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Long-term chlorophyll trends in Florida lakes

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ABSTRACT

The State of Florida promulgated numeric nutrient criteria in 2013 because of a concern that nutrient enrichment had led to widespread increases in algal abundance and blooms. Chlorophyll was identified as a nutrient response variable and examination of historical chlorophyll trends was identified as one approach to help identify nutrient-impaired lakes. Examination of a 508-lake database with 10+ yr of data found that 371 (73%) lakes showed no statistically significant chlorophyll trends over time. Significant decreasing chlorophyll trends were identified at 67 (13%) lakes and 70 (14%) lakes had positive chlorophyll trends. For those lakes with significant trends, only 19 of the 67 lakes and 14 of the 70 lakes had R^2 values > 0.65. There were also 153 lakes with more than 20 yr of data, but only 53 had significant trends in chlorophyll concentration. Of those lakes, 32 had positive trends, but only 3 of those had R^2 values > 0.65. When the presence of an algal bloom was statistically defined as chlorophyll values exceeding two standard deviations of the individual lake's long-term average (geometric) chlorophyll or as a specific fixed chlorophyll value (> 20, > 40, > 80, or > 100 µg/L), less than 5% of the lakes in the 153-lake database had increasing algal bloom trends. These lines of evidence suggest that there has not been widespread nutrient impairment of Florida lakes and that there is a frequent lack of nutrient limitation, suggesting why nonpoint nutrient control programs have yet to achieve management goals at some Florida lakes.

Key words: algal blooms, chlorophyll, clearing events, eutrophication, Florida lakes.

INTRODUCTION

Growing concerns over problems associated with the eutrophication of lakes, streams, and estuaries led the National Academy of Sciences to sponsor an international symposium on eutrophication (NAS 1969). This symposium linked the introduction of excess nutrients into the world's waters to increased human population growth. Participants also presented a strong case that the nutrients were causing excessive growth of algae, with some participants suggesting that chlorophyll measurements could provide an index of algal abundance because of correlations with cell counts, biomass, and productivity. Besides recommendations for more education and research programs, there were also calls for political actions.

Lake Erie was experiencing algal blooms, beach closures, and fish kills by 1969 because of the discharge of raw sewage and other industrial pollutants. Cleveland's Cuyahoga River caught fire, leading to Lake Erie being called a "dead" lake (Time 1969). The burning river and the dead lake designation were major impetuses for the Federal government to establish the U.S. Environmental Protection Agency (USEPA) in 1970, and pass the Clean Water Act in 1972. For Florida, these political actions contributed to some of the seminal work on the trophic status of Florida lakes (Brezonik et al. 1969, Shannon 1970, Shannon and Brezonik 1972) and set the foundation for future government actions (i.e., USEPA numeric nutrient criteria).

Lake Okeechobee, the second largest (1,900 km^2) lake in the continental United States, had a 311-km^2 algal bloom in August 1986 (Nordheimer 1986), which garnered extensive national and local attention. The Florida legislature responded in 1987 by passing the Surface Water Improvement and Management Act (SWIM: Chapter 87-97, Laws of Florida and Rule 17-43.035, Florida Administrative Code) to combat nonpoint pollution sources. The focus was on nonpoint nutrient sources (e.g., agriculture) because nearly all point-source discharges (e.g., municipal wastewater treatment and citrus processing facilities) to Florida lakes had been mitigated by the late 1980s because of success of the Clean Water Act. With passage of SWIM, government agencies implemented a host of management strategies to mitigate eutrophication associated with nonpoint sources (Swift et al. 1987).

Florida's population expanded from about 5 million in 1960 to over 19 million by 2014 (U.S. Census Bureau, Washington, DC). With this growth, an assumption developed that phytoplankton (free-floating microscopic algae and cyanobacteria) abundance and blooms in Florida lakes were increasing over time because of accelerated anthropogenic nutrient inputs. In 2009, environmental groups filed a lawsuit against USEPA that alleged that nutrient pollution was the cause of water quality impairment in Florida (http://water.epa.gov/lawsregs/rulesregs/upload/Numeric-Nutrient-Criteria-for-the-State-of-Florida). USEPA subsequently directed the State of Florida to establish numeric nutrient criteria, which the state did in 2013 (Chapter 62-302.531, Florida Administrative Code). The establishment of numeric nutrient criteria, however, was still based on the untested assumption that phytoplankton abundance and blooms in Florida lakes were increasing because of anthropogenic total phosphorus (TP) and total nitrogen (TN) inputs (FDEP 2014).

Many Florida lakes have substantial phytoplankton populations (i.e., chlorophyll measurements) due to natural factors like geology and lake mean depth (Canfield and Hoyer 1988a,b, Bachmann et al. 2003a, 2012). Limiting environmental factors other than nutrients, however, can

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also influence these algal populations. For example, submerged aquatic macrophytes (SAVs) can alter nutrient concentrations in Florida's shallow lake (< 5 m) systems by absorbing nutrients directly, reducing wind mixing of nutrient-rich bottom sediments, or providing substrate for periphyton, which also affects nutrient availability (Canfield et al. 1984). Fortunately, an extensive water-quality database (the Water Atlas, URL http://www.wateratlas.usf.edu) has indexed phytoplankton abundance using chlorophyll measurements at hundreds of Florida lakes over the past decades. This database now provides the information needed for testing the assumption that phytoplankton abundance and blooms have increased during Florida's period of rapid population growth.

In this paper, we use linear regression analyses to ascertain if in-lake chlorophyll concentrations have increased over time. The data were also analyzed to determine if algal blooms were increasing or if the occurrence of lake-clearing events (i.e., in-lake chlorophyll crashes resulting in increased water clarity) was decreasing over time because these limnological changes are very visible to user groups and are often used by nonprofessionals to judge lake quality. Finally, we examined the long-term results of Florida's nutrient control efforts at three major SWIM lakes because nutrient control is being increasingly relied upon as the lake management tool needed to achieve Florida's water-quality goals.

MATERIALS AND METHODS

We chose chlorophyll concentration as the variable of concern because Florida's numeric nutrient criteria are based on chlorophyll being the response variable to two stressors, TP and TN. More important, researchers and government monitoring agencies have measured chlorophyll for years because studies have related concentrations of TP (Sakamoto 1966, Dillon and Rigler 1974, Jones and Bachmann 1976) and TN (Smith 1982, Canfield 1983) to chlorophyll concentrations in lakes. Chlorophyll measurement also represents an alternative for the more costly and tedious algal counting approach used to estimate algal abundance (Canfield et al. 1985).

Chlorophyll (uncorrected for pheophytin) measurements and associated water-quality data collected from lakes throughout Florida between 1968 and 2015 were retrieved from the University of South Florida Water Institute's Water Atlas (www.wateratlas.usf.edu). The Water Atlas contained over 410,000 chlorophyll measurements from 1,735 lakes, and the first archived measurements were from Lake Thonotosassa (Hillsborough County) in 1969. Before 1989, chlorophyll data based on at least four independent months of sampling per year (a requirement of Florida's numeric nutrient criteria) were available for fewer than 35 lakes (Figure 1). After 1990, more than 294 lakes had the required monthly data for each year. The maximum number of lakes (627) was monitored in 2007, but monitoring efforts declined after 2007 in part because of the 2008 fiscal crisis; thus, sufficient chlorophyll data were available for only 407 lakes by 2014 (Figure 1). Florida LAKEWATCH, the State of Florida's citizen water-quality monitoring program (University of Florida, Gainesville, FL), provided 64% of the chlorophyll measurements, but these citizen-collected measurements are comparable with those collected by professionals (Hoyer et al. 2012).

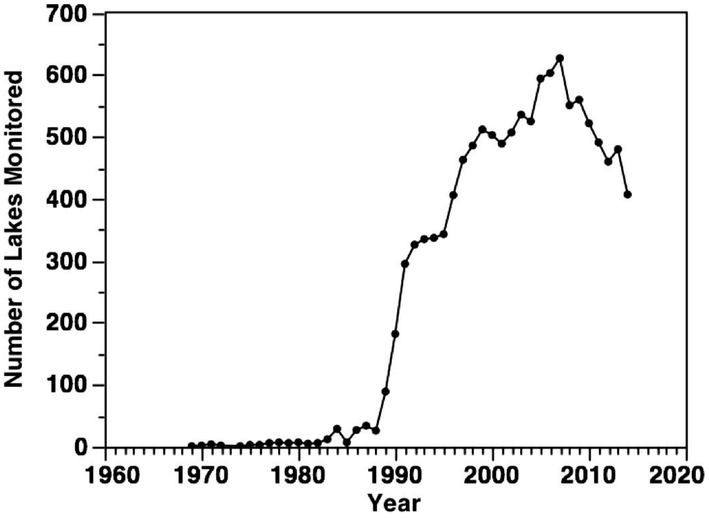

Figure 1. Number of Florida lakes monitored each year that were archived in the University of South Florida's Water Atlas database.

Within the Water Atlas database, multiple stations may have been sampled on any single day at an individual water body. For those situations, all station measurements were averaged (arithmetic) to obtain an average daily estimate and then all data were logarithmically (base 10) transformed. The transformed data were then averaged to obtain a monthly average and the monthly averages were averaged to obtain a yearly average (a lake-year observation). For each lake, a grand geometric average and standard deviation were determined for the period of record at each lake using the annual geometric averages.

Florida's numeric nutrient criteria are based on annual geometric means (Chapters 62-302.531[6] and 62-303.350[2b], Florida Administrative Code). When trend analyses are performed with linear regression, water-quality data are often logarithmically (base 10) transformed before statistical analyses to reduce the influence of any "extreme" values on trend analyses and to accommodate heteroscedasticity (Sokal and Rohlf 1981). Because an algal bloom represents an extreme value, we also examined nontransformed chlorophyll concentrations exceeding specific fixed values at each water body to make sure that transforming the data did not overlook blooms.

Data sets. Water bodies (995) with less than 10 yr of data were removed before examining long-term trends in chlorophyll concentrations, algal blooms, and clearing events, resulting in 740 lakes with more than 10 yr of data. Many of these waters, however, had fewer than four samples per year. The numeric nutrient criteria require that there be at least four temporally independent samples per year, with at least one sample taken between May 1 and September 30 (Chapter 62-302.531[6], Florida Administrative Code). After applying these criteria, the 740-lake data set was reduced to a 508-lake data set, in which each annual chlorophyll geometric lake average was calculated from a minimum of four monthly samples.

TABLE 1. STATISTICAL DISTRIBUTION FOR NONTRANSFORMED TROPHIC STATE VARIABLES REPRESENTING LAKES INCLUDED IN THE 508-LAKE DATA SET.

Variable[1]	Minimum	25th Percentile	Mean	Median	75th Percentile	Maximum
CHL (µg/L)	1	6	25	12	26	1,012
TP (µg/L)	4	14	49	25	52	803
TN (µg/L)	105	575	984	808	1,140	7,190
Secchi (m)	0.2	0.8	1.7	1.4	2.2	6.9

[1] CHL = chlorophyll; TP = total phosphorus; TN = total nitrogen; Secchi = water clarity depth as measured by use of a Secchi disc.

The 508-lake database included not only lakes with a wide range of limnological conditions (Table 1), but lakes that were used in establishing the numeric nutrient criteria's nutrient zones (Bachmann et al. 2012). Within the 508-lake data set, lake-year chlorophyll observations were based on 4 to 12 mo of samples, with over 76% (8,611) of the observations calculated from six or more monthly samples. There were 2,267 (26%) lake-year observations calculated using 12 mo of data, but there were also 1,482 (17%) observations based on just 4 mo of data, resulting in 341 lakes having at least one annual geometric chlorophyll concentration calculated from just four monthly samples. Only nine lakes had their entire period of record based on just four monthly samples per year, but an index of precision (standard error divided by the arithmetic mean) was calculated (Elliot 1977) to determine the number of monthly samples needed to obtain a mean value within an acceptable error.

The 508-lake data set was further winnowed to include only those lakes (160 lakes) with 20 or more years of chlorophyll measurements. This data set, however, was further modified to include only the years from 1991 to 2014 to encompass the period when the greatest number of lakes was being monitored in Florida and SWIM initiatives were underway. This resulted in a 153-lake data set.

To assess algal bloom trends over the years, only the 153-lake data set having lakes with 20 or more years of chlorophyll measurements was used. Algal blooms have traditionally been described as sudden large increases in algal populations, but monthly chlorophyll averages exceeding specific fixed chlorophyll values (> 20, > 40, > 80, or > 100 µg/L) have also been defined as algal blooms. Algal bloom trends were investigated using the specific chlorophyll concentrations and chlorophyll values exceeding two standard deviations of the individual lake's long-term average (geometric) chlorophyll as these values represent a rare event. There are also events in lakes when the water column suddenly clears because of a collapse (reduced chlorophyll concentration) in the phytoplankton. A clearing event was designated when chlorophyll concentrations were less than two standard deviations of a lake's long-term average chlorophyll.

Statistical analyses. Linear regression was used to judge long-term trends for each water body because the initial hypothesis was that large numbers of Florida lakes would show an increasing chlorophyll trend (positive slope) consonant with Florida's rapid population growth. When conducting numerous repeated analyses, the probability of false-positive results (type I error), however, increases rapidly. This is termed the false discovery rate (FDR). Analyses were therefore corrected for FDR by using the approach of Benjamini and Hochberg (1995). The number of lakes in each data set having: 1) no trend, 2) a negative trend (decreasing), or 3) a positive trend (increasing) over the period of record was then reported.

Another problem encountered when regressions are based on a large sample size is that significant differences can be recorded that intuitively have little practical utility (i.e., very low R^2 values). The criterion ($R^2 > 0.65$) of Prairie (1996) and Bryhn and Dimberg (2011) was, therefore, used to provide a measure of the predictive utility of the developed regression equations. Regressions with $R^2 > 0.65$ were identified because the predictive power of regression models increases rapidly for higher R^2 values (Prairie 1996) and Bryhn and Dimberg (2011) identified those regressions as statistically meaningful.

Case-study lakes. After passage of the SWIM Act in the late 1980s, 29 lakes had SWIM management plans approved by 1997. Three of these lakes (Lake Thonotosassa, Lake Apopka, and Lake Okeechobee) had long-term chlorophyll measurements and were targeted for major nutrient reduction programs. Various government organizations, however, were involved in nutrient control activities on these lakes before the SWIM Act; thus, these three lakes represent an experimental test of long-term nutrient control and its impact on chlorophyll levels in Florida lakes. The Saint Johns River Water Management District and South Florida Water Management District (SFWMD) provided annual mean TP, TN, chlorophyll, and Secchi data as well as nutrient-loading data for Lake Apopka and Lake Okeechobee. SFWMD also provided water-loading data for Lake Okeechobee.

All data analyses for the lake data sets and the case-study lakes were performed using the JMP statistical package (SAS 2000) and all statements of significance were for $P \leq 0.05$.

RESULTS AND DISCUSSION

Florida's population expanded by over 14 million people between 1960 and 2014, resulting in a visible anthropogenic footprint on the land in Florida (Drummond et al. 2015). Concurrent with this growth, many individuals in the public and the scientific community have come to accept as factual that anthropogenic activities have led to widespread cultural eutrophication of Florida's lakes (FDEP 2014). This belief was codified in Florida law with the passage of the SWIM Act in 1987, laws focusing on the eutrophication of Lake Apopka and Lake Okeechobee, and the establishment of numeric nutrient criteria in 2013. However, long-term studies are lacking to show the linkage between population growth and nonpoint-source pollution in Florida.

Florida's numeric nutrient criteria are based on annual geometric averages calculated from at least four monthly

Table 2. Trends for chlorophyll concentration in Florida lakes analyzed with 10 plus (508 lakes) and 20 plus (153 lakes) years of data. Each lake-year observation is based on a minimum of four monthly samples and trends were determined using the long-term geometric chlorophyll average for the individual lake. Significance was determined after correcting for the false discovery rate (Benjamini and Hochberg 1995) and numbers in parentheses are the lakes with R^2 values > 0.65, which are used to identify statistically meaningful trends.

	Number of Lakes		
Data Set	None	Negative	Positive
508 lakes	371	67 (19)	70 (14)
153 lakes	107	21 (5)	32 (3)

samples. We used the data contained in the 508-lake database to determine how many monthly samples would be needed to obtain reliable annual geometric chlorophyll estimates. When using nontransformed chlorophyll data, the calculated indices of precision (standard error divided by the arithmetic mean) had a median of 17%, with 100% of the lake-year observations having index values < 50%. Using logarithmically transformed data, 99% of the lakes have an index of precision < 50%. If a standard error of 25% is accepted as tolerable, and the data are log transformed, 90% of the lake-year observations only require four monthly samples per year. With a standard error of 50%, 98% of the observations require no more than four monthly samples per year. Terrell et al. (2000) calculated a yearly median background variance for chlorophyll of 22% on the basis of 127 lakes with 4 to 11 yr of data. For median month-to-month variance, they calculated a value of 52%, with the 95th percentile of background variance reaching 103%. On the basis of all this information, we concluded that the 508-lake database was appropriate for examining long-term chlorophyll trends in Florida lakes.

Trends. When linear regression analysis was used to judge chlorophyll concentration trends in the Florida lakes, 371 (73%) lakes in the 508-lake database with 10+ yr of data showed no statistically significant trends (Table 2). Significant negative trends were found for 67 of the lakes and 70 of the lakes had positive trends. However, only 19 of the lakes with negative trends and 14 lakes with positive trends had R^2 values > 0.65, indicating that most of the identified chlorophyll trends had large amounts of variance (i.e., weak trends). The start sampling date for those lakes with only 10 yr of measurement, however, ranged from 1986 to 2004; thus, the monitoring of the lakes represents different periods of time, complicating trend analyses because the 1986 to 2015 period was a time of major stochastic events and climatic variability that were affecting lake water quality (Canfield et al. 2016).

Given that Knowlton and Jones (2006) concluded that at least 20 yr of measurements are needed to detect accurate limnological trends, we used linear regression to examine lakes in the 153-lake data set (20 to 44 yr; median 23 yr). There were 107 lakes (67%) that showed no trend over time, 21 lakes with a negative trend, and 32 lakes with a positive chlorophyll trend (Table 2). Only three of the lakes with a positive trend had an R^2 value > 0.65 and five lakes with significant chlorophyll declines had an R^2 value > 0.65. On the basis of our analyses of the 508-lake database and the 153-lake data set, the evidence indicated that the belief that there has been extensive cultural eutrophication of Florida's lakes should be questioned.

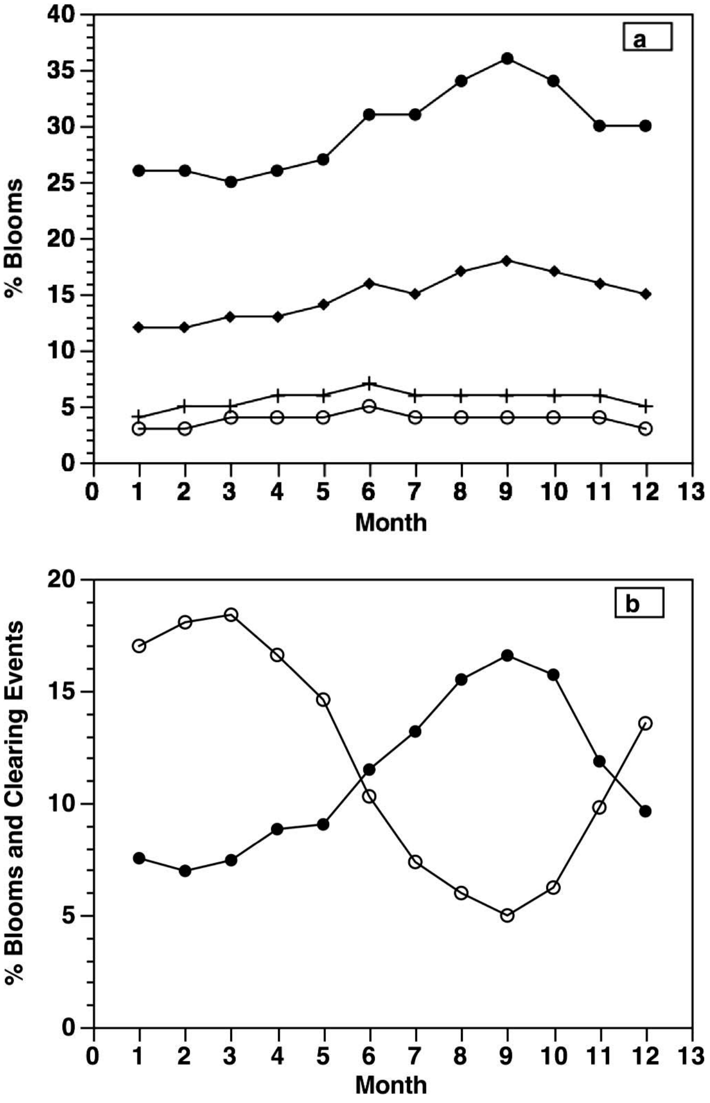

Figure 2. Percentage of samples within the 153-lake data set exhibiting a bloom condition during different months of the year when algal blooms are defined using fixed chlorophyll value > 20 (filled circle), 40 (filled diamond), 80 (+), or 100 (open circle) μg/L (a) and monthly occurrence of algal blooms (filled circle) and clearing events (open circle) when defined as a chlorophyll value > or < 2 standard deviations of the water body's long-term geometric chlorophyll average, respectively (b).

Although the 153-lake data set is not sufficient to measure nonlakewide algal blooms (e.g., near shore, adjoining canals, or specific quadrants with no sampling stations) because of wind or current concentrations of algae or blooms of periphyton and benthic algae (e.g., *Lyngbya* sp.), it does provide a lakewide representation of blooms. Regardless of whether an algal bloom was defined as a statistical deviation from a long-term average chlorophyll value or as a fixed chlorophyll value, algal blooms occurred in every month during the 1991 to 2014 period of record (Figure 2). Blooms tended to occur more frequently in the months of August, September, and October. Only five lakes,

Table 3. Number of Florida lakes in different phytoplankton bloom categories that had significant positive bloom trends for those lakes having significant long-term positive (+) and negative (–) chlorophyll trends in the 508-lake data set. TP and TN trends for those lakes are also provided ([–] negative, [+] positive, [0] no trend). The >2 STDev bloom category includes chlorophyll values exceeding two standard deviations of the individual lake's long-term average geometric chlorophyll values and < 2STDev bloom category represents clearing events when chlorophyll concentrations were less than two standard deviations of a lake's long-term average chlorophyll.

Bloom Category	Long-Term Chlorophyll Trend	# Lakes with Significant Trends	Total Phosphorus Trends (–)	Total Phosphorus Trends (+)	Total Phosphorus Trends (0)	Total Nitrogen Trends (–)	Total Nitrogen Trends (+)	Total Nitrogen Trends (0)
> 2STDev	(+)	5	0	4	1	0	4	1
> 2STDev	(-)	5	4	0	1	2	0	4
> 20 µg/L	(+)	6	1	2	3	0	4	2
> 20 µg/L	(-)	7	7	0	0	6	0	1
> 40 µg/L	(+)	3	1	0	2	0	1	2
> 40 µg/L	(-)	8	8	0	0	6	0	2
> 80 µg/L	(+)	5	2	1	2	0	2	3
> 80 µg/L	(-)	3	3	0	0	3	0	0
> 100 µg/L	(+)	2	1	1	0	0	0	2
> 100 µg/L	(-)	3	3	0	0	3	0	0
< 2STDev	(+)	10	7	1	2	5	1	4
< 2STDev	(-)	11	2	3	6	5	1	5

however, demonstrated a significant increase in algal blooms when a bloom was statistically defined, and five lakes had negative trends (Table 3). For blooms defined as chlorophyll values > 20 µg/L, six lakes had positive trends and seven lakes had negative trends. Fewer than six lakes had positive trends for the algal bloom categories defined as chlorophyll concentrations > 40, > 80, and > 100 µg/L (Table 3).

Sometimes the public's perceptions are influenced not by blooms, but by extreme clearing events. A historical clearing event can cause people to remember the lake as a clear-water lake when the chlorophyll values are naturally sufficient to provide reduced water clarity. For the 1991 to 2014 period, clear-water events dominated from November to April (Figure 2). The greatest frequencies of occurrence of these events (> 15%) were in the months of January, February, March, and April. The statistically defined clearing events increased in 10 lakes, but decreased in 11 lakes. Finding that fewer than 7 lakes in the 153-lake data set had positive algal blooms and that clearing events only decreased in 11 lakes provides additional evidence for questioning whether the concern that widespread nutrient enrichment is causing water-quality impairment in Florida lakes has merit.

A probabilistic sampling approach is now recommended by water-quality monitoring agencies for ascertaining statewide trends in water quality (USEPA 2010, FDEP 2014). The data sets analyzed in this paper were not constructed from probabilistic sampling programs, but we believe that finding so few lakes with positive chlorophyll trends provides evidence that Florida water quality is not experiencing ongoing major degradation, despite a major increase in the anthropogenic footprint. The use of linear regression to assess trends could be questioned, but studies by Terrell et al. (2000) and Bigham (2012) have reached similar conclusions using other approaches. Bigham (2012) not only used linear regression, but Kendall–Tau and ARMA/ARIMA time series models for 193 lakes.

Another disadvantage of selecting chlorophyll alone for assessing phytoplankton trends is that there is no information on the algal community composition (i.e., genera and species cell counts and biovolumes). Unfortunately, there is no comparable long-term database using microscopic algal counts like the 508-lake or the153-lake data set because the algal counting approach is more costly and tedious (Canfield et al. 1985). We, however, believe the findings based on chlorophyll concentrations should not be dismissed because of lack of information on algal composition. Canfield et al. (1985) found significant correlations (log-10-transformed data) between chlorophyll and phytoplankton biomass per liter ($r = 0.80$) and total algal cell count per liter ($r = 0.83$). Canfield et al. (1985) also found that the coefficients of determination (R^2) for the nutrient–phytoplankton and Secchi–phytoplankton relationships were significantly higher when chlorophyll values were used rather than cell counts. Consequently, it was recommended that using chlorophyll measurements was preferable when many samples are needed to characterize the limnology of a lake. Furthermore, Agusti et al. (1990) provided evidence for the frequent lack of nutrient limitation after examining algal communities by use of a microscope and water chemistry from 165 Florida lakes.

Trends, blooms, and nutrients. The foundation of Florida's numeric nutrient criteria is based on chlorophyll being the response variable to the two stressors, TP and TN. Within the 508-lake database (Table 4), significant TP trends were found for only 35 of the 70 lakes with increasing chlorophyll

Table 4. Total phosphorus (TP) and total nitrogen (TN) trends over time for number of lakes in the 508-lake and 153-lake data sets demonstrating significant declines or increases in chlorophyll concentrations. Numbers in parentheses are the total number of lakes in the data sets with significant trends.

Nutrient	Trend	Negative Chlorophyll Trends 508 Lakes (67)	Negative Chlorophyll Trends 153 Lakes (21)	Positive Chlorophyll Trends 508 Lakes (70)	Positive Chlorophyll Trends 153 Lakes (32)
TP	None	16	0	35	6
TP	Negative	49	20	6	7
TP	Positive	2	1	29	19
TN	None	30	4	22	5
TN	Negative	35	17	2	3
TN	Positive	2	0	46	24

trends, and only 48 lakes had significant TN trends. TP concentrations were increasing over time for 29 of the 35 lakes, but 6 lakes had TP-negative trends. In the case of TN, 46 of the 48 lakes had positive TN trends and 2 lakes had negative TN trends. For the 67 lakes having significant declining chlorophyll trends, 49 of the lakes had significant declining TP trends and 35 of the lakes had significant declining TN trends. Assuming TP or TN was the limiting nutrient, declining nutrient trends were expected, but there were 2 lakes of the 67 that had significant increasing TP trends and 2 lakes had significant increases in TN.

For those lakes with over 20 yr of data and long-term significant increases in chlorophyll (32 lakes), 19 lakes had significant increases in TP, but 7 lakes had significant TP declines (Table 4). TN increased significantly in 24 of the 32 lakes, but 3 lakes had significant TN declines. The 21 lakes in the 153-lake data set having significant chlorophyll declines exhibited 20 significant TP declines (one positive trend) and 17 TN declines, with 4 lakes showing no trend. For lakes with positive increases in algal blooms, there were significant increases in TN and TP in most lakes, but there were situations where TP was declining and there was an increase in the number of nonsignificant regressions (Table 3). When examining lakes with significant decreases in the occurrence of algal blooms, nearly all lakes had significant declines in TP (Table 3). TN also tended to decline, but there were more lakes with nonsignificant regressions.

These findings indicate that the chlorophyll–stressor relationship is not operational in all lakes. Furthermore, there were 371 lakes in the 508-lake database that showed no statistically significant chlorophyll trends (Table 2). Significant positive TP trends were found at 58 lakes and 77 lakes had declining TP trends. TN increased significantly in 66 lakes and 20 lakes had declining TN trends. Water clarity as measured by use of the Secchi disc is influenced by organic color and nonalgal suspended sediments, but primarily by chlorophyll concentrations (Canfield and Hodgson 1983). Significant declining trends in water clarity were identified in 47 lakes, but 23 lakes showed improved water clarity. Given these findings, we conclude, like Agusti et al. (1990), that phytoplankton abundance in many Florida lakes must be influenced more by other factors than just TP and TN.

If these conclusions and those of Agusti et al. (1990) are correct, nonnutrient constraints have implications for nutrient control programs that could be implemented under the numeric nutrient criteria. Empirical studies that sample large numbers of lakes located over a broad geographic expanse and then conduct different statistical tests can provide important insights regarding the functioning of lakes. Experimental evidence, however, is needed to confirm observations/hypotheses. Fortunately, Florida has experimented with nutrient control to limit phytoplankton abundance in lakes before and since the passage of the 1987 SWIM Act.

Case-study lakes. Fifty SWIM lakes were identified within the 508-lake database and 78% of the lakes had either no trend or a downward trend in chlorophyll concentrations over time. When analyses were restricted to those lakes with 20 or more years of chlorophyll measurements (34 lakes), the same trend patterns were found, with 7 (21%) lakes having an upward trend in chlorophyll concentrations. Although these lakes have been targeted for nutrient control, trends in chlorophyll concentrations are similar to non-SWIM lakes. However, some of the lakes, such as Lake Jackson (Leon County) and Alligator Lake (Columbia County), drained dry when sinkholes opened, and other lakes had whole-lake alum treatments (Lake Conine, Polk County). Most of the lakes also were not intensively studied, but there were three lakes (Lake Thonotosassa, Lake Apopka, and Lake Okeechobee) that had nutrient mitigation (focused on phosphorus) efforts ongoing for over 25 yr and have been well studied (Figures 3–5).

Chlorophyll concentrations increased in Lake Thonotosassa (Figure 3) over time even with a significant decline in TP concentrations. TP did not decline below 100 μg/L, a break point where nitrogen limitation assumes a greater role in Florida lakes (Canfield 1983), and there was a significant increase in TN (Figure 3). The reason for the nitrogen increase is unknown, but Lake Thonotosassa is in a geologic region where phosphorus tends to be high (Canfield and Hoyer 1988a, Bachmann et al. 2012). Given the edaphic setting of Lake Thonotosassa, efforts to mitigate anthropogenic impacts will, at best, yield the eutrophic conditions that characterized the lake before human disturbance (Brenner et al. 1996).

TP concentrations also declined significantly in Lake Apopka, but chlorophyll and TN concentrations did not change significantly (Figure 4). TP concentrations remained above the legislatively established target of 55 μg/L despite treatment of inflowing waters with alum. The TP decline also began before the buyout of the agricultural farms (presumed source of nutrient pollution) in the late 1990s, suggesting that water inflows to the farms and subsequent pumping influenced annual loads (Canfield et al. 2000). In the case of Lake Apopka, the farms were converted to wetlands behind the dike that had separated the farms from the lake. Water flows in and out of the wetlands, so the converted wetlands delivering water to the lake could be considered a controllable point source for nutrients.

TP concentrations in Lake Okeechobee, a focal point for the State of Florida's nutrient mitigation efforts because the lake is a source of water for the Everglades, did not decline over the years as expected, but increased significantly (Figure 5). Chlorophyll concentrations did not increase, nor did TN. Back-pumping of nitrogen-rich water from farms south of Lake Okeechobee was stopped and low chlorophylls result because resuspended bottom sediments reduce light availability (Canfield and Hoyer 1988b).

Combining these experimental results with the statistical chlorophyll and algal bloom trends presented in this paper suggests that the continued reliance and emphasis on watershed nutrient control will most likely be problematic in Florida for the foreseeable future. Why will watershed nutrient control be problematic? External TP inputs to Lake Okeechobee from 1973 to 2010 ranged from 156 metric tons (mt) yr^{-1} to 1,012 mt yr^{-1}, with an average input of 495 mt yr^{-1} (Figure 6a). Annual TP inputs have not shown a significant decline since implementation of the 1987 SWIM Act. TP inputs yr^{-1} at Lake Okeechobee, however,

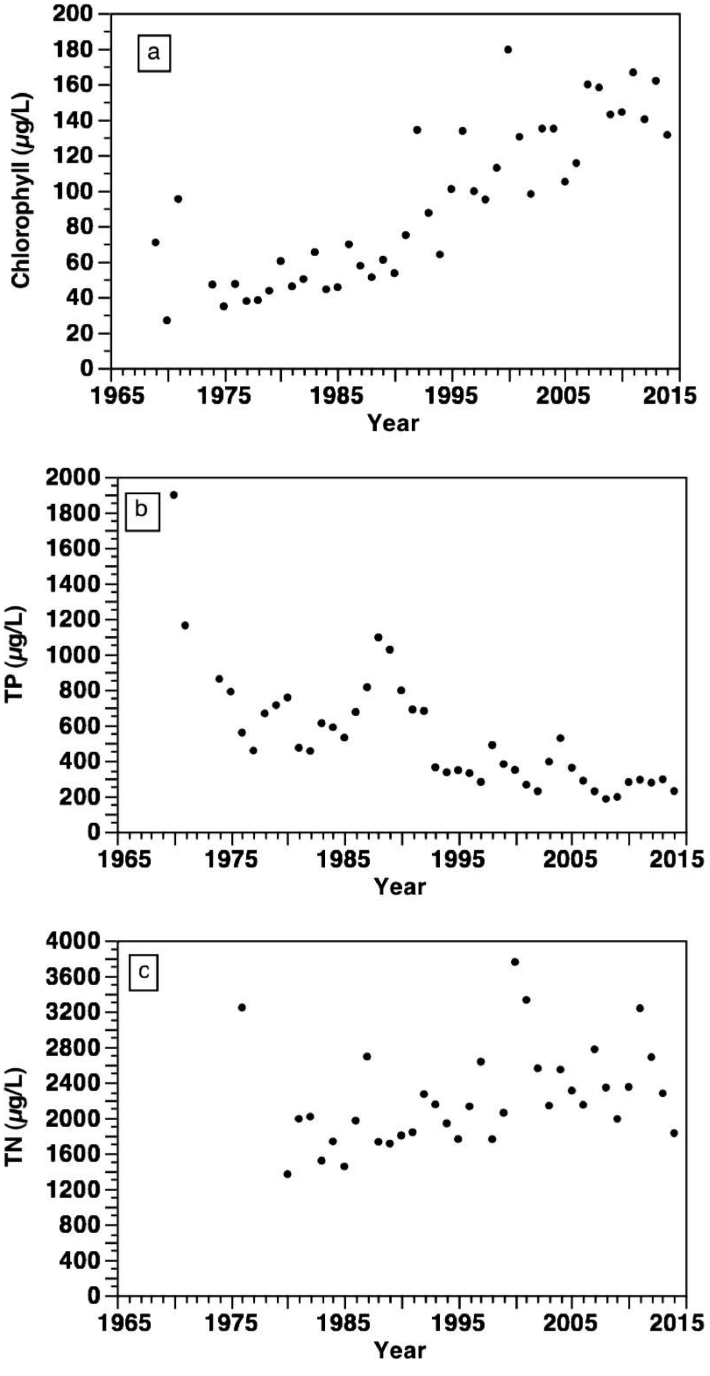

Figure 3. Average chlorophyll (a), TP (b), and TN (c) concentrations (µg/L) measured at Lake Thonotosassa (Florida) from 1969 to 2014.

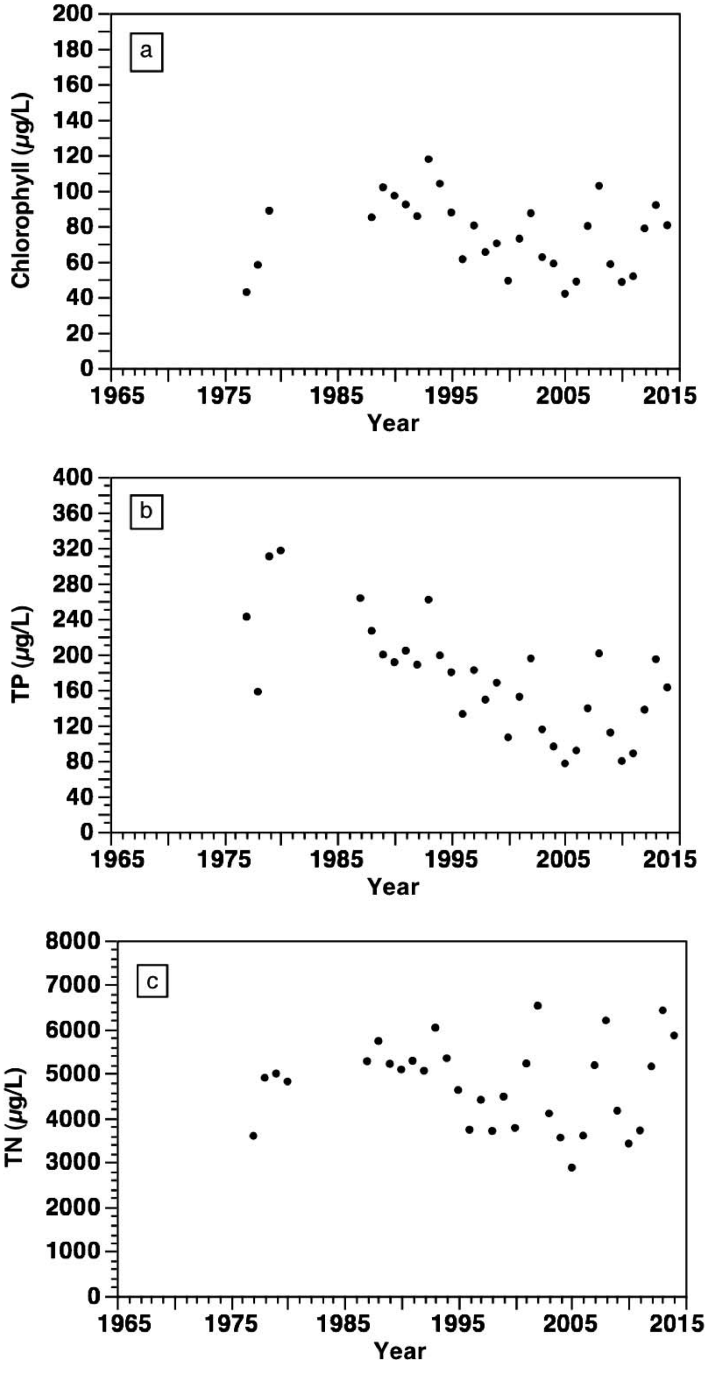

Figure 4. Average chlorophyll (a), TP (b), and TN (c) concentrations (µg/L) measured at Lake Apopka (Florida) from 1977 to 2014.

were highly correlated ($r = 0.86$) with annual water inputs (Figure 7). Estimated TP loads at Lake Apopka ranged from 6.2 mt yr^{-1} to 126 mt yr^{-1}, with an average input of 33 mt yr^{-1} (Figure 6b). Annual external TP loads at Lake Apopka have declined significantly, but the lowest TP loads at Lake Apopka were associated with the 2000 to 2001 and 2006 to 2007 droughts. Central Florida entered a period of decreasing precipitation as lake restoration efforts began in the 1980s (Canfield et al. 2016). Decreasing precipitation has been related to climate variability reflecting phase changes in the Atlantic Multidecadal Oscillation (AMO). Gaiser et al. (2009a,b) recognized the potential importance of teleconnections such as the AMO on restoration programs.

Florida's numeric nutrient criteria require the establishment of a nutrient total maximum daily load (TMDL) for lakes verified as impaired. TMDLs are based on the premise of widespread cultural eutrophication. The USEPA (2000) proposed a TMDL for Lake Okeechobee of 196 mt yr^{-1} of TP and FDEP (2001) set the TMDL at 140 mt TP yr^{-1}.

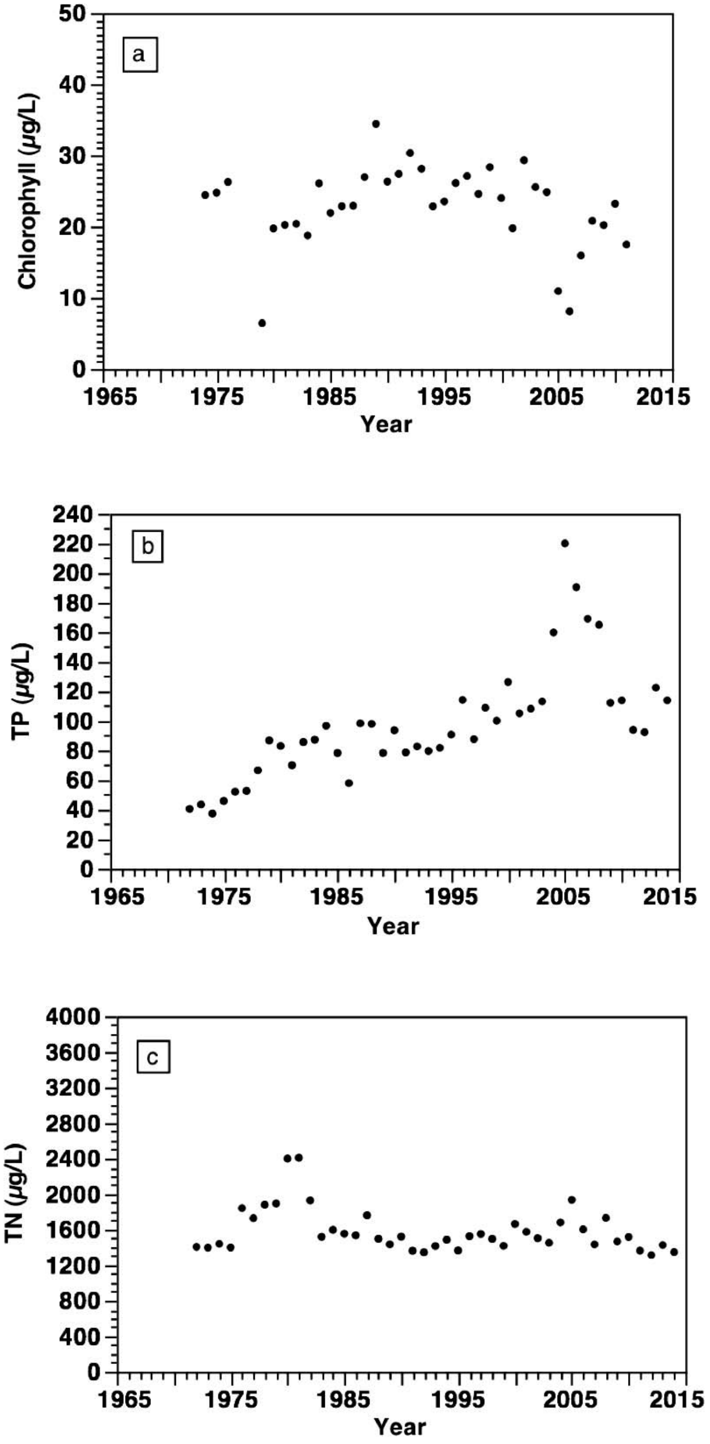

Figure 5. Average chlorophyll (a), TP (b), and TN (c) concentrations (μg/L) measured at Lake Okeechobee (Florida) from 1980 to 2014.

Bachmann et al. (2003b) criticized both recommendations as unrealistic and suggested that the presettlement phosphorus loading was much higher at 377 mt TP yr^{-1} on the basis of the relationship between water inflow and loading (Figure 7). Consideration, therefore, needs to be given to climatic variability when establishing TMDLs, as the impact of anthropogenic activities on lake limnology may pale in

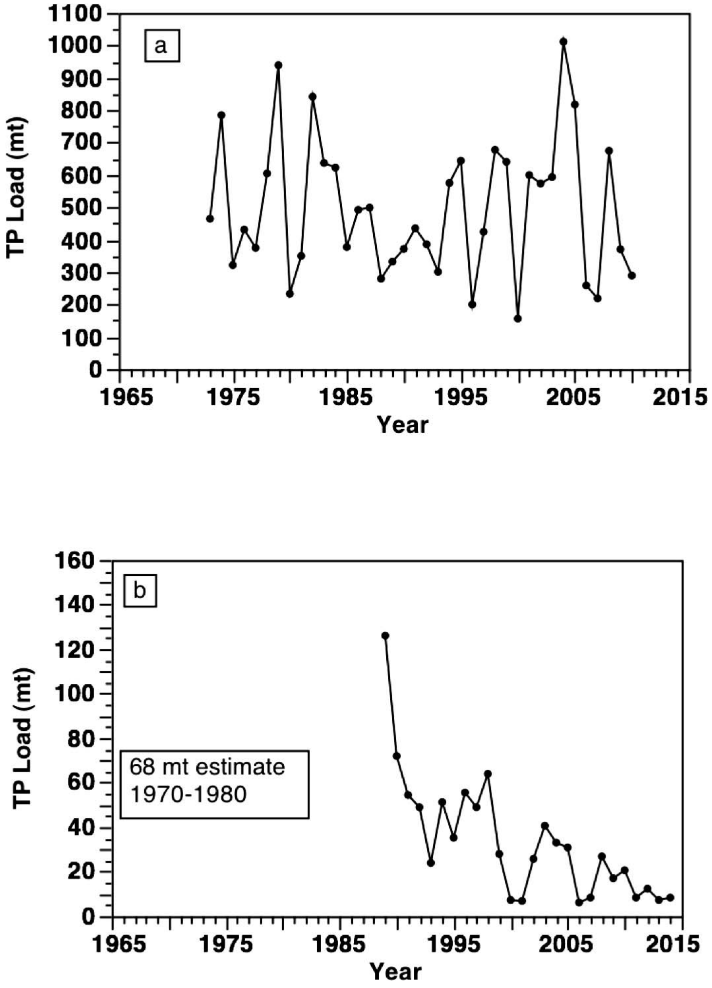

Figure 6. Annual total phosphorus (TP) inputs in metric tons (mt) measured at Lake Okeechobee (a) and Lake Apopka (b), Florida.

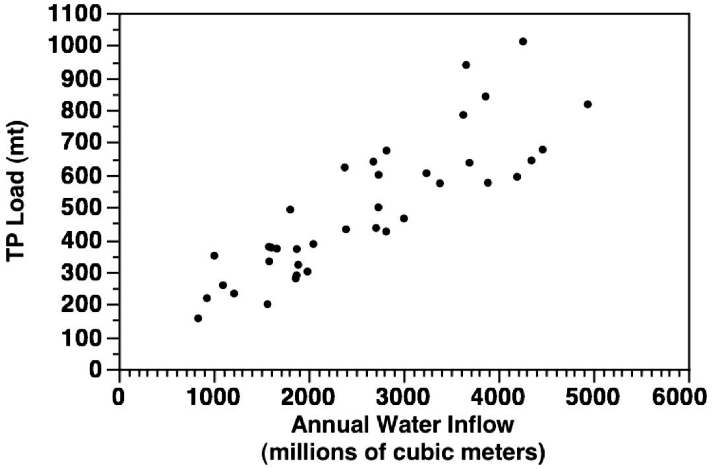

Figure 7. Annual total phosphorus (TP) inputs in metric tons (mt) measured at Lake Okeechobee and the relationship with annual water inflow.

comparison with the impacts by teleconnections such as the AMO and El Niño/La Niña events that influence lake limnology (Gaiser et al. 2009a,b, Canfield et al. 2016).

Eutrophication has many definitions but means the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned. On the basis of the analyses performed with chlorophyll in this paper, the hypothesis that algal abundance and blooms have increased during Florida's period of rapid population growth must be rejected. The experimental results at the SWIM lakes have also demonstrated that nonpoint nutrient control programs have not been as successful as anticipated. The eutrophication debate, however, will most likely continue for many years despite this study and others (Terrell et al. 2000, Bachmann et al. 2013a). Besides, the arguments will be made that lake conditions would be worse if nothing had been done or we have not waited long enough.

Using chlorophyll measurements alone to assess nutrient impairment is problematic not only because many nonnutrient factors (e.g., inorganic solids; Hoyer and Jones 1983) can influence chlorophyll concentrations, but because a complete picture of nutrient-impaired conditions may require other information such as changes in algal community composition, occurrence of nuisance and potentially toxic species, fish kills, and the distribution of aquatic macrophytes. Florida's numeric nutrient criteria (Chapter 62-303, Florida Administrative Code) recognized the limitation of using chlorophyll alone and defined other nutrient response variables such as the structure of phytoplankton, periphyton, or aquatic macrophyte communities. Of importance was the lake vegetation index (LVI).

The LVI was proposed as a measure of lake biological health in freshwaters using vascular aquatic and wetland plants. Although use of the LVI has been criticized because the index did not identify Florida lakes that were impaired because of excess loading of phosphorus or nitrogen from anthropogenic sources (Bachmann et al. 2013b), the index demonstrated that the regulatory community recognized the importance of aquatic macrophytes in Florida lakes. The type of plant, however, is not as important as plant abundance (percent of a water body's volume infested/inhabited) for determining chlorophyll concentrations and water clarity in Florida lakes (Canfield et al. 1984). The importance of SAV in lake limnology is also now codified in the concept of alternative steady states (Blindow et al. 1993, Scheffer et al. 1993, Moss et al. 1996, Bachmann et al. 1999).

The State of Florida has committed to nutrient control efforts with the establishment of numeric nutrient criteria. Control of point-source discharge is needed, especially when the source delivers large volumes of nutrient-rich water relative to the water body's total volume of water. Oppaga (1998) reported to the Florida legislature that after the expenditure of hundreds of millions of dollars, many of the adverse conditions that created the need for SWIM still existed in 1995 and that government agencies had not defined the overall outcome they hoped to achieve for each water body. Twenty years later, the adverse conditions still exist. The continued focus on nonpoint-source nutrients probably will not achieve the desired chlorophyll results at many lakes because of nonnutrient constraints.

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