

LETTER

Impacts of residential fertilizer ordinances on Florida lacustrine water quality

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Scientific Significance Statement

Residential fertilizer ordinances are widely adopted in populated coastal regions as a best management practice for mitigating nutrient loading to prevent toxic algal blooms, groundwater contamination, and other ecosystem disruptions. However, few studies have analyzed the impacts of these ordinances, leaving a critical knowledge gap between ordinance design/implementation and their impacts on environmental systems. Moreover, the impacts of these ordinances at larger spatial (e.g., statewide) and temporal scales (e.g., decades) remain largely unknown. Here, we analyze long-term ordinance impacts on four water quality metrics (total phosphorus, total nitrogen, chlorophyll *a*, and Secchi depth) across Florida lakes under different ordinances. Results show fertilizer ordinances favorably impact water quality metrics and winter fertilizer bans are the most comprehensive and effective relative to other ordinance types.

Abstract

Despite the assumption that residential fertilizer ordinances improve regional water quality, their impacts across space and time largely remain unknown. Here, we analyze changes in water quality of lakes throughout the State of Florida from 1987 to 2018, comparing trends in water quality parameters before and after implementation of county-wide fertilizer ordinances. We used a large dataset of publicly collected water quality data and linear mixed models to analyze ordinance impacts on total nitrogen, total phosphorus, chlorophyll *a*, and Secchi depth across 160 lakes throughout Florida. We further analyze water quality impacts relative to the type of ordinance (winter fertilizer ban, summer ban, nonseasonal ban, no ban). We found fertilizer ordinances favorably impacted lacustrine water quality, and winter (dry season) fertilizer bans had the greatest effect across all water quality metrics. Results of this study can be used to support the effectiveness of fertilizer ordinances across humid tropical and subtropical climate regions.

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Additional Supporting Information may be found in the online version of this article.

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Fertilizer use across the United States has contributed to increased nutrient levels throughout inland and marine waters due to landscape runoff and leaching; increased nutrient levels have led to harmful algal blooms, eutrophication, and ultimately ecosystem degradation (Carpenter et al. 1998; Dewar et al. 2011; Carey et al. 2012). To help mitigate the negative impacts of nutrient loading to local ecosystems, many municipalities in coastal settings have enacted municipal fertilizer ordinances (often targeted for turfgrass applications) which prohibit applications over a specified time period (e.g., summer or winter season; Miller 2012). For example, more than 50 counties and municipalities in the State of Florida have adopted a residential fertilizer ordinance, starting first in 2001 and seeing a large increase in 2007 (Hartman et al. 2008; Dukes et al. 2020). Florida has been particularly active in adopting these regulations given its history with harmful algal blooms and red tide events that have challenged the local economy (Bechard 2020). However, ordinances have been documented to both impact (Lehman et al. 2009, 2011; Qiu et al. 2014; Vega and Ryan 2016; Motsch 2018) and not impact (Kirkpatrick et al. 2014, 2021) water quality in both inland and marine settings.

Very little is known about the collective impacts of fertilizer ordinances on aquatic and marine ecosystems despite their potential as a valuable best management practice for coastal watersheds. Most studies have focused on a single bay, municipality, or watershed and do not cover large spatial areas. Past studies also have not captured a variety of ordinance designs and typically analyzed impacts across relatively short timescales (e.g., 1–5 yr). Adding to these limitations is the possibility that other drivers, such as hydrology (Hoyer et al. 2005), macrophytes (Bachmann et al. 2002), or fish communities (Bachmann et al. 1996; Jeppesen et al. 2020) may exhibit top-down control of eutrophication in place of bottom-up nutrient limitation. Furthermore, the lack of impacts seen in some studies may be because ordinances did not actually affect nutrient loading due to a lack of enforcement, education, or awareness (Souto et al. 2019). Despite these knowledge gaps and disparate impacts, fertilizer ordinances continue to be adopted and promoted as a successful environmental management strategy throughout coastal communities.

The purpose of this study is to identify the long-term impacts of Florida fertilizer ordinances on four water quality metrics in freshwater lakes (total nitrogen [TN], total phosphorus [TP], chlorophyll *a* [Chl *a*], and Secchi depth) based on four categories of county-level ordinances (winter ban, summer ban, nonseasonal ban, and no ban) using community-science data collected from 1987 to 2018. We specifically use linear mixed modeling to identify the before and after changes in long-term water quality trends relative to the adoption of fertilizer ordinances. We then use results to categorize water quality impacts by ordinance type to aid in decision-making for the management of urbanized watersheds and waters in the humid tropic/subtropic Florida climate.

Methods

Site description

The State of Florida follows a north–south temperature gradient with humid subtropical conditions in the north and humid tropical conditions in the south. The state averages 134 cm of rain each year and has wet (summer) and dry (winter) seasons, with statewide precipitation averaging 89 cm during the wet season and 45 cm during the dry season (Irizarry-Ortiz et al. 2013; Data Collection Bureau 2021). The state also has a shallow groundwater table which is intimately connected to surface waters (Katz et al. 1997; Sutton et al. 2015) through karst topography and highly permeable sandy soils, leading to relatively rapid surface water and groundwater movement throughout a nutrient rich landscape (Obeysekera et al. 1999; Lee et al. 2003). Florida has 2173 km of coastline which is home to approximately 77% of the state's 19.6 million residents (National Oceanic and Atmospheric Administration n.d.; Beaver 2006). The state is rapidly urbanizing with nearly 280,000 residents added each year (Carr and Zwick 2016). This population boom has increased total residential lawn area and subsequent residential fertilizer applications (Nair and Graetz 2004; Yang et al. 2007), largely in coastal areas, though nearly all portions of the state are hydrologically connected to coastal estuaries.

Water quality data

Data were used from the Florida LAKEWATCH database, one of the nation's largest community volunteer monitoring programs with over 248,000 geotagged data entries. The LAKEWATCH program trains participants in the management of waterbodies through the collection of water samples from various lakes, rivers, coastal sites, and springs. Samples are then sent to the LAKEWATCH laboratory in Gainesville, Florida, for analysis of Chl *a*, TP, TN, and specific conductance, among other metrics; Secchi depth (Secchi) is collected in the field (Hoyer et al. 2014). Data have been collected monthly since 1986 and coordinated by faculty and staff most commonly associated with the University of Florida/Institute of Food and Agricultural Sciences (Hoyer et al. 2014). Refer to Supporting Information for more information on LAKEWATCH data collection.

Data filtering

LAKEWATCH data entries were initially filtered using R (R Core Development Team 2020) by the following criteria: (1) must be a lake site, (2) must contain TN, TP, Chl *a*, and Secchi data records, (3) sites must have at least 10 yr of data records, where (4) at least 5 yr of data must have been collected in 2000–2009 and at least 5 yr of data must have been collected in 2010–2019. Lakes that met these criteria were then categorized by their county's residential fertilizer ordinance: summer ban (e.g., fertilizer is prohibited during the summer wet/growing season), winter ban (e.g., fertilizer is prohibited during the winter dry/dormant season),

nonseasonal ban (e.g., restrictions after seeding or sodding), and no ban. In Florida, fertilizer ordinances are adopted at the county level but can further be modified at the municipal level for different restriction periods or more stringent restrictions on nutrient loading. For example, Hillsborough County adopted a nonseasonal ban that applies to the entire county. But in the City of Tampa (within Hillsborough County), a seasonal restriction period was adopted during the summer months. Samples located within the boundaries of municipal ordinances that differed from the respective county ordinance were manually assigned to their proper ordinance category. All GPS coordinates of filtered samples were loaded into Google Earth Imagery to verify lakes were within ordinance boundaries and were properly categorized. Samples with erroneous GPS coordinates were eliminated from the analysis. Samples were also cross-referenced by their lake name using ArcMAP (v10.6.1), as some samples included multiple lake names for the same waterbody. These data were averaged to represent a single site. Lastly, samples from transboundary lakes (i.e., crossing county borders) were removed to substantiate the impact of a single-county ordinance on waterbodies. After filtering, 3751 samples spanning mean annual TP, TN, Chl *a*, and Secchi from a total of 160 lakes were used in this analysis (Fig. 1).

Linear mixed modeling

To investigate if fertilizer ordinances affected trends in lake water quality, data were binned into periods of before or after fertilizer bans came into effect. For comparison, lakes in areas with no fertilizer ordinance (no ban) were temporally divided based on the median year (2009) that Florida adopted fertilizer ordinances. Temporal trends in mean annual water quality parameters (TP, TN, Chl *a*, Secchi) were estimated for the before and after periods using a linear mixed effect model with site and site \times year interaction as random effects to

account for variation in the slopes given local site complexities (Bolker 2015). A continuous autoregressive (CAR1) correlation structure was added to the model to account for temporal autocorrelation within sites. Mean annual estimates were weighted by the number of observations within each site-year combination. We used a Student's *t*-test of the differences in estimated slopes to determine significant differences (at $p \leq 0.05$) in the trends of water quality metrics through time between the before and after ban periods within each type of fertilizer ordinance (summer ban, nonseasonal ban, winter ban, and no ban). We also calculated Cohen's *d* statistic using the standard deviation estimate of the slope estimates, and we interpret effect sizes based on the magnitude of Cohen's *d*: $d < 0.2$ = no effect, $0.2 \leq d < 0.5$ = small effect, $0.5 \leq d < 0.8$ = medium effect, $d \geq 0.8$ = large effect (Sullivan and Feinn 2012). All models were fitted using the *base* and *nlme* (version 3.1-148; Pinheiro et al. 2020) packages; graphics were produced with the *tidyverse* package (Wickham et al. 2019) in R (R Core Development Team 2020). We defined water quality improvements as decreased concentration for TP, TN, and Chl *a*, and increased Secchi (i.e., when nutrients are reduced, and water visibility has increased). Refer to the Supporting Information for more information on Student's *t*-test and Cohen's *d* statistic. Refer to Aviles et al. (2022) for study data and modeling code.

Results

Modeling results indicated that fertilizer ordinances favorably impacted lacustrine water quality, but impacts were dependent on ordinance timing and water quality metric. For example, filtered data entries for phosphorus summarized by ordinance type are displayed in Fig. 2, with plots of the other water quality parameters available in Supporting Information (Figs. S1–S3).

The rate of TP concentration increase showed reductions coinciding with seasonal fertilizer ordinances, regardless of the season the ban was applied (Fig. 2). The largest rate reduction (Δ slope) was seen in lakes with winter bans ($0.027 \mu\text{g L}^{-1} \text{yr}^{-1}$), while rates decreased by 0.013 and $0.015 \mu\text{g L}^{-1} \text{yr}^{-1}$ in lakes with summer and nonseasonal bans, respectively. Conversely, there was a continued increase (i.e., no change in trend) in phosphorus concentration in lakes without a fertilizer ordinance over the same time period.

All water quality metrics were summarized by ban type (Table 1; see the Supporting Information Table S1 for parameter estimates and test statistics). Counties with no bans did not observe any changes in TN or Chl *a* trends, whereas there was an observed increase in the TP trend after 2009. However, lakes in no ban counties did exhibit a small improvement in Secchi (i.e., an increase in visibility). Lakes in counties with nonseasonal ordinances exhibited a small decrease in TP and TN trends, no change in Chl *a*, and mixed result in Secchi (no to minimal effect). Lakes in counties with a summer (wet

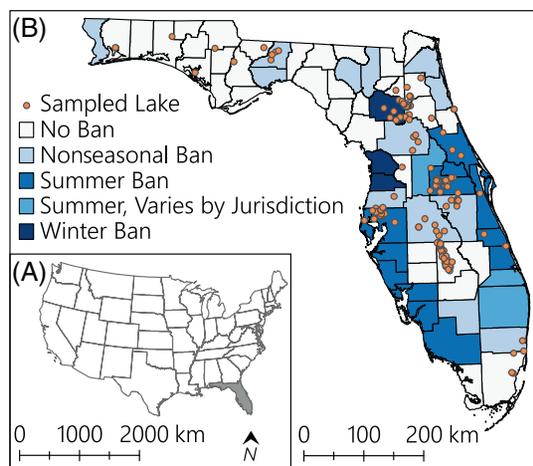


Fig. 1. Florida site map (A) of county fertilizer ordinance by type with lake locations of filtered LAKEWATCH samples used in this study (B).

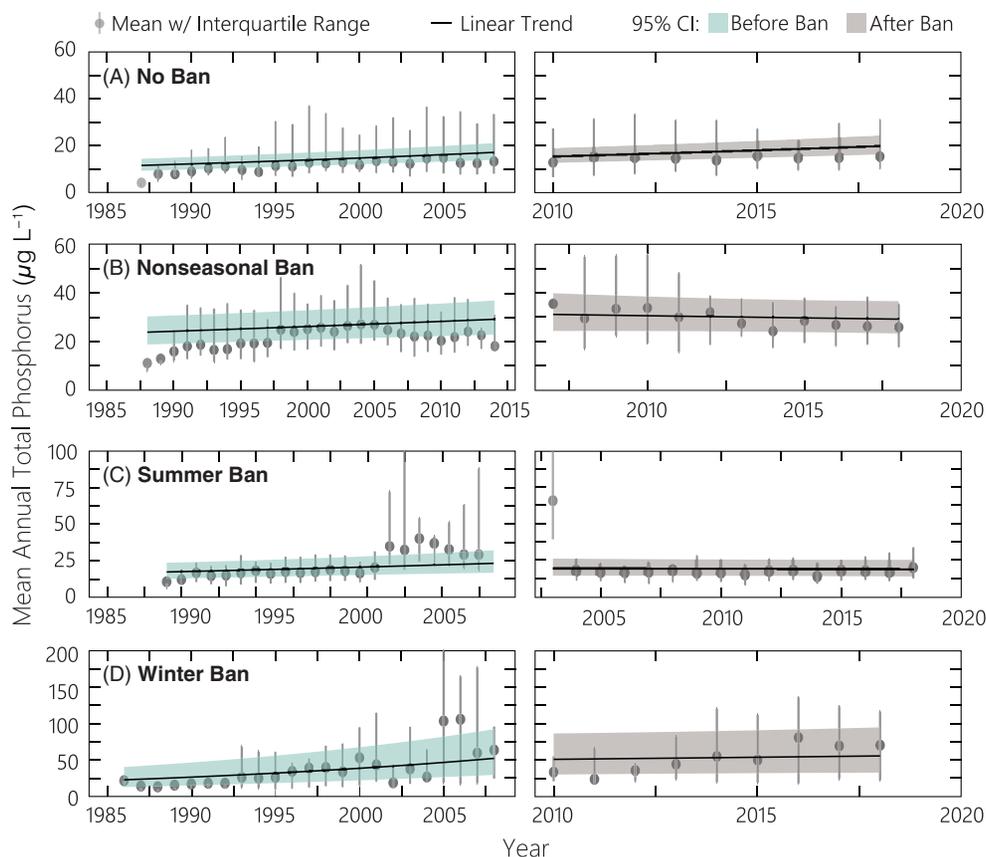


Fig. 2. Trends in mean annual TP concentration (black solid line with 95% confidence intervals) before and after ordinance adoption, with gray points depicting the measured annual average concentration and vertical lines showing the interquartile range. Axis scales vary among subplots and non-homogeneous splitting and overlap exists between before and after periods due to the variation of ordinance start dates within ban types.

season) ban exhibited medium improvements in TP and Secchi trends but no change in TN. Like Secchi for non-seasonal lakes, Chl *a* in summer ban lakes was also a mixed result (no to minimal effect). Finally, lakes in counties with a winter (dry season) ban exhibited large reductions (i.e., improvements) in all metric trends.

Discussion

Impacts on aquatic ecosystems

Results from this study highlight the potential water quality benefits of altered residential fertilizer practices throughout a watershed. Urban and suburban ecosystems are an increasingly prominent feature of the landscape across the United States (Alig et al. 2004) and the world (Seto et al. 2012) and can drive eutrophication associated with anthropogenic nutrient enrichment from human activities (Carpenter et al. 1998; Smith and Schindler 2009; Hobbie et al. 2017). There is a wide range of nutrient sources in urban landscapes (Hobbie et al. 2017) and reducing anthropogenic fertilizer applications is not likely to be a standalone solution to preventing nutrient pollution in downstream water bodies.

Furthermore, legacy nutrients from previous land uses can obscure the effects of current nutrient load reductions (Sharpley et al. 2013), which necessitates long-term monitoring to detect effects of regional practices like fertilizer ordinances (Souto et al. 2019). Despite the multitude of nutrient sources and the potential for delayed responses, we were able to detect an effect of fertilizer ordinances on various water quality parameters from publicly collected data. However, the differences in trends seen between chemical (TP, TN) and ecological (Chl *a*, Secchi) metrics suggests other factors must be considered to meet larger goals throughout a watershed like reducing eutrophication and algal blooms. These results show fertilizer ordinances do have beneficial effects on lake water quality and potentially algal biomass, but not all ordinances have the same impacts.

Limnological mechanisms

Due to the subtropical climate of Florida, the timing of a fertilizer ordinance can substantially influence limnological processes. Florida lakes can exhibit substantial fluctuations in water level throughout the year, particularly given the seasonal variability in precipitation. Despite this seasonality,

Table 1. Summary of ordinance impacts on water quality metrics. The top statistic in each cell is the *t*-test result (*p*-value) and the bottom statistic is the effect size (Cohen's *d*).

Ban type	Water quality impact ($\begin{matrix} p\text{-value} \\ \text{Cohen's } d \end{matrix}$)			
	Total Phosphorus	Total Nitrogen	Chlorophyll <i>a</i>	Secchi
No ban	Increase (0.01**)	No change (0.13)	No change (0.37)	Increase (0.02*)
	Small effect (0.33)	No effect (0.18)	No effect (0.11)	Small effect (0.30)
Nonseasonal	Decrease (0.02*)	Decrease (0.01**)	No change (0.26)	No change (0.13)
	Small effect (0.32)	Small effect (0.39)	No effect (0.15)	Small effect (0.20)
Summer	Decrease (0.00**)	No change (0.31)	No change (0.09)	Increase (0.00**)
	Medium effect (0.56)	No effect (0.17)	Small effect (0.30)	Medium effect (0.67)
Winter	Decrease (0.01**)	Decrease (0.00**)	Decrease (0.01*)	Increase (0.01**)
	Large effect (0.93)	Large effect (1.57)	Large effect (0.83)	Large effect (0.95)

■, Small quality degradation; ■, small quality improvement; ■, medium quality improvement; ■, large quality improvement; ■, mixed result.
p* < 0.05; *p* < 0.01.

water-level variability does not consistently predict lake trophic status (Hoyer et al. 2005). Nutrient limitation of lakes by either nitrogen or phosphorus is common across freshwater and marine ecosystems (Elser et al. 2007), so reducing nutrient inputs to subsequently reduce eutrophication and improve water quality is the primary justification for fertilizer ordinances.

The water chemistry responses to fertilizer ordinances (decreases in TP and TN) were more consistent than subsequent biological responses (Chl *a*, Secchi). In fact, we found improved Secchi depth for no-ban lakes, suggesting that other factors (e.g., climate, land-use) may be causing reductions in water clarity throughout Florida. Another potential reason for the lack of biological responses may be that many lakes in Florida are naturally eutrophic due to naturally elevated levels of phosphorus from geological features (Bachmann et al. 2012). Decreasing nutrient loading into already eutrophic ecosystems may not elicit a detectable change in algal biomass or water clarity, or it may take multiple years to decades for a response to be evident. It is also possible that these ecosystems are controlled via top-down mechanisms such as reductions in zooplankton due to fish grazing (Bachmann et al. 1996; Jeppesen et al. 2020). Previous work has shown that fish communities in Floridian lakes are less sensitive to eutrophication due to the relatively shallow nature of these lakes and lack of ice cover in winter (Bachmann et al. 1996). Elevated fish biomass in subtropical lakes can in turn allow for greater algal biomass after accounting for differences in nutrient availability due to trophic cascades (Jeppesen et al. 2020). Despite these possible top-down controls, high levels of phosphorus have been shown to preclude macrophytes from subtropical lakes, shifting to the alternate, algal-dominated state (Bachmann et al. 2002). Reductions in N:P in these warm, shallow lakes can shift primary producer communities toward potentially harmful N-fixing species (Havens et al. 2003), although harmful

blooms can also exhibit N limitation in this region (Kramer et al. 2018). It is possible that reductions in nutrient loading due to fertilizer ordinances, as shown here, may not significantly elicit a subsequent ecological response, but recent harmful algal blooms throughout Florida necessitate a focus on reducing nutrient inputs to prevent harmful algal species and potentially reduce eutrophication.

Fertilizer timing

Careful consideration of fertilizer timing can maximize nutrient utilization efficiency while reducing the risk of nutrient loss through appropriate rate, timing, and placement (Carey et al. 2012). In the same way, we found ordinance timing plays a significant role in reducing nutrient loading to adjacent waterbodies. Not all ordinances have the same water quality impact, which likely explains the mixed conclusions of fertilizer ordinance impacts (Lehman et al. 2009, 2011; Kirkpatrick et al. 2014). For example, Krismky et al. (2021) found fertilizer ordinances had no impact in Satellite Beach, Florida (Brevard County). Brevard County has a summer (wet season) fertilizer ban, and their conclusion largely stemmed from their assessment of nitrogen. Our results support their observations that wet-season ordinances have no detectable impact on nitrogen runoff. Fertilization during active growth periods (i.e., wet season) has been observed to improve turfgrass nutrient uptake efficiencies (Carey et al. 2012; Hochmuth et al. 2012), further suggesting ordinance timing plays a critical role in overall watershed management. In contrast to temperate regions, lakes in subtropical regions remain ice-free year-round. This lack of ice cover in subtropical regions coupled with warm temperatures and relatively shallow lakes, particularly in Florida, indicates that controlling nutrient export is important for limiting algal growth year-round (Jeppesen et al. 2020).

Limitations

There are many complexities that can impact lacustrine water quality beyond fertilizer ordinances, such as climatic gradients, watershed land cover, soil types, urban densities, homeowner knowledge, age of the residential landscape, and ecological communities (Souto et al. 2019; Bachmann et al. 1996, 2002; Jeppesen et al. 2020; Hoyer et al. 2005). Some of these complexities are widely variable and can rapidly change (e.g., homeowner knowledge), where others like climatic gradients carry longer, less rapidly dynamic impacts. Here, we assume these externalities can be grouped collectively into a random effects term of the mixed models, allowing us to analyze the impacts of ordinances alone. This assumption is justified by the long-term (30 yr) data records processed here which inherently capture both short and long-term externality impacts. Refer to the Supporting Information for more information on ordinance influence.

Conclusions

Fertilizer ordinances are increasingly adopted in populated areas to reduce nutrient loading, but their effects have been observed with mixed results. Previous assessments of fertilizer ordinances have lacked large spatial and/or temporal scales and have not analyzed multiple types of ordinance strategies. Despite the importance of nutrient management for aquatic environments, knowledge is limited about the impacts of fertilizer ordinances. Here, we provide the most comprehensive analysis to date of fertilizer ordinance impacts on water quality, spanning 160 lakes across 30 yr and analyzed by ordinance type. Based on the results of this study, we conclude that:

1. Fertilizer ordinances do positively affect water quality in subtropical/tropical watersheds to varying degrees. Here, each ordinance type resulted in at least two improved water quality trends.
2. Ordinance timing is important when implementing and evaluating their role. As a result, this study can be used to support both sides that conclude ordinances *do* and *do not* have a positive impact across water quality metrics. The impact of ordinances is specific to the timing and tested water quality metric.
3. Collectively, a winter (dry season) ban was observed to be the most robust across all water quality variables (i.e., it had the greatest positive impacts of the tested ordinances). Based on our results, and supported by the results of others, counties that do not have a winter ban should revisit their ordinance intentions to evaluate if switching to a winter ban alone (when turfgrass is usually least active in Florida) can achieve their target objectives.

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Conflict of Interest

None declared.

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