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Sources and concentrations of nutrients in surface runoff from waterfront homes with different landscape practices

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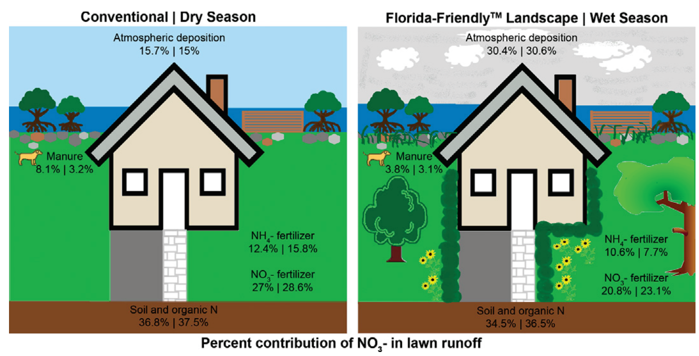
HIGHLIGHTS

- The study examined source and concentration of nutrients in residential lawn runoff.
- Fertilizer control methods did not reduce the concentration of nutrients in runoff.
- 53–65% of NO_3^- in runoff is from soil nutrient pools and atmospheric deposition.
- Nutrient management at the community level needs to address multiple sources.

GRAPHICAL ABSTRACT



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ABSTRACT

Development along Florida's coastal waterways has led to significant degradation in water quality over time. Numerous sources have contributed to increased nutrient loads in surface waters. Nitrogen (N) and phosphorus (P) pollution from urban fertilizer use has been addressed at the state, county, and municipality level yet the success of these efforts is rarely evaluated. This study aimed to validate these efforts by assessing the source and concentration of nutrients from surface water associated with waterfront homes with or without Florida Friendly Landscaping™, a nonstructural best management practice. The objectives were: to compare nutrient concentrations in runoff from differing landscape designs; compare the NO_3^- isotopic signature to that of known N sources; and evaluate the impact of a fertilizer ordinance blackout that is in effect during the wet season. Results from the study indicate no statistical reduction in the nutrient concentration of lawn runoff from either landscape design or the implementation of a fertilizer blackout ordinance. Results show that the sources of N in home landscapes are highly variable and cannot be solely attributed to fertilizer sources and highlight the influence of atmospheric depositions and soil nutrient pools which contribute 53–65% of the nitrate in lawn runoff. Nutrient management strategies need to address multiple sources of urban nutrients and mitigation efforts will not be immediate.

1. Introduction

Lawns are a dominant landscape in many urban neighborhoods. In the United States, the monocultured lawn first took root in the nineteenth century and became synonymous with post World War II suburbia (Fraser et al., 2013; Whitney, 2010). Today, lawn aesthetics have become part of American social culture, and the manicured lawn has

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become a symbol for civil society and neighborhood conformity (Feagan and Ripmeester, 1999; Robbins and Birkenholtz, 2003). These expectations are reinforced through formal and informal neighborhood institutions including homeowners associations and neighborhood associations, both of which are becoming more prevalent in the United States and elsewhere (Chen and Webster, 2005; Clarke and Freedman, 2019). In addition to the sometime substantial financial and social investments required to cultivate and maintain the idea of suburban perfection, so too can be the potential environmental costs associated with these heavily manicured yards when not managed properly (Conley et al., 2009; Horner et al., 1994; Wayand, 1993).

It is well established that human behavior plays a key role in landscape management and function. Chemical use for management of turf dominant lawns has been shown to be positively associated with higher income, housing values, and education (Robbins and Birkenholtz, 2003). Paradoxically, many of these same applicators are aware of the potential negative environmental impacts and opt for application anyways, prioritizing neighborhood norms and expectation over environmental values (Robbins and Sharp, 2006).

Non-point sources of nutrient pollution, mainly nitrogen (N) and phosphorus (P), are being recognized nationally and globally as significant contributors to environmental contamination because of their role in supporting harmful algal blooms (Conley et al., 2009). In urban environments, numerous sources of nutrients have contributed to increased nutrient loads in surface waters including sewage, stormwater, atmospheric deposition, organic materials (grass clippings, leaf litter, yard waste, etc.), pet waste, and urban fertilizer (Kaushal et al., 2011; Jani et al., 2020; Lusk et al., 2020). Population growth, increasing water demands, and environmental degradation of urban waterways has shifted attention towards urban landscapes and the residential yard. Excess nutrients can be lost from urban landscapes through runoff or leaching, and lead to water body impairment, eutrophication, algae blooms, oxygen depletion, and possible fish and aquatic species die-off (Howarth and Paerl, 2008; Conley et al., 2009).

Whereas "weed laws" were historically implemented in nearly every municipality in the United States to ensure property was well-maintained with aesthetically pleasing lawns (Byrne, 2005), today, many municipal, county and state governments have passed legislation to manage and sometimes prohibit fertilizer application in an attempt to balance aesthetics with chemical inputs that may lead to environmental degradation (Hartman, 2008; Miller, 2012; Ryan et al., 2019). To date, at least twelve states have adopted laws restricting the sale or use of P fertilizer for residential lawns. Florida is unique in that restrictions are limited to certain counties.

There is limited information regarding the efficacy of these ordinances and the consequent impacts on downstream water quality (Persaud et al., 2016), although a study in Ann Arbor, MI showed an 11 to 23% reduction of TP post-ordinance (Lehman et al., 2011). There is also limited understanding as to the contribution and source of nutrients, and the relative contribution of fertilizer among other possible nutrient sources associated with residential landscapes. Numerous studies evaluate the drainage volumes and nutrient losses from a variety of turf and mixed-assemblage landscape designs (Erickson et al., 2001; Erickson et al., 2008; Pannkuk et al., 2011; Qin et al., 2013; Lusk et al., 2018). These studies, however, yield mixed conclusions depending on species composition, assemblage, and establishment (Qin et al., 2013) and few studies exist that examine nutrient runoff and leaching outside of experimentally manipulated plots (Cheng et al., 2014).

In addition to fertilizer ordinances, various other structural and non-structural Best Management Practices (BMPs) have been developed to minimize the environmental impacts of the urban landscape (Yang and Lusk, 2018). One of these in Florida is the Florida-Friendly Landscaping™ (FFL) Program, a voluntary non-structural BMP cooperatively designed and implemented through the University of Florida Institute of Food and Agricultural Sciences (IFAS) and the Florida Department of Environmental Protection. This residential landscape BMP program promotes lawn management behavior associated with nine principles that address water conservation, water quality, chemical and fertilizer management, and wildlife protection. (https://ffl.ifas.ufl.edu/). The FFL Program is delivered locally through the Cooperative Extension Service by county extension agents and Master Gardener volunteers. Program participants learn through a variety of educational activities (e.g., workshops, field tours, seminars, classes). In some counties, an agent or Master Gardener conducts an on-site assessment of a homeowner's landscape. The assessment assigns scores to the nine principles. If the landscape scores meet expectations, the landscape is designated as a Florida-Friendly Landscape and the homeowner receives an FFL sign to post in the lawn. The FFL Program is the cornerstone program of the Extension Master Gardener program in Florida, however similar programs are exist in all 50 states, the District of Columbia, Canada and South Korea (https://mastergardener.extension.org/).

While recent efforts have reported water quantity savings associated with the successful implementation of the FFL practices, the effect of these practices on nutrient reductions and the subsequent impact on water quality is limited (Trenholm et al., 2002; Johns et al., 2007; Boyer et al., 2014). This research sought to address three key objectives regarding nutrient runoff and urban landscapes: 1) compare nutrient concentrations in runoff from two lawn types: those with and without FFL features; 2) utilize stable isotopes of nitrate to infer sources of N to runoff from the different lawn types; and 3) evaluate the impact of a summer fertilizer blackout ordinance on the concentrations and sources of nutrients in runoff from the different lawn types.

2. Methods

2.1. Site description

The research site is within the watershed of the Indian River Lagoon (IRL) system, a shallow-water estuary located along the east coast of Florida. It includes the Mosquito Lagoon, Banana River Lagoon, and Indian River and spans 156 miles from Ponce de Leon Inlet in Volusia County to the southern border of Martin County (Fig. 1). The lagoon is within a subtropical climate with average annual rainfall of 140 cm, 66% of which occurs during a summer rainy season from June to September. During the study period (May to August 2018), the site received 52.8 cm of rainfall. Soils in the area are predominantly sandy, well-drained spodosols.

Seventy-one percent of the lagoon's area, including the southern portion of the Mosquito Lagoon, Banana River Lagoon, and North IRL, is within Brevard County. The entire IRL region, including Brevard County is undergoing rapid population growth and increasing coastal development and urbanization (IRLNEP, 2008). Brevard County has experienced a 14.1% increase in population between 2000 and 2010 (U.S. Census Bureau, 2010). Much of the land along the northern portions of the Banana and Indian Rivers is federally owned, restricting development to existing confined residential areas. Development along the Indian River Lagoon has resulted in significant degradation in water quality over time (Graves et al., 2004; IRLNEP, 2008; Qian et al., 2007). In 2011, an algal "superbloom" caused a massive seagrass mortality event indicating that the lagoon has lost its buffering capacity. In 2016, a prolonged algal bloom induced a hypoxic event that resulted in the lagoon's largest fish kill in recorded history.

The state of Florida has identified the entire IRL system as impaired for nutrients, and Basin Management Action Plans (BMAPs) have been adopted for the various watersheds in the greater IRL region. Nearly all counties and municipalities adjacent to the Indian River Lagoon have passed fertilizer ordinances to help meet the nitrogen and phosphorus reduction targets. Between 2013 and 2014, Brevard County and its municipalities passed a fertilizer blackout ordinance that prohibits N and P fertilizer application to urban landscapes (non-farm) between June 1st and September 30th each year (https://sfyl.ifas.ufl.edu/

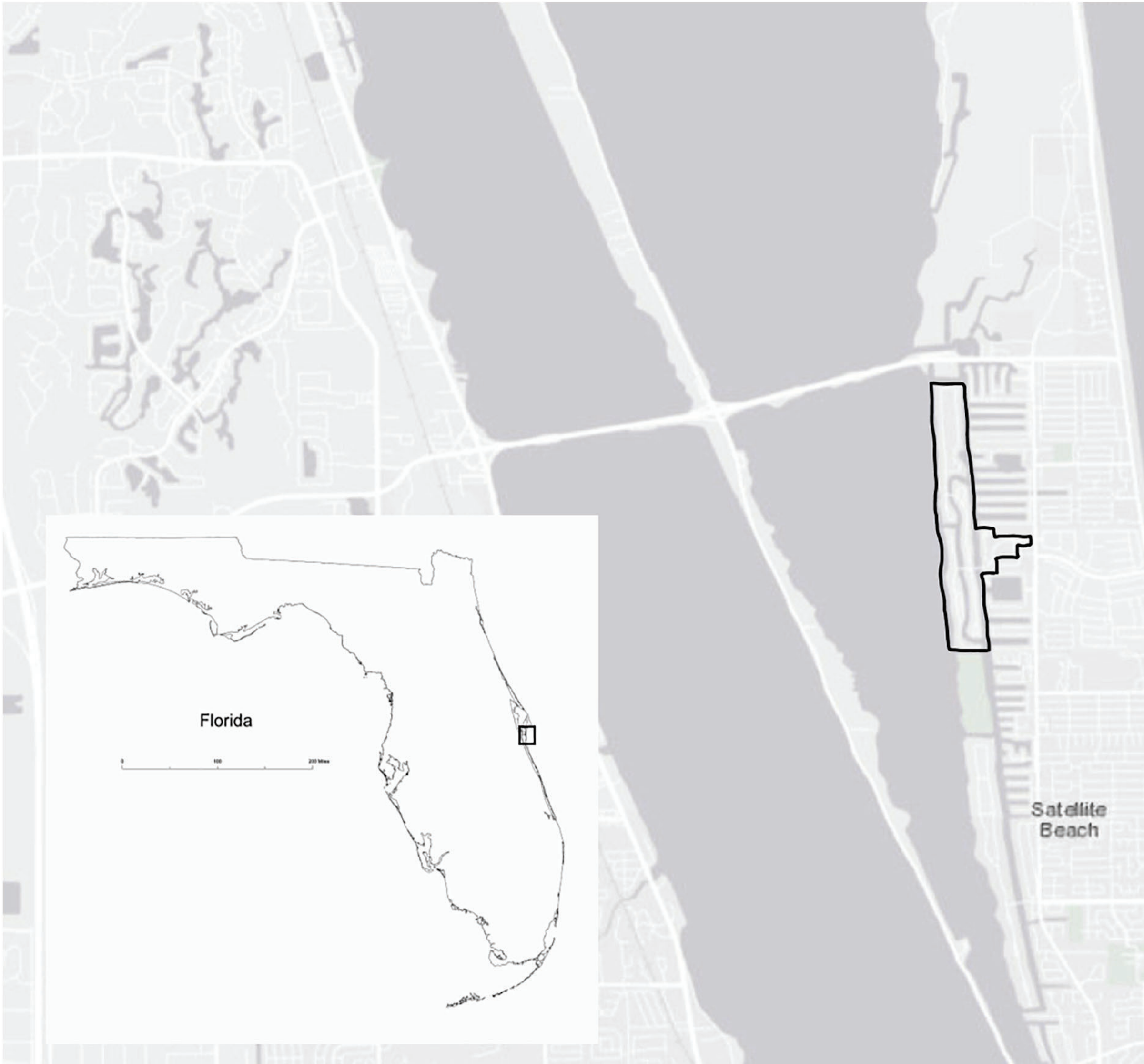

Fig. 1. The research study site. Tortoise Island subdivision, Satellite Beach, Florida.

brevard/lawn-and-garden/fertilizer-ordinances/). The premise behind the fertilizer blackout period is that wet season (June to September) rains mobilize urban fertilizer nutrients via runoff and leaching, leading to transport to nearby waterbodies.

2.2. Classification of lawn treatments

This study was conducted May through August 2018, within the medium-density subdivision of Tortoise Island in Satellite Beach, FL (28°11′48.7″N, 80°36′26.6″W). Tortoise Island is a homeowner association (HOA) community of approximately 340 single-family homes located on navigable canal waterfront lots along the Banana River. Homes were constructed in the mid-1980s to early 1990s and are on central sewer line. Ten of these homes were selected for the study via active recruitment to the community residents. Participation in the study required access to the yard by members of the project team and volunteers and installation of a water collection device throughout the duration of the study. Twelve homeowners agreed to participate in the project.

Homeowners were asked survey questions about the practices employed in the landscape and each of the twelve landscapes was evaluated using a modified version of the FFL Home Landscape Recognition checklist (Table S.1). The checklist includes practices related to the nine FFL Principles: (1) Right Plant, Right Place, (2) Water Efficiently, (3) Fertilize Appropriately, (4) Mulch, (5) Attract Wildlife, (6) Manage Yard Pests Responsibly, (7) Recycle, (8) Reduce Stormwater Runoff, and (9) Protect the Waterfront. The checklist for this study was modified to include only those FFL criteria related to water quality (principles 2–4; 8–9, Table S.1). Points were received for each FFL practice based on answers to the survey and evaluation of the landscape. Based on the modified criteria of the FFL Home Landscape Recognition checklist, homes that received a threshold level of 39 or greater met the necessary number of voluntary non-structural BMPs to be classified as FFL. Landscapes that scored lower than 39 were assigned conventional designation. For the purposes of this project, conventional landscapes are those not managed to minimize their impact on water quality. According to survey scores, six yards met the criteria for FFL and six yards were determined to be conventional. The project team selected the top and bottom five yards to participate in the project as FFL and conventional, respectively. The other two yards served as potential backup yards but were ultimately not needed for the study. Table 1 shows designation of each yard/landscape as either FFL or conventional. The table also highlights whether homeowners owned a pet (i.e. dog or outdoor cat) that would utilize the yard and whether they used a landscape service for lawn maintenance as opposed to doing the work themselves.

Table 1
Landscape types, identification of pets such as dog or outdoor cat in home, and whether a landscape service managed the yard for each landscape in the study.

Landscape #	Landscape type	Pet in home	Landscape service used and what type (if applicable)
1	FFL	Yes	Yes, flowers only
2	FFL	No	Yes, flowers only
3	FFL	No	No
4	FFL	Yes	No
5	FFL	Unknown	Unknown
6	Conventional	Yes	Yes before study, but not during study period
7	Conventional	Yes	Yes
8	Conventional	Yes	No
9	Conventional	Yes	Yes
10	Conventional	Yes	No

2.3. Nutrient pools and supply rates from landscape soils

At the beginning of the project in May 2018 a surface soil sample was collected from each of the ten yards and analyzed for extractable soil nutrient pools. Soil was collected from the top 30 cm, coarse roots were removed by visual inspection, and samples were placed in plastic bags for transport back to the lab. Samples were then air-dried and passed through a 2-mm sieve in preparation for analysis of N and P pools, which was conducted at the University of Florida Analytical Research Laboratories in Gainesville, Florida. Extractable NO_3^--N and NH_4^+-N pools were determined by extraction with 1 M KCl. Organic N was determined via Kjeldahl digestion. The Mehlich-3 solution was used to determine soil extractable P pools.

Additionally, six Plant Root Simulator (PRS) probes were buried in the top 15 cm of each of the ten yards and removed 21 days later for analysis of nutrient supply rates. PRS probes are plastic probes that contain ion exchange membranes. We used both anion probes—which absorb negatively-charged anions such as nitrate—and cation probes, which adsorb positively-charged cations. The probes provided a measure of nutrient supply rate that correlates to the in situ plant available nutrient pools (Qian and Schoenau, 2002). For this study, we used 3 anion probes and 3 cation probes in each lawn and composited them later for single measurements from each lawn. After 21 days of deployment, probes were shipped to Western Ag Innovations, where the probes were eluted for 1 h with a 0.5 N HCl solution. Eluate from the probes was analyzed for NO_3^--N and NH_4^+-N by colorimetry using an automated flow injection analysis system. The eluate was analyzed for P using inductively-coupled plasma spectrometry.

2.4. Runoff and rainfall sample collection

At the beginning of the study, each home had a surface water runoff collection system installed in their landscape. Surface water runoff from the landscape was collected in a 500-ml Nalgene bottle attached to a modified aluminum base vent pipe flashing with adjustable rubber collar, which was placed in a 5-in. wide diameter dug-out hole in the landscape. The lip of the flashing was in contact with the surface of the soil to collect water runoff during precipitation events with 0.64 cm or more rainfall. A plastic cover was anchored into the ground above the collection system. This prevented rainwater from dripping in the system while still allowing runoff to drain into the sample water bottle. Two homes had a rain gauge for collecting rainwater into a separate 500-ml Nalgene bottle.

Homeowners were trained and responsible for attaching a sample water bottle to the systems before a rain event and removal and storage at 4 °C after a rain event until it could be picked up by a project team member (within 48 h). A chain of custody form was developed for residents and project team members to be completed for every surface water sample collected and processed.

On day of collection, each sample water bottle was labeled with yard number, date of rain event, date bottle was taken off the collection system, and time of collection. Bottles were stored in a refrigerator onsite at the home until pickup for processing. Runoff and rainfall water samples were 0.45 μl filtered. One 25-ml scintillation vial of each filtered sample was preserved by adjusting sample pH to 2.0 with sulfuric acid and storing the vials at 4 °C up to 28 days until nutrient analysis. A second 25-ml vial of each filtered sample was preserved by freezing, without acidification, up to 3 months before isotopic characterization analysis.

2.5. Runoff and rainfall nutrient and isotopic characterization analysis

Runoff and rainwater samples were analyzed for forms and concentrations of N and P and for the isotopic characterization of nitrate (NO_3^-). A total of 97 samples were collected for the project—36 dry season (month of May) samples were collected from 6 separate rain events and 61 wet season (June 1st to August 31st) samples were collected from 12 separate rain events.

Acid-preserved and 0.45 μ-filtered samples were analyzed for inorganic nutrient forms of NO_3^-, ammonium (NH_4^+), and orthophosphate (PO_4^+) at the University of Florida IFAS Analytical Research Laboratory using air-segmented continuous autoflow analyzers via EPA methods 353.2, 350.1, and 365.1, respectively.

For isotopic characterization of NO_3^-, the frozen samples were shipped overnight to the University of California Riverside Facility for Isotope Ratio Mass Spectrometry (FIRMS), where the microbial denitrifier method was used to measure δ^{15}N and δ^{18}O of NO_3^-. The facility uses a Delta-V Advantage isotope ratio mass spectrometer operating in continuous-flow mode (https://ccb.ucr.edu/firms.html). The measured stable isotope values (δ^{18}O–NO_3^- and δ^{15}N–NO_3^-) of the samples were compared with literature-reported values of potential NO_3^- sources (Kendall et al., 2007) to infer the NO_3^- sources in stormwater runoff and rainfall after methods described by Jani et al. (2020). The following potential NO_3^- sources were considered: atmospheric deposition, NH_4^+ fertilizer, NO_3^- fertilizer, manure/sewage, and soil and organic N. The Bayesian stable isotope mixing model Stable Isotope Analysis in R (MixSIAR) was used to quantify the contribution of potential NO_3^- sources. In the Bayesian mixing model, measured δ^{18}O–NO_3^- and δ^{15}N–NO_3^- values for each of the runoff and rainfall samples were assigned as "customers" and the mean isotopic values of the NO_3^- sources from the literature were assigned as "sources".

Data for runoff and rainfall nutrient concentrations was analyzed using a two-tailed *t*-test assuming unequal variances in JMP statistical software. Statistical significance was calculated at a value of $p = 0.05$.

3. Results and discussion

3.1. Nutrient pools and supply rates from landscape soils

A baseline analysis of extractable soil nutrients was conducted at the beginning of the study as it was predicted that lawn soils might be one source of nutrients in runoff. Extractable nutrient pools and nutrient supply rates were highly variable among the 10 study lawns, highlighting the small-scale heterogeneity that may characterize many urban landscapes (Table 2). It was assumed that predevelopment soil nutrient pools were similar for all soils in the neighborhood, but it was beyond the scope of this study to determine why soil nutrient pools in lawns were so variable at the time of the study, 20–30 years after home construction. The heterogeneity could be due to differences among homeowners' lawn management practices or due to soil heterogeneity that developed as a result of the home construction process—such as whether or not construction fill materials were used on each homesite's landscape.

Organic N was the dominant N form in all lawn soils (Table 2). This result is expected as most soil N is typically associated with soil organic matter even in turfgrass systems that have been fertilized with inorganic N (NO_3^- or NH_4^+) (Lusk et al., 2018; Pare et al., 2008). This organic N may

Table 2
Soil extractable nutrient pools and nutrient supply rates in Florida Friendly Landscaping (FFL) and Conventional (Conv) lawns. n.d. = not detected.

Landscape #	Extractable nutrients, mg/kg				Nutrient supply rates, μg/10cm²/21d		
	Organic N	NH_4^+-N	NO_3^--N	P	NH_4^+-N	NO_3^--N	P
FFL-1	1550	1.71	25.94	60.78	2.86	82.28	28.35
FFL-2	509	0.66	7.81	14.07	n.d.	44.08	2.63
FFL-3	596	1.20	12.33	32.85	n.d.	9.22	3.31
FFL-4	1249	2.71	23.27	62.47	2.20	64.68	16.79
FFL-5	809	1.45	11.17	47.91	2.10	130.70	8.95
Conv-6	855	6.43	4.24	39.85	9.04	24.54	1.06
Conv-7	2103	9.60	17.36	38.09	4.44	5.20	1.46
Conv-8	256	1.62	1.02	202.62	2.12	4.54	0.47
Conv-9	5343	21.02	57.5	133.0	n.d.	83.48	25.22
Conv-10	988	1.95	13.0	67.38	2.40	12.00	1.64

be mobilized by runoff water, or a portion of it may produce soil NH_4^+ and NO_3^- through mineralization and nitrification (Raciti et al., 2011). Soil extractable NO_3^--N, NH_4^+-N, and P represent inorganic pools of these nutrients that are expected to be readily available and that may be easily mobilized by runoff water (Yang and Toor, 2017). Yang and Toor (2017) attributed P in runoff from lawns to eroded soil particles, while soils and fertilizers applied to lawn soils were the dominant NO_3^- source in a study conducted in west central Florida. Soldat et al. (2009), however, found that dissolved P in lawn runoff could not be adequately predicted by soil extractable P alone, suggesting that some other source of P such as vegetation may have been confounding the relationship between soil extractable P and P concentrations in lawn runoff.

While soil extractable nutrient pools represent nutrient concentrations at one point in time, nutrient supply rates provided by the PRS probes (Table 2) represent conditions over an extended period of time —21 days in this study. The nutrient supply rates account for the kinetics of nutrient release and transport that a static one-time extraction cannot (Qian and Schoenau, 2002). Like the extractable nutrient pools, nutrient supply rates were highly variable among lawn soils, again demonstrating soil heterogeneity. Variability aside, the nutrient supply rate data do indicate a supply of inorganic N and P in all lawn soils.

3.2. Nutrient concentrations in rainfall and runoff

A total of 57 and 40 runoff samples were collected and analyzed for the FFL and conventional lawns, respectively, over the entire study period (May 2018 to August 2018). An additional 16 rainfall samples were collected as a study control. Mean concentrations of NO_3^--N, NH_4^+-N, and PO_4^+-P in rainfall were 0.09, 0.08, and 0.09 mg/l, respectively, for the full study period. Mean concentrations of NO_3^--N, NH_4^+-N, and PO_4^+-P in runoff for the full study period varied widely among lawns but were always equal to or higher than those in rainfall, with observed data ranges by lawn displayed in Fig. 2. Variations among lawns highlight how nutrient sources, mobilization, and transport processes

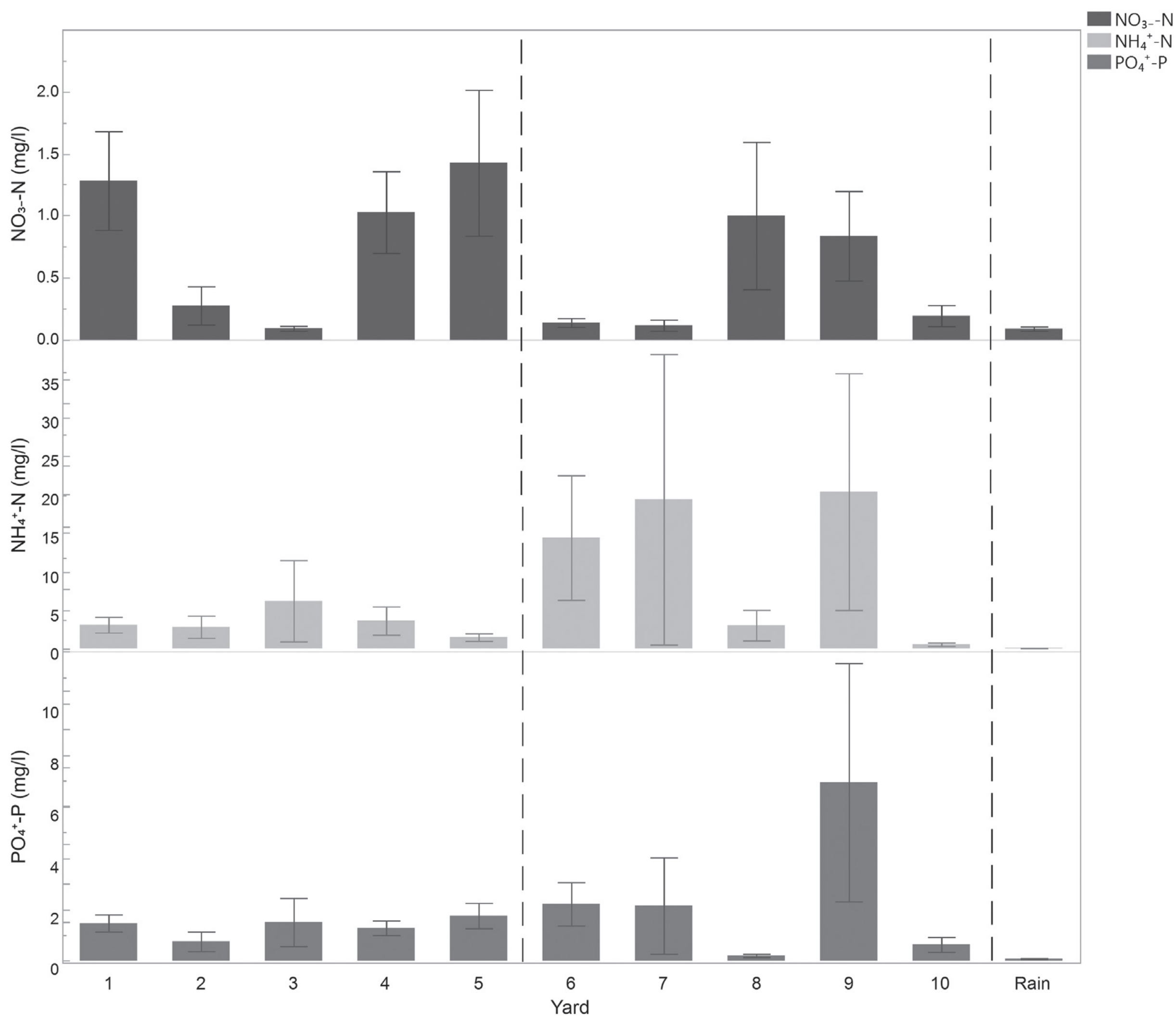

Fig. 2. Mean nutrient concentrations in runoff by lawn. Yards 1–5 = FFL, yards 6–10 = conventional.

may be highly variable at small landscape scales, especially in residential settings where homeowner behaviors at the parcel scale likely play a role in nutrient inputs as well as runoff generation and nutrient transport. Potential sources of nutrients at the parcel scale include turf fertilizers, soils, pet waste, atmospheric deposition, and leaky sewer lines. While homeowners may have little influence over nutrient inputs via soils, atmospheric deposition, and sewer lines, they may affect mobilization of nutrients from these sources by landscaping choices—such as the degree to which vegetation covers the soil—or by practices such as rainwater harvesting that mitigate atmospheric inputs. Homeowners also have considerable influence over fertilizer and pet waste inputs to individual lawns. Grouping of lawns into FFL and conventional landscape types demonstrates how landscaping choices can vary at a general scale, but even within treatment groups, choices are expected to vary. For example, there may be a link to high NH_4^+-N concentrations associated with those homes that employed a professional landscape service (Fig. 2, Table 1), although this trend was not significant (data not reported). Homeowner behaviors can be affected by public education and outreach campaigns that target nutrient management strategies such as reduced fertilizer use, pet waste pick up, and management of plant debris such as grass clippings (Fore, 2013; Bos and Brown, 2015; Brown et al., 2016). The degree to which individual homeowners adopt certain nutrient management behaviors creates an urban patchwork, or mosaic, in which each parcel differs from adjacent parcels (Band et al., 2005; Pickett and Cadenasso, 2008).

Very few studies have investigated parcel-scale surface runoff of nutrients from individual urban lawns (but see e.g., Morton et al., 1988). There are, however, numerous studies that have reported N and P forms and concentrations in urban residential runoff at neighborhood and catchment scales. Yang and Lusk (2018) provide a comprehensive review of urban runoff concentrations from a variety of scales and geographic locations. This study's mean NH_4^+-N and PO_4^+-P concentrations from lawn runoff are often higher than those in the studies evaluated by Yang and Lusk (2018). This is likely due to the effect of scale—with the runoff concentrations from individual lawns being diluted by runoff from other surfaces such as the streets, sidewalks, roofs, and natural green spaces that all contribute runoff to samples collected by the neighborhood- and catchment-scale studies. In other neighborhood-scale studies of residential runoff in Florida's wet season, NO_3^--N concentrations ranged from 0.1 to 0.2 mg/l and PO_4^+-P concentrations were reported at 0.25 mg/l (Yang and Toor, 2016; Yang and Toor, 2017). The values for NO_3^--N are similar to half of the lawns in this study but for PO_4^+-P are 2 to 30 times lower than our study results. The runoff from study lawns interacted with surface soils, and this interaction could be another reason for the higher PO_4^+-P concentrations as compared to other studies (Song et al., 2015; Yang and Toor, 2017).

3.3. Nutrient concentrations in runoff from FFL versus conventional lawns

Mean NO_3^--N concentrations over the full study period were higher in runoff from the FFL lawns than in the conventional lawns (0.89 and 0.47 mg/l, respectively). Conversely, mean NH_4^+-N and PO_4^+-P concentrations were higher in runoff from the conventional than the FFL lawns (NH_4^+-N: 9.51 and 3.38 mg/l for conventional and FFL, respectively) (PO_4^+-P: 2.02 and 1.40 mg/l for conventional and FFL, respectively). However, none of these trends were statistically significant (NO_3^--N, $p = 0.10$; NH_4^+-N, $p = 0.11$; PO_4^+-P, $p = 0.45$) (Fig. 3). Differences in lawn management practices (i.e., FFL vs. conventional) were expected to result in differences in nutrient concentrations in lawn runoff. In particular, the FFL principle of "fertilize appropriately" was expected to translate into

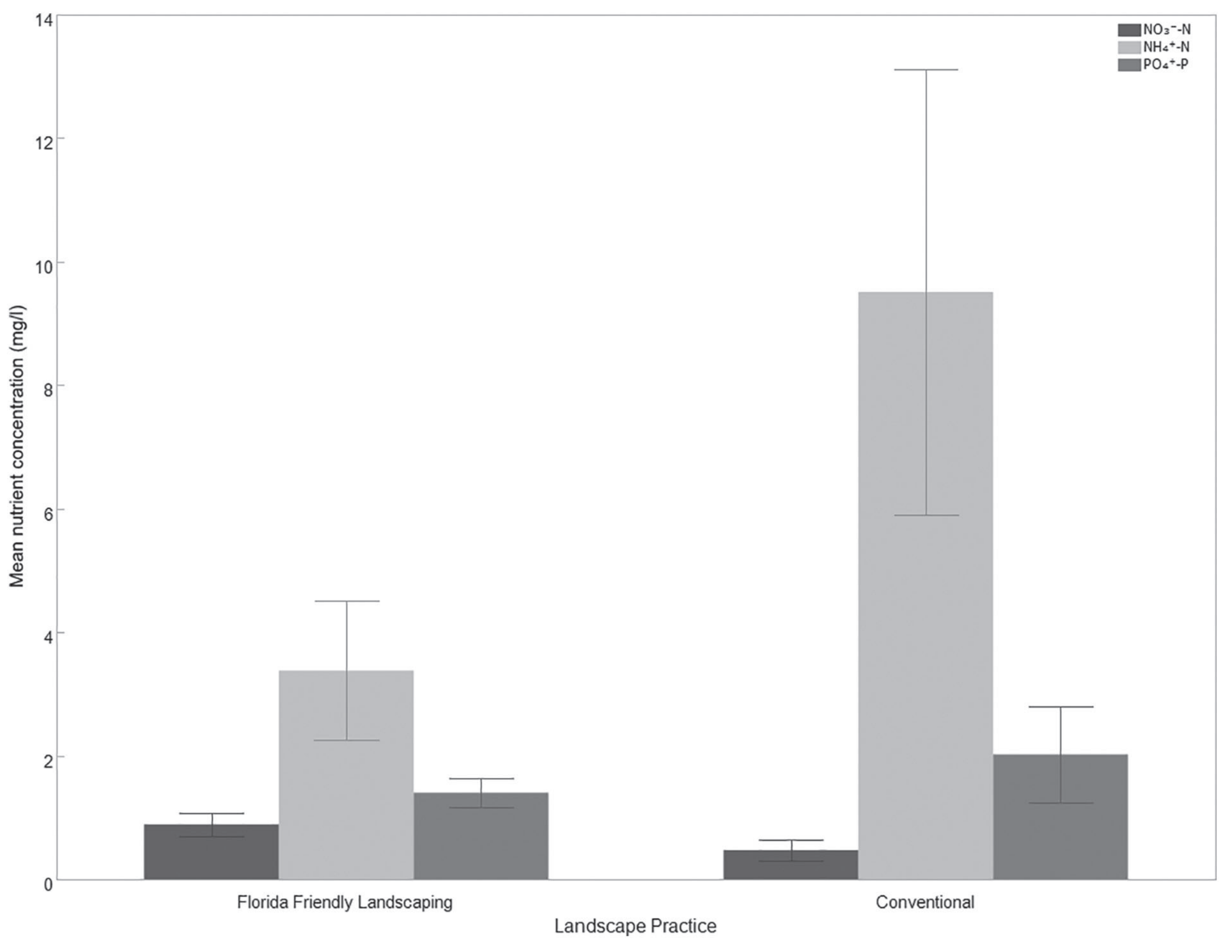

Fig. 3. Mean nutrient concentrations in runoff in FFL and conventional lawns.

discernible differences in nutrient mobilization via runoff between the two lawn types. Since these differences were either not significant or counter to the hypothesis, the two landscape types may behave similarly in the extent to which they capture applied nutrients. However, it is also possible that variability within each treatment group (variation in post-construction soils, vegetation, homeowner behaviors, etc.) confounded any direct relationships between runoff nutrient concentrations and lawn management practices alone. This has been observed for studies at the neighborhood scale—for example, Yang and Toor (2017), who studied nutrient runoff from multiple urban neighborhoods in close proximity to each other and concluded that differences in development designs and patterns, various fill materials used during homesite construction, and different landscaping behaviors resulted in highly variable nutrient concentrations in residential runoff.

3.4. Nutrient concentrations in runoff before and during the fertilizer blackout period

The study site has a summer rainy season fertilizer ordinance mandating that no N- or P-bearing lawn fertilizers are applied to residential landscapes from June 1 to September 30 each year. For all lawns in this study, the mean NO_3^--N concentration in runoff for the dry season (before the fertilizer ordinance was in effect) was 0.99 mg/l ($n = 34$) and was 0.57 mg/l for the wet season, during which the ordinance was in effect ($n = 63$, $p = 0.15$). While these NO_3^--N concentrations were lower during the time in which the ordinance was in effect and assumedly no fertilizers were applied, the dry versus wet season trend was not statistically significant (Fig. 4).

In contrast, Mean PO_4^+-P concentration in runoff for the dry season was 1.16 mg/l (n = 34) and 1.92 mg/l for the wet season (n = 63, $p = 0.19$) and dry season NH_4^+-N concentration in runoff was significantly lower (2.35 mg/l, n = 34) than the wet season concentration (7.83 mg/l, n = 63, $p = 0.05$) (Fig. 4). It is beyond the scope of this project to fully examine the underlying mechanisms that may be accounting for dry versus wet season differences in runoff nutrient concentrations. However, the data does show that even in the absence of fertilizer application, nutrients (especially NH_4^+-N) were still mobilized from lawn surfaces during the wet season, likely due to interaction with lawn soils, which all had pools of available nutrients (Table 2) and/or residual nutrients from the dry season, an assertion supported by the isotope data and discussed later.

The impact of the fertilizer ordinance blackout period was also examined by landscape treatment type. Results show that there was no significant difference in the concentration of nutrients by season within either the FFL or the conventional yards treatment groups. For the FFL yards, mean NO_3^--N concentration in runoff was 1.17 mg/l for the dry season ($n = 19$) and 0.75 mg/l for the wet season ($n = 38$, $p = 0.31$). Mean NH_4^+-N concentration in runoff for FFL yards was 1.30 mg/l (n = 19) for the dry season and 4.42 mg/l for the wet season (n = 38, $p = 0.07$). Mean PO_4^+-P concentration in runoff for FFL yards was 1.44 mg/l and 1.38 mg/l for the dry (n = 19) and wet (n = 38) seasons, respectively ($p = 0.89$). For the conventional yards, the mean NO_3^--N concentration in runoff was 0.78 mg/l for the dry season ($n = 15$) and 0.29 mg/l for the wet season ($n = 25$, $p = 0.25$). Mean NH_4^+-N concentration in runoff for conventional yards was 3.68 mg/l (n = 15) for the dry season and 13.01 mg/l for the wet season (n = 25, $p = 0.14$). Mean PO_4^+-P concentration for conventional yards was 0.80 mg/l and 2.75 mg/l for the dry (n = 15) and wet (n = 25, $p = 0.13$) seasons, respectively. The authors are aware of no other studies that have investigated parcel-scale or neighborhood-scale nutrient concentrations in runoff in response to a fertilizer blackout period. These results show that discernible outcomes in water quality may not accompany fertilizer blackouts, at least not on the timescale of months to seasons.

3.5. Sources of nitrate in runoff

Hobbie et al. (2017) reported that chemical fertilizers were 37 to 59% of total N in runoff from a Minnesota urban area. In a Florida study, NO_3- and NH_4^+ bearing fertilizers contributed up to 35% of inorganic N in runoff collected at the neighborhood scale (Yang and Toor, 2016), but other sources of N, such as atmospheric deposition and soils, were also important contributors to runoff N. This study's final objective was to use isotopic characterization of NO_3^- in the runoff samples to place fertilizer contributions in context with other sources (Fig. 5).

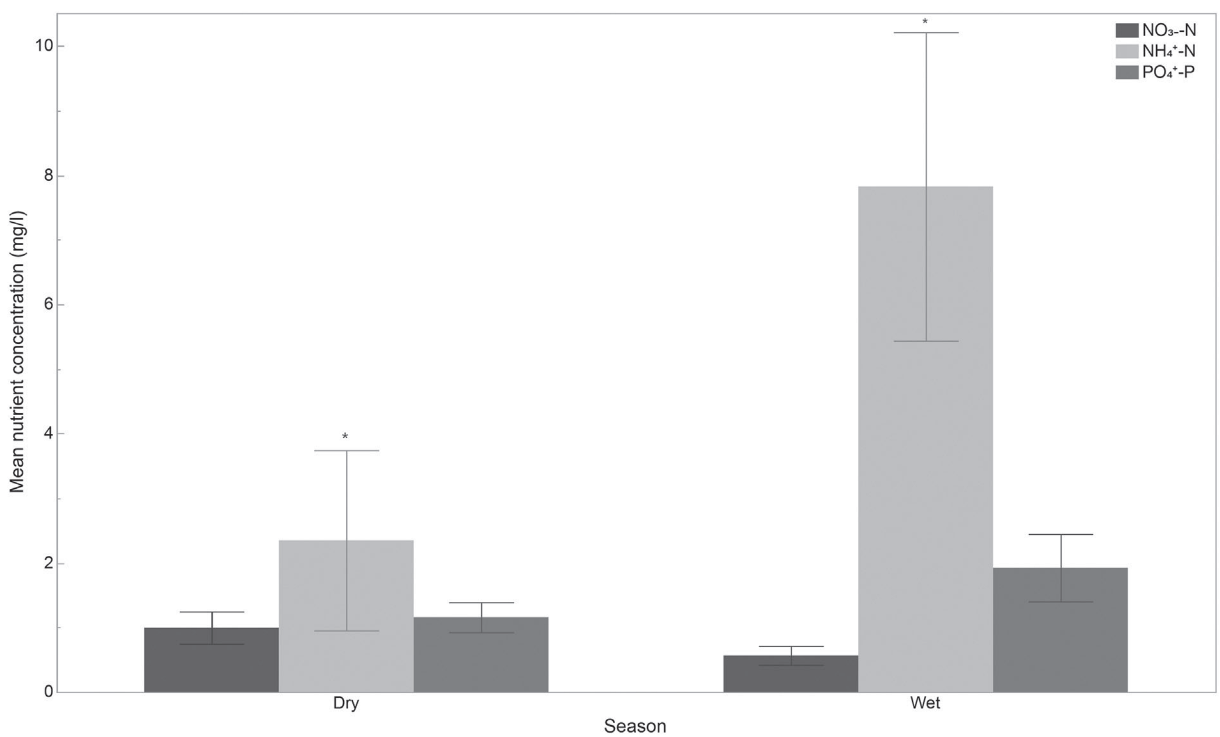

Fig. 4. Mean nutrient concentration in dry (no fertilizer ban) and wet (fertilizer ban) seasons. * indicates significance at $p = 0.05$.

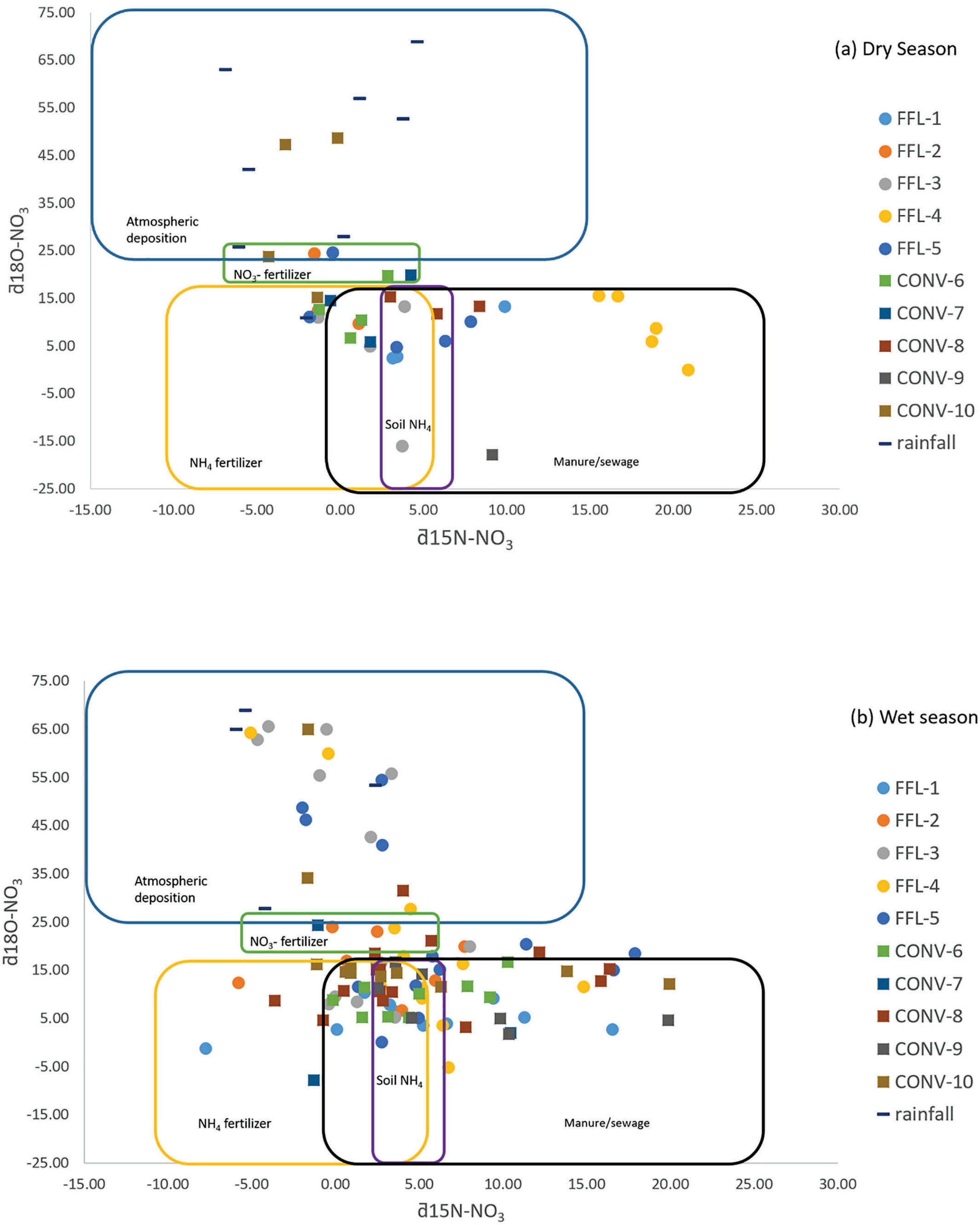

Fig. 5. Isotopic characterization of N and O in NO_3 for rainfall and runoff samples in (a) dry season and (b) wet season.

The $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- in the runoff samples ranged from −4.5‰ to 21.2‰ and −16.2‰ to 47.2‰, respectively. These results are in line with results from Jani et al. (2020), who also used isotopic source tracking to infer NO_3^- sources in urban runoff. Variability among lawns (Fig. 5) demonstrates how individual lawns may each have a unique nutrient source signal. Aside for Lawn FFL-4, NO_3^- was shown to be from a mixture of potential sources. In Lawn FFL-4, isotopic characterization of NO_3^- indicated that the source was most likely manure and/or sewage waste. In this case, we attribute NO_3^- in runoff to pet waste from a large dog on the property of Lawn FFL-4. Mixing model results of a dry season versus wet season analysis and an FFL versus conventional lawn analysis are shown in Table 3.

For the seasonal comparison we were interested in whether fertilizers were a lower contributor to runoff N during the wet season blackout period than during the dry season. In both seasons, soil and organic N were the dominant sources of NO_3^- (37.5 and 36.5%, in the dry and wet seasons, respectively) (Table 3). Atmospheric deposition accounted for 15% and 30.6% of NO_3^- in all samples from the dry and wet seasons, respectively. These results are in line with Jani et al. (2020), who observed that atmospheric deposition contributed on average about 30% of the NO_3^- in wet season runoff from a Florida study in the Tampa Bay urban area. These results highlight the important contribution that rainfall itself can have to nutrient loading from urban runoff and underscores the role that stormwater management practices, such as rain gardens that infiltrate stormwater, may have in managing urban nutrient runoff.

While we did not investigate the effects of storm size (rainfall depth and duration) on N sources, the Jani et al. (2020) study found that atmospheric deposition was the primary N source in runoff during the first few minutes of rainfall and that as rainfall progressed, other sources such as fertilizers became more important, suggesting that longer duration storms are able to mobilize nutrients on urban surfaces or from urban soils. Inorganic N fertilizers were indeed a source of N in both seasons, contributing up to 44.2% of NO_3^- in dry season runoff and 30.8% in wet season runoff (Table 3). A small percentage of runoff NO_3^- was also attributed to manure/sewage waste (~3% in both seasons). As the study neighborhood is on central sewer and there are no septic systems in the neighborhood, we attribute this NO_3^- to pet manure, though leaky sewer pipes could also be a contributor. Pet waste contains a large amount of N, and Fissore et al. (2011) estimate that 40% of pet waste ends up on the landscape. Hobbie et al. (2017) estimated that 28% of total N in urban runoff in a St. Paul MN study was from pet waste. These studies point out how "scoop the poop" campaigns may be important educational tools for reducing N concentrations in urban residential runoff (Reisinger et al., 2020).

Though not relevant for this study site, additional considerations for future studies should include whether a community uses reclaimed water for irrigation due to elevated levels of N and P, when compared to potable water. Reclaimed water usage may also confound NO_3^- source results. Since it is derived from a wastewater source it may be discernible as a "manure/sewage" contributor to NO_3^- in studies for which it is used for landscape irrigation (Badruzzaman et al., 2012; Toor and Lusk, 2011). Likewise, it should be noted whether a home lawn has a septic tank, as septic waste from poorly functioning or improperly-sited septic systems can also be a source of "manure/sewage" N (Toor et al., 2011).

Table 3
Mixing model results showing mean relative percent contributions of various sources of NO_3^- in lawn runoff.

Nitrate source	Seasonal comparison		Landscape comparison	
	Dry season	Wet season	FFL	Conventional
Atmospheric deposition	15	30.6	30.4	15.7
NH_4^+-fertilizer	15.8	7.7	10.6	12.4
NO_3^--fertilizer	28.6	23.1	20.8	27.0
Soil and organic N	37.5	36.5	34.5	36.8
Manure/sewage	3.2	3.1	3.8	8.1

The seasonal and landscape comparisons of NO_3^- sources point out that there are multiple N sources in runoff from this study site and that even during the summer fertilizer blackout period fertilizers can still be an important contributor to runoff N, even though their relative contribution was lower in the wet season than the dry season (Fig. 5, Table 3). Residues of inorganic fertilizers applied before the onset of the blackout period or soil processes (mineralization and nitrification) that convert soil organic N pools (Table 2) to NO_3^- may both be sources of wet season N (Jani et al., 2020). Like the nutrient concentration data discussed previously, the comparison of NO_3^- sources in FFL and conventional landscapes highlights the possibility that within treatment variability confounds discernible differences between lawn types.

3.6. Nutrient management implications for residential landscapes

To our knowledge, this study is one of only a few that have examined sources and concentration of nutrients in residential settings at the parcel scale. The small sample size of this study and the heterogeneity between lots precluded our ability to determine the influence of landscape practices on nutrient runoff, however; this study highlights the complexities of managing for a diverse source of nutrients at the local level and the importance of human behavior in influencing change.

Atmospheric deposition, soil nutrient pools, and leaky sewer lines are nutrient sources that are generally beyond the control of individual homeowners. In this study, atmospheric deposition and soil nutrient pools contributed 53–67% of the total NO_3^- in surface water runoff. We presume that leaky sewers were not a source of nutrients in the site location, though verification of that was beyond the scope of the project. In locations where septic systems or leaky sewers are known sources of nutrients, remediation should be considered as it can be done at the community or catchment level and may not be dependent on changing individual behavior.

This study was not able to confirm the efficacy of fertilizer blackout periods, but it has been estimated that a minimum of 7 years of monitoring would be necessary to see any statistically significant effects on water quality (Tampa Bay Estuary Program, 2015). This study affirms that fertilizer ordinances are a long-term nutrient management strategy, particularly in areas with considerable organic nutrient pools such as in this study site. Legacy loads have been identified as important contributors to nutrients in large lacustrine and estuarine environments but have rarely been considered in the context of urban residential areas. However, as these results suggest, soil nutrient pools have the potential to be mobilized during the wet season, thereby nullifying any impact a blackout period may have.

In communities such as Tortoise Island, Satellite Beach, FL, nutrient reduction strategies need to address fertilizer and manure/sewage inputs if water quality improvements are to be made. Homeowners can have considerable impact on the inputs of these sources, but success is dependent on comprehensive and strategic outreach and education campaigns. While P-limiting fertilizer ordinances have been successful in reducing P concentrations in downstream waters, these results do not imply ordinance compliance; instead success may be associated with the inability to purchase the restricted product (Lehman et al., 2011). Nutrient reductions can be achieved with management strategies that rely on voluntary actions and compliance, but reductions are dependent on robust outreach and education campaigns developed in consideration of the public's acceptance and concerns regarding the implementation of non-structural BMPs (Persaud et al., 2016; Warner et al., 2018; Souto et al., 2019).

The nation's largest cities have seen a recent decline in population resulting in a concomitant return to suburbia and the expansion of exurban households (Theobald, 2005). Similarly, the number of community associations across the country is growing. HOAs currently house an estimated 25 to 27% of the entire U.S. population. Approximately 80% of single-family homes in new subdivisions are within an HOA and the number of associations are projected to increase 50% in the next two decades (Clarke and Freedman, 2019; Community Associations Institute, 2018). These trends are not unique to the United States. Housing reform in China has led to an expansion of HOAs and community associations exist, though are not as prevalent within Canada, Australia, the United Kingdom, and Japan (Chen and Webster, 2005; Clarke and Freedman, 2019). Considering this, there is substantial opportunity to engage residents in nutrient management practices at the parcel and community scale. The residential framework of formal and informal community associations provide an opportunity for natural resource managers and educators alike to develop targeted and specific nutrient management outreach campaigns. Homeowners and neighborhood associations have a large influence over choices regarding landscape design and contracts, stormwater management practices (e.g. rain gardens, rain barrels, and permeable pavers), and pet waste rules. Many communities, such as the Tortoise Island study site, are willing to make these changes and want to be part of the solution, if only to maintain high aesthetic and property values. These communities need to be looked at as partners and opportunities exist to change the acceptable social norms at the community level.

4. Conclusions

This study highlights the complexities of managing for nutrients in urban residential areas due to the small-scale heterogeneity that characterizes these communities. Results confirm that lawn soils might be a contributing source of nutrients in runoff. Soil and organic N nutrient pools contributed more than one-third the NO_3^--N in all of samples regardless of landscape management practice (conventional or Florida-Friendly Landscaping™ (FFL), a voluntary non-structural BMP) or season (wet season fertilizer ban and dry). However, both soil nutrient pools and nutrient supply rates were highly variable by lawn. These findings also show high intra-treatment variability in NO_3^--N, NH_4^+-N, and PO_4^+-P among the 10 studies lawns, again demonstrating parcel heterogeneity, although these differences were not significant between treatments. Nutrient concentration from lawns was always higher or equal to that of rainfall, yet we did not see the expected influence of landscape management or a fertilizer ordinance blackout period. Despite this, stable isotope mixing model results suggest that NO_3^- and NH_4^+ based fertilizers contributed a combined 31 to 44% of NO_3^- in lawn runoff. This study highlights how homeowner behavior (fertilization and irrigation rates, pet waste clean-up, and using a professional landscape service, etc.) can influence the source and concentration of nutrients in lawn runoff. Based on this research, nutrient management strategies in residential communities should address multiple sources of nutrients and management should be coupled with comprehensive outreach and education to residents and community associations.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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