Articles

Where's the Grass? Disappearing Submerged Aquatic Vegetation and Declining Water Quality in Lake Mattamuskeet

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Abstract

Major threats to aquatic systems such as shallow lakes can include declining water quality, the loss of macrophyte beds, and the occurrence of harmful algal blooms. Often, these changes go unnoticed until a shift from a clear, oligotrophic system dominated by macrophyte beds to a turbid, eutrophic system dominated by phytoplankton and associated harmful algal blooms has occurred. Lake Mattamuskeet, which mostly lies within the boundary of Mattamuskeet National Wildlife Refuge, North Carolina, is a shallow lake that has recently experienced a reduction in water clarity and macrophyte beds, also referred to as submerged aquatic vegetation (SAV), and an increase in nutrients, phytoplankton, harmful algal blooms, and cyanotoxin production. At Lake Mattamuskeet, SAV coverage and water clarity declined between the 1980s and 2015. During the same time, significantly increasing trends in nitrogen, phosphorus, turbidity, suspended sediments, chlorophyll *a,* and pH occurred. Current water-quality conditions (2012–2015) are not conducive to SAV survival and, in some cases, do not meet North Carolina water-quality standards for the protection of aquatic life. Water clarity declines appear to predate the SAV die-offs on the east side. Moving forward, SAV will serve as a primary indicator for lake health; and lake monitoring, research, and management efforts will focus on the restoration of aquatic grasses and water quality at Lake Mattamuskeet.

Keywords: cyanobacteria; eutrophication; SAV; submerged aquatic vegetation; water quality

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Introduction

Eutrophication of aquatic ecosystems threatens aquatic resources and many of the organisms that depend on aquatic habitats for survival (Smith 2003; Paerl and Huisman 2008). Nutrient loadings, particularly of nitrogen and phosphorus, have increased concurrently with the production of food and energy in the 20th and 21st century (Smil 1994, 2000). The effect of eutrophication on water bodies varies depending on physical characteristics of the waterbody such as residence time, depth, temperature, and turbidity as well as total nitrogen and phosphorus loads and standing algal biomass (Lee et al. 1978; Downing et al. 2001; Havens and Gawlik 2005; Paerl and Huisman 2008; Kosten et al. 2012). Eutrophication can reduce water clarity if suspended sediment and phytoplankton production increase as a result of excess sediment and nutrient inputs. This chain of events can trigger a progression of adverse effects on other organisms in lakes, including the loss of macrophyte beds (Davis and Brinson 1980; Kemp et al. 1983, 2004). This loss is a particular concern for wildlife managers because these plants create rich habitat and a food resource for waterfowl, fish, and invertebrate populations (Lubbers et al.1990; Heck et al. 1995).

Shallow lakes can provide important habitat for wildlife because of their ability to maintain thick stands of emergent and submerged vegetation, but can also be highly susceptible to eutrophication (Scheffer 2004). Shallow lakes dominated by macrophytes, also known as submerged aquatic vegetation (SAV), generally provide relatively clear water, better food sources for waterfowl, and healthier populations of recreational fish than phytoplankton-dominated lakes (Jeppesen et al. 1997; Sponberg and Lodge 2005; Blindow et al. 2006). An undesirable shift to turbid water and cyanobacteria dominance can occur if the lake becomes eutrophic from excess nitrogen, phosphorus, and sediment (Scheffer 2004; Havens and Gawlick 2005). Understanding the mechanisms that determine when macrophyte-dominated lakes become phytoplankton-dominated is a critical research and management challenge (Scheffer et al. 2001; Jeppesen et al. 2003), with the concomitant challenge of macrophyte restoration in phytoplankton-dominated systems (Moss 1990; Gulati et al. 2008).

Attempts to restore eutrophic shallow lakes to a clear, SAV-dominated system have had mixed success. For example, the limited success of restoration of SAV in Lake Okeechobee and Lake Apopka in Florida has been partially attributed to a narrow focus on phosphorus reduction (Bachman et al. 1999; Havens 2003). Conversely, restoration strategies that included nitrogen and phosphorus reductions and dredging of bottom sediments induced significant reductions in surface water nutrient and phytoplankton concentrations in other shallow lakes such as Wuli Lake, China; Lake Tohopekaliga, Florida; and Lake Albufera, Spain (Paerl et al. 2016). This evidence suggests that a watershed restoration plan may need to include a multifaceted approach to restoration that includes nutrient reductions and in-lake restoration strategies.

Lake Mattamuskeet is a 16,720-ha shallow lake located on the Albemarle–Pamlico Peninsula on the eastern coast of North Carolina (Figure 1). Lake Mattamuskeet is the centerpiece of the U.S. Fish and Wildlife Service (USFWS) Mattamuskeet National Wildlife Refuge (hereafter, "Refuge"), established in 1934 to maintain and promote wetland habitats for migratory bird populations and specifically wintering waterfowl in and around the lake. The Refuge's location along the Atlantic Flyway makes it a vital stopover for wintering waterfowl, and the lake annually hosts hundreds of thousands of wintering ducks, geese, and swans that feed on its macrophyte beds. Submerged aquatic vegetation in Lake Mattamuskeet has historically consisted of wild celery *Vallisneria americana,* sago pondweed *Stuckenia pectinata,* southern naiad *Najas guadalupensis,* redhead grass *Potamogeton perfoliatus,* with the branched algae, muskgrass *Chara* spp. and nitella spp. The lake's macrophytes provide quality habitat for other wetland-dependent wildlife such as migrating shorebirds, wading birds, fish, and shellfish that spawn or develop in the lake in addition to supporting wintering waterfowl.

Many of the Refuge's wildlife and habitat objectives in the Refuge Comprehensive Conservation Plan (USFWS 2008) are supported by SAV in the lake. However, recent research (Waters et al. 2009, 2010) concluded that partitioning the lake into two basins influenced SAV such that only one basin remained macrophyte-dominated. They concluded the partitioning was caused by the construction of the North Carolina Highway 94 causeway (in 1942), which included five culverts through which the lake's two basins exchange water. The partition resulted in a phytoplankton-dominated western basin and a macrophyte-dominated eastern basin characterized by more stable sediments (Waters et al. 2010). Additional work likewise documented differences in water and sediment quality between the east and west basins (Waters 2007; Waters et al. 2009, 2010). The fact that Lake Mattamuskeet drains a small, coastal watershed with little point source or urban influences provides an ideal setting to study the impacts of agriculture land uses in the coastal plain on shallow lakes.

In 2012, a collaborative monitoring effort that included the Refuge, North Carolina Division of Water Resources (NCDWR), and U.S. Geological Survey (USGS) began to examine factors that limited regeneration or survival of SAV in the western basin of the lake and that threatened SAV in the eastern basin of the lake. The purpose of this paper is to evaluate long-term trends in SAV and water quality at Lake Mattamuskeet from historical data sets. Our first objective was to model SAV distribution and abundance from field survey data collected between 1989 and 2015 so that historical changes in SAV could be illustrated. We hypothesized that water depth would influence SAV distribution and abundance if water clarity was affecting SAV growth. Our next objective was to compile and analyze existing data sets from the Refuge, NCDWR, and USGS for factors identified in conceptual models of SAV growth (Davis and Brinson 1980; Dennison et al. 1993; Kemp et al. 2004), including water clarity, nutrients, sediment, and pesticides. We hypothesized that there would be significant increases in

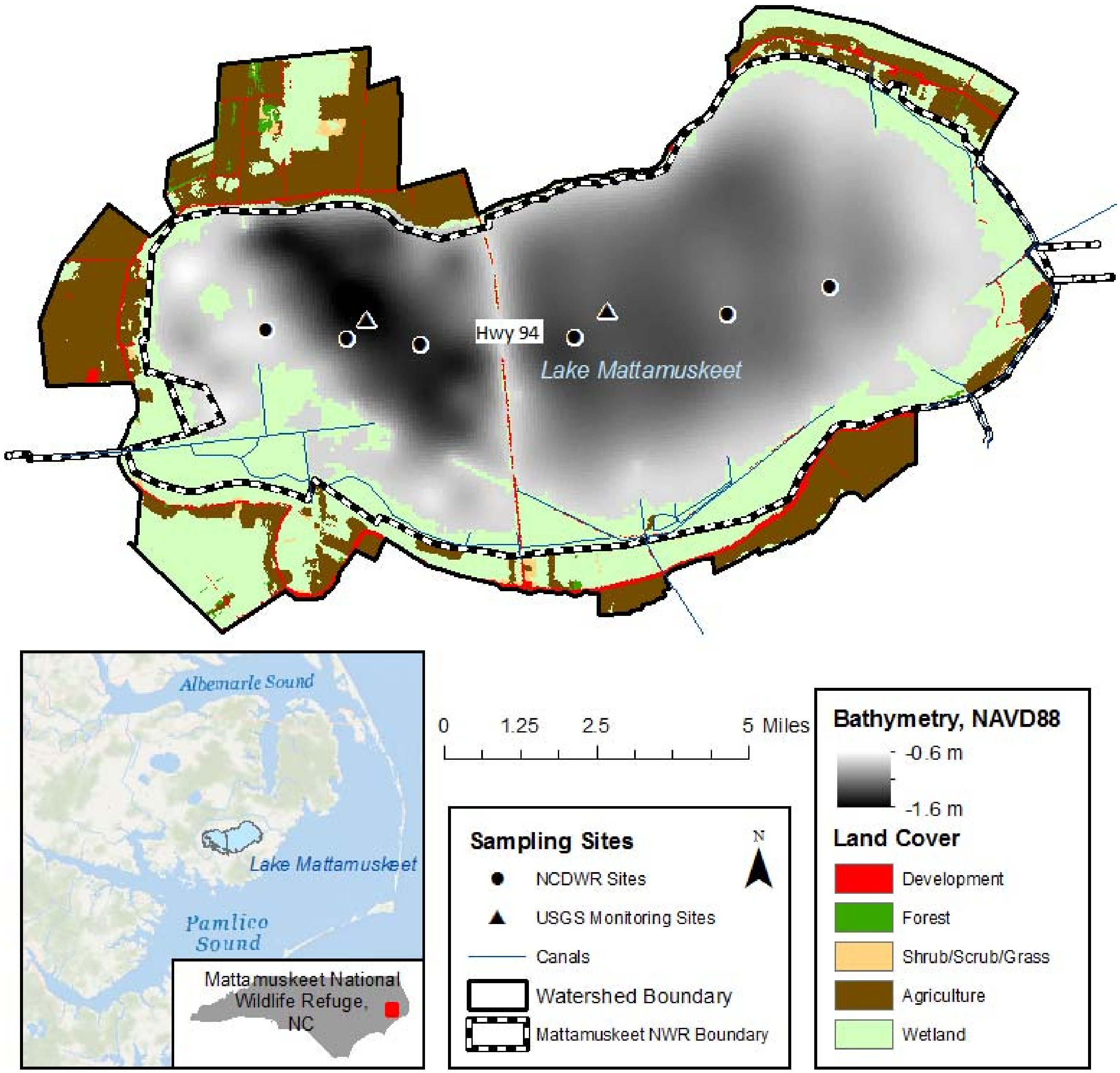

Figure 1. Map of Lake Mattamuskeet, Mattamuskeet National Wildlife Refuge, North Carolina, illustrating historical and current water-quality monitoring locations, lake bathymetry, Refuge and watershed boundaries, and land use. (Hwy, Highway; m, meters; NCDWR, NC Division of Water Resources; NAVD88, North American Datum of 1988; USGS, U.S. Geological Survey).

sediment, nutrients, and phytoplankton abundance resulting in significant decreases in water clarity from 1981 to 2015 if eutrophication was a primary driver behind SAV declines. Finally, we identified water quality parameters and other factors potentially contributing to the considerable decline in SAV to guide future research and inform strategies for the management, restoration, and enhancement of SAV.

Study Site

Mattamuskeet National Wildlife Refuge is located on the Albemarle–Pamlico Peninsula in the outer coastal plain of North Carolina. The bottom of the lake (approx. −0.6 to −1.6 m North American Vertical Datum of 1988 [NAVD88]) is lower than average water levels in nearby Pamlico Sound (average water level of 0 m NAVD88, N. Rankin, U.S. Fish and Wildlife Service, unpublished data). Average water-surface elevations ranged from above 1.5 to below −1.0 m NAVD88 between September 2012 and August 2016 (Data S1, *Supplemental Material*). The landscape of this region has been highly altered; vast areas of pocosin peatlands have been ditched and drained to facilitate agriculture (Copeland et al. 1983). Today, 4,430 ha of the 11,890 ha of land draining into Lake Mattamuskeet are intensively farmed, mostly for

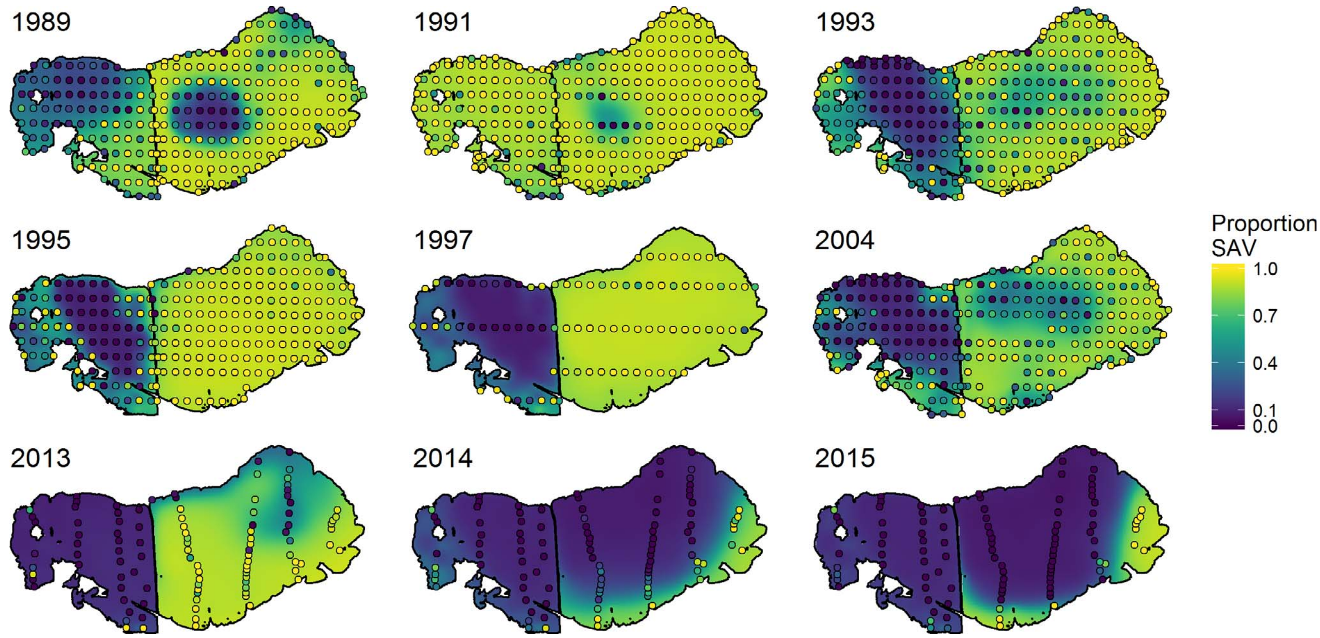

Figure 2. Estimated proportion of submerged aquatic vegetation (SAV) coverage in Lake Mattamuskeet, North Carolina, from 1989 to 2015, estimated with generalized additive models. Points indicate location of 1-m^2 survey plots and are shaded to indicate the recorded proportion of SAV coverage.

cotton, soybeans, and corn (Homer et al. 2015). Most of these farmlands connect to the lake via a series of drainage ditches, some of which are equipped with pumps that move water rapidly off the landscape and into the lake. In addition, approximately 6,880 ha of farmland and wetlands are managed intensively for waterfowl during the winter, and these lands typically pump their waters into the lake in late winter and early spring each year (Winton et al. 2016). Although precipitation is the main hydrologic input, drainage from managed wetlands and agriculture are secondary water inputs into the lake. Evaporation and drainage through the four outfall canals are the main hydrologic outputs from the lake (Benkert 1990). Groundwater inputs and outputs in this region are considered negligible (Heath 1975).

Despite its Refuge status, Lake Mattamuskeet has a long history of human modification and hydrological alteration (Forrest 1999; Waters et al. 2010). Several attempts to drain Lake Mattamuskeet for farming occurred in the late 19th and early 20th centuries, including the construction of four drainage canals to connect the lake to the Pamlico Sound and the installation of pumps to drain the lake completely. Between 1915 and 1932, portions of the lake bottom were drained three times and farmed twice (Harris 1995; Forrest 1999). The drainage project ultimately failed because the deepest portions of the lake are $>$1.6 m below mean sea level; the pumps could not keep up. However, the drainage project was successful in reducing the surface area of the lake from 48,560 to 16,750 ha (Forrest 1999; Waters et al. 2010). In 1934, the Refuge was created, but the enabling legislation provided continued authorization for adjacent landowners to drain into the lake. Prior to the 1950s, but after the establishment of the Refuge, turbid water conditions prevailed in the lake and were attributed to the large number of carp (Cyprinidae) present. It was presumed that the turbidity prevented the growth and survival of SAV in the lake and that SAV was restored following carp removal program during the 1940s and 1950s. Other management actions that may have increased water clarity during the same period included the construction of a causeway on Highway 94, which potentially reduced wave action in the lake; a series of lake drawdowns from 1949 to 1951, which would have lowered water levels, decreased lake residence times, and increased flushing rates; and transplantation of SAV (Cahoon 1953). Additionally, the lake bottom would have needed time to recover from the farming practices that occurred prior to establishment of the Refuge.

Methods

Submerged aquatic vegetation surveys and composition

Refuge staff conducted nine surveys of SAV coverage from 1989 to 2015, primarily during July and August but occasionally into September (Data S1, *Supplemental Material*). Prior to 2013, Refuge staff surveyed SAV species composition and cover on a regularly spaced grid of approximately 300 1-m^2 plots (separated by approx. 755 m longitudinally and approx. 930 m latitudinally), although with reduced effort in 1997 (Figure 2). All sample points were located using a LORAN system. Beginning in 2013, the survey was reduced on account of staff constraints, and Refuge staff annually surveyed SAV species composition and cover at 102 plots along 8 roughly north–south transects located using global positioning system (GPS; Figure 2). During all surveys, staff visually estimated the proportion of each 1-m^2 plot covered by each species or bare ground (i.e., percent cover). Water depth was also recorded at each plot location.

Modelling submerged aquatic vegetation

We used generalized additive models (Wood 2006) to generate spatially explicit models of SAV coverage on the west and east basins of Lake Mattamuskeet during the 9 y of SAV surveys between 1989 and 2015. This model-based approach (Sterba 2009) accommodates the variable, nonrandom sampling scheme and intensity over the course of the study. The response variable was the proportion of a 1-m^2 plot covered by SAV. Our model accommodates a potentially nonlinear relationship between SAV and water depth, and accounts for spatial autocorrelation in SAV coverage (see below). We modeled the proportion of SAV (P_{SAV}) using beta regression to accommodate a response variable measured on the interval [0,1] (Ferrari and Cribari-Neto 2004; Cribari-Neto and Zeileis 2010). However, a beta-distributed variable is restricted to the interval (0,1) and P_{SAV} regularly assumed the boundary values. Thus, we substituted P_{SAV} with $(P_{SAV} \cdot (n-1) + 0.5) / n$, where n is the total sample size ($n = 1{,}745$; Smithson and Verkuilen 2006). We fit generalized additive models separately for the west and east basins using the mgcv package (Wood 2016) within R (R Core Team 2016; Version 3.2.5).

Depth was the only environmental variable measured during all SAV surveys. This allowed us to relate SAV coverage only with water depth measured at the survey plots. The generalized additive models accommodated potential nonlinearity in this relationship. Macrophyte growth is limited by the depth to which a percentage of the incoming surface photosynthetically active radiation can penetrate the water column to support adequate photosynthesis (Dennison et al. 1993; Havens 2003; Kemp et al. 2004). We expected that the relationship of SAV to water depth to be significant, and potentially nonlinear, if water clarity was limiting at a certain depth. We assumed this relationship was homogeneous (i.e., did not vary geographically) within the west or east basin of the lake. We modelled spatial correlation in SAV coverage with a bivariate smooth surface of survey plot spatial (UTM) coordinates (Kneib et al. 2008). We modified the recorded spatial coordinates of several historical (i.e., pre-GPS) survey locations that fell outside of the current lake boundary to the nearest location on the lake boundary.

We used thin-plate regression splines for all smooths. We allowed separate estimates of the association between SAV coverage and depth, as well as the spatial correlation surfaces, for each survey year. We also used a cauchit link, rather than the canonical logit link, which better accommodated extreme SAV coverage measurements (i.e., no SAV or complete SAV coverage) in conflict with the expected SAV coverage at that location (Koenker and Yoon 2009). Model assessment (i.e., information criteria, the percentage of deviance explained, and bootstrapped root mean squared error) invariably supported the more complex model specification compared with simpler alternatives as well as the noncanonical link function (A. D. Smith, USFWS, unpublished data). The final models for the east and west basins predict SAV coverage on the entire lake based on a gridded bathymetry model with 100-m resolution and the spatial coordinates of the center of each raster cell. We categorized the predictive SAV coverage based on the classification used in Chesapeake Bay (Orth et al. 2015): very sparse (<10% coverage), sparse (10–40%), moderate (40–70%), or dense (70–100%). From this categorization, we estimated the total hectares SAV for each category, by lake basin, for each survey year. We evaluated uncertainty around these estimates using 1,000 posterior simulations from the final generalized additive models. We provide the data and code necessary to reproduce the SAV analysis (Data S1, *Supplemental Material*).

Water quality monitoring

Historically, water quality samples were collected in the east and west basins of Lake Mattamuskeet as part of NCDWR lakes monitoring program (Figure 1; Data S2, *Supplemental Material*). Samples were collected at two to six sites (NCDWR sites; Figure 1) over eight summers between 1981 and 2012. Photic zone samples (a depth equal to integration over twice the Secchi depth; NCDENR 2012) were analyzed for turbidity, total suspended solids, chlorophyll *a,* ammonia, total Kjeldahl nitrogen, nitrate + nitrite, and phosphorus by the NCDWR Water Sciences Chemistry Laboratory under standard protocols (NCDWQ 1986; NCDWR 2015).

Beginning in September 2012, the Refuge began a monitoring program that expanded on the NCDWR's lake monitoring program by increasing the sampling frequency and the measured parameters. Monthly (spring–summer) and bimonthly (autumn–winter) samples were collected at one site in each basin (USGS Monitoring Sites [Figure 1; Data S2, *Supplemental Material*]). Field parameters included surface and subsurface photosynthetically active radiation measured with a Li-Cor® (Li-192) underwater quantum sensor, Secchi depth (m) measured with a Secchi disk, and specific conductivity–salinity, dissolved oxygen, pH, temperature, and turbidity measured with a Hydrolab® MS 5 datasonde. All equipment was calibrated and all field measurements were taken following USGS protocols (USGS variously dated). Light attenuation coefficients were calculated from both photosynthetically active radiation and Secchi depth using standard methods, and the field data and calculated values are provided as supplemental material (Data S3, *Supplemental Material*; Scheffer 2004; USGS variously dated). We collected surface-water grab samples integrated over the top 0.15 m of the water column and processed all water samples in accordance with the NCDENR (2012) procedures.

The NCDWR Water Sciences Chemistry Laboratory analyzed samples under the same procedures used for their own lakes monitoring (NCDWQ 1986; NCDWR 2015). Total Kjeldahl nitrogen was quantified via acid digestion and colorimetry following EPA Method 351.1 (EPA 1979) using a Technicon Auto Analyzer (1981–2000) or EPA Method 351.2 (EPA 1993a) using a Lachat Flow Injection Analysis system (2000–2015). Total phosphorus was measured via ammonium peroxydisulfate digestion and colorimetry following EPA Method 365.1 using a Technicon Auto Analyzer (1981–2000; EPA 1979) or a Lachat Flow Injection Analysis system (2000–2015; EPA 1993b). Chlorophyll *a* was measured by fluorometry following the latest approved edition of Standard Methods for the Examination of Water and Wastewater Method 1002G 2&4 (1981–2005; APHA 1980 and later versions) or EPA Method 445.0 (2005–2015; EPA 1997). Turbidity was determined using the nephelometric Method 2130B-2001 (APHA 1980 and later versions). Total suspended solids were measured by gravimetric analysis using Method 2540D-1997 (APHA 1980 and later versions).

All nutrient, solids, turbidity, and chlorophyll *a* sample batches included duplicates at the lab and from the field for determining analytical precision and accuracy. The typical relative percent deviation among laboratory duplicates was $\leq$15% for phosphorus and $\leq$20% for other analytes. The typical relative percent deviation among the three sets of field duplicates collected at Lake Mattamuskeet between 2013 and 2015 after the Refuge began its own water-quality monitoring program was $\leq$20% for all analytes except that relative percent deviation was 22% for one set of turbidity duplicates and 28.9% for one set of chlorophyll *a* duplicates.

Refuge monitoring sites were co-located with in situ, continuous monitors (USGS Monitoring Sites, Figure 1), deployed by the USGS September 2012 to present to measure pH, temperature, water level, specific conductivity–salinity, dissolved oxygen, and turbidity every 15 min (Wagner et al. 2006). In addition, phytoplankton community composition was sampled on the west side of the lake during August of 2012 and cyanobacterial toxins (cyanotoxins) and pesticides were sampled on the east and west sides of the lake during August of 2013 and July of 2014 at the USGS Monitoring Sites. Phytoplankton samples were collected, preserved, and analyzed in accordance with the standard operating procedure of NCDWR (2016). Cyanotoxins, microcystin, cylindrospermopsin, and saxitoxin, as well as the pesticides atrazine and glyphosate, were analyzed by USGS's Kansas Organic Chemistry Lab and Auburn University by magnetic particle enzyme-linked immunosorbent assay kits obtained from Abraxis, LLC (Warminster, PA).

All discrete sample chemical data was stored in the North Carolina Ambient Lakes Monitoring Program Database. Data retrieval from Lake Mattamuskeet sample sites for the period 1981 to 2015 was completed by NCDWR. We removed all duplicates and flagged data from the data set. We used simple substitution to convert one value of total phosphorus that was reported as $<$20 μg/L on 11 July 1997 to 10 μg/L (Data S4, *Supplemental Material*). We compiled physical data on Secchi depth and light attenuation computed from photosynthetically active radiation and Secchi depth from Refuge files (Data S3, *Supplemental Material*). We retrieved daily minimum, maximum, mean, and median values for dissolved oxygen, salinity–specific conductance, and pH recorded on the USGS continuous monitors from September 2012 to 31 December 2015 from the National Water Information System (Data S5, *Supplemental Material*). Total nitrogen was calculated as the sum of Kjeldahl nitrogen and nitrate plus nitrite. If nitrite plus nitrate values were censored, we used simple substitution of half the censored value of nitrate plus nitrite to calculate total nitrogen. Kjeldahl nitrogen concentrations were above the reporting level and accounted for $\geq$92% of total nitrogen in all samples.

Water quality analysis

To examine trends in water quality over time, we used summer data (June–August) from the entire chemical data set from 1981 through 2015. We limited the trend analyses to samples collected in these months because they were the only months represented in the database prior to 2012. We augmented the pH and dissolved oxygen data from the North Carolina Ambient Lakes Monitoring Program Database with those from the continuous monitoring stations. We retrieved daily median and mean values for pH and dissolved oxygen respectively, from June to August between 2013 and 2015, and included those in the trends analyses. For each parameter, we analyzed concentrations for goodness of fit to a normal distribution with the Shapiro–Wilk Test (JMP Pro 11.2; SAS Institute, Inc., Cary, NC). All data were not normally distributed, even after data were log-transformed. Accordingly, we assessed the correlation of concentrations with time (sample date) with the nonparametric Kendall's Tau (JMP Pro 11.2). We deemed trend analyses significant with alpha = 0.05. We conducted no trend analyses for the constituents, nitrate plus nitrite and ammonia, both of which we detected in $<$50% of the samples.

To evaluate current conditions, we compared water quality data for the east and west sides of the lake from 2012 through 2015 using a Wilcoxon rank sum test (JMP Pro 11.2). Only three water quality parameters—salinity, dissolved oxygen, and pH—differed between the east and west basins; in excess of 1,000 measures for these three parameters on each side of the lake were available, so small differences that were not biologically relevant were able to be distinguished. For this reason, we

Table 1. Water quality constituents, standards, and guidelines assessed at Lake Mattamuskeet, 2012–2015. (mg/L, milligrams per liter; μg/L, micrograms per liter; <, less than; m, meters; NTU, Nephelometric Turbidity Unit).

Constituent	Standard or guideline	Reference
Dissolved oxygen	Daily average not <5 mg/L	NCOAH 2016
pH	Between 6.8 and 8.5 standard units	NCOAH 2016
Chlorophyll *a*	Not >40 μg/L	NCOAH 2016
Cyanobacteria (density)	Not >100,000 cells/mL	Chorus and Bartram 1999
Suspended residue, total	Not >15 mg/L	Dennison et al. 1993
Total microcystins plus nodularins	Not >4 μg/L	EPA 2016a
Total nitrogen	Range of 0.32–0.41 mg/L	EPA 2001
Total phosphorus	Range of 8–20 μg/L	EPA 2001
Total cylindrospermopsins	Not >8 μg/L	EPA 2016a
Turbidity	Not >25 NTU	NCOAH 2016
Min. light requirement (light attenuation coefficient)	Not >2/m	Dennison et al. 1993
Secchi depth	>0.5 m	Dennison et al. 1993

combined data from the east and west side of the lake to produce summary statistics on all data from 2012 to 2015 using the smwrStats package (Lorenz 2015) in R (R Core Team 2016, Version 3.2.5). Summary statistics included minimum, maximum, mean, standard deviation, median, and 10% and 90% percentile. We compared the number of samples collected with the number of samples exceeding a state, federal, or World Health Organization guideline or regulation when one existed to determine the percentage of samples that would be considered above the guideline from 2012 through 2015 (Table 1). We compared median growing-season sample results (April–October) with habitat requirements for SAV growth and survival for the east and west side of the lake from 2012 to 2015 using the dplyr package (Wickham and Francois 2016) in R (R Core Team 2016, Version 3.2.5), an approach adopted by the Chesapeake Bay initiative (Kemp et al. 2004).

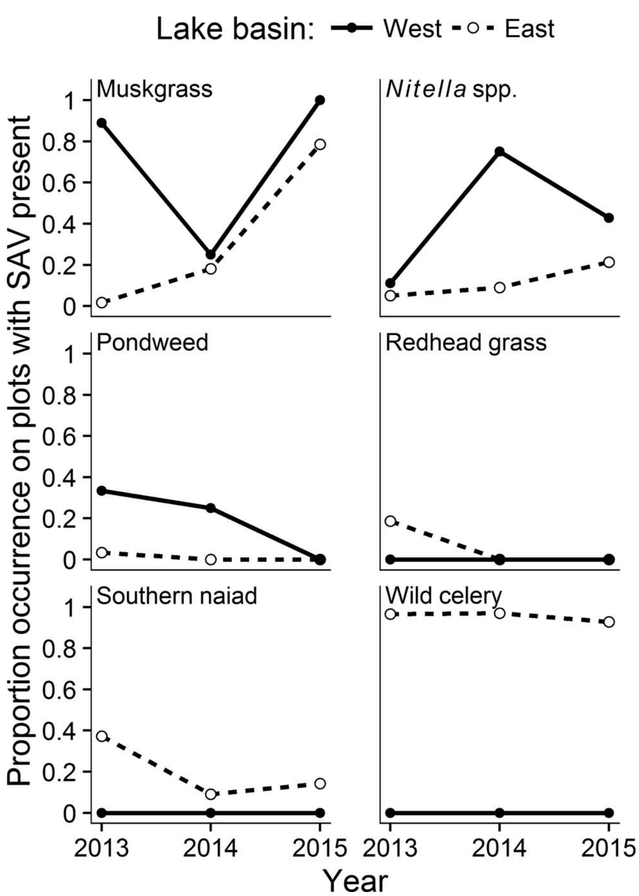

Figure 3. Composition of submerged aquatic vegetation (SAV) in the west and east basins of Lake Mattamuskeet, North Carolina, during 2013–2015, as indicated by the proportion of plots with a given species present conditional on any SAV present.

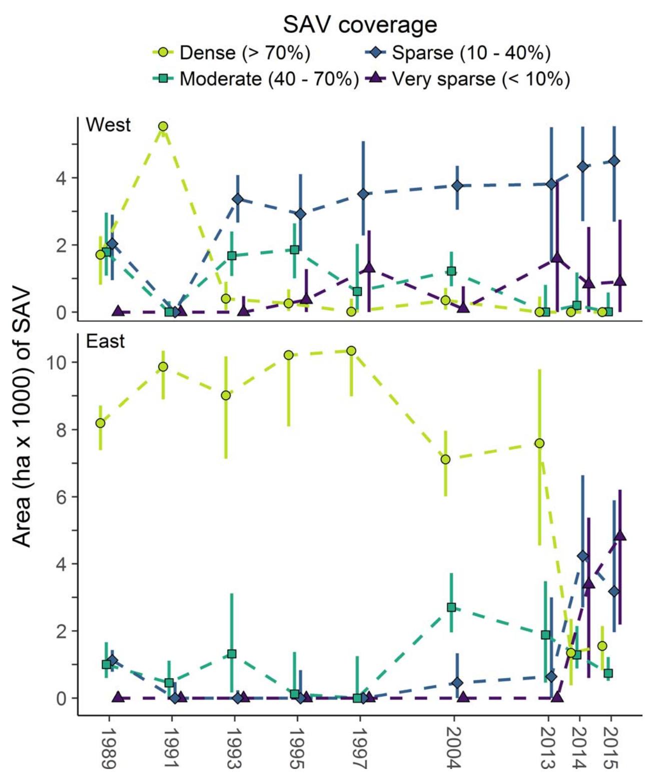

Figure 4. Estimated area in thousands of hectares (ha) of submerged aquatic vegetation (SAV) in four coverage categories (Orth et al. 2015) in the west and east basins of Lake Mattamuskeet, North Carolina, from 1989 to 2015. Error bars indicate the 90% confidence interval based on 1,000 posterior simulations from the underlying generalized additive models.

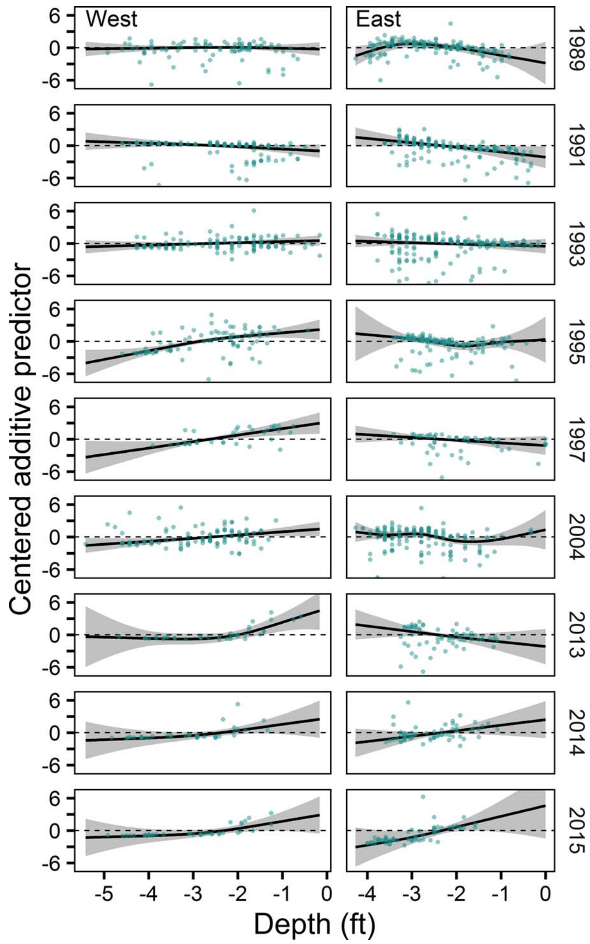

Figure 5. Association between water depth and submerged aquatic vegetation (SAV) for the west and east basins of Lake Mattamuskeet, North Carolina, from 1989 to 2015. Positive (negative) contributions to the additive predictor (y-axis) correspond to proportional increases (decreases) in SAV coverage. Although nearly linear on the scale of the additive predictor, the relationship between depth and SAV coverage is not linear on the original scale (i.e., proportion SAV coverage). For example, contributions of 1 (–1), 2.4 (–2.4), and 6.3 (–6.3) to the additive predictor correspond to 50%, 75%, and 90% increases (decreases) in SAV coverage, respectively. Shading illustrates the 95% pointwise confidence interval and circles the deviations of the observed data from the fitted associations, respectively (ft, feet).

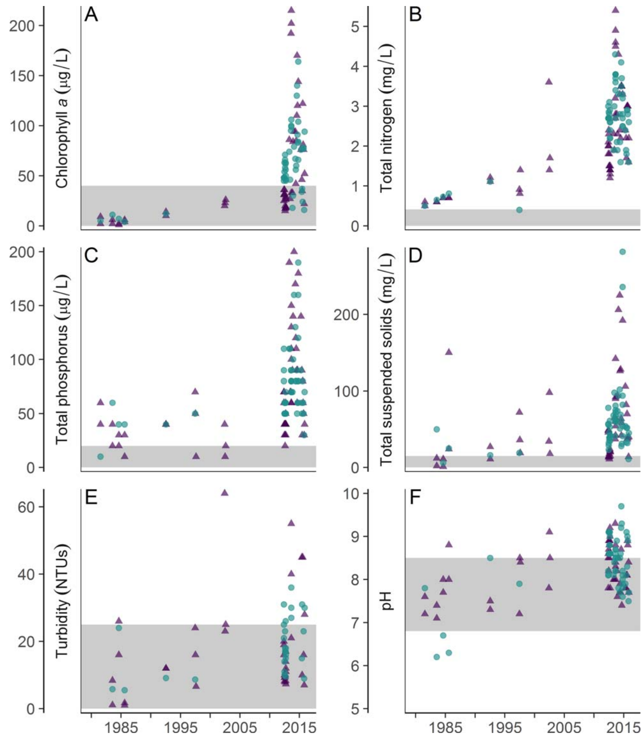

Figure 6. Trends in summer values of **(A)** chlorophyll *a,* **(B)** total nitrogen, **(C)** total phosphorus, **(D)** total suspended solids, **(E)** turbidity, and **(F)** pH measured at Lake Mattamuskeet, North Carolina, during 1983–2015. Triangles indicate samples collected in the west basin; circles represent samples from the east basin. Shading indicates the existing water-quality standards and guidelines for each parameter. Increases over time were statistically significant ($p < 0.05$) for all six of these water quality parameters. (µg/L, micrograms per liter; mg/L, milligrams per liter; NTU, Nephelometric Turbidity Unit).

Results

Submerged aquatic vegetation trends through time

Submerged aquatic vegetation in Lake Mattamuskeet has historically been composed of wild celery, sago pondweed, southern naiad, redhead grass, and with branched algae muskgrass and nitella (Figure 3). Currently, SAV in Lake Mattamuskeet is composed of wild celery, southern naiad, muskgrass and nitella. Submerged aquatic vegetation cover in Lake Mattamuskeet has declined dramatically, although the timeline and magnitude of the loss varies by lake basin (Figure 3). Generalized additive models explained ≥80% of the null deviance (a generalization of R^2 applicable to generalized additive models; Wood 2006) in SAV coverage in both basins. In the west basin of Lake Mattamuskeet, the loss of dense and moderate SAV coverage began in the mid-1990s, and in the past decade the loss of dense and moderate SAV appears nearly complete. We estimate that <200 ha of moderate to dense SAV coverage remain of >2,000–5,000 ha in the early 1990s (Figure 4). The loss of SAV in the east basin is more recent and more catastrophic in its rapidity and extent. Although several thousand hectares of dense SAV thinned to moderate coverage between 1997 and 2004, roughly 7,000 ha of dense SAV converted to approximately equal parts sparse and very sparse coverage between 2013 and 2014. As of 2015, the last stands of SAV are located in the east basin on the south and east rims of the lake bordering the Refuge (Figure 2).

Concurrent with changes in SAV coverage over time, generalized additive models detected changes in the relationship between water depth and SAV coverage. Early in the survey period (1989–1993), SAV coverage was relatively consistent across the range of measured depths for both basins (Figure 5), suggesting few

Table 2. Water quality statistics, including the percentage of values exceeding a water quality standard or guideline (from Table 1) at Lake Mattamuskeet, 2012–2015. (s.u., standard units; ppt, parts per a thousand; μg/L, micrograms per liter; mg/L, milligrams per liter; N, nitrogen; <, less than; NTU, Nephelometric Turbidity Unit; m, meters).

Constituent	% Exceedances	# Exceedances	# Samples	Min.	10%	Median	Mean	SD	90%	Max.
Dissolved oxygen, daily avg., mg/L	0	0	3,120	5.5	7.6	9.5	9.6	1.6	11.7	13.8
pH, daily median, s.u.	36	1,143	3,202	6.8	7.6	8.2	—	—	8.9	9.8
Salinity, ppt	—	—	2,013	0.4	0.6	1.0	1.0	0.3	1.3	1.5
Chlorophyll *a,* μg/L	68	56	82	15	22	59	68	44	122	215
Nitrogen, total, mg/L	100	90	90	1.2	1.6	2.7	2.7	0.9	3.8	5.4
Phosphorus, total, μg/L	99	89	90	20	40	70	80	40	140	200
Cyanobacteria (density, units per mL)	100	1	1	—	—	220,020		—	—	—
Ammonia plus organic nitrogen as N, mg/L	—	—	90	1.2	1.6	2.7	2.7	0.9	3.8	5.4
Atrazine, μg/L	0	0	2	—	—	<0.1	—	—	—	—
Glyphosate, μg/L	0	0	2	—	—	<0.02	—	—	—	—
Suspended residue, total, mg/L	91	80	88	11	18	52	63	50	106	282
Total microcystins plus nodularins, μg/L	0	0	2	—	—	0.43		—	—	—
Total cylindrospermopsins, μg/L	50	2	4	2.6	4.3				5.9	6.9
Total saxitoxins, μg/L	0	0	2	—	—	<0.02		—	—	—
Turbidity, NTU	26	12	47	7	8	17	20	11	36	55
Min. light requirement (light attenuation coefficient)	96	50	52	0.0	2.8	6.9	7.3	5.0	11.2	23.3
Secchi depth, m.	79	42	53	0.05	0.10	0.20	2.10	0.10	0.35	0.60

limitations to SAV growth and survival associated with water depth and, presumably, certain water quality attributes such as water clarity. Beginning in 1995, SAV coverage in the west basin was reduced in areas with deeper water, a pattern that has persisted thereafter (Figure 5, left column). The east basin exhibited a similar shift in this relationship, but on a different time frame; specifically, the reduction in SAV coverage associated with deeper water was not observed until 2014 (Figure 5, right column).

Water quality trends

Mattamuskeet water-quality data collected between 1981 and 2015 showed significant increases in water quality parameters associated with eutrophication (chlorophyll *a,* total nitrogen, total phosphorus, total suspended solids, turbidity, and pH; $p \leq 0.05$; Figure 6). The majority of samples analyzed for parameters associated with eutrophication have become elevated above published guidelines and standards since 2012 (Figure 6; Table 2). These parameters included chlorophyll *a,* an algal pigment used both to approximate algal biomass and as an indicator of nitrogen and phosphorus enrichment; pH, the measure of acidity of a solution that can be an indicator of photosynthetic activity; total suspended residue, an indicator of sediment resuspension; and turbidity, light attenuation coefficients, and Secchi depth, all of which are indicators of water clarity. Sixty-eight percent of the chlorophyll *a* samples collected during 2012–2015 were above the North Carolina (NCOAH 2016) regulatory water-quality standard of 40 μg/L (56 of 82 samples); whereas, no samples exceeded the standard prior to 2002. Thirty-six percent of daily median pH values during 2012–2015 were above the 8.5 standard units State water-quality standard (1,143 of 3,202 samples). Only 9% (2 of 22) of the samples exceeded the standard between 1981 and 2002, and that was in a single exceedance from July 2002. Twenty-six percent of turbidity samples during 2012–2015 were above the State water-quality standard for turbidity of 25 NTUs (12 of 47 samples), while only 1 of 16 samples exceeded the State standard prior to 2012. Water clarity was also consistently poor, reflected by the percent of samples that have not met Chesapeake Bay Guideline for

Table 3. Comparison of Lake Mattamuskeet median growing season values (April–October) to SAV median habitat requirements published for the Chesapeake Bay (Batiuk et al. 2000) and SAV acreage estimated to be <10% coverage. (<, less than; μg/L, micrograms per liter; mg/L, milligrams per liter; m, meters; SAV, submerged aquatic vegetation).

Constituent	Recommended median habitat requirement for SAV growth and survival	Summer 2012 median concentration		Summer 2013 median concentration		Summer 2014 median concentration		Summer 2015 median concentration	
		East	West	East	West	East	West	East	West
Chlorophyll *a*, μg/L	Not >15	26	54	86	95	110	84	76	37
Suspended sediment, total, mg/L	Not >15	20	42	62	67	126	65	54	40
Secchi depth, m	Not <0.5	0.35	0.25	0.25	0.30	0.10	0.20	0.20	0.25
Depth of 13% incoming solar radiation, m	Not greater than depth of 13% incoming solar radiation	0.7	0.6	0.3	0.6	0.2	0.4	0.4	0.6
Hectares estimated to have a SAV density of <10% with confidence levels.		—	—	0 (0–19)	1,611 (0–3,598)	3,473 (618–5,658)	857 (0–2,250)	4,983 (2,254–6,366)	911 (0–2,800)

SAV growth since 2012: 96% of the light-attenuation coefficient estimates, 79% of the Secchi depths, and 91% of total suspended residue samples (Dennison et al. 1993). Additionally, the EPA (2001) provides guidelines for total nitrogen of 0.32 to 0.41 mg/L and total phosphorus of 8 to 20 μg/L for coastal plain lakes. These guidelines were exceeded 100% of the time for total nitrogen and 99% of the time for total phosphorus (Table 2). Total nitrogen has increased 400% and total phosphorus has increased 100% since the 1980s. The majority of total nitrogen was organic nitrogen.

Trends for total suspended residue, dissolved oxygen, and specific conductivity were not significant. All summertime dissolved oxygen values from 2012 to 2015 met the daily average State water-quality standard of 5 mg/L. Lake salinities that were monitored continually between 2012 until 2015 ranged from 0.4 to 1.6 parts per thousand ($n = 2013$), indicating that Mattamuskeet should be classified as an oligohaline lake, with little saltwater influence on the conditions in the lake's center during this period. Only two pesticides samples were collected for atrazine and glyphosate during the study period, and the pesticides were less than the method detection limits of 0.1 and 0.02 μg/L, respectively.

Median growing season concentrations of chlorophyll *a,* suspended solids, minimum light requirements, and Secchi depth from both sides of the lake for the period between 2012 and 2015 were compared with Chesapeake Bay SAV guidelines for oligohaline waters (Table 3; Kemp et al. 2004). None of the median values reported met the minimum water-quality guidelines for SAV growth. Phytoplankton communities from a sampled algal bloom on the west side of Lake Mattamuskeet in July 2012 indicated dominance by a genera of cyanobacteria with the potential to produce cyanotoxin: *Cylindrospermopsis* spp., *Aphanizomenon* spp., and *Anabaena* spp. In August 2013 and July 2014, a limited number of samples from the east and west basins of Lake Mattamuskeet were analyzed independently by USGS Kansas Water Science Center (2013) and Auburn University (2014). During both summers, cylindrospermopsin concentrations in this limited sample set ranged between 2.6 and 6.9 μg/L, which is below the proposed EPA recreational-use guideline of 8 μg/L, but above recreational guidelines set by several states (EPA 2016a). During the summer of 2013, microcystin was detected at concentrations <1 μg/L, well below the proposed recreational-use guideline of 4 μg/L (EPA 2016a).

Discussion

All lakes age, but excess nutrient and sediment enrichment and increased residence times can accelerate the pace at which a clear, SAV-dominated lake converts to a turbid, phytoplankton-dominated lake (Novotny and Olem 1994; Wetzel 2001; Scheffer 2004). Reversing these regime shifts is complicated and often requires a multifaceted approach to restoration including reductions of nitrogen and phosphorus and in-lake restoration strategies such as carp removal, dredging, SAV transplantation, and water level management. Depending on objectives, restoration success is often measured by the return of a waterbody to a clear, SAV-dominated system (Scheffer 2004; Paerl et al. 2016).

Our analysis shows that a regime shift has occurred in Lake Mattamuskeet, where declines in SAV occurred in the west basin in the 1990s and in the east basin in 2014. We believe this shift can be attributed to a series of events that started with declining water quality as indicated by significant increases in nitrogen and phosphorus during this period. Phytoplankton blooms have increased as evidenced by increasing trends in chlorophyll *a* and high pH, both indicators of phytoplankton productivity. Concurrently, we have observed increasing trends in total suspended sediments, potentially due to loss of SAV that help trap sediments. We suggest that poor water clarity associated with increasing concentrations of nutrients and phytoplankton, as well as suspended sediment, is a primary factor limiting SAV growth and survival in the lake, a finding common in shallow eutrophic lakes (Scheffer 2004). Additionally, these conditions are associated with a proliferation of toxin-producing cyanobacteria in Lake Mattamuskeet.

This hypothesis is supported by the dramatic reduction in water clarity observed in the east basin just prior to the SAV die-off in 2014. Additionally, we observed a significant relationship between water depth and SAV declines beginning in the west basin in 1995 and in the east basin in 2014. Subsequent to this decline in east basin water quality, little evidence remains for the water quality difference between the west and east basins of Lake Mattamuskeet reported previously (Waters et al. 2010), and neither basin currently meets North Carolina water-quality standards. Specifically because of the lake's elevated pH and chlorophyll *a* levels, the lake was recently (2016) proposed for EPA's impaired waters list (EPA 2016b). Our preliminary sampling provides no evidence that pesticides are important in local SAV decline. Although we have few herbicide samples and analytes, we note findings from the Chesapeake Bay that effects from herbicides are not likely to be the cause of SAV declines, especially when water clarity is poor because of nutrients and sediment (Hurley 1991). We did not evaluate other potential factors affecting SAV growth and survival including biomass loss in winter, herbivory losses, and damage by waves (Scheffer et al. 1993), or periphyton growth on SAV leaves (Van Dijk 1993).

Paleopigment profiles suggest that a slow shift to cyanobacterial dominance has occurred in Lake Mattamuskeet since the 1850s, when canal construction and land clearance began in the region (Waters et al. 2009). It is likely that the abundance of cyanobacteria in Lake Mattamuskeet has recently increased based on the significant increases in chlorophyll *a* documented herein, but limited phytoplankton community data are available. We are unsure why tipping points have been reached, causing the recent dramatic and rapid loss of SAV in the east basin of the lake; however, chlorophyll *a* and limited cyanobacteria and cyanotoxin data support the hypothesis that lakes with high rates of light absorption are dominated by cyanobacteria (Paerl et al. 2016). This dominance often creates a positive feedback loop between increased nutrient loading, increased cyanobacteria abundance and density, and poor light availability (Kosten et al. 2012). As a result, cyanobacteria are abundant and producing the cyanotoxin—cylindrospermopsin—at some of the highest concentrations detected in lakes nationwide (Loftin et al. 2016). There is a need to better understand the potential human and wildlife health impacts that the cyanotoxin could have on the lake's ecosystem.

Moving forward, we will use SAV conceptual models to better understand the causes of SAV declines and reduced water quality and to explore management actions to restore SAV habitat at Lake Mattamuskeet (Davis and Brinson 1980; Havens 2003; Kemp et al. 2004). Ongoing research projects focus on identifying sources of light attenuation and harmful algal blooms in the lake. One future research goal is to use continuous, remotely sensed, and discrete data collected between 2012 and the present to better elucidate the dramatic loss in SAV between 2013 and 2014. Additionally, identification of nutrient sources and magnitudes is needed in order to target nutrient-reduction strategies. Previous experiments suggest that nitrogen and phosphorus were colimiting the growth of algae and suggested efforts should focus on reducing loadings of both these nutrients from the watershed (MF Piehler, UNC Chapel Hill Institute of Marine Sciences, unpublished data). The sources of these nutrients are diverse, but primarily include agricultural run-off, atmospheric deposition, and pumping of waterfowl impoundments. Waterfowl themselves appear to be an insignificant source (Winton et al. 2016). In-situ recycling of sediment and nutrients in the lake could also play a major role in the nutrient budget and is being investigated. This includes evaluating the role that benthivorous carp play in the system and the potential of removing carp as part of a restoration strategy. Finally, we need to consider the role of climate change in eutrophication. The impact of Pamlico Sound's rising water levels, which have been measured at 2.1 mm/y, could accelerate eutrophication by increasing lake residence times (Kemp et al. 2011). Alternative strategies for moving water may need to be considered.

Protecting and enhancing healthy wetland and aquatic ecosystems, with a focus on the ecological integrity of Lake Mattamuskeet, is the goal of the Refuge. Although water quality could be managed based on historical conditions or the life requisites of particular fish and wildlife species, we have decided that organizing monitoring and research around the conservation of the lake's SAV as an overall indicator of the health of the lake is an appropriate approach to adaptively manage the lake's ecosystem. Moving forward, the success and failures of various management strategies will be monitored and assessed to determine the efficacy of various management decisions. As a result, work at Lake Mattamuskeet can improve our understanding of what practices are likely to facilitate restoration success in other coastal plain waterbodies dominated by agriculture in the southeastern United States that are shifting to turbid, phytoplankton-dominated systems. These strategies include, but are not limited to, installation and management of water control structures on surrounding lands, timing hydrologic releases from impoundments and the lake, nutrient abatement strategies with local farmers, sediment removal from the lake, carp removal in the lake, and large-scale projects aimed at changing lake level management. This will be especially important in elucidating what additional management strategies beyond nutrient reductions are needed in order to shift a lake back to a clear, macrophyte-dominated system (Paerl et al. 2016).

Supplemental Material

Please note: The *Journal of Fish and Wildlife Management* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

Data S1. All submerged aquatic vegetation (SAV) field data (location, depth, and estimate of SAV coverage for each sample plot), and associated code used for the modeling and analysis of occurrence and distribution patterns of submerged aquatic vegetation (SAV) at Lake Mattamuskeet, 1989–2015. This code and data produced Figures 2, 4, and 5 in the article.

Found at DOI: http://dx.doi.org/10.3996/082016-JFWM-068.S1 (56,741 KB ZIP).

Data S2. Latitude and longitude in decimal degrees (World Geodetic System 1984) for all Lake Mattamuskeet water-quality sample sites including sites samples as part of North Carolina Division of Water Resources (NCDWR) lakes monitoring program (1981–2012, DWR Monitoring Sites) and by the U.S. Fish and Wildlife Service through collaboration with NCDWR (2013–2015, U.S. Geological Survey Monitoring Sites).

Found at DOI: http://dx.doi.org/10.3996/082016-JFWM-068.S2 (26 KB xls).

Data S3. Calculated light-attenuation coefficients and field data, which includes both photosynthetically active radiation (PAR) and Secchi depth measurements collected at Lake Mattamuskeet, 2012–2015. Light attenuation coefficients were calculated from both PAR and Secchi depth using standard methods, and the field data and calculated values are provided as supplemental material.

Found at DOI: http://dx.doi.org/10.3996/082016-JFWM-068.S3 (886 KB xls).

Data S4. Discrete chemical data collected at Lake Mattamuskeet, 1981–2015, and stored in the North Carolina Ambient Lakes Monitoring Program Database. All duplicates and flagged data were removed from the data set.

Found at DOI: http://dx.doi.org/10.3996/082016-JFWM-068.S4 (57 KB xls).

Data S5. Daily minimum, maximum, mean, and median values for dissolved oxygen, salinity–specific conductance, and pH recorded by the U.S. Geological Survey continuous monitors from the National Water Information System from September 2012 to December 2015.

Found at DOI: http://dx.doi.org/10.3996/082016-JFWM-068.S5 (608 KB xls).

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