TP), (c) total nitrogen (TN), (d) Chl:TP, (e) Secchi depth, (f) nonvolatile suspended solids (NVSS), and (g) filterable suspended solids (fTSS). Regime shifts are identified by vertical dashed lines (Table 3).

maximum historical Chl concentration (58.2 μg/L; Table 2) was also measured in 2012 (Fig. 1a). Cyanobacteria biovolume more than tripled between samples collected in 2003 and 2015 (1 363 532–4 845 134 μm^3/mL).

Similar to the broader Missouri dataset analyzed in Jones et al. (2008a), after 2001, Little Dixie Chl was higher than predicted by TP (TSI(Chl) – TSI (TP) > 1; Fig. 2a). TSI deviations shifted from

Table 3. Detection of regime shifts and trends in long-term summer values from the 3 study reservoirs. The years STARS regime shifts (RS) occurred and the geometric mean of each identified time segment are shown chronologically. If a significant trend ($p < 0.05$) was found within each RS time segment, Sen's slopes (Q) were reported, showing the changes in units per year (e.g., Secchi depth [m/yr]) from Mann-Kendall (MK) monotonic trend tests. A horizontal line indicates no trend was detected. If none of the reservoirs exhibited an MK trend then it was not included in the table. Chlorophyll (Chl), total phosphorus (TP), total nitrogen (TN), nonvolatile suspended solids (NVSS), and filterable suspended solids (fTSS).

Parameter		Units	Little Dixie	Carl DiSalvo	Little Prairie
Chl	RS	year	2000, 2004	2011, 2019	—
		μg/L	14.0, 25.1, 39.7	9.4, 84.2, 83.3	—
Secchi	RS	year	1983, 1994, 1999, 2007	2006, 2011	2000, 2010, 2017
		m	1.1, 0.6, 0.4, 0.7, 0.6	2.0, 1.1, 0.4	0.8, 1.5, 2.3, 1.6
TP	RS	year	1983, 1993, 1999, 2005, 2015	2009, 2017	1993, 1999, 2010
		μg/L	32, 55, 84, 50, 65, 57	21, 88, 177	26, 35, 21, 17
	MK	Q	—, —, —, —, —, —	1, —, —	—, —, —, —
TN	RS	year	1990, 1998, 2004, 2019	2011, 2019, 2020	1999, 2018
		μg/L	622, 799, 670, 982, 1227	422, 1206, 1319	532, 417, 505
Chl:TP	RS	year	1992, 1999, 2015	2008	2013
		mass ratio	0.4, 0.2, 0.6, 0.7	0.3, 0.7	0.3, 0.5
	MK	Q	—, —, —, —	—, —	0.01, —
Chl:TN	RS	year	2000	2008, 2014	—
		mass ratio	0.02, 0.04	0.02, 0.06, 0.07	—
ln(TN:TP)	RS	year	1993, 1999, 2015	2007, 2017, 2020	2010
		mass ratio	2.63, 2.21, 2.71, 2.97	2.97, 2.48, 2.26	2.90, 3.36
NVSS	RS	year	1984, 1999	2011	1997, 2001, 2010
		mg/L	2.8, 7.0, 3.2	0.6, 3.1	4.3, 2.7, 1.4, 0.6
	MK	Q	—, —, −0.1	—, —, —	—, —, −0.1, —
fTSS	RS	year	1999	2013	1997, 2003
		mg/L	9.5, 1.4	0.7, 1.6	4.2, 1.9, 0.9

negative to positive over the 42-year record. In the recent 2 decades, TSI analysis indicates an increase in P deficiency, with turbidity dominated by large particles. This analysis also implies that zooplankton grazing is negligible. Application of a variety of nutrient status indicators suggested Little Dixie was P sufficient early in summer 2018 but switched to P deficiency by August (Petty et al. 2020). The natural log (ln) of the TN:TP mass ratios averaged 2.60 prior to 2015, when it displayed an RS, and 2.97 for 2015–2020 (Table 3). In Little Dixie, the ln(TN:TP) is <3 most of the time, which indicates N deficiency; however, application of a variety of nutrient status indicators in 2018 suggested Little Dixie was N sufficient (Petty et al. 2020). A progressive temporal increase in TN occurred during the study; values increased 22% from 1978–1989 to 1991–1997, decreased 16% from 1991–1997 to 1999–2003, increased 32% from 1999–2003 to 2004–2018, and then increased another 20% in 2020 (Table 3, Fig. 1c). Between 1999 and 2020 the temporal increase in TN is significant ($r = 0.74$) while the pattern for TP was not. This difference suggests sources of these nutrients likely differed during this time frame, but further analysis is outside the scope of this dataset.

During summers when NVSS was <5 mg/L (2001–2020; Fig. 1f), the Chl:TP ratio averaged 0.7. By contrast, when NVSS was >5 mg/L (1985–1998; average 7.0 mg/L; Table 3) the Chl:TP ratio averaged 0.22. These findings, in a single system over time, support the modifications of phytoplankton–nutrient relations by mineral turbidity shown in cross-system analyses in Missouri reservoirs (Knowlton and Jones 2000, Jones et al. 2008b, 2020b).

Carl DiSalvo Lake

In Carl DiSalvo Lake, long-term geometric means (Table 2) deviated considerably from typical mesotrophic conditions in Ozark Highland reservoirs (median values, $n = 199$, TP = 15 μg/L, TN = 400 μg/L, Chl = 5 μg/L, NVSS = 1.0 mg/L, and Secchi disk depth = 1.7 m; Jones et al. 2020b). Specifically, TP was 37 μg/L, TN 295 μg/L, and Chl 21 μg/L higher, and Secchi depth 0.8 m shallower than would be expected in this forested landscape (Jones et al. 2020b). Recent measurements are consistent with eutrophic conditions, with several seasonal mean values in the hypereutrophic category, which is uncommon among reservoirs in the Ozark Highlands (Jones et al. 2008b; Fig. 3). The impact of grass carp (2004) and glyphosate herbicide additions (2014) on limnological characteristics are evidenced in the 11-fold range in TP, 5-fold range in TN, 40-fold range in Chl, 9-fold range in Secchi, 51-fold range in NVSS, and 7-fold range in fTSS between minimum and maximum summer geometric mean values (Table 2), which collectively indicate a temporal decline in water quality.

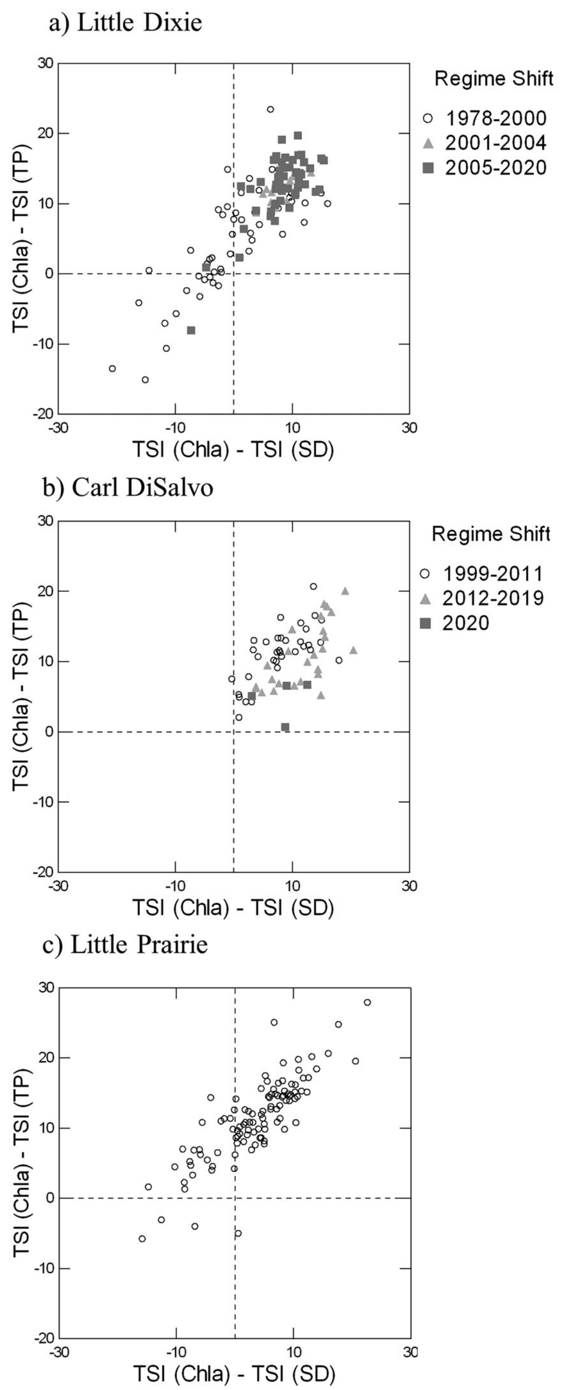

Figure 2. Trophic State Index (TSI) plots as per Carlson and Havens (2005) for each reservoir. (a) Little Dixie, (b) Carl DiSalvo, (c) Little Prairie. Shown are individual values from the long-term datasets, with zero indicated by horizontal and vertical lines. Data is grouped by regime shifts for Chl (Table 3).

Prior to management applications (Table 1), plant nutrients, Chl, and Secchi transparency closely matched values in mesotrophic reservoirs in the Ozark Highlands (Jones et al. 2008a). Water quality changes between pre-grass-carp years (1999–2003) and post-grass-carp (2006–2020) additions were, respectively: TP = 18–78 μg/L, TN = 367–897 μg/L, Chl = 5.4–48.5 μg/L, NVSS = 0.3–2.2 mg/L, fTSS = 0.5–1.2 mg/L, and Secchi disk depth = 2.0–0.6 m. Following treatment, plant nutrients and Chl rapidly increased; average increases from the mean prior to the first RS to the mean following the last RS were 91% for Chl, 92% for TP, 97% for TN, 96% for NVSS, 98% for fTSS, and 98% for Chl:TP. Secchi depth and ln (TN:TP) declined by 96% and 99%, respectively (Table 3, Fig. 3). Across the data record, the correlation (r) between Chl, TP, TN, and year of collection was >0.90, and among Chl, TP, and TN the correlation was >0.94. This strong multicollinearity supports that increases in nutrient release from senescing macrophytes (Dibble and Kovalenko 2009) promoted a phytoplankton response. The fractions of mineral turbidity, NVSS, and fTSS were also correlated with year of collection ($r = 0.79$ and 0.77, respectively) as was Secchi transparency ($r = -0.91$).

These temporal changes, as a result of human intervention, stand out as exceptional in the long-term dataset from Missouri reservoirs (Jones et al. 2020b). The switch from macrophytes to an alternative state was characterized by regime shifts in Chl, TP, and TN in 2009–2011 (Table 3, Fig. 3), 5 years after the stocking of grass carp (2004; Table 3, Fig. 3). Secchi transparency declined a few years prior to this regime shift (2006) and has decreased from ~2 to 0.4 m (Fig. 3, Table 3).

TSI deviations in Carl DiSalvo were consistently positive (Fig. 2b), with values positioned in the top right quadrat indicating turbidity dominated by large particulates. The ln (TN:TP) mass ratios indicated increasing N deficiency from the early 2000s (2.97; Table 3) to 2020 (2.26; Table 3), although this increase also corresponded with significant increases in TN. Diazotrophs, *Dolichospermum*, and *Aphanizomenon* were dominant in both phytoplankton samples (Table 4), but herbicides are known to inhibit N-fixation (Mishra and Pandey 1989). Overall, these changes in water quality are a common outcome of macrophyte removal and represent an exponential shift to a plankton-dominated community (Scheffer 2001).

Little Prairie Lake

Limnological conditions in Little Prairie Lake closely resemble nearby impoundments in the Ozark Highlands (Table 2; Jones et al. 2020b). The reservoir, however, was noticeably turbid prior to the addition of water willow in 2001 and vegetation cages in 2003 (Table 1) when NVSS averaged 3.4 mg/L, more than triple the regional average (Jones et al. 2020b), while Secchi transparency was less

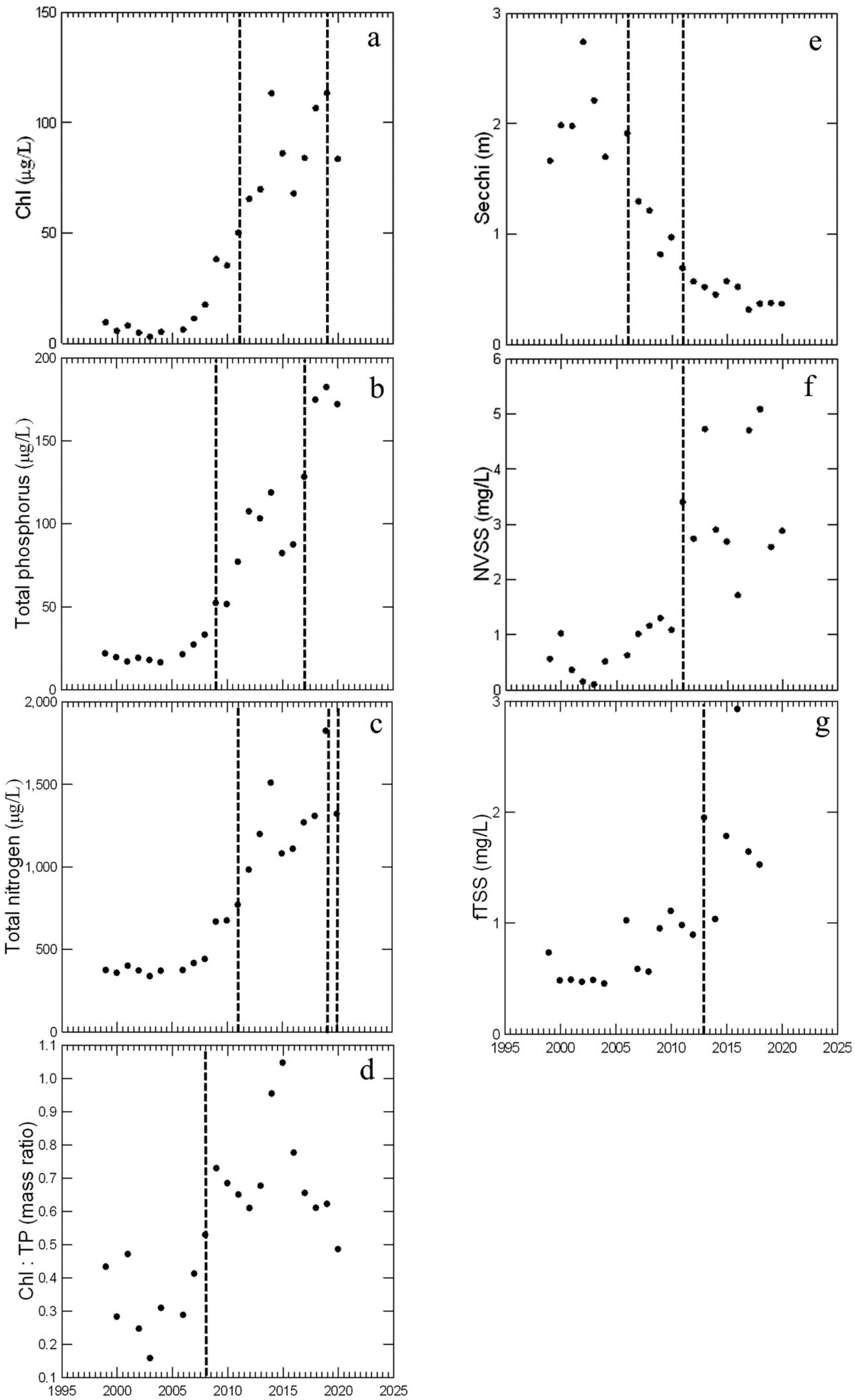

Figure 3. Long-term (1999–2020) limnological parameters for Carl DiSalvo Lake. Shown are geometric means of (a) chlorophyll (Chl), (b) total phosphorus (TP), (c) total nitrogen (TN), (d) Chl:TP, (e) Secchi depth, (f) nonvolatile suspended solids (NVSS), and (g) filterable suspended solids (fTSS). Regime shifts are identified by vertical dashed lines (Table 3).

than half at 0.9 m (Table 2; Jones et al. 2020b). As macrophyte stands expanded, NVSS and fTSS declined by ~60% while Secchi transparency doubled (Fig. 4). Significant RSs were detected in NVSS, fTSS, and Secchi beginning in 1997 (Table 3), prior to records of active management. By 2009, Eurasian watermilfoil covered ~70% of the surface area, negatively affecting the sport fishery. Unlike the response to grass carp stocking in Little Dixie and Carl DiSalvo, NVSS and fTSS, along with N and P, continued to decline following stocking (2012–2017). Concurrently, Secchi transparency, ln (TN:TP), and Chl:TP continued to increase.

Chl ranged 4-fold during the study (Table 2) with no significant temporal pattern (Table 3). No RS or trend

Table 4. Microcystin concentration geometric means and cyanobacteria characterization for the 3 study reservoirs. Geometric mean (min–max); *n* (sample size) in italics. Significant differences ($p < 0.05$) between microcystin concentrations from Mann Whitney *U* test between 2 time periods, 2004–2006 and 2015–2020, are identified in bold. Phytoplankton counts represent one sample collected in July 2003 and one sample from August 2015 for all 3 reservoirs. Cyanobacteria biovolume is the percent of cyanobacteria identified in counts relative to total phytoplankton biovolume, and PTOX is the percent of potentially toxigenic cyanobacteria (Chapman and Foss 2019) for microcystin production relative to cyanobacteria biovolume. MC = microcystin; BDL = below detection limit of 0.1 µg/L.

		2003				2015		
Reservoir	2004–2006 MC (µg/L)	Cyano biovolume %	PTOX %	Dominant genus	2015–2020 MC (µg/L)	Cyano biovolume %	PTOX %	Dominant genus
Little Dixie	0.34 (BDL–0.72) *9*	54	85	*Dolichospermum*	0.24 (BDL–2.14) *28*	91	51	*Sphaerospermopsis* *Sphaerospermum*
DiSalvo	**BDL** *6*	62	82	*Dolichospermum*	**0.18** (BDL–1.97) *27*	44	95	*Sphaerospermopsis* *Aphanizomenon*
Little Prairie	**BDL** *9*	8	65	*Synechococcus* *Synechocystis*	**0.13** (BDL–0.34) *27*	82	57	*Sphaerospermopsis*

was detected in the long-term Chl concentrations, and thus no shift in TSI over the 31-year dataset (Fig. 2c), but recent increases in these water quality metrics suggest that increased stocking and aging of grass carp may now be realized.

The ln (TN:TP) mass ratios indicated N deficiency until 2010 (2.90), when the ratios significantly increased (3.36; Table 3). Ratios since 2011 indicate that N, P, or some other factor is limiting the phytoplankton population (Guildford and Hecky 2000, Isles 2020). TSI deviations in Little Prairie closely resemble those in Little Dixie, with most values indicating P deficiency and turbidity related to large particles (Fig. 2c). Application of nutrient status indicators in 2018 suggested Little Prairie was P deficient and N sufficient (Petty et al. 2020).

Fish management impacts on cyanobacteria and microcystin concentrations

The addition of both benthivorous fish and herbicides have been associated with increased presence of cyanobacteria and associated toxins (Kasinak et al. 2015, Harris and Smith 2016, Wu et al. 2016, Brêda-Alves et al. 2021). Grass carp selectively avoid feeding on potentially toxigenic cyanobacteria (PTOX; Kasinak et al. 2015), thereby conceivably increasing their dominance in waterbodies. The promotion of internal P loading from lake sediments via the disruption caused by benthivorous fish can substantially increase the P concentrations in the water column (Zambrano et al. 2001, Orihel et al. 2017, Lin et al. 2020). Increased microcystin concentrations have been attributed to internal P loading (Orihel et al. 2013). Herbicide application to waterbodies can indirectly and directly promote cyanobacteria growth (Harris and Smith 2016). Indirectly, they can suppress the growth of algae, allowing herbicide-tolerant cyanobacteria to outcompete, and P-containing herbicides can serve as a P source to cyanobacteria (Brêda-Alves et al. 2021). Herbicides can lyse cyanobacteria cells, releasing intracellular microcystin (Liu et al. 2016, Wu et al. 2016), and they can also increase the production of microcystins (Brêda-Alves et al. 2020).

In our long-term dataset from 3 reservoirs, the microcystin geometric means were significantly higher during 2015–2020 than 2004–2006, when the concentrations were below detection in both Little Prairie ($U_{1,132} = 0.000$, $p < 0.0005$) and DiSalvo ($U_{1,89} = 0.000$, $p < 0.0005$; Table 4). In Little Dixie, there is no difference in microcystin geometric means between the 2 time periods ($U_{1,146} = 170.500$, $p = 0.115$; Table 4). The maximum MC concentration has increased 3 (Little Dixie and Little Prairie) and 20 (DiSalvo) times in recent years, although these concentrations are still well below the US Environmental Protection Agency (EPA) recreational health advisory value of 8 µg/L (USEPA 2019). Chronic exposure to low doses of cyanotoxins, however, has been found to promote tumor formation and may be responsible for the development of cancer (Zanchett and Oliveira-Filho 2013). The risk of colorectal cancer was multiplied 8-fold when water with >0.05 µg/L of microcystin was ingested (Zanchett and Oliveira-Filho 2013). This concentration is below the analytical limits of detection for ELISAs; thus, any microcystin detected has the potential to be detrimental to human health. In Little Dixie and DiSalvo, the historically (2003) dominant PTOX (Chapman and Foss 2019) was *Dolichospermum* (formerly *Anabaena*), a diazotroph that produces microcystin and the taste-and-odor (T&O) compound geosmin. In Little Prairie, 65% of the cyanobacteria were PTOX, dominated by *Synechococcus* and *Synechocystis* (Table 4). *Synechococcus* is a diazotroph that, in addition to microcystin, also produces the T&O compounds geosmin and methyl-isoborneol (MIB; Graham et al. 2008). In recent years (2015–2020), the dominant PTOX have been *Sphaerospermopsis*, a diazotroph that

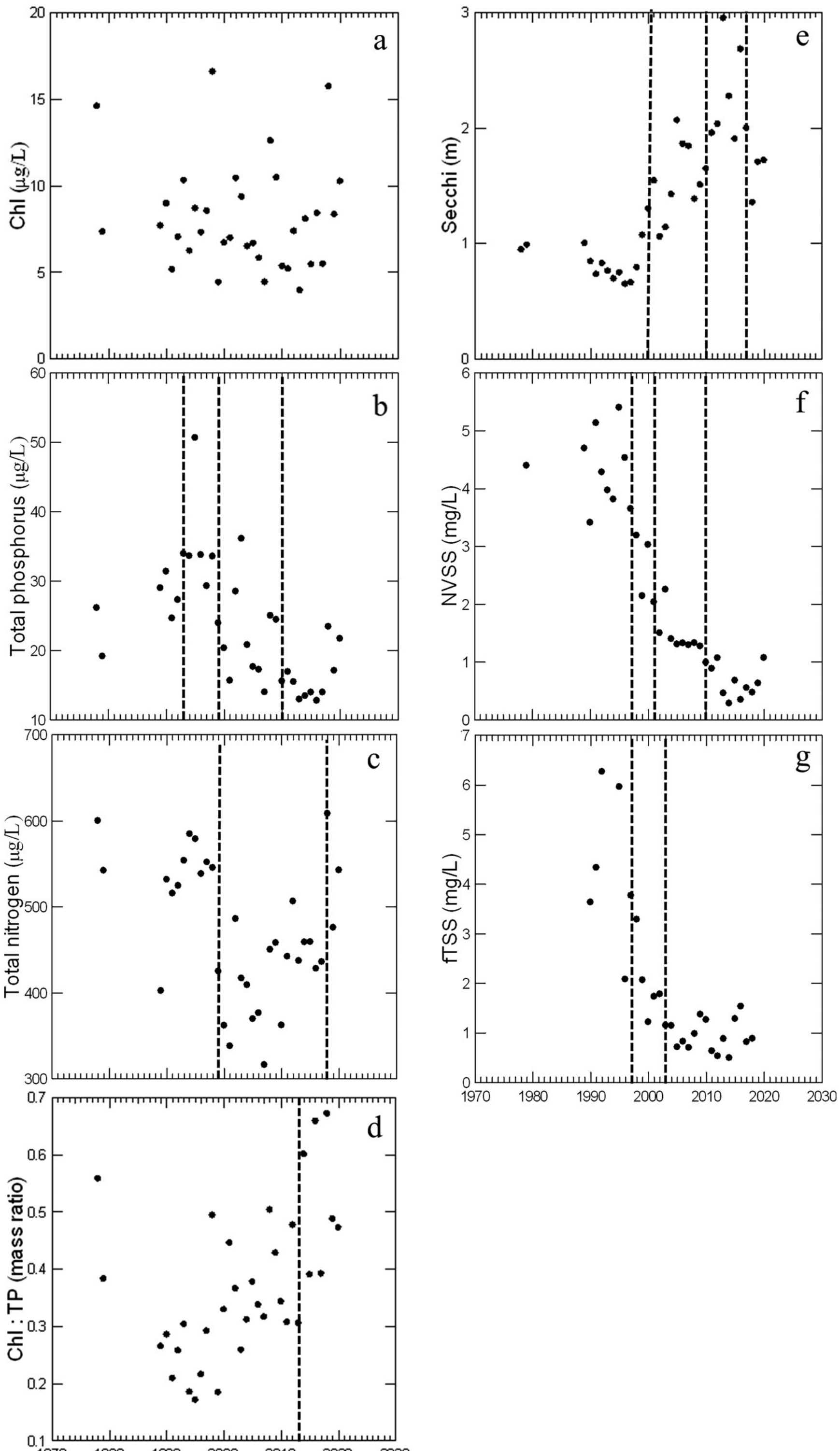

Figure 4. Long-term (1989–2020) limnological parameters for Little Prairie Lake. Shown are geometric means of (a) chlorophyll (Chl), (b) total phosphorus (TP), (c) total nitrogen (TN), (d) Chl:TP, (e) Secchi depth, (f) nonvolatile suspended solids (NVSS), and (g) filterable suspended solids (fTSS). Regime shifts are identified by vertical dashed lines (Table 3).

produces microcystin in all 3 reservoirs, and *Sphaerospermum* in Little Dixie (Table 4). The diazotroph *Aphanizomenon* was dominant in DiSalvo, and while not known to produce microcystin, it does produce the cyanotoxin cylindrospermopsin and the T&O compound geosmin (Chapman and Foss 2019). The increase in cyanobacterial biovolume (with the exception of DiSalvo), presence of PTOX, and increase in microcystin concentrations (with the exception of Little Dixie) may be a response to grass carp and glyphosate additions. Enhancement of internal P loading (Huser et al. 2016) and selective feeding by grass carp (Kasinak et al. 2015) may have contributed to these increases. Cyanobacteria are also favored when glyphosate is present (Saxton et al. 2011, Harris and Smith 2016) because of their decreased sensitivity to glyphosate and capacity to use it as a P source.

Conclusion

Shallow lakes are often characterized as macrophyte-dominated and clear or phytoplankton-dominated and turbid, with the potential to switch between these alternative states in response to environmental change, both internal and external (Scheffer et al. 1993, Scheffer 2001). Given the role of nonpoint source inputs and hydrology in determining nutrients in Missouri reservoirs (Jones et al. 2008a, 2009, 2020b), there is no basis for assuming external nutrient or sediment loads changed systematically in the 3 study reservoirs over these long time periods. The environmental changes documented in these reservoirs are internal and anthropogenic. We posit that fisheries and shoreline management in Missouri has shifted 2 of the study reservoirs (Little Dixie and Carl DiSalvo) between alternative states, and currently left them phytoplankton dominated (specifically cyanobacteria dominated) and less transparent. The desire by the fishing public to free reservoirs of nuisance vegetation has prompted fisheries biologists to stock exotic grass carp and add herbicides to reduce or eradicate macrophyte communities (Dibble and Kovalenko 2009). In-lake processes complicate cross-system comparisons and serve as an unquantified source of error in our holistic land cover–nutrient relationships, with potential influence on interpretation of regional nutrient criteria. Including fish and shoreline management in general models, which serve as the basis for establishing total maximum daily loads (TMDLs) for impaired reservoirs, will be difficult. This study serves as documentation and unique examples of responses to these manipulations; additional work should investigate how fisheries management and shoreline stabilization practices can be incorporated into models. These practices also have the potential to mask the benefits of watershed restoration efforts to reduce nutrient and sediment loss to downstream impoundments. Restoration of nonvegetated turbid lakes is considered difficult (Scheffer 2001) but should be a priority, given the risk of eutrophication and cyanotoxins to human and wildlife health.

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