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Improving Estuarine Water Quality in South Florida: A Quantitative Evaluation of The Efficacy of a Local Nutrient Ordinance

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IMPROVING ESTUARINE WATER QUALITY IN SOUTH FLORIDA: A QUANTITATIVE EVALUATION OF THE EFFICACY OF A LOCAL NUTRIENT ORDINANCE

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IMPROVING ESTUARINE WATER QUALITY IN SOUTH FLORIDA: A QUANTITATIVE EVALUATION OF THE EFFICACY OF A LOCAL NUTRIENT ORDINANCE

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BY
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Abstract

Degraded coastal water quality is a concern in Florida, in part due to nutrient enrichment of aquatic ecosystems causing eutrophication and excessive algal growth. In 2010, a fertilizer ordinance was enacted in Cape Coral located in Lee County Florida with the objective of reducing nutrient loads from local fertilizing practices in order to improve water quality within the city. In order to assess its efficacy, a before after control impact (BACI) design was implemented using Fort Lauderdale in Broward County Florida as a reference location. A total of twenty estuarine canal sampling locations were identified in both Lee and Broward Counties. The analysis used data spanning three years prior to (2007-2009) and post (2011-2013) the enactment of the ordinance. This study examined (1) the effect of the ordinance and seasonality on total nitrogen and total phosphorus concentrations within the estuarine canal system and (2) the relationship between post-ordinance nutrient and chlorophyll-a concentrations. The results showed mean total nitrogen concentrations declined from pre-to post-ordinance calendar years in both cities and total phosphorus concentrations were higher in summer months than winter. Furthermore, total nitrogen and total phosphorus were only correlated to chlorophyll concentrations in Broward County. The study suggests that the fertilizer ordinance may have had a positive effect on the reduction of nutrient concentrations at the estuarine canal sampling locations in Cape Coral, Florida however results raise questions about whether larger-scale factors derived from upstream source waters play a role in nutrient loading. An association was found between total nitrogen/total phosphorus and chlorophyll-a in the Fort Lauderdale estuarine canal sampling locations suggesting algae are nitrogen and phosphorus co-limited. Factors such as light attenuation, upstream loading and ocean mixing which influence water quality in the two

locations differ indicating a need for different management approaches in each of the municipalities.

Acknowledgements

I would like to thank the members of my committee, for their unwavering encouragement and constructive comments, without whom the culmination of this project would not have been possible. I would like to thank Dr. Troy Keller for his patience and support despite being across the world. I would also like to thank Dr. Stacey Blersch and Dr. Brad Huff who provided me with the confidence and advocacy which were crucial throughout the scientific process. I am grateful to Columbus State University's Department of Earth and Space Sciences for allowing me to use their resources during the completion of this research and for providing me with the opportunity to learn and explore a field which profoundly interests me.

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Introduction

Travel and tourism account for over 9% of global GDP and support over 100 million jobs; coastal tourism is one of the largest components of this economic activity (The Nature Conservancy, 2016). In highly desirable areas, this income can serve as a leading source of local revenue. For example, tourism accounts for 46% of Florida's gulf economy, grossing more than $100 billion a year in revenue (Hargreaves, 2010). According to Visit Florida, the state's tourism marketing arm, the State of Florida alone welcomed over 85 million tourists in the first nine months of 2017 and has regularly exceeded 100 million tourists annually since 2015 (Visit Florida, 2017). Much of Florida's allure comes from its pristine beaches, clear water and uniquely diverse ecosystems which are vital to the economic success of the sunshine state. Healthy aquatic ecosystems are crucial to the economic vitality in Florida.

The degradation of aquatic ecosystems throughout Florida can have deleterious effects on Florida's tourism industry. Larkin et al. (2007) reported that harmful algal blooms resulted in significant revenue losses in the panhandle of Florida in the restaurant and lodging sectors, $2.8 and $3.8 million/month respectively, during red tide events. Red tide induced losses, caused by blooms of toxic red dinoflagellates, were also found to exceed those incurred by tropical storms (Larkin et al., 2007). The economic impact on fisheries and tourism in Florida associated with a single algal bloom was estimated at $20 million in losses (Habas and Gilbert, 1975). Human health risks associated with toxic algal blooms are also a major concern impacting coastal economies (Glasgow et al., 1995; Carmichael, 2001).

Widespread eutrophication of aquatic systems throughout Florida also influences the integrity and function of the state's ecosystems (Gilbert, 1975; Burkholder, 2001). Phytoplankton blooms, stimulated by increased nutrient inputs to aquatic ecosystems, can limit light penetration through the water column, impeding submerged plant growth (Carpenter and Lodge, 1986). As the algae from blooms senesce, microbial decomposition depletes oxygen within the water column (i.e., hypoxia) which leads to a higher incidence of fish kills (Breitburg, 2002). The conventional oxygen threshold used to designate marine waters as hypoxic is 2mg/l or lower which can induce fisheries collapse depending on the species (Vaquer-Sunyer and Duarte, 2008). This threshold has been found to be even higher for larval stages of organisms such as crustaceans which can experience oxygen stress at higher oxygen concentrations (e.g. 8.69mg/l Vaquer-Sunyer and Duarte, 2008). Baird et al. (2004) noted that hypoxia in Neuse River estuaries and coastal embayments has changed the trophic structure within the ecosystem as intense algal blooms lead to fewer aquatic plants and depleted benthic grazers. These changes also affected apex predators by lowering the ecosystem's ability to transfer energy to higher trophic levels (Baird et al., 2004; Buskey, 2008).

Estuarine primary productivity is often related to nutrient discharges which are typically dictated by seasonal, hydrological and land use factors (Rudek et al., 1991; Mallin et al., 1993; Harris, 2001). Nitrogen and phosphorus play an integral role in aquatic systems by acting as limiting nutrients (Correll, 1988; Elser et al. 2007). However, their relative importance in controlling algal productivity depends critically on the type of aquatic ecosystem (i.e., river, lake, estuary or ocean). Nitrogen often limits primary productivity in estuarine and marine ecosystems (Boards et al., 2000; Howarth et al., 2006; Bruesewitz et al., 2013). Marine phytoplankton require 16 moles of nitrogen for every mole of phosphorus they assimilate (16:1). If the nutrient ratio in water is less than 16:1, theoretically primary production will be nitrogen limited and if the ratio is higher it will tend to be phosphorus limited (Redfield, 1958). Low inorganic nitrogen:phosphorus ratios found in estuaries at the time of peak primary production suggest that nitrogen availability regulates algal growth, in coastal, estuarine ecosystems (Boynton, 1982).

Cities throughout Florida that rely heavily on robust, aesthetically pleasing saltwater ecosystems suffer both ecologically and economically during algal blooms. Cape Coral, a water front community located in Lee County Florida, has experienced water quality degradation in its canal system (Division of Public Works, 2016). Fertilizers associated with routine lawn care contribute to storm water runoff saturated in phosphates and nitrates. These nutrients facilitate eutrophic conditions such as unsightly and detrimental algal blooms (Nixon, 1995; Michalak et al., 2013). These blooms are not only problematic for the local ecosystems, but they negatively affect Cape Coral's economy. Nicholls and Crompton (2018) found that poor water quality in Lee County, Florida has affected the housing market. Their study showed that improved water clarity resulted in a gross property value increase of $541 million within the county. Results also indicated that homebuyers considered instances of poor, long-term water quality (i.e. routine algal blooms) in their purchasing decisions (Nicholls and Crompton, 2018).

Many sources contribute to higher nutrient loads and eutrophication of surface waters (Gilbert et al., 2005; Alcock, 2007; Heisler et al., 2008; Roach et al., 2008). In urban areas, nutrient loads derive from sewage-effluent discharges (Anderson et al., 2002), nutrient fluxes from runoff (Vargo et al., 2008), plant litter and debris (Cowen et al., 1973; Dorney, 1986; Strynchuk et al., 2004), soil characteristics (Petrovic, 1990; Soldat and Petrovic, 2008) and atmospheric deposition (Zarbock et al., 1996; Howarth, 2002; Greening et al., 2006). This broad array of nutrient sources causes a need for comprehensive nutrient controls and regular water quality monitoring in urban areas.

Currently, a variety of approaches exist within Florida to reduce nutrients including, local ordinances, state/federal regulations and best management practices (BMPs). All of these approaches are designed to prevent water quality degradation caused by urban and agricultural runoff (Hochmuth et al., 2011; Sharpley et al., 1994) and point source discharges (Anderson et al., 2002). The solutions to these water quality challenges associated with nutrient over enrichment are most effective when jurisdictions implement comprehensive nutrient control programs which include incentives and detailed scientific monitoring (Grove et al., 2006; Baker, 2007). While fertilizer controls that use science-based BMPs and public education programs have been shown to improve water quality (Dietz, 2004), little scientific attention has been focused on the efficacy of fertilizer ordinances for protecting estuarine water quality.

To address water quality problems in their extensive canal system, the city of Cape Coral enacted a local nutrient ordinance to regulate the use of fertilizers (November 29, 2010). Reducing nutrient loading was thought to slow or eliminate the eutrophication problem throughout the canal system (Ordinance 86-10, 2010). The major components of the ordinance included fertilizer timing restrictions and bans during severe weather watches and warnings and during the summer months (June 1st – September 30th). Fertilizer-free zones were also enforced, which prohibit fertilizing within three meters of a water body. The ordinance also required the use of shields and proper disposal techniques when working near impervious surfaces. The ordinance included guidelines for fertilizer content (i.e. at least 50% of the nitrogen in fertilizer must be slow release) and enforcement of application practices for commercial applicators and homeowners alike (Ordinance 86 – 10). A quantitative scientific assessment of the efficacy of the fertilizer ordinance enacted in Cape Coral, Florida will contribute to our understanding of the effectiveness of local laws for solving environmental challenges. This evaluation will address how the ordinance affects water chemistry and quality in estuarine canals which have an economic and ecological impact on the city.

The Cape Coral study area spans the northwestern region of Lee County Florida; it is located in southwestern Florida along the eastern coastline on the Gulf of Mexico (26.5629° N, 81.9495° W, Fig.1). Cape Coral, the “waterfront capital of the world”, contains over 643km of canals (About Cape Coral, 2013). Approximately 16% of the total length of these canals are estuarine, with salinities ranging from 0.5 to >30 ppt (CHNEP, 2016). Although initially dredged in order to drain wet lands and encourage property sales (i.e., providing ocean access), the City’s Environmental Resources Division manages the canals for flood protection, irrigation supply and recreation. About 180,000 people live within the city of Cape Coral and in Lee County; tourism employs 1 out of every 5 people as they receive ~5 million visitors annually who spend $3 billion each year in the county (Census, 2016; Lee County Visitor and Convention Bureau, 2018). The land use in Cape Coral consists primarily of large residential zoning districts with single family and multifamily residents totaling nearly 59% of the area; about 24% of Cape Coral’s land is classified as open space, parks, preserves, recreation facilities or public facilities. Mixed use areas consisting of commercial activity centers, downtown, flexible development districts and preserves account for ~13% of the municipality’s area and the final ~4% of the area is defined as commercial/industrial (Appendix A, Burr, 2011).

Cape Coral resides within Florida’s humid subtropical climate zone, characterized by hot and humid summer months with mean temperatures of 22° C or higher and mild winter months with mean temperatures below 18° C (Belda et al., 2014). The warm months (May – September) are characterized by high precipitation; these months receive over half of their 1.4 meters (56 inches) of annual rainfall from June through September (Climate Data Records, 2016).

In order to assess the effect of the ordinance in the Cape Coral canal system (i.e. a treatment that could not be controlled for) and account for natural variation within the system a reference location was selected for comparison. Fort Lauderdale, located in southeastern Florida on the Atlantic Ocean (26.1224° N, 80.1373° W), was selected as a reference location (i.e. control) because its estuarine canal system is similar to Cape Coral, but it lacked any formal restrictions on fertilizer applications prior to 2014. The Fort Lauderdale reference area (i.e., control site, Fig. 2) spans the eastern region of Broward County Florida. Fort Lauderdale has 428km of salt (24.5%) and freshwater (75.5%) waterways within the city limits (Broward County Planning Council, 1989). The fresh water canals are located to the west of the salinity control structures. Canals are primarily used for flood control. The primary drainage system is managed by the South Florida Water Management District and consists of nine major canals and their corresponding drainage basins. Secondary canal uses include recreation, drainage of land for development, discharge of excess water to and from water conservation areas and prevention of saltwater intrusion (Cooper and Lane, 1987).

Like Cape Coral, Fort Lauderdale has a population of nearly 180,000 (178,752, Census, 2016). Unlike Cape Coral, Fort Lauderdale's residential areas consist of more multi-family residences and commercial properties. Fort Lauderdale's residential zoning area comprises only 9% of the area and the city's larger commercial/industrial area totals 59%. The remaining areas include transportation (4%), community and recreation facilities (27%) and conservation areas (<1%, Appendix A, City of Fort Lauderdale, 2018).

Fort Lauderdale exists within the tropical monsoon climate zone, which is defined by monthly mean temperatures above 18° C in every month of the year and monthly precipitation above 6.07 centimeters (2.39 inches, Belda et al., 2014). The city receives an annual average precipitation of 1.63 meters (64.2 inches, Climate Data Records, 2016).

The Fort Lauderdale and Cape Coral canal systems are dynamic as they are influenced by a variety of fresh and saltwater source waters. Saltwater inputs in Fort Lauderdale are attributed to the Atlantic Ocean which experiences low mid-summer water temperatures attributed to upwelling as cooler, nutrient rich open ocean water is replaced with coastal continental shelf water (Pitts and Smith, 1997). The saltwater sources in Cape Coral originate from the Gulf of Mexico whose southeastward circulation is more contained. On the west Florida shelf this circulation is interrupted by the Florida Keys and characterized by seasonal upwelling in the fall and winter; water flowing to Cape Coral from the gulf is buffered by Pine and Sanibel Islands (Zavala-Hidalgo et al., 2014). The Matlacha Pass runs along Cape Coral to the west receiving runoff from the city through spreader waterways as well as nutrient inputs from San Carlos Bay and Charlotte Harbor. The single largest freshwater source for both municipalities is Lake Okeechobee which is located north of Fort Lauderdale and northeast of Cape Coral and is the largest freshwater lake in the state of Florida (Jackson et al., 1948). Wetter conditions throughout the area trigger water releases from the lake in order to preserve the structural integrity of the Herbert Hoover dike. When this occurs, water is discharged into the St. Luice estuary to the east of Lake Okeechobee, and down the Caloosahatchee River through the Moore Haven Lock and Dam to the west of the lake (which runs through Cape Coral), water is also discharged into the Everglades agricultural area just south of the lake which travels through Fort Lauderdale to the Atlantic in drainage canals (Fig. 1).

Total nitrogen and total phosphorus were selected as water quality parameters to be used in this study as they are limiting nutrients in aquatic ecosystems in salt and freshwater respectively, and their presence or absence dictates primary productivity (Elser et al., 2007). This study compared total phosphorus and total nitrogen concentrations from sampling stations in saltwater canals of Cape Coral and Fort Lauderdale prior to (2007-2009) and after (2011-2013) the implementation of Cape Corals' fertilizer ordinance. As the ordinance specifically targeted nitrogen, I hypothesized there would be a reduction in nitrogen concentrations in Cape Coral between pre- and post- ordinance timeframes and an increase or no change in nitrogen concentrations over the same period of time in Fort Lauderdale as they did not have a nutrient ordinance in place during the calendar years in question. Phosphorus data were hypothesized to follow this same pattern albeit to a lesser extent, because phosphorus was not specifically regulated by Cape Coral's ordinance. Chlorophyll-a was also selected as a parameter as the presence and abundance of chlorophyll-a can be directly attributed to algal biomass (Nixon, 1995; Bricker et al., 2008; Roach et al., 2008; Boyer et al., 2009; Michalak et al., 2013). It was hypothesized that chlorophyll-a concentrations would not differ seasonally between summer and mild winter months as temperature does not vary drastically between the two. However, a difference in chlorophyll-a concentrations was expected between the two locations with Fort Lauderdale having higher concentrations overall. Higher chlorophyll-a concentrations were expected in Fort Lauderdale as the city did not have a nutrient ordinance in place during the calendar years observed in this study. The lack of ordinance in Fort Lauderdale was expected to result in higher nitrogen inputs within the system which would fuel primary productivity.

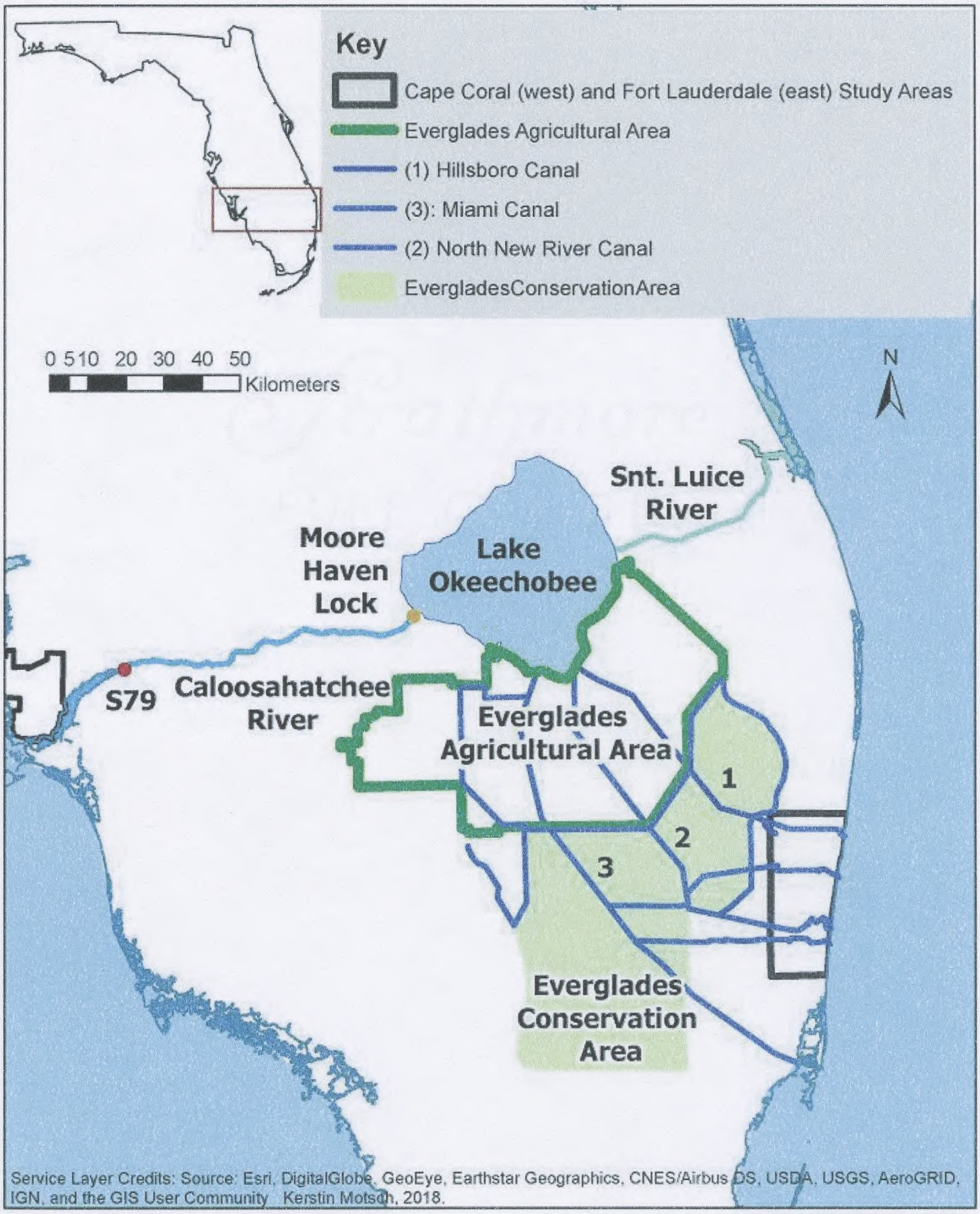

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Figure 1. The study areas of Cape Coral and Fort Lauderdale with their hydrologic connections to Lake Okeechobee. Dark blue lines represent the canals which channel water to Fort Lauderdale from Lake Okeechobee through the Everglades agricultural area.

Materials and Methods

Data Acquisition and Processing

In order to assess the efficacy of the ordinance enacted in Cape Coral, Florida in situ total nitrogen, total phosphorus and chlorophyll-a concentrations spanning the calendar years of 2007-2009 and 2011-2013 were collected for both study sites; 2010 data were not included as that was the year in which the ordinance took effect. Cape Coral data were acquired from wateratlas.org through the Charlotte Harbor National Estuary Program. Fort Lauderdale data were collected from Broward County's Ambient Water Quality Program at broward.org. Estuarine sites were determined for both locations based on available salinity data ranging from 0.5 – 35 ppt, as estuarine salinities usually range from 0.5 - >30 ppt (Bulger et al., 1993). Sampling location coordinates were then compared, using ArcMap, with known brackish water zones and the locations of salinity control structures, locks and dams.

Estuarine sites located in Cape Coral were selected based on the availability of total phosphorus and total nitrogen data. Not all parameters were consistently recorded in Cape Coral for all sites; thus, it was important to pick sites that had at least one observation for both parameters, in each season, throughout each of the study's focal years. Ten such sites were identified that met these criteria (Fig. 2).

The Fort Lauderdale estuarine dataset was comparatively more consistent than Cape Coral with sampling occurring on a quarterly basis. This regular sampling provided more sites with data for total nitrogen and total phosphorus throughout the pre/post ordinance timeframe. Of the twenty-three potential estuarine monitoring sites identified in Fort Lauderdale, ten sites were randomly selected from the dataset to create a balanced statistical model (Fig. 3).

The ten estuarine sites identified in Cape Coral were then further examined for availability of chlorophyll-a data. Because of the lack of data prior to 2010 pre-ordinance (2007-2009) chlorophyll-a data were not included in this assessment. Post-ordinance (2011-2013) chlorophyll-a data for the monitoring stations identified in the afore mentioned nitrogen and phosphorus analysis were used (Table 1).

Chlorophyll-a, total nitrogen and total phosphorus data were aggregated by calculating the arithmetic means of observations acquired from multiple sampling events made during a single season in each calendar year (Table 1, Appendix B, C & D). Such methods are common for freshwater and marine ecosystem eutrophication modeling as samples at individual locations collected over time may not be independent of one another or consistently sampled (Smith 1982, Howarth et al. 2006, Smith 2006). Furthermore, seasonal averages help balance the statistical model by providing similar sample sizes across locations while depicting a more accurate representation of water quality trends (e.g. Giovanardi and Troellini, 1992; Meeuwig et al., 2000; Hoyer et al., 2002). Data were grouped into summer and winter for each calendar year. April-September, the six months with the highest average temperature based on historical data was categorized as summer (Climate Data Records, 2016). The remaining six months, October – March, were designated as the winter season. This categorization allowed the model to account for all calendar years and seasons while maintaining a balanced design.

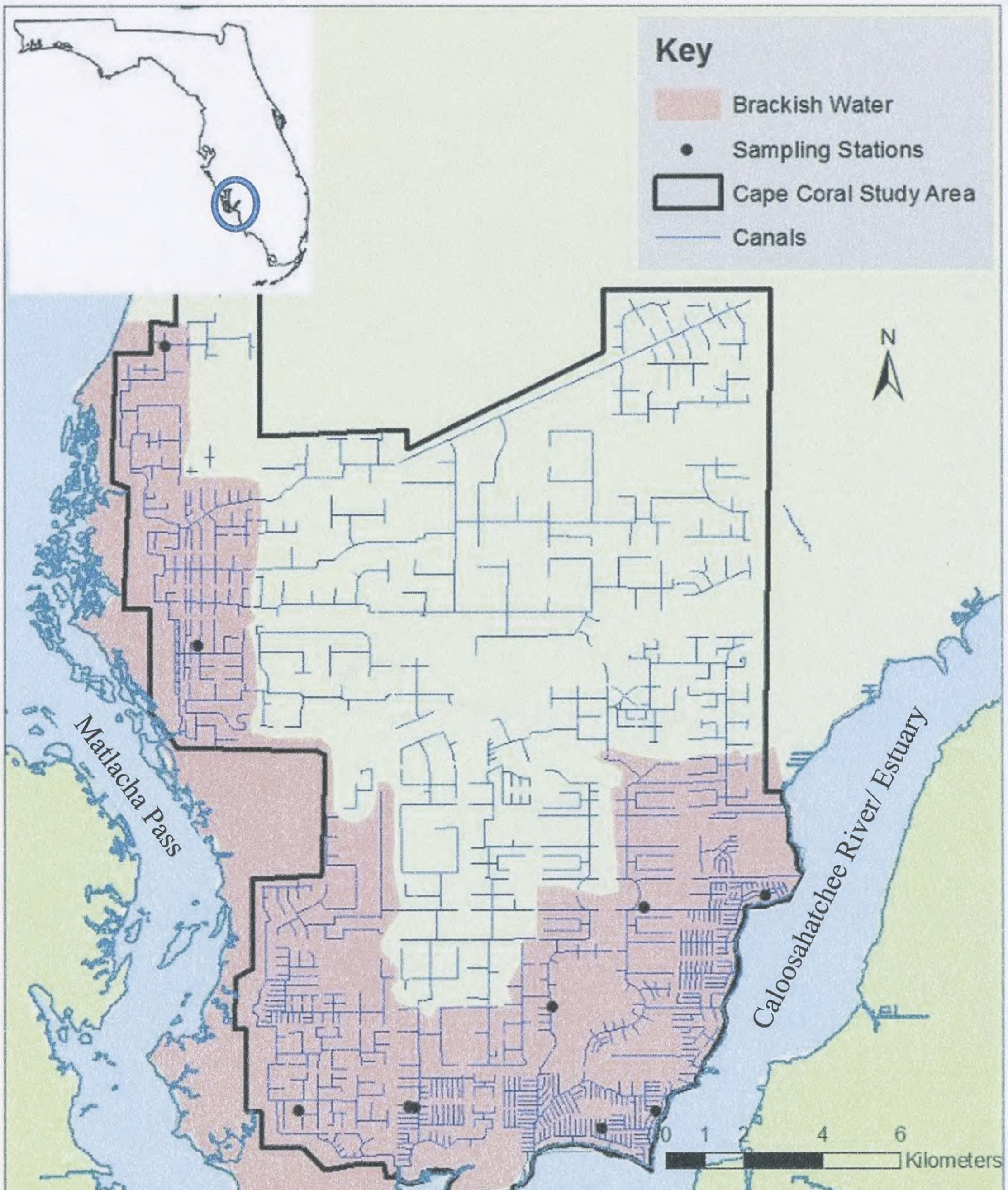

Figure 2. Estuarine sampling sites (black) used in Cape Coral analysis (black). Sites were selected because they have sufficient total nitrogen and total phosphorus data in both the pre (2007-2009) and post (2011-2013) ordinance periods.

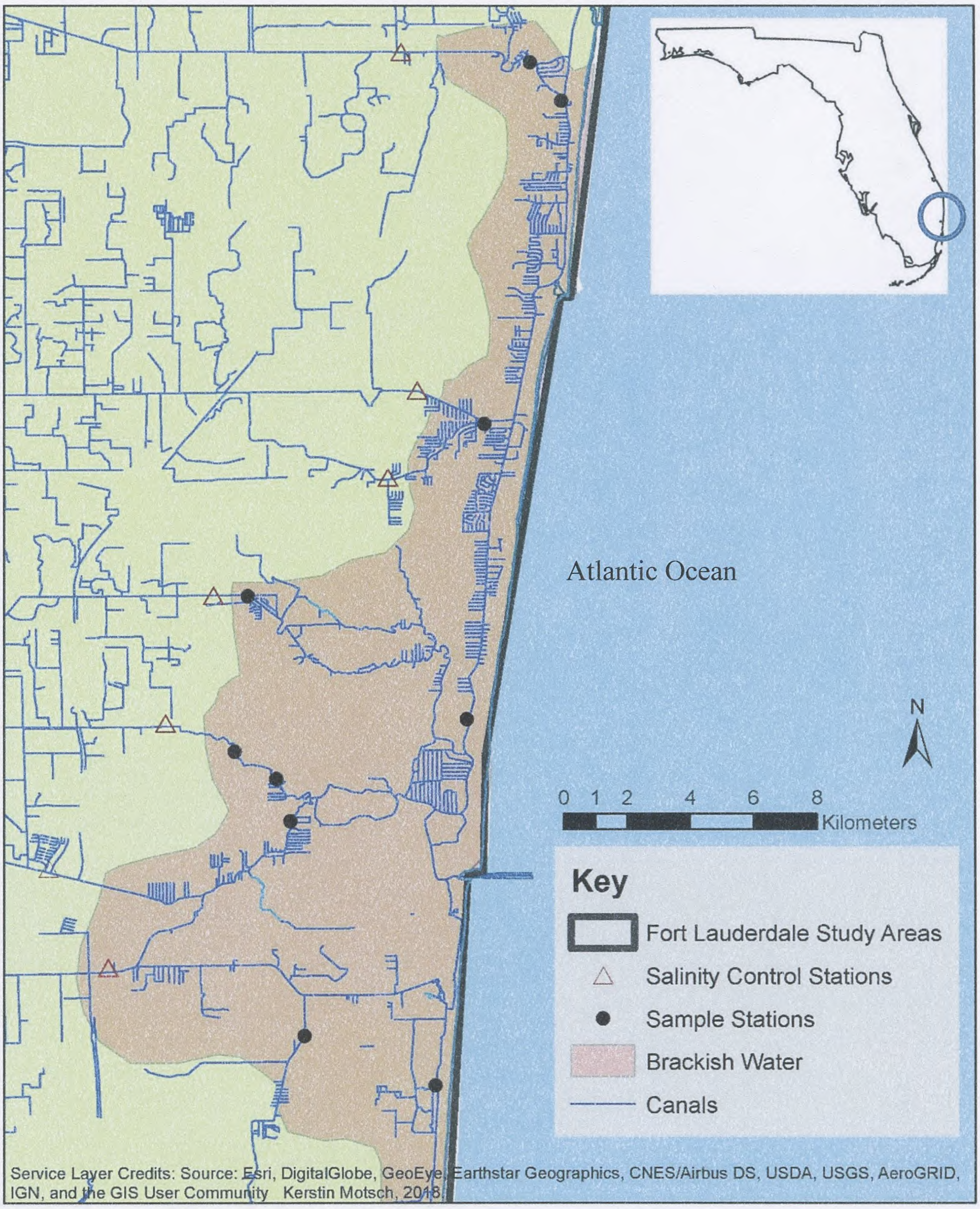

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Figure 3. Randomly selected estuarine sampling sites in Fort Lauderdale Florida (black) identified as having sufficient total nitrogen and total phosphorus data in both the pre (2007-2009) and post (2011-2013) ordinance periods.

Table 1. Total number of sampling events (before averaging across seasons) for the sampling stations used in the analysis of Cape Coral and Fort Lauderdale water chemistry encompassing pre-(2007-2009) and post-(2011-2013) ordinance calendar years.

		Year					
		Pre			**Post**		
Location & Parameter	**# Stations**	**2007**	**2008**	**2009**	**2011**	**2012**	**2013**
Fort Lauderdale							
Total Phosphorus	10	36	36	36	48	48	40
Total Nitrogen	10	33	33	44	44	44	40
Chlorophyll a	9				46	38	32
Cape Coral							
Total Phosphorus	10	105	111	105	106	106	106
Total Nitrogen	10	104	113	105	106	107	107
Chlorophyll a	9				50	43	45

Data Analysis

A fully factorial three-way analysis of variance (ANOVA) was used to assess temporal (i.e. pre and post), seasonal (i.e. summer and winter) and spatial (i.e. Cape Coral and Fort Lauderdale) effects on total nitrogen and total phosphorus concentrations. Outliers (i.e. observations which fell at least 1.5 times the interquartile range above the third quartile) were not removed as their presence did not affect the assumptions of normality and homoscedasticity in the model. Twenty sample locations were included in the analysis and six sample years were analyzed in each treatment.

In order to assess the fertilizer ordinance's effectiveness to reduce algae within the canal system, chlorophyll-a concentrations were also analyzed statistically. In order to maintain a balanced design with regard to seasonal comparisons, nine sample locations with chlorophyll-a data for both seasons (summer and winter) in at least one of the post-ordinance calendar years (2011-2013) were identified in the Cape Coral dataset. In order to maintain an overall balanced design, nine of the ten sample locations in the Fort Lauderdale dataset were randomly selected for comparison of the same years. A two-way, fully factorial ANOVA was used to compare post-ordinance chlorophyll-a concentrations between locations and seasons. Outliers (i.e. observations which fell at least 1.5 times the interquartile range above the third quartile) were not removed as their presence indicated incidences of high algal biomass (i.e. algal blooms) and did not affect the assumptions of normality and homoscedasticity in the model.

In order to assess the nutrient association with algal abundance, the relationship between total nitrogen/total phosphorus and chlorophyll-a were assessed statistically for each location using a Pearson's correlation coefficient. The relationships between nitrogen and phosphorus in Cape Coral and Fort Lauderdale during the post-ordinance (2011-2013) calendar years were also evaluated using a Pearson's correlation coefficient.

All statistical analyses described in this section were conducted using IBM SPSS Statistics for Windows, Version 21.0. (IBM 2012). Alpha (statistical significance α) was set to 0.05, two-tailed. A Levene's Equality of Variances test was used to validate the assumption of homoscedasticity in the model.

Results

Ordinance Effects on Total Phosphorus

This study examined the effects of the fertilizer ordinance enacted in 2010 on total phosphorus and total nitrogen concentrations in Cape Coral and Fort Lauderdale saltwater canals. There was no statistically significant difference between pre- (2007-2009) and post-ordinance (2011-2013) total phosphorus concentrations (three-way ANOVA, $F_{1,232} = 0.084$, $p = 0.773$). Similarly, estuarine average total phosphorus concentrations did not differ significantly between Cape Coral and Fort Lauderdale (three-way ANOVA, $F_{1,232} = 0.531$, $p = 0.467$). On average, estuarine canals showed 28% higher total phosphorus concentrations during summer months compared to those in winter (three-way ANOVA, $F_{1,232} = 14.294$, $p = 0.001$, Fig. 4). The interaction term between season and location (i.e. Cape Coral and Fort Lauderdale) was statistically significant (three-way ANOVA, $F_{1,232} = 6.103$, $p = 0.014$). Fort Lauderdale and Cape Coral increased differently in total phosphorus concentration from winter to summer months (9% and 51% respectively, Fig. 5). The interaction between seasonality and time for total phosphorus concentrations was not statistically significant (three-way ANOVA, F1, 232 = 1.818, $p = 0.179$), nor was the interaction of total phosphorus concentrations between location and time (three-way ANOVA, F1, 232 = 0.753, $p = 0.386$). The complex interaction between seasonality (i.e. summer/winter), time and location was also not statistically significant (three-way ANOVA, $F_{1,232} = 1.712$, $p = 0.192$). Because total phosphorus ANOVA model variances were not homoscedastic (Levene's test, $p = 0.0001$) log and square root transformations were attempted. These transformations were abandoned for this model because the transformations failed to correct the problem.

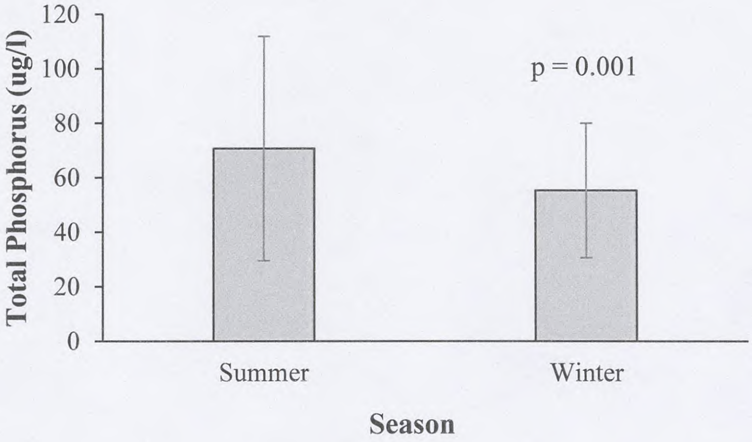


Figure 4: Mean total phosphorus concentrations (bars ± 1 *SD),* for estuarine canal stations across summer and winter seasons. Probability values indicate three-way ANOVA results for seasonality effect.

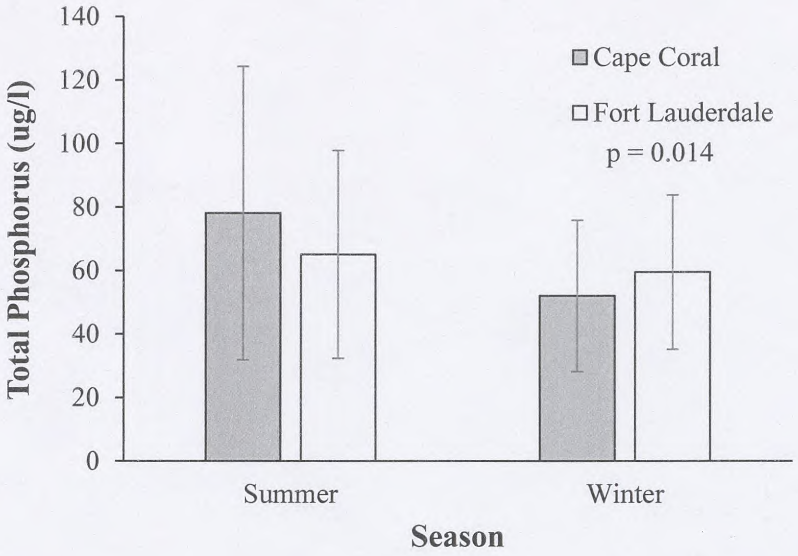


Figure 5: Mean total phosphorus concentrations (bars ± 1 *SD),* for estuarine canal stations in Cape Coral (filled) and Fort Lauderdale (open) across seasons (winter/summer). Probability values indicate three-way ANOVA results (i.e., season by location interaction).

Ordinance Effects on Total Nitrogen

Analysis of total nitrogen concentrations in Cape Coral and Fort Lauderdale saltwater canals revealed different results than those of total phosphorus. Unlike total phosphorus, there was no statistically significant seasonal variation in total nitrogen concentrations (three-way ANOVA, $F_{1,\ 232} = 0.718$, $p = 0.398$). There was however, a significant difference in mean total nitrogen concentrations between the pre- (2007-2009) and post-ordinance (20011-2013) calendar years (three-way ANOVA, $F_{1,\ 232} = 20.219$, $p = 0.001$, Fig. 6). Overall, mean pre-ordinance total nitrogen concentrations were 28% higher than post-ordinance (including both cities). Furthermore, Cape Coral and Fort Lauderdale differed in their canal total nitrogen concentrations (three-way ANOVA, $F_{1,\ 232} = 7.233$, $p = 0.008$, Fig. 7). Mean total nitrogen concentrations in Cape Coral were 16% higher than those in Fort Lauderdale.

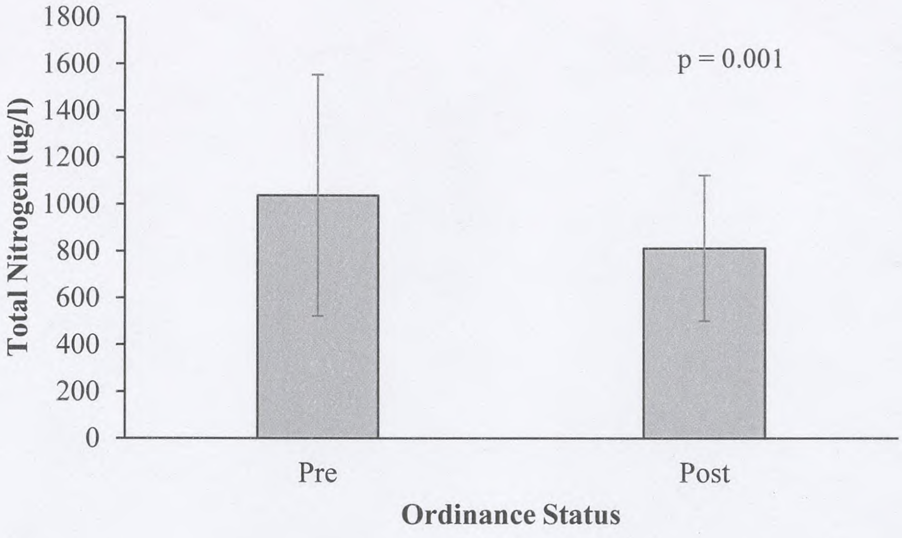


Figure 6: Mean total nitrogen concentrations (bars ± 1 *SD),* for estuarine canal stations during pre (2007-2009) and post (2011-2013) ordinance calendar years. Probability values indicate three-way ANOVA results for time effects.

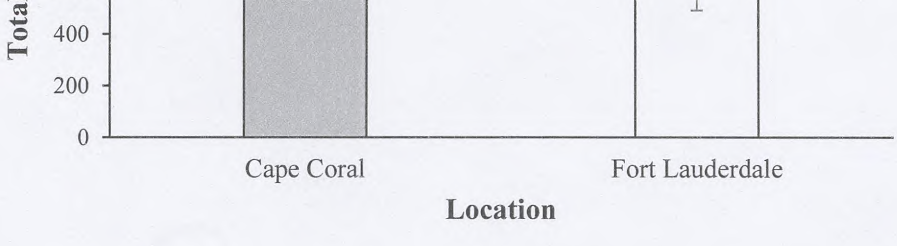


Figure 7: Mean total nitrogen concentrations (bars ± 1 *SD),* for estuarine canal stations in Cape Coral (filled) and Fort Lauderdale (open). Probability values indicate three-way ANOVA results for site effect.

In order to assess the relationship between different factors, interaction terms were calculated in the statistical model. The interaction between location and time (pre- and post-ordinance) for total nitrogen concentrations was not statistically significant (three-way ANOVA, $F_{1, 232} = 0.020$, $p = 0.887$) indicating that both Cape Coral and Fort Lauderdale showed a similar improvement (i.e. decline) in mean total nitrogen concentrations from pre- to post-ordinance (24% and 33% respectively, Fig. 8). The interaction term between season and time was statistically significant (three-way ANOVA, $F_{1, 232} = 7.233$, $p = 0.038$), indicating that patterns in seasonal variation of total nitrogen concentrations changed across time (Fig. 9). The interaction between season and location was not statistically significant (three-way ANOVA, $F_{1, 232} = 2.458$, $p = 0.118$), nor was the interaction between location, time and season (three-way ANOVA, $F_{1, 232} = 2.480$, $p = 0.117$).

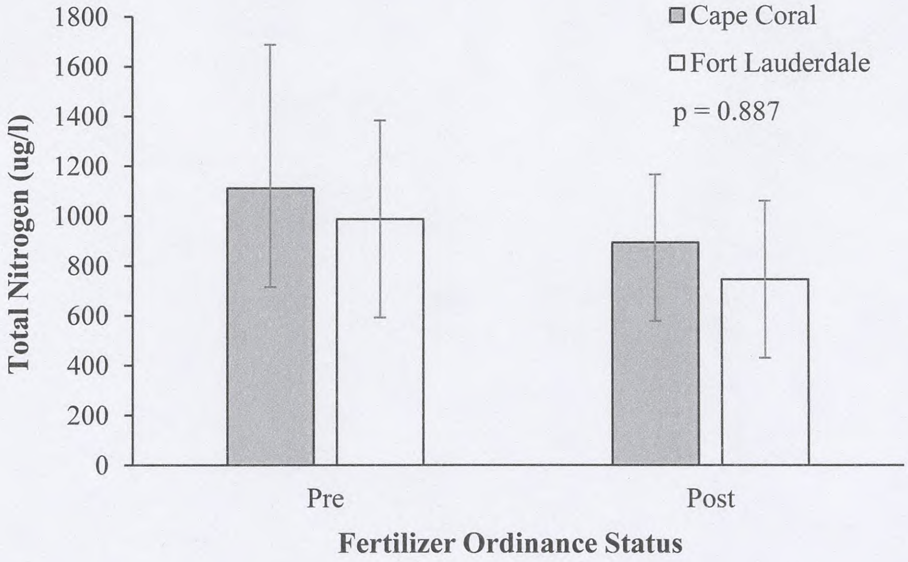


Figure 8. Mean total nitrogen concentrations for estuarine canal stations (bars ± 1 *SD*), in Cape Coral (filled) and Fort Lauderdale (open), between pre-(2007-2009) and post-ordinance (2011-2013) calendar years. Probability values indicate three-way ANOVA results for the time and location interaction.

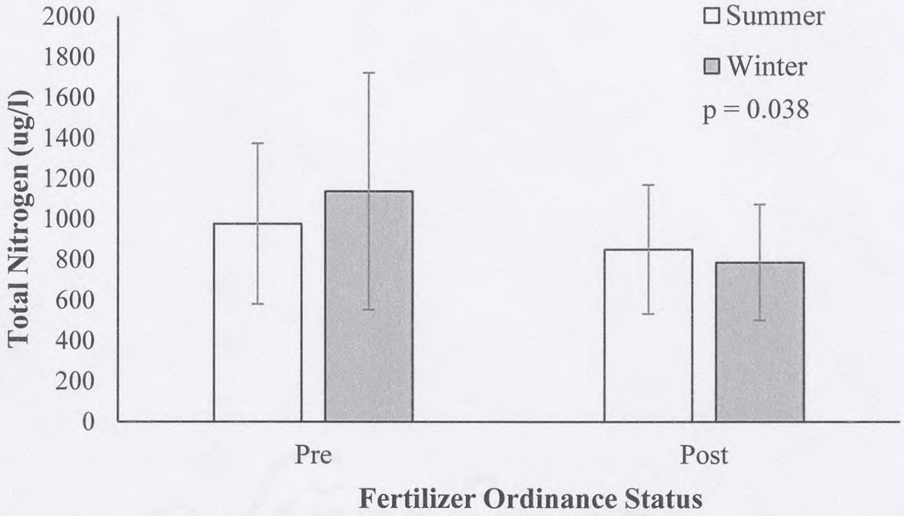


Figure 9. Mean total nitrogen concentrations for estuarine canal stations (bars ± 1 *SD*), for both locations across summer (open) and winter (filled) seasons between pre-(2007-2009) and post-ordinance (2011-2013) calendar years. Probability values indicate three-way ANOVA results for the time and season interaction.

Chlorophyll-a Response to Fertilizer Ordinance

In order to determine whether nutrient concentrations influenced algal growth, post-ordinance chlorophyll-a concentrations, a common indicator of algal biomass, were also analyzed. Overall, there was no effect of seasonality on chlorophyll-a concentrations (two-way ANOVA, $F_{1,\ 84} = 0.416$, $p = 0.521$). Similar to total nitrogen, there was a significant difference in chlorophyll-a concentrations between Cape Coral and Fort Lauderdale (two-way ANOVA, $F_{1,\ 84} = 4.587$, $p = 0.035$). Fort Lauderdale had 58% higher chlorophyll-a concentrations post-ordinance than Cape Coral (Fig. 10). The interaction term between season and site was not statistically significant (two-way ANOVA, $F_{1,\ 84} = 0.001$, $p = 0.970$). This result indicated that chlorophyll-a concentrations exhibited the same seasonal patterns at both locations.

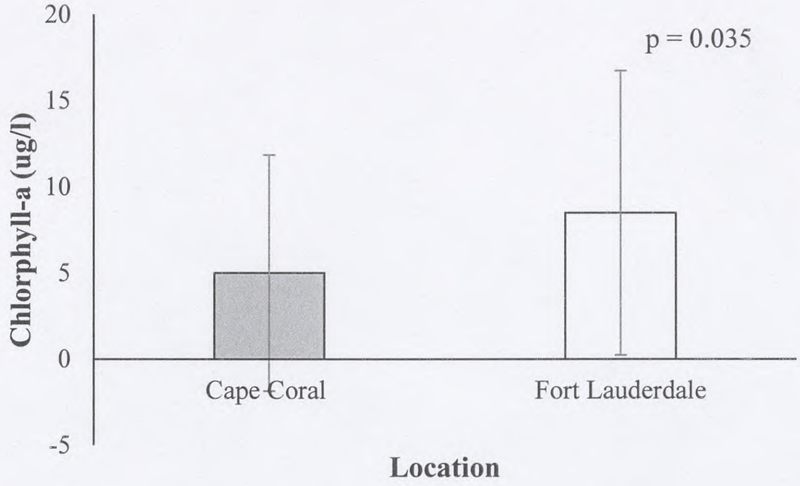


Figure 10: Mean chlorophyll-a concentrations (bars ± 1 *SD*) for estuarine canal stations in Cape Coral (filled) and Fort Lauderdale (open) groups spanning post-ordinance (2011-2013) calendar years. Probability values indicate two-way ANOVA results for site effect.

Post-ordinance (2011-2013) total nitrogen and total phosphorus data were paired with the chlorophyll-a data in order to examine the association between nutrients and chlorophyll-a concentrations (i.e. indicator of nutrient limitation). There existed no detectable correlation between total nitrogen or total phosphorus and chlorophyll-a measurements in Cape Coral canals (Fig.11A & 11B, Table 2). Conversely, in Fort Lauderdale, chlorophyll-a was positively correlated to total nitrogen (Fig. 11C, Pearson's Correlation, $r = 0.375$, $p = 0.012$) and total phosphorus (Fig. 11D, Pearson's Correlation, $r = 0.430$, $p = 0.004$).

In order to determine if total nitrogen and total phosphorus co-vary, post-ordinance (2011-2013), data were paired based on location (i.e. Cape Coral and Fort Lauderdale) and analyzed separately. No statistically significant correlation was found between total phosphorus and total nitrogen for the Cape Coral estuarine canals (Table 2). However, in Fort Lauderdale, total phosphorus and total nitrogen were positively correlated (Pearson's Correlation, r = 0.267, p = 0.039, Fig. 12).

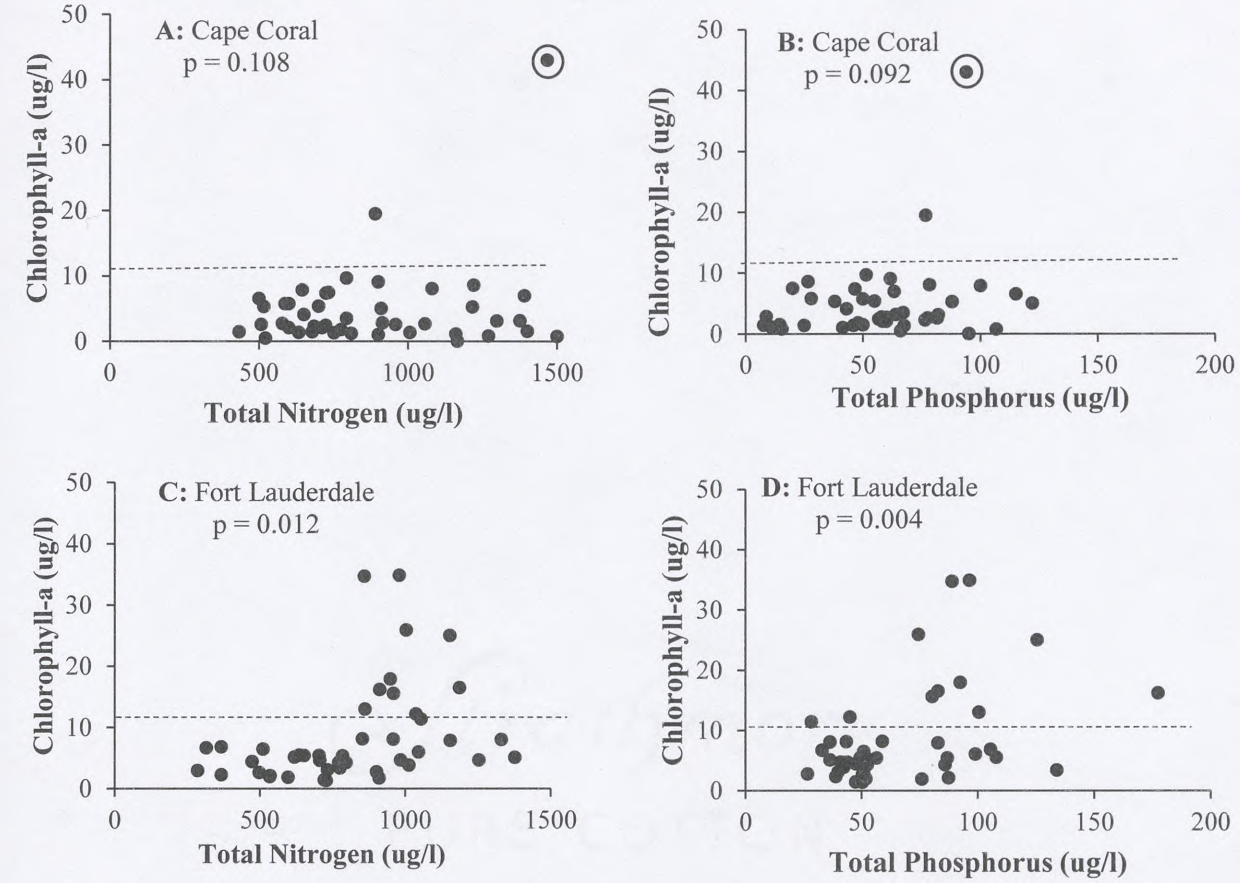


Figure 11. Estuarine canal chlorophyll-a concentrations post-ordinance (2011-2013) calendar years. (A) Cape Coral total nitrogen, (B) Cape Coral total phosphorus (C) Fort Lauderdale total nitrogen and (D) Fort Lauderdale total phosphorus. Probability values indicate Pearson's correlation results. Circled point indicates algal bloom, dashed line indicates Impaired Waters Rule threshold for average chlorophyll-a concentrations with values above 11ug/l being impaired (EPA, n.d.).

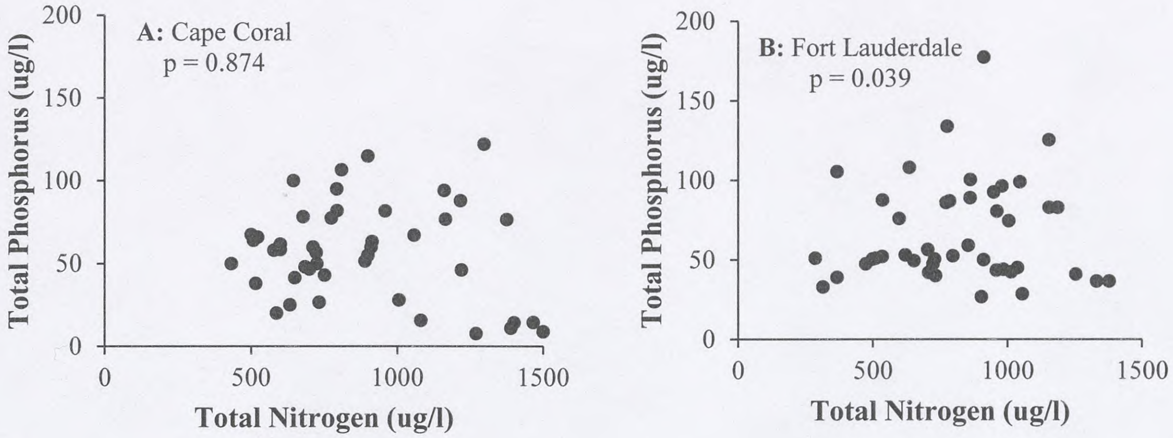


Figure 12. Estuarine canal total phosphorus and total nitrogen concentrations in (A) Cape Coral and (B) Fort Lauderdale post-ordinance (2011-2013) calendar years. Probability values indicate Pearson's correlation results.

Table 2: Pearson's correlation relating Cape Coral and Fort Lauderdale total phosphorus and total nitrogen concentrations to chlorophyll-a, as well as Cape Coral and Fort Lauderdale total phosphorus and total nitrogen concentrations for post-ordinance (2011-2013) calendar years.

Location	**Parameter**	**r (correlation coefficient)**	**r^2**	**P-value**
Cape Coral	Total Nitrogen vs. Chlorophyll-a	0.484	0.234	0.108
	Total Phosphorus vs. Chlorophyll-a	0.257	0.066	0.092
Fort Lauderdale	Total Nitrogen vs. Chlorophyll-a	0.375	0.140	0.012*
	Total Phosphorus vs. Chlorophyll-a	0.430	0.184	0.004**
Cape Coral	Total Phosphorus vs. Total Nitrogen	-0.021	0.0004	0.874
Fort Lauderdale	Total Phosphorus vs. Total Nitrogen	0.267	0.071	0.039*

*. Correlation is significant at the 0.05 level (two-tailed).

**. Correlation is significant at the 0.01 level (two-tailed).

Discussion:

Degradation of estuarine water quality throughout Florida has been an environmental concern (Barnes, 2005; Boyer et al., 2009). Excess nutrients entering aquatic ecosystems can result in excessive algal growth which can impede ecosystem functions (Smith et al., 1999). This year Lee County experienced a slew of poor water quality trends, associated with discharges from Lake Okeechobee, including red tide events which have lingered since October and cyanobacterial blooms which have persisted since June (Gillis, 2018). This combination has impacted the city ecologically and economically as red tide, caused by toxic dinoflagellates, has taken the lives of countless fish, manatees and sea turtles and the need for swimming advisories and the pungent smell of fish kills have driven tourists from coastal towns (Gillis, 2018). These poor water quality events have led to government action to alleviate these impacts, on July 9, 2018 governor Rick Scott declared a state of emergency in Lee, Glades, Hendry, Martin, Okeechobee, Palm Beach and St. Luice counties (Staff, 2018). In the past, concerns surrounding the ecological health and aesthetic quality of the estuarine canals in Cape Coral have caused water resource managers to analyze practices that contribute to nutrient loading. Cape Coral's solution was the implementation of fertilizer regulations for its urban landscapes. Lessons learned from quantifying the effectiveness of Cape Coral's nutrient ordinance can be used to protect aquatic environmental resources and develop more effective environmental policies, rules and regulations.

This analysis found evidence consistent with the hypothesis that Cape Coral's fertilizer ordinance would cause a reduction in total nitrogen concentrations within the Cape Coral estuarine canal system. This study found that mean total nitrogen concentrations declined by 24% after the implementation of the ordinance (2011-2013). However, this water quality improvement was also documented in Fort Lauderdale (total nitrogen declined by 33%). Thus, both locations exhibited a mean total nitrogen decline over time. This pattern was not expected in the Fort Lauderdale dataset as the city had no ordinance in place, during the calendar years observed in this study. This result indicates that other factors may have contributed to the observed decline in nutrient concentration (i.e. total nitrogen) within the Fort Lauderdale estuarine canal system.

Nutrient Management Initiatives: Total Nitrogen

Turfgrass landscapes are a prominent feature in urban watersheds (Carey et al., 2012). Aerial estimates indicate turfgrass covers 10 to 16 million hectares of U.S. surface area (Robbinson and Birkenholtz, 2003), which is similar to the estimate made by Milesi et al. (2005) that turfgrass covers 1.9% of total U.S. surface area. Factors that have contributed to the expansion of urban U.S turfgrass coverage include the association of turfgrass aesthetics and function with community and family values (Robbins and Sharp, 2003). Ornamental plants have also been associated with urbanized environments (Amador et al., 2007; Shober et al., 2010). Plant nutrients, such as nitrogen and phosphorus, are necessary for maintaining landscape plants. Fertilizer is used on urban soils to promote healthy plant growth; however, the mismanagement of fertilizer contributes to nutrient runoff which can facilitate water quality impairment (Carey et al., 2012).

In efforts to eliminate impairment within the state the Florida Department of Environmental Protection, under the federal Clean Water Act, established the Total Maximum Daily Load Program which oversee and set quantitative thresholds for nutrient loading in aquatic systems (FDEP, 2009; EPA, 2010; FDEP, 2012). Cape Coral's reasoning behind the enactment of the fertilizer ordinance was thought to be justified, as previous studies have indicated urban nutrients from fertilizers can be carried in runoff during heavy rainfall (Soldat and Petrovic, 2008) or when fertilizer is applied in excess (Trenholm et al., 2011). In 2013 the city of Fort Lauderdale discussed preparing for the implementation of a state-wide nutrient reduction ordinance. On January 1st, 2014 a statewide law required all licensed lawn care businesses to use nutrient best management practices (Ordinance 13–35, 2013). According to the cooperative extension office (Llanes, personal communication), many businesses had already complied with the law, as early as ~2009, in order to work in nearby counties (Palm Beach and Collier Counties) with cities which had previously adopted fertilizer regulation. The state law mirrored Cape Coral's ordinance in that it, consisted of fertilizer timing restrictions, fertilizer nitrogen content restrictions and voluntary compliance by homeowners (Ordinance 13–35, 2013).

Results from this study indicated that Cape Coral estuarine canals had 16% higher mean total nitrogen concentrations than those found in Fort Lauderdale. This finding could be partially influenced by local land practices, lawn care and maintenance activities. According to the Florida Department of Agriculture's annual reports the fertilizer tonnage distribution by district shows Lee County (Cape Coral) uses more than twice as much fertilizer as Broward County (Fort Lauderdale). In a study assessing the sale and use of fertilizers to homeowners in Lee County, Brown and Becker (2012) found that lawn fertilizer comprised the highest percentage (22.6%, with an average N(nitrogen):P(phosphorus):K(potassium) ratio of 22:2:6) of fertilizers on sale, followed by flowering plants (7.03%, with an average N:P:K ratio of 9:6:7), and palms (6.5%, with an average N:P:K ratio of 8:4:8). The same study also found that only 2% of all the fertilizers surveyed were labeled as "Summer Blend", which contains no nitrogen and phosphorus (Brown and Becker, 2012). This blend is approved for use during the wet summer seasons when nitrogen and phosphorus applications are prohibited. Furthermore, over 95% of the fertilizers sold during the summer months of 2012 did not meet the slow release nitrogen guidelines (i.e. 50% of the nitrogen must be slow release) set forth by the ordinance (Brown and Becker, 2012). Thus, residents in Cape Coral who participate in lawn and garden care are doing so without following ordinance guidelines.

State-wide, nitrogen fertilizer applied to turf grass contributes 11% of the nitrogen applied in Florida (FDACS, 2017). Although this percentage is low relative to other markets such as agriculture (80%), the land use within Cape Coral and Fort Lauderdale consists of residential areas and manicured public spaces where turf grass and garden maintenance is a primary reason for fertilizer application (Hostetler and Main, 2010). Both locations have similar populations, however, Cape Coral residential areas consist mainly of single family and multi-family homes with lawns which take up a greater area within the city (59% of area) whereas Fort Lauderdale residential areas contain more high rises and apartment complexes (9% of area). Multi-family residential areas in Fort Lauderdale include the cost of professional lawn care in rental fees, many of whom had been previously certified in best management practices. Conversely, single family homeowners in Florida often self-fertilize their lawns as deed restrictions and homeowner association agreements require a level of ‘greenness’ and aesthetic desirability putting homeowners at odds with regulatory fertilizer application practices (Hartman et al., 2008). This juxtaposition in living style provides Cape Coral residents with opportunities to participate in gardening and lawn maintenance practices, which could negatively impact the water quality in canals near their homes if they fail to follow fertilizer ordinance guidelines.

Hydrology and Precipitation

Although local factors such as land use can contribute to differences in water chemistry between Cape Coral and Fort Lauderdale, hydrology could also contribute to the nutrient patterns observed in this study. The estuarine canal systems of Cape Coral and Fort Lauderdale have freshwater inputs originating primarily from Lake Okeechobee which influences nutrient loads in both cities. The water from Lake Okeechobee, laden with phosphorus and nitrogen from sediment and runoff, reaches Cape Coral from the Caloosahatchee River and Fort Lauderdale through drainage canals, which travel through agricultural and storm water treatment areas. (Fig. 1). The Everglades Agricultural Area, designed in 1948 by The Central and Southern Florida Project for Flood Control and Other Purposes, is an area of ~2832 km^2 of farmland. Created from the drainage of the northern Everglades, the agricultural area has been cited as the cause of eutrophication in both Lake Okeechobee and the wetlands south of it (Izuno et al., 1991). The Everglades Agricultural Area, whose major crop is sugar cane, has also contributed to Lake Okeechobee's phosphorus loading through back-pumping during months of high precipitation (Izuno et al., 1991; Reid, 2017). Phosphorus and nitrogen runoff from upstream dairy and cattle farms as well as inputs from northern tributaries also contribute to Lake Okeechobee's degradation (Byrne et al., 2011; Capece et al., 2007). Phosphorus loading rates to Lake Okeechobee have averaged 641 metric tons/year and have exceeded target levels by over 200 metric tons/year since 1995 (FDEP, 2001). In previous years these nutrient loads, coupled with nutrient inputs from the everglades agricultural area, have increased total phosphorus concentrations in the water conservation areas to the south (Belanger et al., 1989). South Florida's three Water Conservation Areas are vast tracts of remnant Everglades sawgrass marsh located adjacent to Everglades National Park and south of the Everglades Agricultural Area spanning ~188 square km (SFWMD, 2018). The Water Conservation Areas serve multiple water resource and environmental purposes, including flood control, water supply, habitat for local flora and fauna, recreational bird watching and fishing (FWC, 2018; SFWMD, 2018). Their construction was authorized by U.S. Congress in 1949 in order to provide flood control and water supply for South Florida (SFWMD, 2018).

Lee County has also experienced nutrient loads linked with water released from Lake Okeechobee (Flaig et al., 1998; Doering & Chaimberlain, 1999; Barnes, 2005; Doering, 2006). The Caloosahatchee River which carries the nutrient rich lake water is combined with additional runoff from non-point sources within the river basin. This water is released into Charlotte Harbor and the Caloosahatchee estuary and has been linked to nutrient loads within the county (Hartman et al., 2008). Results of this study indicated that Cape Coral estuarine canals had 28% higher total phosphorus concentrations in the summer compared to the winter. The US Climate Data database reports June to September as the four wettest months of the year on average. The pattern observed in this study is consistent with previous studies which have attributed increased nutrient inputs from run-off to water bodies during periods of increased precipitation (Nixon 1995; Smith et al., 1999; Howarth, 2002; Greening et al., 2006; Roach et al., 2008; Michalak et al., 2013).

Higher summer precipitation leads to Lake Okeechobee discharges, however the path the water must take from Lake Okeechobee to both municipalities is quite different. Before the water from Lake Okeechobee reaches the Fort Lauderdale canal system it must pass through large constructed stormwater treatment areas (STA), created to aid in nutrient removal. These STAs were designed and first implemented by the South Florida Water Management District to reduce phosphorus concentrations in order to comply with the Everglades Forever Act (1994). The Act seeks to reduce phosphorus concentrations to 10 ug/l, to ensure the health of flora and fauna indigenous to the Everglades ecosystem (FDEP, 2004). These STAs are manmade wetlands designed to filter pollutants from urban and agricultural lands and they serve as a barrier between the pollutants of the Lake Okeechobee basin and the Everglades Protected Area to the south (Fig. 13).

Of the six Everglades STAs located in the southern agricultural area STAs 1-4 channel water directly into Fort Lauderdale. In a study examining outflow water quality in the STAs from 1996-2012 it was found that in general STAs 1-4 and 6 achieved the lowest phosphorus outflow concentrations, below 50ppb and often below 25ppb with STA 3-4 having the lowest observed outflow of 18-23ppb over an eight-year period (Pietro, 2012). The South Florida Water Management District (2008) also found that the stormwater treatment areas effectively removed phosphorus (Table 3) and nitrogen (Table 4) concentrations from the water originating in Lake Okeechobee. Although total phosphorus has been cited as the main cause for eutrophication in Lake Okeechobee as it is a freshwater system (Havens et al., 2003), nitrogen concentrations were analyzed as part of the assessment in order to quantify overall nutrient removal within the stormwater treatment areas and determine compliance with permit requirements. These stormwater treatment area assessments indicate that the water moving from the STAs into the Fort Lauderdale canal system is cleaner than it was at its point of origin in Lake Okeechobee (Table 3 & 4, SFWMD, 2008).

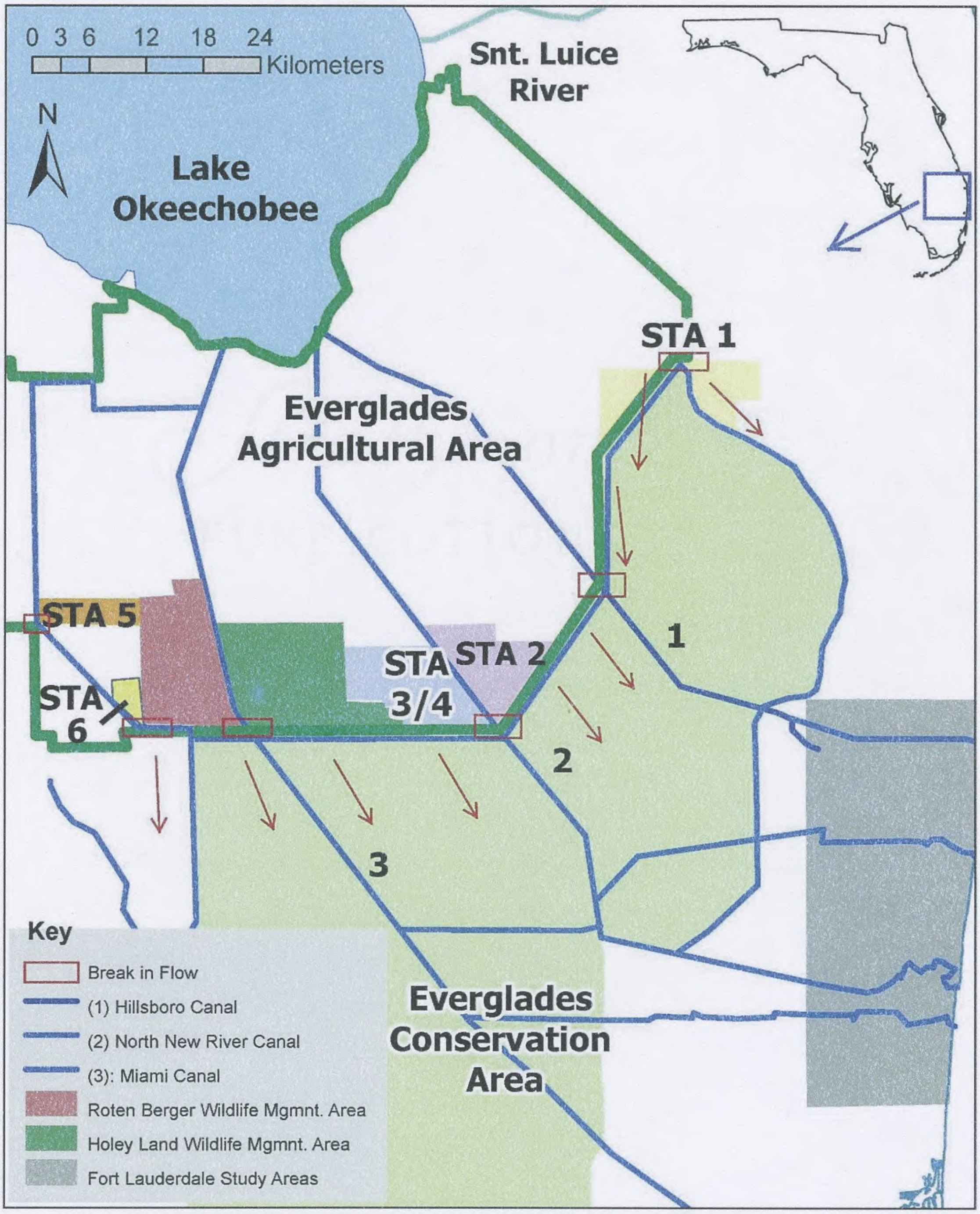
Table 3: South Florida Water Management District summary of total estimates of Lake Okeechobee storm water treatment area (STA) efficiency for total phosphorus removal in STAs 1-6 (SFWMD, 2008).

STA	**Water**	**------------Inflow------------**			**-----------Outflow----------**			**% TP**
number	**years**	ac-ft	TP kg	TP ppb	ac-ft	TP kg	TP ppb	**Removed**
STA-1E	’04 - ‘07	179,869	48,254	217	155,955	23,966	125	50%
STA-1W	’95 – ‘07	2,551,898	514,148	163	2,574,781	175,534	55	66%
STA - 2	’99 – ‘07	1,742,691	226,123	105	1,744,660	45,139	21	80%
STA – 3/4	’04 – ‘07	1,779,945	263,992	120	1,764,243	41,907	19	84%
STA - 5	’00 – ‘07	932,711	270,132	235	851,442	111,731	106	59%
STA - 6	’99 – ‘07	438,893	43,250	80	302,439	7,617	20	82%

Table 4: South Florida Water Management District summary of annual arithmetic averages and flow weight means for total nitrogen of Lake Okeechobee storm water treatment area (STA) efficiency through inflow and outflow sources in STAs 1-6 during the 2007 water year. These parameters were measured from grab samples and not flow-proportional samples so both the arithmetic of all the samples collected as well as the means for those samples collected only during flow events (flow-weighted means, FWM) are shown (SFWMD, 2008).

STA	**Arithmetic Means**										**FWM**	
number	**------------Inflow---------**				**------------------Outflow----------------**						**-In-** Conc.	**-Out-** Conc.
STA-1E	2.4	1.5	2				2.1				3.5	2.2
STA-1W	2.76						2.58	2.64			5.08	2.52
STA - 2	2.86	2.44					2.21				4.06	2.26
STA – 3/4	2.10	2.23			2.26	2.37	2.95	2.77	2.94	2.60	3.51	1.99
STA - 5	1.58	1.26	1.75	1.46			1.87	1.93	2.31	2.23	2.05	1.48

In contrast, the Caloosahatchee River which flows from Lake Okeechobee through Cape Coral, does not have extensive storm water treatment areas. Furthermore, agricultural and urban development along the river and the regulated releases of freshwater from Lake Okeechobee have been linked to water quality declines in the Caloosahatchee Estuary (Flaig et al., 1998; Barnes 2005; Doering 2006). In a three-year project (2000-2002) external loading entering the Caloosahatchee Estuary was quantified (ERD, 2003). Sampling was performed at 15 estuary sites, and 14 nutrient monitoring sites (8 were located at significant tributaries to the Caloosahatchee River based on magnitude of freshwater discharge into the estuary) and 4 wastewater treatment facilities were also monitored. Monitoring occurred during summer (wet) and winter (dry) seasons over the three-year period. ERD (2003) concluded that the S79 spillway and lock, located where the Caloosahatchee River meets the estuary, had the dominant impact on estuarine nutrient loading during summer and winter accounting for 90% and 97% respectively of the total phosphorus mean daily mass loads. The S79 spillway and lock was also found to be the most dominant impact on total nitrogen mean daily mass loads within the Caloosahatchee estuary during the wet summer (90%) and dry winter (92%) months. This study found that phosphorus and nitrogen loading within the Caloosahatchee estuary is significantly impacted by the water which travels from Lake Okeechobee down the Caloosahatchee River. These data indicate that the water which originates in Lake Okeechobee is contributing to nutrient loading within the Caloosahatchee Estuary and Cape Coral estuarine canal system. Lake Okeechobee discharge may have also contributed to the greater seasonal variation in total phosphorus concentrations found in this study in the Cape Coral estuarine canal sampling locations. However, this finding may not necessarily apply to stormwater treatment ponds farther inland. De la Vaga and Ryan (2016) tested nine stormwater treatment ponds in the years prior to and post the enactment of a nutrient ordinance in nearby Fort Myers, Florida found a decline in both total phosphorus and chlorophyll-a concentrations during the wet months. Because Fort Myers's ordinance reduced phosphorus concentrations in the stormwater treatment ponds (disconnected from upstream freshwater inputs from Lake Okeechobee) it is possible that differing hydrology can influence the efficacy of nutrient control ordinances.



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community Kerstin Motsch, 2018.

Figure 13: The six stormwater treatment areas (STA) in operation south of Lake Okeechobee and their relation to Fort Lauderdale.

Chlorophyll-a Trends: Post-Ordinance (2011-2013)

Chlorophyll-a is often selected as an indicator for water quality as its presence and abundance can be directly attributed to algal biomass within fresh and estuarine systems (Nixon 1995; Bricker et al., 2008; Roach et al., 2008; Boyer et al., 2009; Michalak et al., 2013). High chlorophyll-a concentrations indicate eutrophic conditions characterized by algal blooms (Bricker et al., 2008; Boyer et al., 2009). Florida has established water quality standards for nutrients that prevent nutrient concentrations from causing an imbalance in natural populations of aquatic flora or fauna (FAC, rule 62-302.530(47)(b)). The Impaired Waters Rule (EPA, 2008), established by the Florida Department of Environmental Protection, has quantitative thresholds that indicate impairment. Those criteria are used to identify water bodies that fail to meet water quality standards. In the case of average chlorophyll-a, estuarine waters with concentrations above 11ug/l are considered to be impaired (EPA, n.d.). In this study, the data indicated eleven points in Fort Lauderdale and two in Cape Coral as impaired (Fig.7). In Florida, chlorophyll-a concentrations exceeding 40ug/l are considered to be an algal bloom, in this study of the two observations considered above the impaired threshold, only one bloom was documented in the Cape Coral data (Fig.7 A&B). This study found that Fort Lauderdale had 58% higher average chlorophyll-a concentrations than Cape Coral. The elevated chlorophyll-a in Fort Lauderdale could result in lower diversity, fish and shellfish die offs and displaced sea grass habitats in aquatic systems which effect the state economically and ecologically. Consider the effects of phytoplankton on water clarity in Lemon Bay, within the Charlotte Harbor estuary. Tomasko et al., (2001) found that water clarity was inversely related to phytoplankton abundance and nitrogen loads. With mean chlorophyll-a levels ranging from 3.66 – 16.24 μg/l, phytoplankton biomass was calculated to contribute to an average of 29% of light attenuation within the water column, influencing the depth distribution of sea grass beds (Tomasko et al., 2001). The deleterious effect between phytoplankton and seagrass is of concern as seagrass habitats support coastal food chains and serve as nurseries for fish and shellfish of economic importance, and stabilize shallow water sediments (Orth et al., 2006).

The proliferation and success of algae is dependent on a variety of factors, algae are a diverse group of photosynthetic organisms whose biomass has been found to correlate with seasonal temperature changes and nutrient availability in both fresh and estuarine systems (Vymazal et al., 1995; Valiela et al., 1997; Human et al., 2018). Further examination of the post-ordinance data indicated a significant positive correlation between total nitrogen concentrations and chlorophyll-a in Fort Lauderdale. There also existed a significant positive relationship between total phosphorus concentrations and chlorophyll-a in Fort Lauderdale. The pattern observed in this study could indicate nutrient co-limitation within the Fort Lauderdale canal system. For the various species in phytoplankton communities to be successful their cellular growth rate must exceed or equal losses to dilution, sedimentation, death, and grazing. Abundance can only increase by lowering one of the loss terms or increasing cellular growth rate and any single species can be limited by its loss terms, growth rate or both (Reynolds, 1984). Nutrient inputs to aquatic ecosystems influence phytoplankton cellular growth rate (Vymazal et al., 1995; Valiela et al., 1997; Human et al., 2018).

Typically, when modeling nutrient limited growth and relating growth rates to internal nutrient concentrations, the addition of non-limiting nutrients within a system should have no effect on the internal concentration of limiting nutrients. Conversely the addition of limiting nutrients should decrease the internal concentrations of other nutrients as the addition of limiting nutrients increases primary productivity (Elser et al., 2007). Total nitrogen and total phosphorus co-limitation occurs when the addition of either nutrient decreases the concentration of the other, results in no change or even an increase of nitrogen in response to phosphorus additions. This community level co-limitation can occur when different organisms within the phytoplankton community are limited by different nutrients, in marine phytoplankton assemblage's growth of nitrogen fixing species (e.g. cyanobacteria) can be enhanced by phosphorus addition resulting in an increase in both nitrogen and phosphorus within the aquatic system (Karl et al., 1997; Wu et al., 2000; Arrigo, 2005; Elser et al., 2007; Bracken et al., 2015). Furthermore, larger growth responses in phytoplankton can occur when nitrogen and phosphorus are added together, indicating that although instantaneous growth may be limited by a single nutrient total algal biomass production can be limited by the availability of both nitrogen and phosphorus (Elser et al., 1990). This co-limitation hypothesis was supported by the significant positive relationship found during the post-ordinance calendar years between total nitrogen and total phosphorus in the Fort Lauderdale estuarine canal sampling sites and could indicate an increase in nitrogen fixing species within Fort Lauderdale's estuarine canal sampling locations.

The correlation between chlorophyll-a and total nitrogen, observed in Cape Coral was not significant which may indicate other water quality factors influence algal growth within that canal system. The lack of relationship observed between total nitrogen and chlorophyll-a in Cape Coral was unexpected as nitrogen often limits nutrient primary productivity in estuarine and marine ecosystems (Boards et al., 2000; Howarth et al., 2006; Bruesewitz et al., 2013). Elevated nitrogen inputs to marine ecosystems would be expected to yield higher primary productivity and enhanced chlorophyll-a, thus a positive association would be expected. However, algal growth can be affected by factors such as turbidity, light, temperature, mixing and salinity (Alpine et al., 1992; Richardson et al., 1995; Colern 1999). Light availability plays an integral role in controlling the growth and proliferation of algae (Cloern, 1987; Cloern 1999). The South Florida Water Management District has reported declines in water clarity and darker color associated with river basin discharges into the Caloosahatchee Estuary. Increased turbidity and color, which limits light transmission through the water column, would limit algal growth. Freshwater inputs to the Caloosahatchee Estuary and Charlotte Harbor add both color and nutrients causing vertical color shading within the water column. This highly colored fresh water is less dense than the sea water and remains above the saltier sea water. This dark freshwater restricts light from penetrating the water column and can limit primary productivity (Wetland Solutions Inc., 2005). McPherson et al. (1990) found that although the Caloosahatchee River introduced nutrient rich freshwater to the Charlotte Harbor Estuary the highly colored water restricted light penetration and phytoplankton productivity. Maximum productivity only occurred where the color associated with freshwater inflow had been diluted by seawater so that light and nutrients were both available. These findings indicated that light availability may control phytoplankton growth more than nutrients in parts of these estuaries implying that the water entering the Cape Coral area is darker than that which is entering Fort Lauderdale, however more data are needed to evaluate the role of color in controlling algal proliferation in both Cape Coral and Fort Lauderdale.

Conclusion

The goal of this study was to determine the efficacy of the fertilizer ordinance, enacted in 2010 in Cape Coral, FL, at lowering nitrogen concentrations within the estuarine canal system. Cape Coral estuarine canals exhibited a reduction in total nitrogen concentrations of 24% in the three years post ordinance. However, data also indicated that Fort Lauderdale, a site without a

2010 nutrient ordinance, showed total nitrogen concentrations declined similarly (33%) over the same period of time. This observed pattern in Cape Coral could indicate an effective implementation and desired result of the local fertilizer ordinance. However, it begs the question whether state regulations and the pre-emptive actions taken by Fort Lauderdale commercial fertilizer applicators, in order to prepare for the regulations, have contributed to water quality improvements throughout the city of Fort Lauderdale. The decline in total nitrogen concentrations in both municipalities may suggest that local and state regulations have improved water quality in the estuarine canal sampling stations in both Fort Lauderdale and Cape Coral.

Both municipalities are diverse systems, hydrologically the Cape Coral canal system is influenced by fresh and saltwater inputs whose unique source waters and nutrient concentrations have impacted Cape Coral’s water chemistry. Seasonal influences, precipitation rates and land use practices can be identified as factors which influence Cape Coral’s dynamic ecosystem. Understanding and controlling for the influences of these larger scale nutrient loading sources in both municipalities is important in mitigating their effects on local scales. Creating policies in conjunction with local ordinances which account for and control the impacts of these outside nutrient loading sources would be far more effective at improving local and state water quality than an ordinance focused on reducing local fertilizer use would be alone.

Controlling for the nutrient loading from these large-scale source waters has the potential of reducing nutrient loading and improving water quality throughout the watershed as Lake Okeechobee inputs influence both Cape Coral and Fort Lauderdale. Due to the fact that each of the municipalities in the study exhibited differences in nutrient limitation and algal abundance it remains clear that a single regulation, city wide or otherwise, will not improve water quality in both municipalities equally. Understanding the pattern of co-limitation throughout the Fort

Lauderdale canal sampling sites would suggest that estuarine water quality at that location would not be improved by limiting nitrogen inputs from fertilizer application alone. However, implementing site specific management practices could create a better depiction of water quality and facilitate more effective management efforts.

In order to create a better depiction of nutrient loading and cycling within the canal system future studies would need to employ consistent monitoring throughout the canal system as well as the surrounding estuary. Examining the interaction between fresh and saltwater canals and focusing on how other parameters such as flow, urban runoff from the city and water clarity influence water quality would allow water resource managers to track the source from which nutrients originate and direction in which they travel. This information would provide them with a more comprehensive understanding of the factors which influence nutrient loading within the canal system and a clearer idea of where resources should be allocated as they move toward improving the city's water quality. Eutrophication is a common problem whose solutions require information identifying the sources of nutrient loading. Characterizing nutrient loading is pivotal to developing regulatory tools to solve these challenging environmental issues. More scientific studies such as this are needed to evaluate regulatory options and their effectiveness and are crucial in understanding how anthropogenic influences impact ecologically and economically vital resources on local and global scales.

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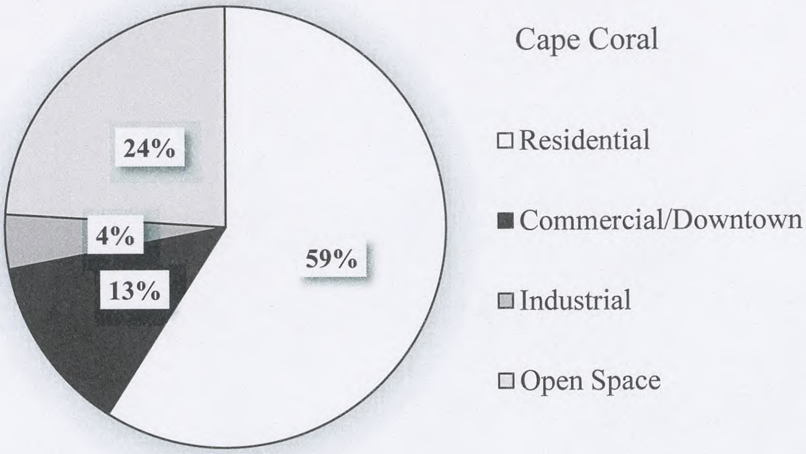
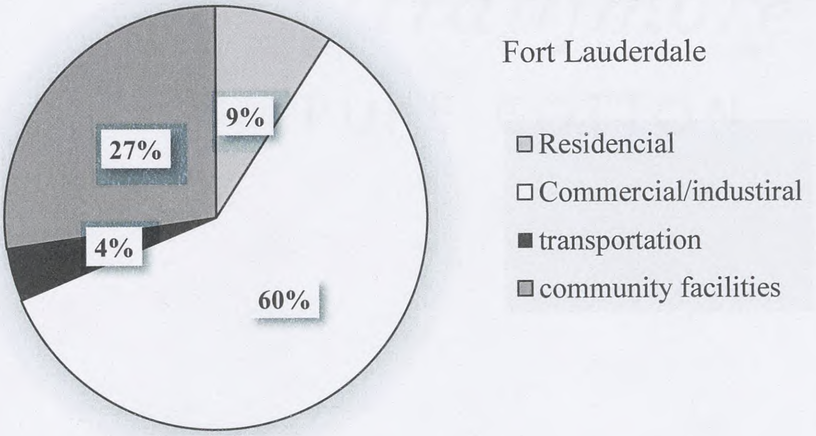
Appendix A

Total land use area percentages in Cape Coral and Fort Lauderdale





Appendix B

Total sampling events occurring across Cape Coral and Fort Lauderdale sampling stations for total phosphorus, total nitrogen and chlorophyll-a.

Station Name & Season	2007	2008	2009	2011	2012	2013
#1 Hillsboro Canal US 1: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#5 Pompano Canal US1: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#11 Middle River NW 21ST Ave: Fort Lauderdale						
Total Phosphorus: summer	4	4	4	4	4	2
Total Phosphorus: winter	2	2	2	4	4	2
#16 North Fork Broward Blvd: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#19 New River River Reach: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#25 Hollywood Canal Stirling: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#33 ICW South of Hillsboro Brg: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#64 N. Fork at Sistrunk : Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
#40 ICW Sheridan St: Fort Lauderdale						
Total Phosphorus: summer	4	4	4	4	4	2

Total Phosphorus: winter	2	2	2	4	4	2
#37 ICW Sunrise Blvd.: Fort Lauderdale						
Total Phosphorus: summer	2	2	2	2	2	2
Total Phosphorus: winter	1	1	1	2	2	2
Lido: Cape Coral						
Total Phosphorus: summer	6	6	5	6	7	6
Total Phosphorus: winter	6	6	6	5	6	7
Gloriana: Cape Coral						
Total Phosphorus: summer	5	5	4	5	3	3
Total Phosphorus: winter	6	6	5	5	6	7
San Carlos: Cape Coral						
Total Phosphorus: summer	3	4	3	4	4	3
Total Phosphorus: winter	5	5	6	5	5	7
Del Monte: Cape Coral						
Total Phosphorus: summer	4	4	6	5	7	5
Total Phosphorus: winter	3	5	6	5	5	4
Fishingrod: Cape Coral						
Total Phosphorus: summer	6	6	5	6	5	6
Total Phosphorus: winter	4	6	5	6	5	4
Volunteer: Cape Coral						
Total Phosphorus: summer	6	6	5	5	4	1
Total Phosphorus: winter	5	6	4	6	4	5
Windsor: Cape Coral						
Total Phosphorus: summer	6	6	6	6	6	5
Total Phosphorus: winter	5	6	6	6	5	6
Ramsey: Cape Coral						
Total Phosphorus: summer	5	5	6	3	6	6
Total Phosphorus: winter	5	5	4	5	4	6
Meredith and Bronte: Cape Coral						
Total Phosphorus: summer	6	5	6	5	6	5
Total Phosphorus: winter	6	6	5	6	6	7
Water Quality Mon. Old Burnt Store Rd South: Cape Coral						
Total Phosphorus: summer	7	7	6	6	6	6
Total Phosphorus: winter	6	6	6	6	6	7
Station Name & Season	**2007**	**2008**	**2009**	**2011**	**2012**	**2013**

#1 Hillsboro Canal US 1: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#5 Pompano Canal US1: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#11 Middle River NW 21ST Ave: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#16 North Fork Broward Blvd: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#19 NEW River River Reach: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#25 Hollywood Canal Stirling: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#33 ICW South OF Hillsboro Brg: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#64 N. Fork At Sistrunk: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2
#40 ICW Sheridan St: Fort Lauderdale						
Total Nitrogen: summer	4	4	4	4	4	2
Total Nitrogen: winter	2	2	4	4	4	2
#37 ICW Sunrise Blvd: Fort Lauderdale						
Total Nitrogen: summer	2	2	2	2	2	2
Total Nitrogen: winter	1	1	2	2	2	2

Lido: Cape Coral						
Total Nitrogen: summer	6	6	5	6	7	6
Total Nitrogen: winter	6	6	6	5	6	7
Gloriana: Cape Coral						
Total Nitrogen: summer	5	5	4	5	3	3
Total Nitrogen: winter	6	6	5	5	6	7
San Carlos: Cape Coral						
Total Nitrogen: summer	3	5	3	4	4	3
Total Nitrogen: winter	5	5	6	5	5	7
Del Monte: Cape Coral						
Total Nitrogen: summer	4	4	6	5	7	5
Total Nitrogen: winter	3	5	6	5	5	4
Fishingrod: Cape Coral						
Total Nitrogen: summer	6	6	5	6	5	6
Total Nitrogen: winter	4	6	5	6	5	4
Volunteer: Cape Coral						
Total Nitrogen: summer	6	6	5	5	4	2
Total Nitrogen: winter	5	6	4	6	4	4
Windsor: Cape Coral						
Total Nitrogen: summer	6	6	6	6	7	5
Total Nitrogen: winter	5	6	6	6	5	7
Ramsey: Cape Coral						
Total Nitrogen: summer	5	5	6	3	6	6
Total Nitrogen: winter	5	5	4	5	4	6
Meredith and Bronte: Cape Coral						
Total Nitrogen: summer	5	6	6	5	6	5
Total Nitrogen: winter	6	6	5	6	6	7
Water Quality Mon. Old Burnt Store Rd South: Cape Coral						
Total Nitrogen: summer	7	7	6	6	6	6
Total Nitrogen: winter	6	6	6	6	6	7

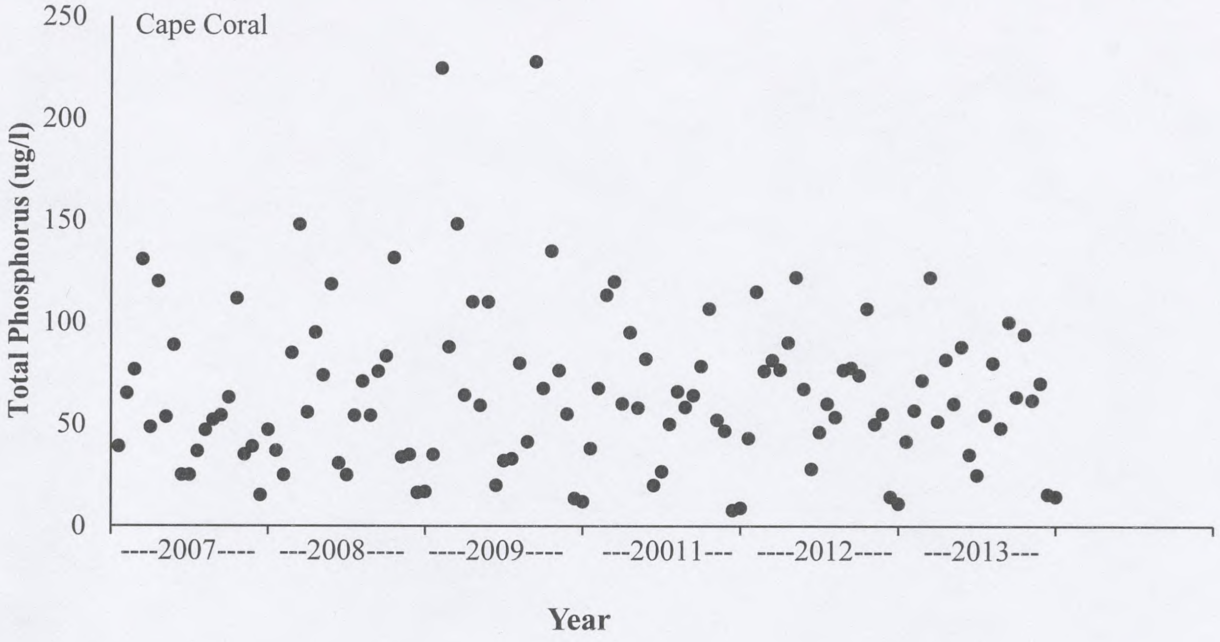
Station Name & Season	2011	2012	2013
#1 Hillsboro Canal US 1: Fort Lauderdale			
summer	2	2	2
winter	2	2	2
#5 Pompano Canal US1: Fort Lauderdale			

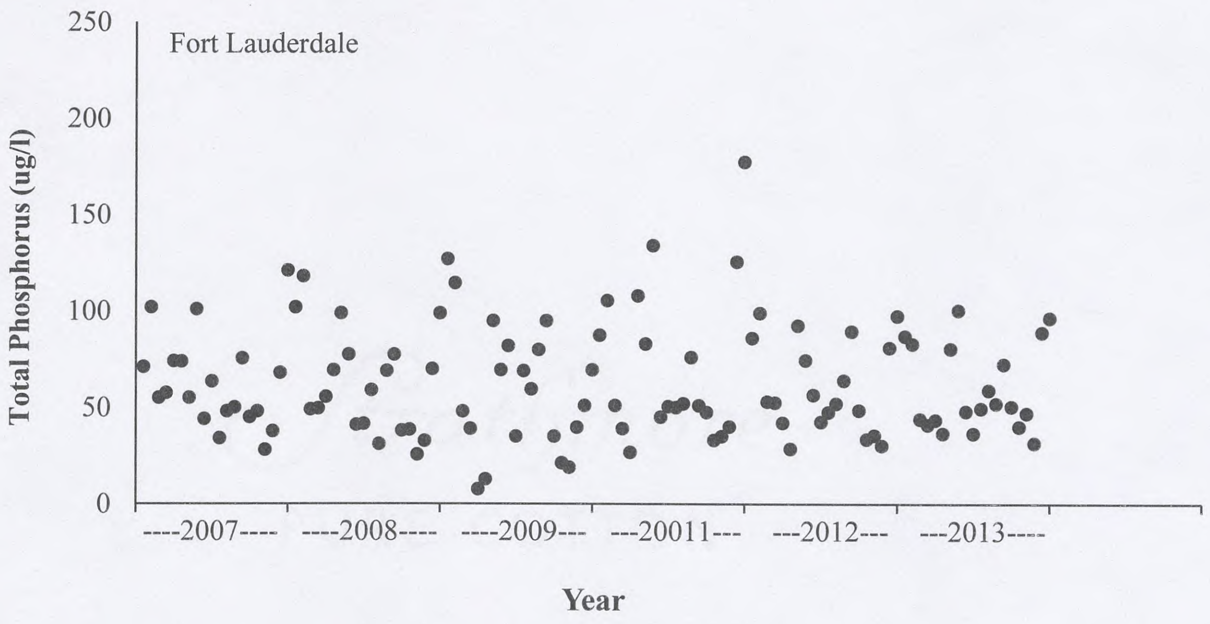
summer	2	2	2
winter	2	2	2
#11 Middle River NW 21ST AVE: Fort Lauderdale			
summer	4	4	2
winter	4	4	2
#16 North Fork Broward BLVD: Fort Lauderdale			
summer	2	2	2
winter	2	2	2
#19 New River River Reach: Fort Lauderdale			
summer	2	2	2
winter	2	2	
#25 Hollywood Canal Stirling: Fort Lauderdale			
summer	2	2	2
winter	2		2
#33 ICW South Of Hillsboro Brg: Fort Lauderdale			
summer	2		
winter	2		
#64 N. Fork At Sistrunk: Fort Lauderdale			
summer	2		2
winter	2		2
#37 ICW Sunrise Blvd: Fort Lauderdale			
summer		2	2
winter	2	2	
Lido: Cape Coral			
summer	1		1
winter	1	1	
Gloriana: Cape Coral			
summer	1		
winter	1		
San Carlos: Cape Coral			
summer	4	4	7
winter	4	3	3
Del Monte: Cape Coral			
summer	5	6	5

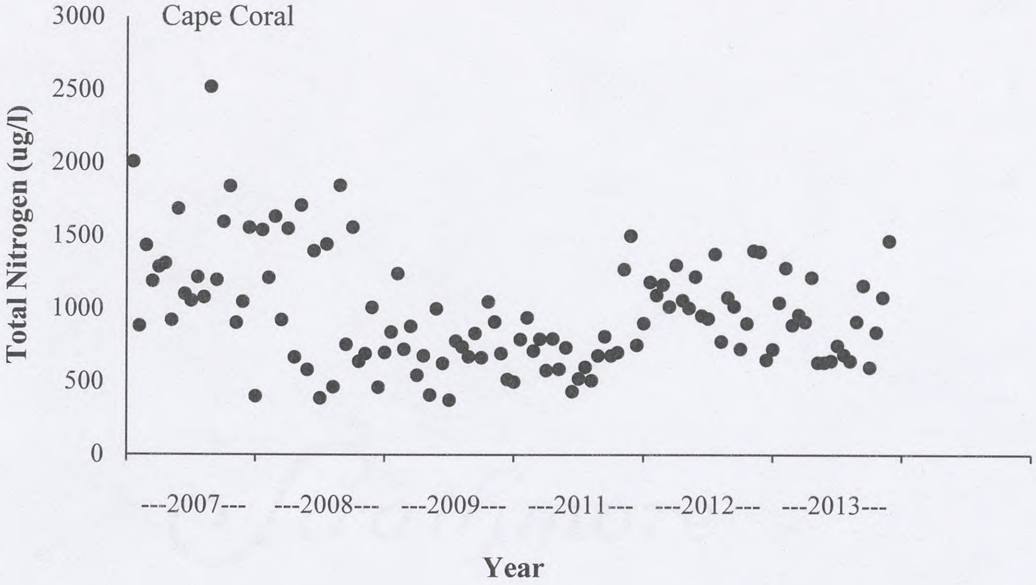
winter	5	4	4
Fishingrod: Cape Coral			
summer	1	1	1
winter	1	1	
Volunteer: Cape Coral			
summer	5	3	1
winter	5	3	5
Windsor: Cape Coral			
summer	1		2
winter	1		1
Ramsey: Cape Coral			
summer	1	3	
winter		1	1
Water Quality Mon. Old Burnt Store Rd South: Cape Coral			
summer	6	6	7
winter	6	6	6

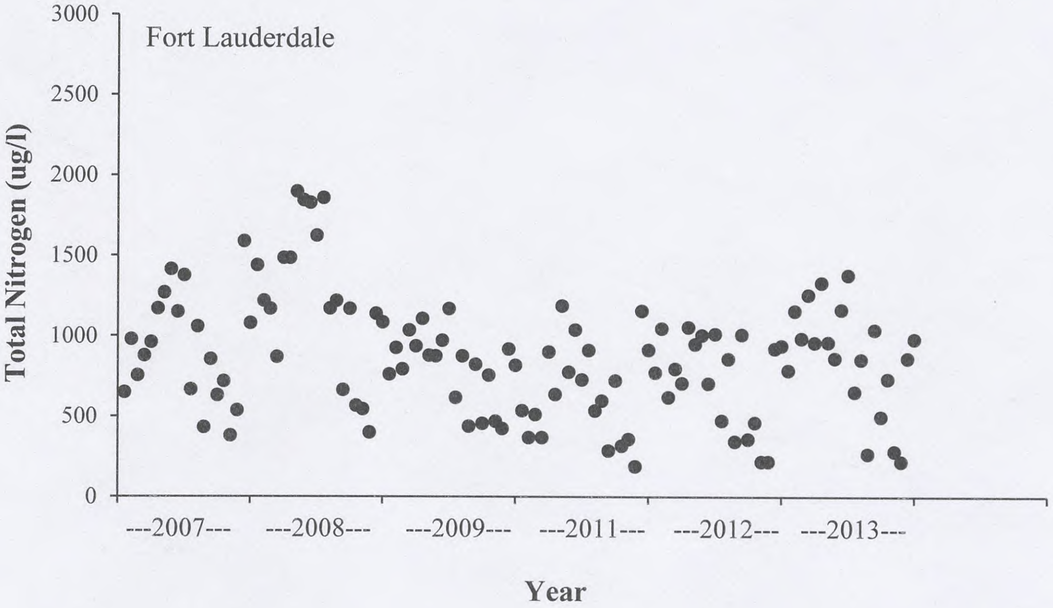
Appendix C:

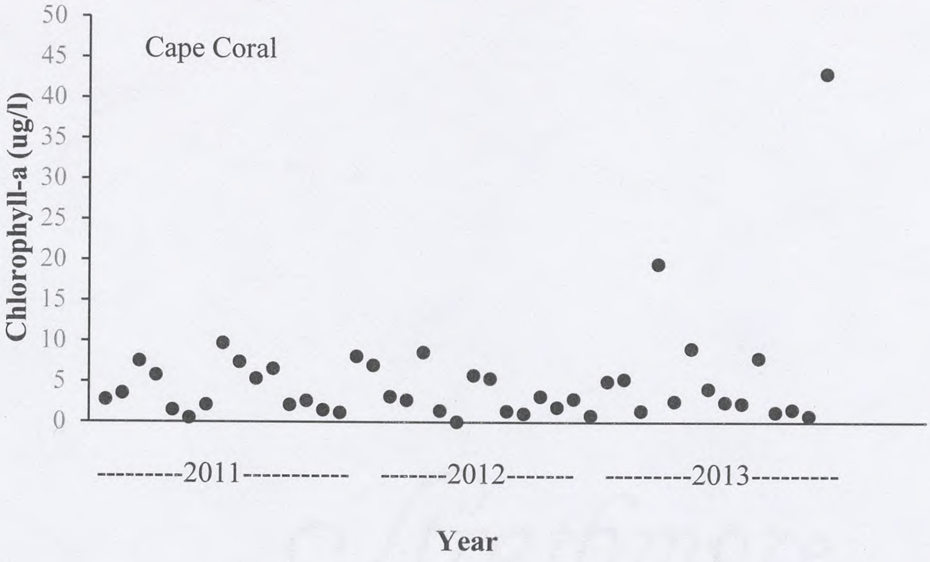
Total phosphorus, total nitrogen and chlorophyll-a seasonal mean data across pre (2007-2009) and post (2011-2013) calendar years in both Cape Coral and Fort Lauderdale.

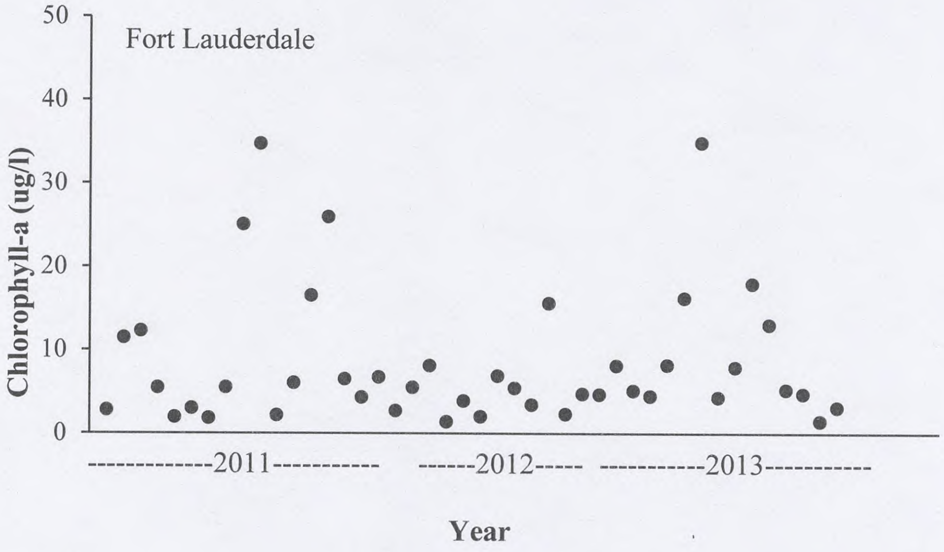





Cape Coral
Total Nitrogen (ug/l)
3000
2500
2000
1500
1000
500
0
---2007---
---2008---
---2009---
---2011---
---2012---
---2013---
Year


Fort Lauderdale
Total Nitrogen (ug/l)
3000
2500
2000
1500
1000
500
0
---2007---
---2008---
---2009---
---2011---
---2012---
---2013---
Year


Cape Coral
Chlorophyll-a (ug/l)
50
45
40
35
30
25
20
15
10
5
0
---------2011-----------
-------2012-------
---------2013---------
Year


Fort Lauderdale
Chlorophyll-a (ug/l)
50
40
30
20
10
0
-------------2011-----------
------2012-----
-----------2013-----------
Year

Appendix D: Cape Coral and Fort Lauderdale, historical ranges of canal sampling station water quality parameters.

Location and Station Name	Salinity (ppt)	pH	Temp (C)	Secchi depth (ft)	Conductivity (umhos/cm @25C)	Dissolved Oxygen
Cape Coral						
San Carlos	0.5 - 25	7.7-8.6	13-31	2.33 - 5.83		
Meredith and Bronte	1 - 19			1.08 - 4.58		
Lido				1.33 - 6.83		
Del Monte	0.5 - 30	7.6-8.8	12-31	2.08 - 6		
Fishingrod	4 - 30		18	2.42 - 8.5		
Gloriana	23 - 24			3.42 - 8.58		
Volunteer	5 - 35	7.6-8.6	17-32	3 - 9.08		
Windsor	15			2.33 - 5.08		
Ramsey	6 - 12			2.17 - 10.38		
Old Burnt Store Rd. South	5 – 30			2 – 5		
Fort Lauderdale						
1-Hillsboro Canal at US 1	1-33				997 – 47800	4.080 – 6.98
5- Pompano Canal Confluence at US 1	1-31				3000 - 47900	3.17 – 9.80
11- Middle River at NW 21st ave.	1-18				481 - 29300	2.99 – 9.61
16- North Fork New River at Broward Blvd.	1-22				475 - 40600	2.90 – 11.1
19 -South Fork New River Canal at River Reach Condo	1-24				1250 - 5100	3.12 – 7.91
25- Hollywood Canal at Stirling Road Bridge	1-30				7500 - 39200	2.88 – 7.48
33- ICW South of Hillsboro Blvd. Bridge	2-31				4580 - 51200	4.08 – 7.31
37- ICW 100 North of Sunrise Blvd	8-31				14400 - 51600	4.13 – 9.32
40- ICW 100 North of Sheridan St.	28-35				45617 - 53500	4.35 – 7.21
64- North Fork New River at Sistrunk Blvd.	1-16				454 - 9500	2.23 – 7.61

**Missing data has been requested from both Cape Coral and Fort Lauderdale monitoring agencies and has not yet been made available at the time of this draft

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A thesis submitted to the College of Letters and Sciences in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

DEPARTMENT OF EARTH AND SPACE SCIENCES

By

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2018

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9-5-2018
Date