BOCC MEETING AGENDA SUPPLEMENT

EST. 1834

Hillsborough County Florida

MEETING DATE: November 17, 2021

D-1: Additional Material Submitted by the County Attorney's Office.

AGENDA ITEM Nº: D-1

This information will be uploaded and available on COIN.

City of Tampa
Jane Castor, Mayor

Office of the City Attorney
Gina K. Grimes, City Attorney
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Tampa, Florida 33602

Office (813) 274-8996
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November 10, 2021

Via Electronic Mail

Vivian Arenas-Battles
Senior Assistant County Attorney
P.O.Box 1110
Tampa, FL 33601-1110
arenasv@hillsboroughcounty.org

RE: Hillsborough County Draft Ordinance Revising Chapter 24 Dated October 8, 2021

Dear Ms. Arenas-Battles:

Thank you for the opportunity to review and comment on the County's proposed revisions to Chapter 24 of its Code of Ordinances regarding the creation of Article V, regulating the use of fertilizers containing nitrogen and/or phosphorous within Hillsborough County.

I have reviewed the proposed provision and although it differs from the City's codified regulation of the use and sale of fertilizers containing nitrogen and/or phosphorus under Chapter 21, Article V, of the City of Tampa's Code of Ordinances, the County's draft ordinance is only applicable to residents within unincorporated Hillsborough County. Therefore, I find no potential conflict with City Code.

Again, thank you for the opportunity to review and comment on the County's draft ordinance.

Sincerely,

McLane Evans
Assistant City Attorney

Cc: Gina Grimes, City Attorney

Agenda Item Cover Sheet

Agenda Item Nº. D-1

Meeting Date 11/17/2021

☐ Consent Section ☐ Regular Section ☒ Public Hearing

Subject: Hold a public hearing to consider an amendment to Chapter 24 of the Hillsborough County Code of Ordinances and Laws which will create Article V regulating the use of fertilizers containing nitrogen and/or phosphorous within unincorporated Hillsborough County.

Department Name: County Attorney's Office

Contact Person: Vivian Arenas-Battles

Contact Phone: 272-5670

Sign-Off Approvals

Richard Tschantz 11/5/2021
Managing County Attorney Date

Christine Beck 11/5/2021
County Attorney Date

Joint Department Director Date

Kevin Brickey 11/5/2021
Management and Budget – Approved as to Financial Impact Accuracy Date

Vivian Arenas-Battles 11/5/2021
Assistant County Attorney Date

Staff's Recommended Board Motion:
Hold a public hearing on November 17, 2021 at 10:00 a.m. to consider an amendment to Chapter 24 of the Hillsborough County Code of Ordinances and Laws which will create Article V regulating the use of fertilizers containing nitrogen and/or phosphorous within unincorporated Hillsborough County. There is no significant financial impact to the County, and any directly related expenses can be accommodated in the departments approved operating budgets.

Financial Impact Statement:
Costs associated with the implementation of the Ordinance will be primarily related to enforcement of the Ordinance, training and any public information program associated with the Ordinance. There is no significant financial impact to the County, and any directly related expenses can be accommodated in the departments approved operating budgets.

Background:
On August 4, 2021, the Board of County Commissioners (BOCC) directed the County Attorney's Office, in conjunction with the Environmental Services Division, to prepare a draft fertilizer use and application Ordinance that addresses best management practices and procedures to mitigate environmental impacts from fertilizer use. On October 20, 2021, the BOCC scheduled a public hearing for November 17, 2021 to consider an amendment to Chapter 24 of the Hillsborough County Code of Ordinances and Laws which will create Article V regulating the use of fertilizers containing nitrogen and/or phosphorous within unincorporated Hillsborough County

The draft Ordinance regulates the proper use of fertilizer by any applicator and requires training and licensing of commercial and institutional fertilizer applicators. The Ordinance will be applicable within unincorporated Hillsborough County and establishes a restricted season from June 1 through September 30 for fertilizer application, unless subject to an exemption. Exemptions are provided for specific users, including farming operations. The Ordinance establishes fertilizer-free zones within 10 feet from the landward extent of any surface water. The Ordinance also provides for enforcement and penalties for violations. The specific penalty amounts would be approved by the BOCC through a resolution at a later date. The Ordinance meets the requirements of Section 403.9337, Florida Statutes in that the County has demonstrated that additional or more stringent standards than the Florida Department of Environmental Protection's (FDEP) Model Ordinance are necessary in order to adequately address urban fertilizer contributions to non-point source nutrient loading to surface water bodies, and the County has considered all relevant scientific information, including input received from the Florida Department of Environmental Protection (FDEP) and the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS). The County requested input from the Florida Department of Agriculture and Consumer Services (FDACS) but did not receive a response. The Ordinance will benefit the citizens of Hillsborough County by protecting the quality of receiving waters from residential and commercial surface water runoff containing excessive nutrients.

Costs associated with the implementation of the Ordinance will be primarily related to enforcement of the Ordinance, training and any public information program associated with the Ordinance. There is no significant financial impact to the County, and any directly related expenses can be accommodated in the departments approved operating budgets.

List Attachments:
Draft Ordinance and staff report.

ORDINANCE No. 21-____

AN ORDINANCE OF THE HILLSBOROUGH COUNTY BOARD OF COUNTY COMMISSIONERS AMENDING CHAPTER 24 OF THE HILLSBOROUGH COUNTY CODE OF ORDINANCES AND LAWS (ENVIRONMENT AND NATURAL RESOURCES); CREATING ARTICLE V REGULATING THE USE OF FERTILIZERS CONTAINING NITROGEN AND/OR PHOSPHOROUS WITHIN UNINCORPORATED HILLSBOROUGH COUNTY; PROVIDING FOR ENFORCEMENT AND PENALTY; PROVIDING FOR SEVERABILITY; AND PROVIDING FOR AN EFFECTIVE DATE

WITNESSETH

WHEREAS, Chapter 24 of the Hillsborough County Code of Ordinances and Laws provides that the contribution of pollutants through discharges from stormwater systems has a significant impact on the receiving waters in Hillsborough County;

WHEREAS, it is in the public interest to protect the quality of receiving waters for the health, safety, and general welfare of the citizens of Hillsborough County; and

WHEREAS, runoff from surface waters containing excessive nutrients from residential, commercial, and other lands within Hillsborough County enter into receiving waters in Hillsborough County; and

WHEREAS, the Florida Department of Environmental Protection has listed various surface water bodies in Hillsborough County as impaired by nutrients; and

WHEREAS, as a result of impairment to Hillsborough County's surface waters caused by excessive nutrients, and/or, as a result of increasing levels of nitrogen and/or phosphorous in the surface waters within the boundaries of Hillsborough County, the Board of County Commissioners has determined that the use of fertilizers on lands within Hillsborough County creates a risk of contributing to adverse effects on surface waters, and finds that management measures for the application of fertilizer require adoption of this ordinance; and

WHEREAS, in adopting this Ordinance, Hillsborough County has considered all relevant scientific information, including input from the Department of Environmental Protection, the Department of Agriculture and Consumer Services, and the University of Florida Institute of Food and Agricultural Sciences, to the extent available, provided and gathered on the need for additional or more stringent provisions to address fertilizer use as a contributor to water quality degradation and such information has been made a part of the public record at the public hearing on this ordinance; and

WHEREAS, the provisions of this Article are applicable only within unincorporated Hillsborough County; and

WHEREAS, to ensure consistency with Chapter 1-15, Rules of the EPC, adopted by the Environmental Protection Commission of Hillsborough County (EPCHC), Hillsborough County intends that all provisions of the EPCHC rule shall remain in effect and enforceable within unincorporated Hillsborough County unless superceded by this ordinance, which is supplemental and more restrictive than the EPC rule.

NOW, THEREFORE, BE IT ORDAINED BY THE BOARD OF COUNTY COMMISSIONERS OF HILLSBOROUGH COUNTY, FLORIDA, IN REGULAR MEETING THIS ____DAY OF ____________, 2021.

Chapter 24 of the Hillsborough County Code of Ordinances and Laws is amended to create Article V, and shall read as follows:

ARTICLE V. REGULATION OF THE USE OF FERTILIZERS CONTAINING NITROGEN AND/OR PHOSPHOROUS

Section 24-194. Purpose and Intent

This ordinance regulates the proper use of fertilizers by any applicator and requires proper training of commercial and institutional fertilizer applicators including establishing a restricted season for fertilizer application, fertilizer-free zones, low maintenance zones, exemptions, training and licensing requirements. The ordinance requires the use of Best Management Practices which provide specific management guidelines to minimize the negative secondary and cumulative environmental effects associated with the misuse of fertilizers. These secondary and cumulative effects have been observed in and on Hillsborough County's natural and artificial stormwater and drainage conveyances, rivers, lakes, canals, estuaries, interior freshwater wetlands, and Tampa Bay. Collectively, these water bodies are an asset critical to the environmental, recreational, cultural and economic well-being of Hillsborough County residents and the health of the public. Overgrowth of algae and vegetation hinder the effectiveness of flood attenuation provided by natural and artificial stormwater and drainage conveyances. Regulation of nutrients, including nitrogen and/or phosphorous contained in fertilizer, will help improve and maintain water and habitat quality.

Section 24-195. Definitions.

For this Article, the following terms shall have the meanings set forth in this section unless The context clearly indicates otherwise.

Application or Apply means the actual physical deposit of fertilizer to turf or landscape plants.

Applicator means any person who applies fertilizer on turf and/or landscape plants in Hillsborough County.

Article means Chapter 24, Article V, of the Hillsborough County Code of Ordinances and Laws, as amended, unless otherwise specified.

Best Management Practices or BMP means turf and landscape practices which minimize the negative environmental impacts of installation and maintenance of landscapes.

Code Enforcement Officer, Official, or Inspector means any employee or agent of Hillsborough County who has been designated to enforce codes and ordinances enacted by Hillsborough County.

Commercial Fertilizer Applicator means any person or an agent or employee of a commercial lawn or landscaping or commercial fertilizer company who applies fertilizer on turf and/or landscape plants in Hillsborough County in exchange for money, goods, services or other valuable consideration.

Fertilize, Fertilizing, or Fertilization means the act of applying fertilizer to turf, specialized turf, or landscape plants.

Fertilizer means any substance or mixture of substances that contains one or more recognized plant nutrients and promotes plant growth, or controls soil acidity or alkalinity, or provides other soil enrichment, or provides other corrective measures to the soil.

Granular means composed of small grains or particles.

Institutional Applicator means any person, other than a non-commercial or commercial applicator, that applies fertilizer for the purpose of maintaining turf and/or landscape plants. Institutional applicators shall include, but shall not be limited to, owners and managers of public lands, schools, parks, religious institutions, utilities, industrial or business sites and any residential properties maintained in condominium and/or common ownership.

Impervious Surface means a surface that has been compacted or covered with a layer of material so that it is highly resistant or prevents infiltration by stormwater. It includes roofed areas and surfaces such as compacted sand, lime rock, or clay, as well as conventionally surfaced streets, sidewalks, parking lots, and other similar surfaces.

Landscape Plant means any native or exotic tree, shrub, or groundcover (excluding turf).

Landscape Maintenance means activities carried out to manage and maintain landscape plants and turf, including but not limited to mowing, edging, and trimming.

Low maintenance zone means an area of a minimum of six (6) feet wide adjacent to surface waters which is planted with non-turf grass vegetation and managed in order to minimize the need for fertilization, mowing, etc.

Person means any natural person, individual, public or private corporation, firm, association, joint venture, partnership, limited partnership, municipality, governmental agency, political subdivision, public officer, or any other entity whatsoever, or any combination of such, jointly or severally.

Restricted Season means June 1 through September 30.

Saturated Soil means a soil in which the voids are filled with water. Saturation does not require flow. For the purposes of this Article, soils shall be considered saturated if standing water is present or the pressure of a person standing on the soil causes the release of free water.

Site Supervisor means the direct supervisor of landscape maintenance personnel.

Slow or Controlled Release Fertilizer means a fertilizer containing a plant nutrient in a form which delays its availability for plant uptake and use after application, or which extends its availability to the plant significantly longer than a referenced "rapidly available nutrient fertilizer."

Specialized Turf means areas of grass used for athletic fields, golf course practice and play areas, and other similar activities.

Specialized Turf Manager means a person responsible for fertilizing or directing the fertilization of specialized turf.

Surface Water means those waters, as identified in Rule 62-340.600, Florida Administrative Code, which include waters upon the surface of the earth whether contained in bounds created naturally or artificially or diffused. They shall include, but not be limited to, bays, rivers, streams, lakes, ponds, swamps, wetlands, canals, springs, impoundments and all other waters or bodies of water, including fresh, brackish or saline, tidal or intermittent, which are located in, either entirely or partially, within the geographic boundaries of Hillsborough County.

Turf, Sod, or Lawn means a piece of grass-covered soil held together by the roots and stems of the turfgrass.

Fruit and Vegetable Garden means an area dedicated to the cultivation of edible plants.

Section 24-196. Applicability and Implementation

The provisions of this Article shall govern any and all applicators of fertilizer and areas of application of fertilizer within unincorporated Hillsborough County unless such applicator or activity is specifically exempted by the terms of this Article from the regulatory provisions of this Article as indicated herein. The provisions of this Article shall be implemented as of the effective date of this Ordinance and no person shall act in a manner inconsistent with this Article after such date.

Section 24-197. Weather and Seasonal Restrictions

(1) No applicator or commercial fertilizer applicator shall apply fertilizers containing nitrogen and/or phosphorous to turf and/or landscape plants during the restricted season

from June 1 through September 30 unless subject to an exemption indicated in this Article.

(2) No applicator shall apply fertilizers containing nitrogen and/or phosphorous to turf and/or landscape plants during a period for which the National Weather Service has issued any of the following advisories for any portion of Hillsborough County: (a) a severe thunderstorm warning or watch, (b) flood warning or watch, (c) tropical storm warning or watch, (d) hurricane warning or watch, or (e) if rain greater than or equal to two (2) inches in a 24-hour period is forecasted.

Section 24-198. Fertilizer Content and Application Manner and Rate.

(1) No fertilizer containing phosphorous shall be applied to turf and/or landscape plants within unincorporated Hillsborough County, except where a phosphorous deficiency has been demonstrated in the soil underlying the turf and/or landscape plants by a soil analysis test performed by a qualified soils or environmental laboratory. Any person who obtains a soil analysis test showing a phosphorous deficiency and who wishes to apply phosphorous to turf and/or landscape plants shall provide a copy of the test results to the County Administrator prior to application of phosphorous.

(2) Granular fertilizers containing nitrogen applied to turf and/or landscape plants within unincorporated Hillsborough County shall contain no less than 50% slow-release nitrogen per guaranteed analysis label.

(3) Fertilizers applied to turf within unincorporated Hillsborough County shall be applied in accordance with requirements and directions provided by Rule 5E-1.003, Florida Administrative Code, except as provided herein in Section 24-197.

(4) Fertilizer containing nitrogen shall not be applied before seeding or sodding a site and shall not be applied for the first thirty (30) days after seeding or sodding, except when hydro-seeding for temporary or permanent erosion control in an emergency situation (wildfire, etc.), or in accordance with the Stormwater Pollution Prevention Plan for that site.

(5) Fertilizers shall be applied to turf and/or landscape plants at the recommended rate per the "Florida Friendly Best Management Practices for Protection of Water Resources by the Green Industries," in effect on the date of application, with no more than four (4) pounds of nitrogen per 1,000 square feet applied in any calendar year.

(6) Spreader deflector shields are required when applying fertilizer by use of any broadcast or rotary spreaders. Deflector shields must be positioned such that fertilizer granules are deflected away from all impervious surfaces and surface waters. Caution shall be used to prevent direct deposition of nutrients into the water.

(7) Liquid fertilizers containing nitrogen applied to turf and/or landscape plants within the County shall not be applied at a rate that exceeds 0.5 pounds per 1,000 square feet per application.

(8) Fertilizer shall not be applied, spilled, or otherwise deposited on any impervious surfaces. Any fertilizer applied, spilled, or deposited, either intentionally or accidently, on any impervious surface shall be immediately and completely removed to the greatest extent practicable. Fertilizer released on an impervious surface must be immediately contained and either legally applied to turf or any other legal site or returned to the original or other appropriate container. Fertilizer shall not be washed, swept, or blown off impervious surfaces into stormwater drains, ditches, drainage conveyances, surface waters, or roadways.

Section 24-199. Fertilizer Free Zones

Fertilizer shall not be applied within ten (10) feet from the landward extent of any surface water, as defined in Rule 62-340.600(2), Florida Administrative Code. Caution shall be used to prevent direct deposition of nutrients into the water.

Section 24-200 Management of Grass Clippings and Vegetative Material

In no case shall grass clippings, vegetative material, and/or vegetative debris either intentionally or accidentally, be washed, swept, or blown off into stormwater drains, ditches, conveyances, surface waters, or roadways.

Section 24-201. Exemptions.

The provisions set forth in Sections 24-194 through 24-199 of this Article shall not apply to:

(1) Golf courses. For all golf courses, the provisions of the Florida Department of Environmental Protection (FDEP) document, “BMPs for the Enhancement of Environmental Quality on Florida Golf Courses, September 2012,” and as revised, are required and shall be followed when applying fertilizer to golf courses.

(2) Specialized turf. Specialized turf managers are required to follow the Best Management Practices embodied in the “Florida Friendly Best Management Practices for Protection of Water Resources by the Green Industries,” in effect on the date of application. However, fertilizer shall not be applied at a rate of more than four (4) pounds of nitrogen per 1000 square feet in any calendar year.

(3) Bona fide farm operations as defined in the Florida Right to Farm Act, Section 823.14, Florida Statutes.

(4) Fruit and vegetable gardens, owned by individual property owners or a community, provided that fertilizer application rates do not exceed UF IFAS recommendations per SP

103 Florida Vegetable Gardening Guide, February 2021, and as revised. Fruit and vegetable crops not covered in SP 103 Florida Vegetable Gardening Guide, February 2021, and as revised, shall follow UF/IFAS recommendations effective on the date of application.

(5) Yard waste compost, mulches, or other similar materials that are primarily organic in nature and are applied to improve the physical condition of the soil.

(6) Tree trunk injection fertilization treatments that are performed by a certified arborist.

(7) Theme park or entertainment complex, as defined in Section 509.013, Florida Statutes, that: operates pursuant to a National Pollution Discharge Elimination System (NPDES) permit, complies with the requirements of the Best Management Practices identified in the "Florida Friendly Best Management Practices for the Protection of Water Resources by the Green Industries", and whose applicators are certified pursuant to this ordinance.

Section 24-202. Certification and Training.

(1) All commercial fertilizer applicators and their supervisors, as well as government and institutional applicators and supervisors performing fertilizer application shall obtain a limited certification for urban landscape commercial fertilizer application from the Florida Department of Agriculture and Consumer Services pursuant to Section 482.1562, Florida Statutes. To be in compliance with the provisions of this Article, a copy of the appropriate certificate indicating the completion of the training and certification as referenced herein shall be with an applicator at all times and provided to the Hillsborough County representative, such as a Code Enforcement Officer, Public Works Administration, Public Utilities Administration, or EPCHC staff, upon request.

(2) A vehicle decal issued by the EPCHC Executive Director or other authorized organization indicating that the company is in compliance with the training and certification requirements of Chapter 1-15.10(a)-(b) of the EPCHC shall be affixed and maintained on the exterior of any vehicle used by the company in connection with landscape maintenance activities and/or the application of fertilizer within the area regulated by this Article.

Section 24-203. Recommendations.

(1) A voluntary six (6) foot low maintenance, no mow zone is strongly recommended from those areas described in as fertilizer free zones in Section 24-199, in order to reduce the potential for fertilizer residue entering adjacent water bodies and wetlands. A swale/berm system is recommended for installation at the landward edge of this low maintenance zone to capture and filter runoff. No vegetative material shall be deposited or left remaining in this zone or in the water. Care should be taken to prevent the overspray of aquatic weed products in this zone.

(2) It is recommended that the application of fertilizer for properties using reclaimed water service be reduced in accordance with the nutrient level contained in the reclaimed water. This information is available through the Hillsborough County Water Resources Department and through the Hillsborough County website.

(3) This County recommends the establishment of training programs using Spanish-speaking certified BMP trainers.

Section 24-204. Enforcement and Penalty.

(1) Hillsborough County's code enforcement officers, law enforcement, or any other person authorized to enforce county ordinances may enforce the provisions of this Ordinance.

(2) Law Enforcement Officers may enforce the provisions of this Ordinance pursuant to any enforcement action or legal remedy available under controlling local or state law including, but not limited to:

(a) Prosecution in the name of the state in the same manner as misdemeanors are prosecuted and, upon conviction, such person shall be punished by a fine not to exceed $500 or by imprisonment in the County Jail not to exceed sixty (60) days, or by both such fine and imprisonment; or

(b) Issuance of a non-criminal citation, punishable pursuant to Section 775.083(1)(e), with a fine of up to $500; and

(c) Each occurrence of a violation, or in the case of continuous violations, each day a violation occurs or continues, constitutes a separate offense and may be punished separately.

(3) Hillsborough County code enforcement officers may enforce this Ordinance pursuant to the enforcement provisions of Chapter 162, Florida Statutes and Chapter 14, Articles II and III of the Hillsborough County Code of Ordinances and Laws.

(a) A violation of this Ordinance shall be considered irreparable or irreversible.

(b) A violation of this Ordinance resulting in the issuance of a citation or notice to appear pursuant to Chapter 14, Article III, shall, upon a determination of guilt, be assessed a fine not to exceed $500 or such amount as may hereafter be prescribed by law for each violation, which fines shall be established by resolution of the Board of the County Commissioners.

(c) Each occurrence of a violation, or in the case of continuous violations, each day a violation occurs or continues, constitutes a separate offense and may be punished separately.

(4) Nothing contained herein shall prevent Hillsborough County from taking such other action in law and equity as may be necessary to remedy any violation of, or refusal to comply with, any part of this Ordinance, including but not limited to:

(a) Code enforcement action pursuant to Hillsborough County Ordinance No. 10-27, as amended;

(b) Pursuit of injunctive and/or declaratory relief in a court of competent jurisdiction;

(c) Initiating an action to recover any and all damages that may result from a violation of, or a refusal to comply with, any part of this Ordinance; or

(d) Utilizing any other action or enforcement method allowable by law.

Section 24-206. Severability.

If any section, phrase, sentence or portion of this article is for any reason held to be invalid or unconstitutional by any court of competent jurisdiction, such section, phrase, sentence or portion shall be deemed to be a separate, distinct and independent provision and such holding shall not affect the validity of the remaining portions hereof.

Section 24-207. Effective Date

Pursuant to Section 125.66, Florida Statutes, a certified copy of this Ordinance shall be filed with the Department of State by the Clerk of the Board of County Commissioners. This Ordinance shall become effective when acknowledgement is received from the Secretary of State that the Ordinance has been duly filed.

STATE OF FLORIDA)
COUNTY OF HILLSBOROUGH)

I, CINDY STUART, Clerk of the Circuit Court and Ex Officio Clerk of the Board of County Commissioners of Hillsborough County, Florida do hereby certify that the above and foregoing is a true and correct copy of an Ordinance adopted by the Board of County Commissioners at its meeting of _____________, 2021, as the same appears of record in Minute Book ____, of the Public Records of Hillsborough County, Florida.

WITNESS my hand and official seal this _____day of ____________, 2021.

CINDY STUART
CLERK OF THE CIRCUIT COURT

BY: ____________________________
Deputy Clerk

Approved by the County Attorney as to
Form and Legal Sufficiency

By:____
Senior Assistant County Attorney

Hillsborough County Florida

To: Board of County Commissioners

From: Environmental Services Division

Date: Wednesday, November 03, 2021

BOCC Regular Meeting

A Report on Scientific Rationale for Fertilizer Application Ban in Unincorporated Hillsborough County

Hillsborough County BOCC Regular Meeting
November 17, 2021

Hillsborough County Board of County Commissioners (BOCC) requested that the County Attorney's Office and the Environmental Services Division draft an ordinance regulating the application of nitrogen and phosphorus-based fertilizers in Hillsborough County. This ordinance would be similar to other ordinances throughout the state of Florida. The intent of the new rules is to limit the negative impacts of nutrients on receiving surface waters in Hillsborough County and Tampa Bay.

Currently, there are limited rules governing the application of fertilizer in Hillsborough County. Effective July 9, 2009, Section 403.9337, Florida Statutes (F.S.) required county and municipal governments with waterbodies impaired by nutrients to adopt the Florida Department of Environmental Protection's (FDEP) model ordinance which includes various rules and recommendations concerning the application of fertilizers and landscape maintenance. Since Hillsborough County has waterbodies impaired by nutrients, it adopted Environmental Protection Commission (EPC) Rule 1-15 Fertilizer Use and Landscape Management to meet the statutory requirement. This rule was adopted in July of 2010. The existing EPC rule does limit the application of fertilizers, but does not prohibit all application during the entire rainy season.

Section 403.9337, F.S. further provides, that in order to adopt additional or more stringent standards than those prescribed by the State's Model Ordinance, a local government must meet specific criteria: (a) the local government must demonstrate, as part of a comprehensive program to address nonpoint sources of nutrient pollution which is science based, and economically and technically feasible, that additional or more stringent standards than the model ordinance are necessary in order to adequately address urban fertilizer contributions to nonpoint source nutrient loading to a water body; and (b) the local government must document that it has considered all relevant scientific information, including input from FDEP, the Florida Department of Agriculture and Consumer Services (FDACS), and the University of Florida Institute of Food and Agricultural Sciences (IFAS), to provide additional or more stringent provisions to address fertilizer use as a contributor to water quality degradation. This report provides data demonstrating that additional or more stringent standards than the Model Ordinance are necessary and includes the science-based rationale for adopting more stringent standards for the application of fertilizer in Hillsborough County after considering all information provided by FDEP, FDACS and IFAS.

Hillsborough County has a number of waterbodies identified by the State of Florida as impaired for nutrients. The state completes these determinations of impairment based on specific water bodies identified by Waterbody Identification Numbers (WBIDs). These WBIDs are segments of a watershed typically centered around a riverine system. Figure 1 is a map of the WBIDs within Hillsborough County Florida. Figure 2 is a map of WBIDs designated as impaired by nitrogen within Hillsborough County. Figure 3 is a map of WBIDs designated as impaired by phosphorus within Hillsborough County. Most of the WBIDs are impaired for both nitrogen and phosphorus.

Nutrient and nutrient-associated impairments of surface waters within Hillsborough County may be due to a variety of causes including atmospheric deposition, stormwater runoff, septage or sanitary sewer contamination, etc. Misapplication of fertilizer may also be a contributing cause, either through direct introduction into the surface water, or through stormwater runoff during rain events after fertilizer has been applied. The unpredictability of rainfall is also a factor since, even if fertilizer is applied properly, an unexpected rainfall event could still cause wash off from fertilizer. As noted in the listed articles 3 and 4 by Yang and Toor, rainfall drives excess nutrient concentrations in stormwater runoff. The risk is higher during the rainy season.

The Tampa Bay Estuary Program (TBEP) was created in 1991 after Congress identified Tampa Bay as an estuary of national significance. Nitrogen was identified by TBEP early on as the limiting nutrient for the Tampa Bay since nitrogen is the nutrient that controls the growth of plants including algae in Tampa Bay. So, by reducing nitrogen inputs to Tampa Bay, the growth of algae and other undesirable plants will be limited allowing more sunlight to penetrate the water which helps the growth of desirable seagrasses and improves water quality. The TBEP publishes an annual report on the health of Tampa Bay. Hills borough County is an active participant of the TBEP. As a participating member of the estuary program Hillsborough County accepts their recommendations for improving Tampa Bay. These recommendations include lowering the load of nutrients especially nitrogen inputs into Tampa Bay.

Unfortunately, TBEP has reported a negative water quality trend in portions of Tampa Bay. More specifically, there are increasing chlorophyll-a levels in Upper Tampa Bay coupled with decreasing seagrass coverage. These conditions have been directly linked to increased nutrient loadings into Tampa Bay. Hillsborough County continues to work towards the goals of the TBEP's Comprehensive Conservation and Management Plan for Tampa Bay, including reducing septic tanks in the watershed, implementing green stormwater management infrastructure, and providing educational outreach for citizens in Hillsborough County. However, Hillsborough County staff believe that the science supports a ban on the application of nitrogen and phosphorous based fertilizers during the rainy season. A summary of the scientific literature used to draw these conclusions is as follows.

Hillsborough County Staff Literature Review for Potential Fertilizer Impacts on Surface Waters

1) *2020 Tampa Bay Nutrient Management Compliance Assessment Results*, 2021, Ed Sherwood, Tampa Bay Estuary Program
    - <u>Report Findings</u>: Water quality indicators including chlorophyll-a and acres of seagrass show that Old Tampa Bay's water quality is declining.
    - <u>Staff's Interpretation</u>: Scientists with TBEP have stated that increasing chlorophyll-a levels and decreasing seagrass beds are a direct result of increased nitrogen. The TBEP has also stated that over 50% of the nitrogen inputs into Tampa Bay are from stormwater runoff. Hillsborough County is required to reduce pollutant discharges from its stormwater system to the maximum extent practicable per its NPDES MS4 permit and has committed as a member of the Nitrogen Management Consortium to reduce nitrogen inputs into Tampa Bay. Controlling the use of nitrogen-based

fertilizer through the proposed ordinance is one tool towards achieving reduced nitrogen loading.

2) *The Fate of Nitrogen Applied to Florida Turfgrass* by Shaddox and Unruh (IFAS)
   - Report Finding: The authors state that the combination of nitrogen leaching and runoff from fertilized lawns ranges from 0% to 55% and 1%-7%, respectively.
   - Staff's Interpretation: There is a probability that excess nitrogen will be released from lawns and landscaping where nitrogen containing fertilizer is used.

3) *Sources and mechanisms of nitrate and orthophosphate transport in urban stormwater runoff from residential Catchments* by Yun-Ya Yang and Gurpal S. Toor, 2017, UF IFAS
   - Report Findings: The main sources of nitrate nitrogen in urban stormwater runoff was atmospheric deposition (range 35-64%), followed by chemical N fertilizers (range 1-39%).
   - Staff's Interpretation: Stormwater runoff, which is attributable to the built environment, contributes significant input of nitrogen load into surface waters including Tampa Bay.

4) *δ15N and δ18O Reveal the Sources of Nitrate-Nitrogen in Urban Residential Stormwater Runoff,* by Yun-Ya Yang and Gurpal S. Toor, 2016, UF IFAS
   - Report Findings: Using advances in water sampling techniques the researchers were able to identify chemical nitrogen fertilizers contributed a range of 1% to 49% of the nitrogen concentration in a residential stormwater catchment.
   - Staff's Interpretation: Nitrogen in residential stormwater runoff is partially attributable to the application of fertilizer to lawns and landscapes.

5) *Urban Water Quality and Fertilizer Ordinances: Avoiding Unintended Consequences: A Review of Scientific Literature*. 2009. IFAS Publication SL283
   - Report Finding: Losses are most likely when fertilizer is applied just before or during heavy rainfall (Soldat and Petrovi 2008).
   - Staff's Interpretation: During Hillsborough County's rainy season, which is June through September, heavy rainfalls are difficult to predict and the risk of applying fertilizer that is washed away from the application site is high.

Taken together, these sources indicate that it is highly probable that the nutrients in fertilizer will become mobilized if fertilizers are misapplied or applied at the wrong time especially in the rainy season. Since all of Hillsborough County, except for a few acres in Northwest Hillsborough County, are located in the Tampa Bay Watershed, these mobilized nutrients will ultimately end up in Tampa Bay and other surface waters. The fugitive nutrients will contribute to the overabundance of nutrients in our rivers, lakes, and the Bay causing numerous problems including algae blooms like red tide, fish kills and loss of seagrasses.

Comments Received From State Agencies

University of Florida Institute of Food and Agricultural Science Comments:

Attached are comments from UF/IFAS. Several of the proposed changes are good. However, there are significant concerns with this proposed ordinance that have not been reasonably addressed. Namely, Section 24-201(2) points "specialized turf" managers to the GI-BMPs. There is no mention of managing "athletic fields, golf courses, golf course practice areas, or other private or public athletic fields" in that training document (other than Appendix C: Rule 5e-1.003(2) Labeling Requirements for Urban Turf Fertilizers). See: *https://ffl.ifas.ufl.edu/media/fflifasufledu/docs/GIBMP_Manual_Web_English.pdf*

UF/IFAS also raises concern that Section 24-201(2) will seriously impact professional sports facilities (e.g., Raymond James Stadium) that are owned by Hillsborough County. This was not addressed in the revision.

Should you have any additional questions or need clarification on any of the comments, please do not hesitate to contact me.

Bryan

J. Bryan Unruh, Ph.D.
Professor and Associate Center Director
West Florida Research and Education Center
University of Florida
4253 Experiment Drive, Hwy. 182
Jay, FL 32565

Staff Analysis: The City of Tampa has had a fertilizer ordinance in place for ten years with no reported issues with either Raymond James Stadium's football turf or Steinbrenner Field's baseball diamond.

Hillsborough County staff discussed the issue with staff who manage specialized turf. They stated they are aware of the Best Management Practices including those published specifically for the Golf Industry. They also stated they get training from fertilizer vendors as well as IFAS staff on fertilizer and pesticide applications.

Has Hillsborough County reconciled recently published research that states:

1.) *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 (https://www.sciencedirect.com/science/article/pii/S0048969720358496)* *and*

2.) *Because of local government "rainy season" bans on fertilizer use, many private citizens and lawn care companies have shifted to the application of urea-based timed-release fertilizers. Thus, the fertilizer ban may have actually increased the observed total N flux into Sarasota Bay during these rainy periods (https://www.mdpi.com/2073-4441/12/10/2755)*

These two articles from Florida-based research need to be addressed if the more-restricted ordinance is to be proposed.

Staff Analysis with Input from Tampa Bay Estuary Program and Hillsborough County Environmental Protection Commission:

Article #1) It was noted that the first article included research from a very small sample size (10 private residences). The article does not include any recommendations concerning black-out dates. The lead author for this article wrote a summary article of the research in Volume 94 Fall 2021 Florida Lake Watch Newsletter which noted nutrients from fertilizer are impacting surface waters and the conclusion '…we need to effectively manage all sources of nutrients in the urban environment…'.

- This research was focused on only ten residential lots and the statistical test indicated that the data gathered had such great variability it did not allow for conclusions. In other words, although the data did not indicate the fertilizer ban was the reason for observed reduction in nitrogen, it did not indicate that the fertilizer ban was unsuccessful in reducing nitrogen inputs into surface waters.
- For the reasons outlined above, we refer UF/IFAS to more locally-derived research which further elucidates the sources of nitrogen in stormwater from residential communities within Hillsborough County (Yang and Toor 2016; 2017).
- Lastly, nutrient concentrations alone are a poor surrogate for assessing nutrient mass loading into coastal systems. Nutrient mass loading is what typically drives primary production and therefore measured algal response in estuaries. Although the study makes tenuous conclusions on stormwater nutrient concentrations (without taking into account rainfall depth and duration), it does not speak to total nutrient loading to the estuarine system that could exacerbate water quality degradation. Managing Hillsborough County's coastal water quality as a result of excessive nutrient inputs (no matter the source) has been the primary motivator for Tampa Bay's nitrogen management strategy to restore seagrass beds.

Article #2) While this was published in 2020, the study relies on data collection efforts from the Summer and Fall of 2009. This period is only 1-year after surrounding municipalities adopted summer rainy season fertilizer restrictions. It preceded an intense, regional community education program focused on educating homeowners on landscape management practices consistent with recently passed ordinances (i.e. the BeFloridian.org campaign was initiated in 2010). The importance of this regional education campaign on modifying homeowner fertilization practices is highlighted in Listopad et al. 2019. Therefore, the one sentence from this research that links results to in-bay urea concentrations to recently enacted regional fertilizer ordinances are tenuous, at best.

Florida Department of Environmental Protection Comments:

From: Kevin Coyne, Florida Department of Environmental Protection

Overall, looks fine – I would consider the comments on the sports field from Bryan – but the changes don't change or impact the overall goal of meeting the basic requirements of the Model Ordinance.

Staff Analysis: Hillsborough County Staff spoke with Mr. Coyne and relayed our appreciation of FDEP's review of the proposed Ordinance.

Figure 1. Waterbody IDs (WBIDs) within Hillsborough County

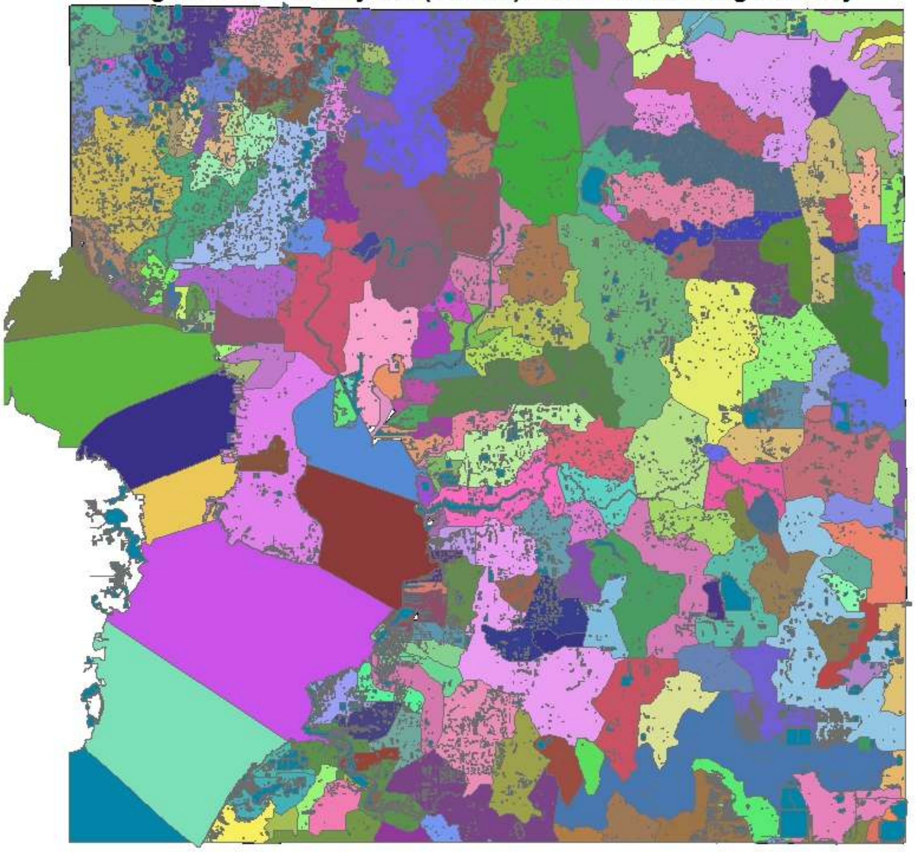


Figure 2. Nitrogen Impaired Waterbody IDs (WBIDS)

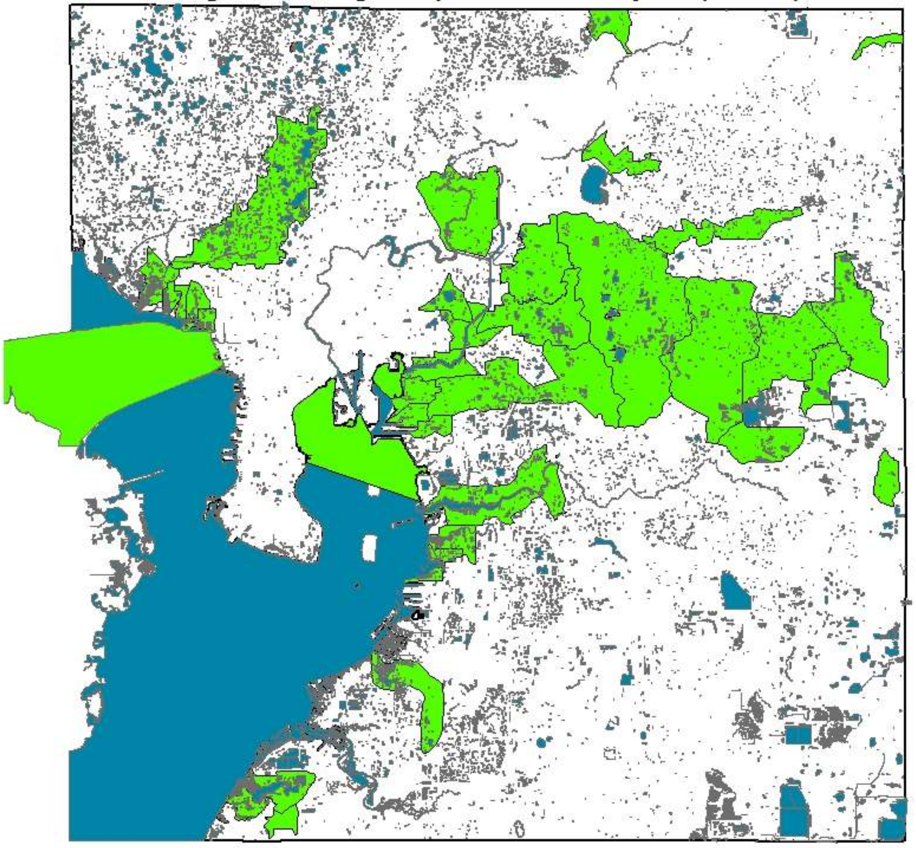
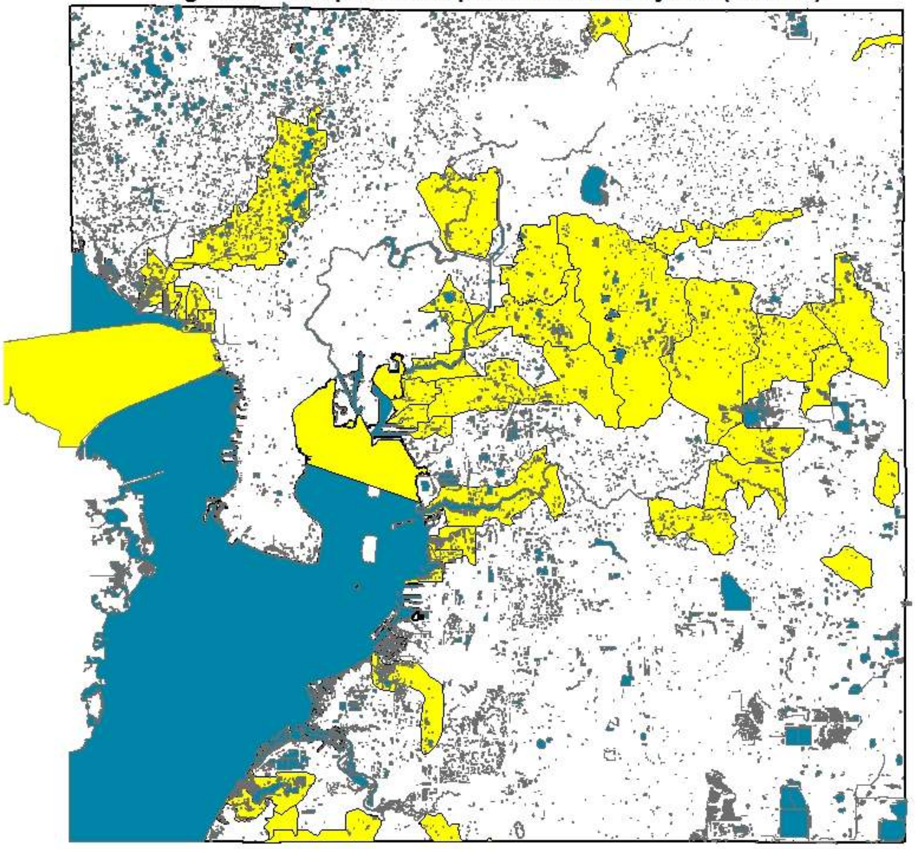


Figure 3. Phosphorus Impaired Waterbody IDs (WBIDS)



THE TAMPA BAY NITROGEN MANAGEMENT CONSORTIUM PARTNERSHIP FOR PROGRESS

2020 Tampa Bay Estuary Nutrient Management Compliance Assessment

2020 Results Summary

References

THE TAMPA BAY NITROGEN MANAGEMENT CONSORTIUM PARTNERSHIP FOR PROGRESS

TO: Adam Blalock, FDEP
John Blevins, US EPA Region 4
FROM: Ed Sherwood, TBEP Executive Director (NMC Facilitator)
DATE: 2021-05-26
SUBJECT: 2020 Tampa Bay Nutrient Management Compliance Assessment Results
cc: Ken Weaver, Jessica Mostyn, Ben Ralys, Kevin O'Donnell, Julie Espy, Daryll Joyner (FDEP Tallahassee)
Ramandeep Kaur, Vishwas Sathe, Amaury Betancourt, Anthony Annibali, Edgar Guerron-Orejuela (FDEP Tampa)
Jeaneanne M. Gettle, Tony Able, Felicia Burks, Tom McGill (EPA Region 4)
Jeff Greenwell, Santino Provenzano, Tony Janicki, Ray Pribble (TBNMC)
Ed Sherwood, Maya Burke, Marcus Beck (TBEP)

Source content: here (https://github.com/tbep-tech/tbnmc-compliance-assessment)

On behalf of the Tampa Bay Nitrogen Management Consortium, please find attached the 2020 update on water quality and seagrass resources in the Tampa Bay estuary. This update has been developed in accordance with the compliance assessment adopted through FDEP's Tampa Bay Reasonable Assurance determination on December 22, 2010 (Link to FDEP Final Order (https://tbep.org/nmc-final-order/)), FDEP's subsequent approval of the 2017 RA Update (Link to FDEP Acceptance Letter (https://drive.google.com/file/d/12xMbQSS6bSqhkzE2odNkOg94iNwRgE-N/view?usp=sharing)), and the federally-recognized TMDL for Tampa Bay (Link to EPA TMDL (http://iaspub.epa.gov/waters10/attains_impaired_waters.tmdl_report?p_tmdl_id=1180&p_tribe=&p_report_type=)). The formal annual compliance assessment utilized by the Consortium is detailed in Section VIII.B of the Final 2009 Reasonable Assurance Addendum: Allocation and Assessment Report (Link to Final Document (https://drive.google.com/file/d/10IjJAfcGFf007a5VdPXAUtUi4dx-cmsA/view)).

During 2020, the COVID-19 pandemic precluded water quality data collection in April and May. As a result of this anomalous event, formal compliance determinations have not been made for any bay segments for 2020. All reported chlorophyll-a concentrations contained in this report are calculated without observations from the months noted above. In summary, chlorophyll-a concentrations in three of four major bay segments were below FDEP-approved numeric nutrient criteria thresholds with the exception being Old Tampa Bay. Elevated concentrations were observed in Old Tampa Bay between June and September, primarily due to annually recurring *Pyrodinium bahamense* blooms.

The approved chlorophyll-a thresholds were adopted as part of FDEP's 2002 Reasonable Assurance determination for Tampa Bay, and, at that time, it was determined that Tampa Bay's seagrass restoration goals could be achieved if annual chlorophyll-a concentrations remained below these thresholds. If a bay segment's chlorophyll-a concentration remains above thresholds for 2 concurrent years, additional compliance assessment steps are required by the Consortium. This nutrient management strategy has been consistently used by the TBEP and Consortium in their Annual Decision Matrix and Assessment reports for Tampa Bay since 2009 when nitrogen load allocations for Tampa Bay were formalized (M. Beck, M. Burke, G. Raulerson 2021).

In 2020, the Tampa Bay Estuary Program also updated the Habitat Master Plan (Environmental Science Associates (D. Robison, T. Ries, J. Saarinen, D. Tomasko, and C. Sciarrino) 2020) for Tampa Bay, adopting a new goal of maintaining at least 40,000 acres of seagrass within the bay. This represents a slight increase from the previous goal of 38,000 acres adopted in the mid-1990s. The Southwest Florida Water Management District's (SWFWMD) 2020 baywide seagrass coverage estimate is 34,297 acres (Figure 5). This latest estimate brings Tampa Bay's total seagrass coverage below the 40,000 acre protection and recovery goal. Reductions in seagrass coverage were observed throughout the coastal waterbodies and estuaries mapped by the SWFWMD, and additional research is being conducted to understand these most recent trends. Notwithstanding these setbacks, implementation of the Consortium's approved nutrient management strategy continues to be a successful, adaptive management approach to address nutrient loading to the Tampa Bay estuary. For the majority of Tampa Bay, water quality continues to be supportive of seagrass resources.

Thank you again for your continued participation in the Consortium's process. Please contact Ed Sherwood (esherwood@tbep.org (mailto:esherwood@tbep.org)) with any questions about the Consortium's Annual Compliance Assessment.

2020 Tampa Bay Estuary Nutrient Management Compliance Assessment

On December 22, 2010, then FDEP Secretary Drew signed a Final Order (FDEP 2010 (http://www.tbeptech.org/attachments/article/50/FDEP_Final_Order_2009_RA_Addendum.pdf)) accepting and approving the 2009 Reasonable Assurance (RA; TBNMC 2010 (https://drive.google.com/file/d/10IjJAfcGFf007a5VdPXAUtUi4dx-cmsA/view?usp=drivesdk)) Addendum for the Tampa Bay estuary. The final order found that the Nitrogen Management Consortium (NMC) provided FDEP reasonable assurance that: 1) completed and proposed management actions in the 2009 RA Addendum will result in the continued attainment of the estuarine nutrient criteria within Tampa Bay, and 2) compliance with the allocations in the 2009 RA Addendum ensures reasonable progress towards continued attainment of the estuarine nutrient criteria and associated Class III designated uses. Furthermore, the FDEP finalized a WQBEL for the Tampa Bay estuary in accordance with the allocations developed under the 2009 RA Addendum in November 2010. The Consortium completed subsequent RA Updates in 2012 (https://tbep.org/reasonable-assurance-plans-updates-2012/) and 2017 (https://tbep.org/reasonable-assurance-plans-updates-2017/) maintaining allocations and expanding upon projects originally defined in the 2002 RA Submittal (https://tbep.org/reasonable-assurance-plans-updates-2002/), 2007 RA Update (https://tbep.org/reasonable-assurance-plans-updates-2007/) and 2009 RA Addendum (https://drive.google.com/file/d/10IjJAfcGFf007a5VdPXAUtUi4dx-cmsA/view?usp=drivesdk).

As part of the compliance assessment stipulated under the 2009 RA Addendum, the NMC committed to annually assess the water quality and seagrass conditions within Tampa Bay and report these to FDEP and EPA. The Consortium's assessment responsibilities are shown in green in Figure 1. It should be noted that the Consortium's reasonable assurance assessment strategy begins with the observation of water quality conditions in the bay for a particular year. As is recommended in numerous EPA guidance documents for the development of numeric nutrient criteria, the Consortium's assessment strategy attempts to apply a stressor-response rationale for the determination of nitrogen load allocation reasonable assurance in the estuary.

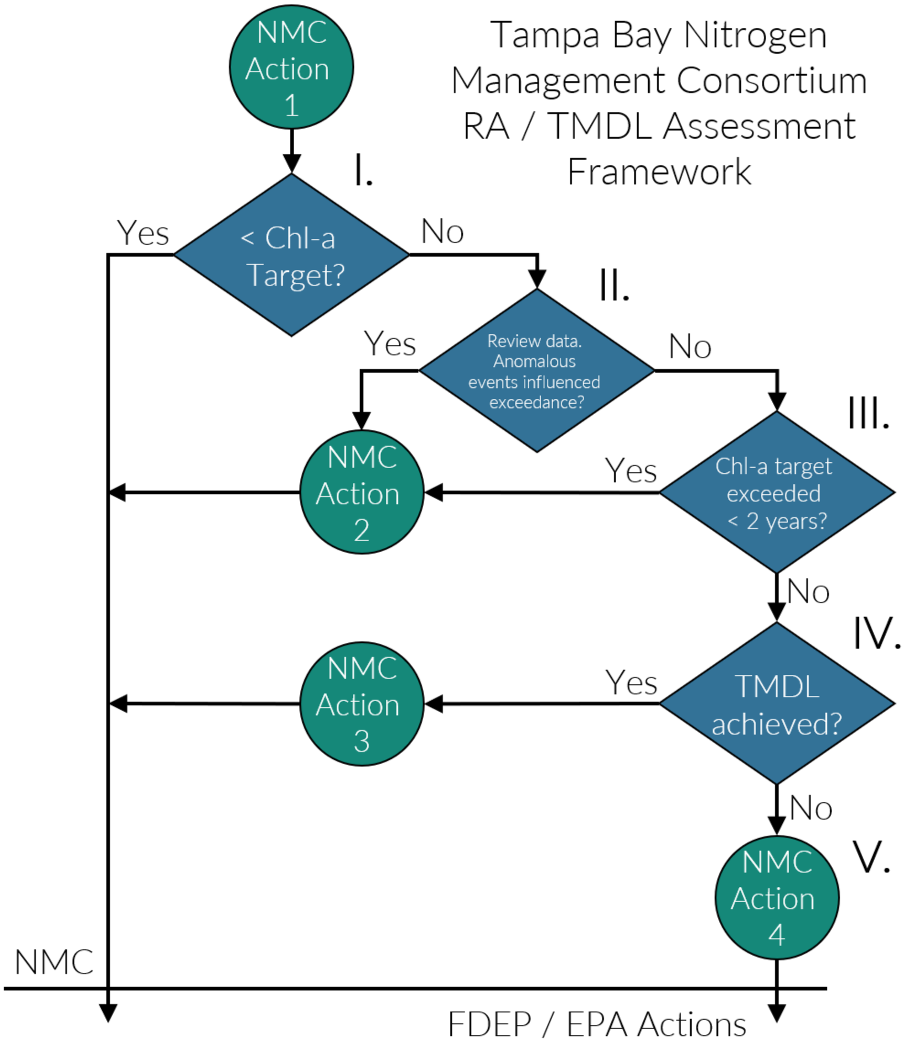


Figure 1: Nitrogen Management Consortium decision framework to assess future reasonable assurance of adopted allocations. Actions and steps to be conducted by the NMC are shown in the circles and diamonds. Steps, decision points, and actions are outlined in Table 1 (below) according to the Roman numerals listed in the figure.

The framework is applied on a bay-segment basis, and is predicated on assessing annual attainment of the bay segment chlorophyll-a concentration threshold as the initial step. If the bay segment-specific chlorophyll-a threshold is met, the Consortium annually reports the results to FDEP and EPA and additional assessment steps are not required by the Consortium (by June of the following year). If annual average chlorophyll-a thresholds are not met in one or more bay segments, additional assessment steps are required by the Consortium as noted in the framework and assessment process (Figure 1, Table 1).

Regardless of the assessment results, the Consortium will annually report (by June of the following year) whether the bay segment specific chlorophyll-a thresholds are met using the Environmental Protection Commission of Hillsborough County (EPCHC) dataset, as traditionally assessed using the "Decision Matrix" management strategy developed by the TBEP (A. Janicki, D.Wade, J.R. Pribble 2000) and will deliver this to FDEP and EPA (Figure 1; NMC Action 1 in the Framework). If an annual, individual exceedence of a bay segment chlorophyll-a threshold is observed, an addendum report outlining the anomalous event(s) or data which influenced the bay segment chlorophyll-a exceedence will be delivered to FDEP and EPA upon review by NMC participants by September of the following year (Figure 1; NMC Action 2 in the Framework). An evaluation of the bay segment assimilative capacity (i.e. revision to the federally-recognized TMDL) is formally considered (if not already considered by the NMC) when bay segment chlorophyll-a thresholds are not met in 2 concurrent years, and hydrologically normalized loads for those years meet the federally-recognized TMDL (Figure 1; NMC Action 3 in the Framework). Alternatively, when bay segment chlorophyll-a thresholds are not met in 2 concurrent years and hydrologically normalized loads for those years also do not meet the federally-recognized TMDL, the Consortium will deliver a full loading report to FDEP and EPA comparing the observed, combined entity/source annual or multiple year loadings to the sources' 5-yr annual average allocation by September of the following year. This report will identify any exceedences among combined entity/source load categories after taking into consideration "set allocation" sources and hydrologically-normalized sources, and if necessary, whether exceedences were observed for individual MS4 or unpermitted (LA) sources (Figure 1; NMC Action 4 in the Framework). It is noted that FDEP will independently assess individual entities for compliance with their allocations.

Table 1: Assessment steps linked to the Nitrogen Management Consortium's decision framework, as depicted in Figure 1.

Assessment Step	**Result**	**Action**
I. Determine annual bay segment specific chlorophyll-a FDEP threshold attainment as traditionally assessed using the Decision Matrix management strategy developed by the TBEP (A. Janicki, D.Wade, J.R. Pribble 2000).	**Yes**	**NMC Action 1**
	No	**NMC Action 1**
II. Review data and determine if an anomalous event(s) influenced non-attainment of the bay segment specific chlorophyll-a threshold.	**Yes**	**NMC Action 2**
	No	**Go to III**
III. Determine if the chlorophyll-a thresholds have been exceeded for <2 consecutive years.	**Yes**	**NMC Action 2**
	No	**Go to IV**
IV. Determine if the bay segment specific federally-recognized TMDL has been achieved using the hydrologically-adjusted compliance assessment outlined in NMC Decision Memo #11 (Appendix 2-11).	**Yes**	**NMC Action 3**
	No	**Go to V**
V. For a given year or for multiple years, compile and report entity-specific combined source loads in comparison to 5-yr annual average reasonable assurance allocation.	**Compile & Report**	**NMC Action 4**

NMC actions outlined in Figure 1 and Table 1 performed during RA Implementation Period (2017-2021) are as follows:

NMC Action 1 -	A report assessing attainment of bay segment specific chlorophyll-a thresholds using the EPCHC dataset, as traditionally assessed using the Decision Matrix management strategy developed by the TBEP (A. Janicki, D.Wade, J.R. Pribble 2000) will be delivered to FDEP and EPA (this report).
NMC Action 2 -	A report of the anomalous event(s) or data which influenced the bay segment chlorophyll-a exceedence will be delivered to FDEP and EPA, upon review by NMC participants (this report).

NMC Action 3 - Consider re-evaluation of the bay segment assimilative capacity based on nonattainment of bay segment chlorophyll-a threshold while meeting federally-recognized TMDL.
NMC Action 4 - If federally-recognized TMDL not achieved, compile results of hydrologic evaluation for FDEP's review and identify potential further actions needed to achieve reasonable assurance for bay segment allocations.

2020 Results Summary

During 2020, the COVID-19 pandemic precluded water quality data collection in April and May. As a result of this anomalous event, compliance determinations have not been made for any bay segments. All reported chlorophyll-a concentrations are calculated without observations from the months noted above. Results from 2020 indicate that all RA bay segments, excluding Old Tampa Bay, met chlorophyll-a thresholds accepted by the FDEP to maintain FDEP Reasonable Assurance for Tampa Bay and to comply with the EPA TMDL (Figure 2) and estuarine numeric nutrient criteria for Tampa Bay (EPA Approval Letter Nov. 30, 2012 (http://www.dep.state.fl.us/water/wqssp/nutrients/docs/new/epa_approval_letter_113012.pdf)). In Old Tampa Bay, chlorophyll-a concentrations were elevated in a poorly flushed region that has typically produced summertime blooms of *Pyrodinium bahamense* since 2009 (Figure 3; *Note that individual station exceedences are not considered in this RA compliance assessment*). This observation is reflected in the majority of summertime months with chlorophyll-a concentrations higher than long-term median values in Old Tampa Bay (Figure 4). In response, the Consortium formed an Old Tampa Bay Working Group in early 2020 to prioritize additional investigations and future management actions that may alleviate the conditions fostering these summertime blooms. Additionally, the Consortium is proactively developing loading information for the 2018-2020 period to assess any anomalous loading conditions.

The TBEP, in partnership with the Southwest Florida Water Management District, has previously developed an integrated ecosystem model to evaluate the net environmental benefits that may result from implementing various management actions in Old Tampa Bay including: reducing point sources, nonpoint sources, and causeway obstructions in Old Tampa Bay (E. Sherwood, H. Greening, L. Garcia, K. Kaufman, T. Janicki, R. Pribble, B. Cunningham, S. Peene, J. Fitzpatrick, K. Dixon, M. Wessel 2015). Furthermore, the TBEP is funding research conducted by the Florida Fish and Wildlife Research Institute to improve understanding of the cell physiology and behavior of *Pyrodinium bahamense* and evaluate the potential for using shellfish to mitigate these algal blooms in Old Tampa Bay. Monthly chlorophyll-a conditions in Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay were largely within or below median historic ranges during 2020 (Figure 4). Finally, a water quality dashboard (https://shiny.tbep.org/wq-dash (https://shiny.tbep.org/wq-dash)) was developed to synthesize the data, assess additional water quality metrics (phytoplankton counts), and inform Consortium participants and other resource managers on the status of water quality in Tampa Bay. The dashboard will allow for enhanced adaptive management response by the community in the future.

Seagrasses remain relatively stable throughout much of Lower to Middle Tampa Bay; however, recent declines to the ephemeral seagrass beds in upper Tampa Bay were observed in 2020. Aerial photographs taken in December 2019 - January 2020 indicate that seagrass coverage decreased by 6,355 acres baywide over the 2018 estimate and have fallen below the TBEP recovery goal (Figure 5). Seagrass acreage showed the greatest decreases in Old Tampa Bay (-4,041 acres) and Hillsborough Bay (-627 acres). Systemic reductions to seagrass coverage estimates were observed throughout the SWFWMD's mapped domain in 2020, and additional research is being pursued to understand the underlying mechanisms influencing these observations. The next SWFWMD seagrass coverage estimate will be developed from aerial photographs acquired over the winter 2021-22 period.

Detailed results for the 2017-2021 RA implementation period are also provided in Tables 2, 3, 4, and 5 for each bay segment. As of the 2020 reporting period, NMC Actions 2-5 are not necessary based upon observed water quality conditions within Tampa Bay, though additional work is being pursued by the TBEP and TBNMC to understand the most recent trends in seagrass coverage. Individual annual reports of the bay's conditions from 2017 – 2020 can be found on the TBEP website, as specified in the following links (E. Sherwood, G. Raulerson 2018; M. Burke, G. Raulerson 2019; M. Beck, M. Burke, G. Raulerson 2020, 2021). A summary of historic attainment of the regulatory chlorophyll-a thresholds for each of the bay segments is depicted in Figure 6.

Lastly, annual hydrologic conditions within two of four bay segments in 2020 were estimated to exceed 1992-1994 levels. Therefore, hydrologic adjustments for evaluating compliance with individual entity load allocations/permitting targets should be applied for the Old Tampa Bay and Hillsborough Bay segments (Janicki Environmental, Inc. 2012, 2016). The estimated hydrologic loads for each bay segment relative to observed 1992-1994 levels are indicated in the table below. The associated compliance load adjustment factors (if applicable) are also specified. A tool to calculate the hydrologic estimates and adjustment factors by bay segment is now available online through an interactive dashboard (https://shiny.tbep.org/tbnmc_hydrologic_estimates/ (https://shiny.tbep.org/tbnmc_hydrologic_estimates/)).

Bay Segment	1992 - 1994 Hydrology (95% Prediction Interval, million m3)	Hydrology Estimate (million m3)	Compliance Load Adjustment Factor
Old Tampa Bay	383 - 548	606.10	1.35
Hillsborough Bay	753-1110	1,118.01	1.23
Middle Tampa Bay	524-756	539.16	
Lower Tampa Bay	312-402	385.11	

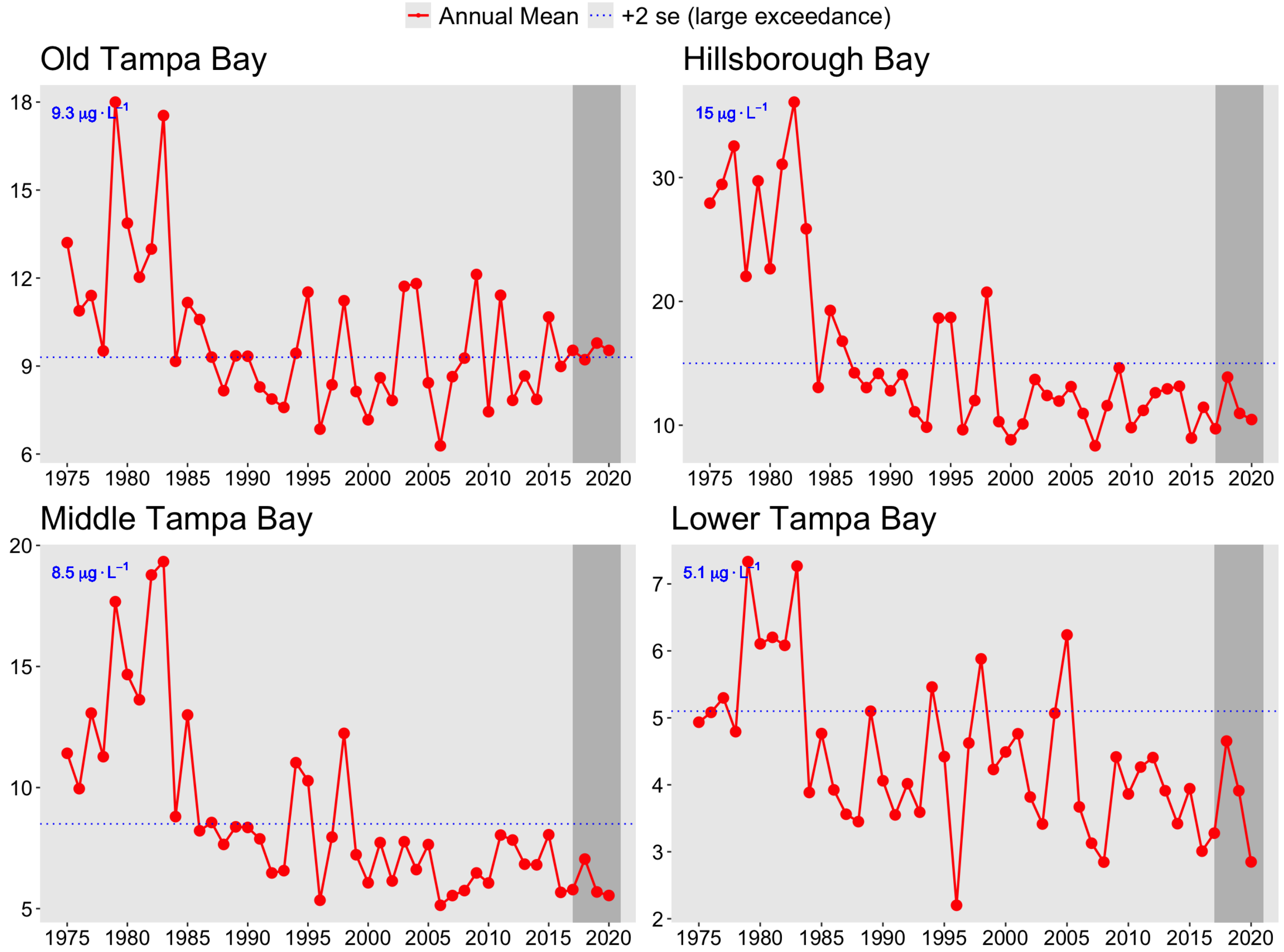


Figure 2: Historic chlorophyll-a annual averages for the four major bay segments of Tampa Bay. Annual averages in 2020 were below the regulatory thresholds developed under the Tampa Nitrogen Management Consortium's nutrient management strategy in three of four bay segments, excluding Old Tampa Bay (April, May data missing for 2020). Vertical grey bars indicate the the 2017-2021 Reasonable Assurance compliance assessment period Data source: EPCHC.

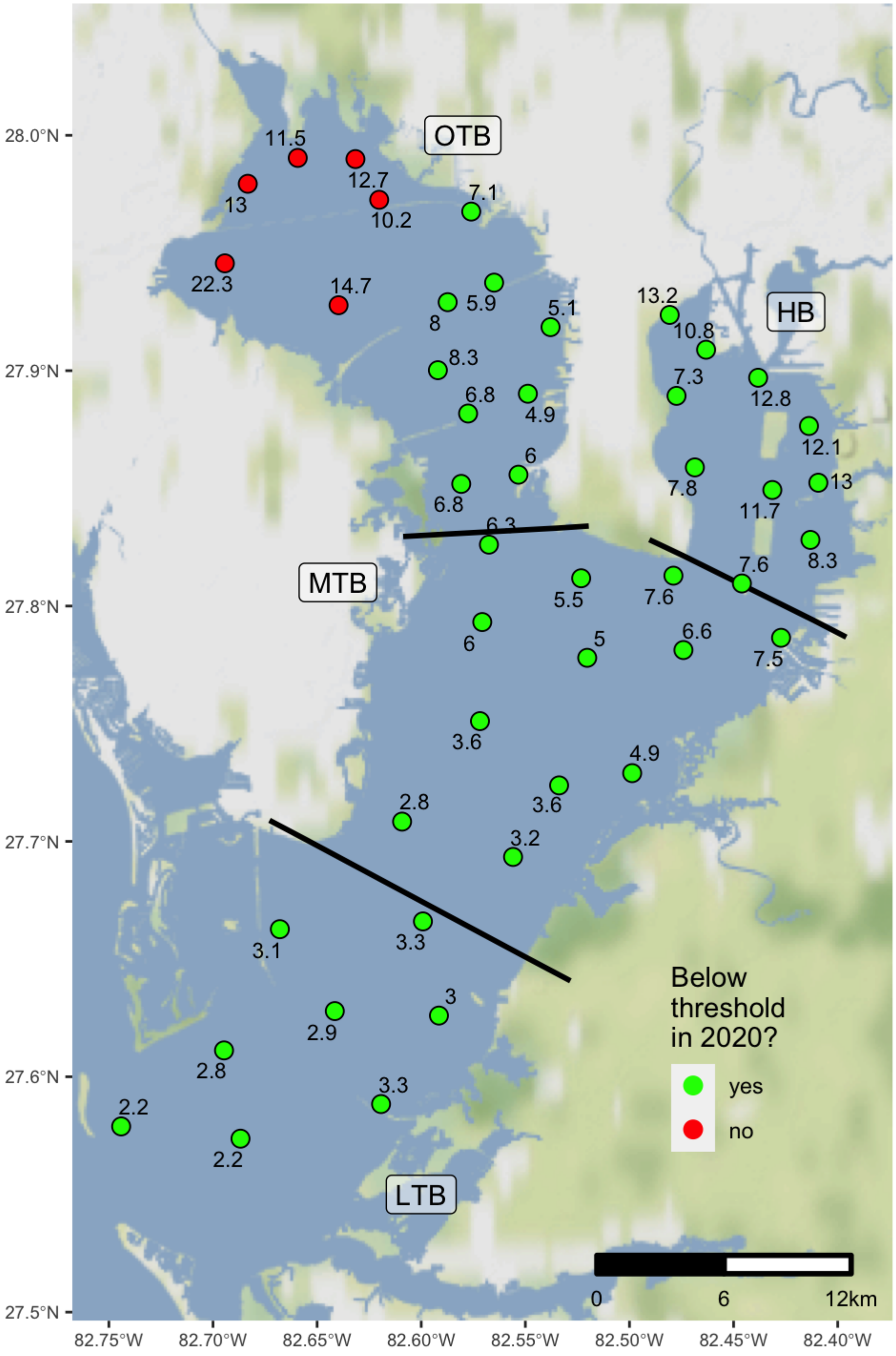


Figure 3: Map depicting individual station chlorophyll-a exceedences in Tampa Bay relative to FDEP regulatory thresholds for chlorophyll-a. Note individual station exceedences do not indicate failed compliance at the bay segment scale.

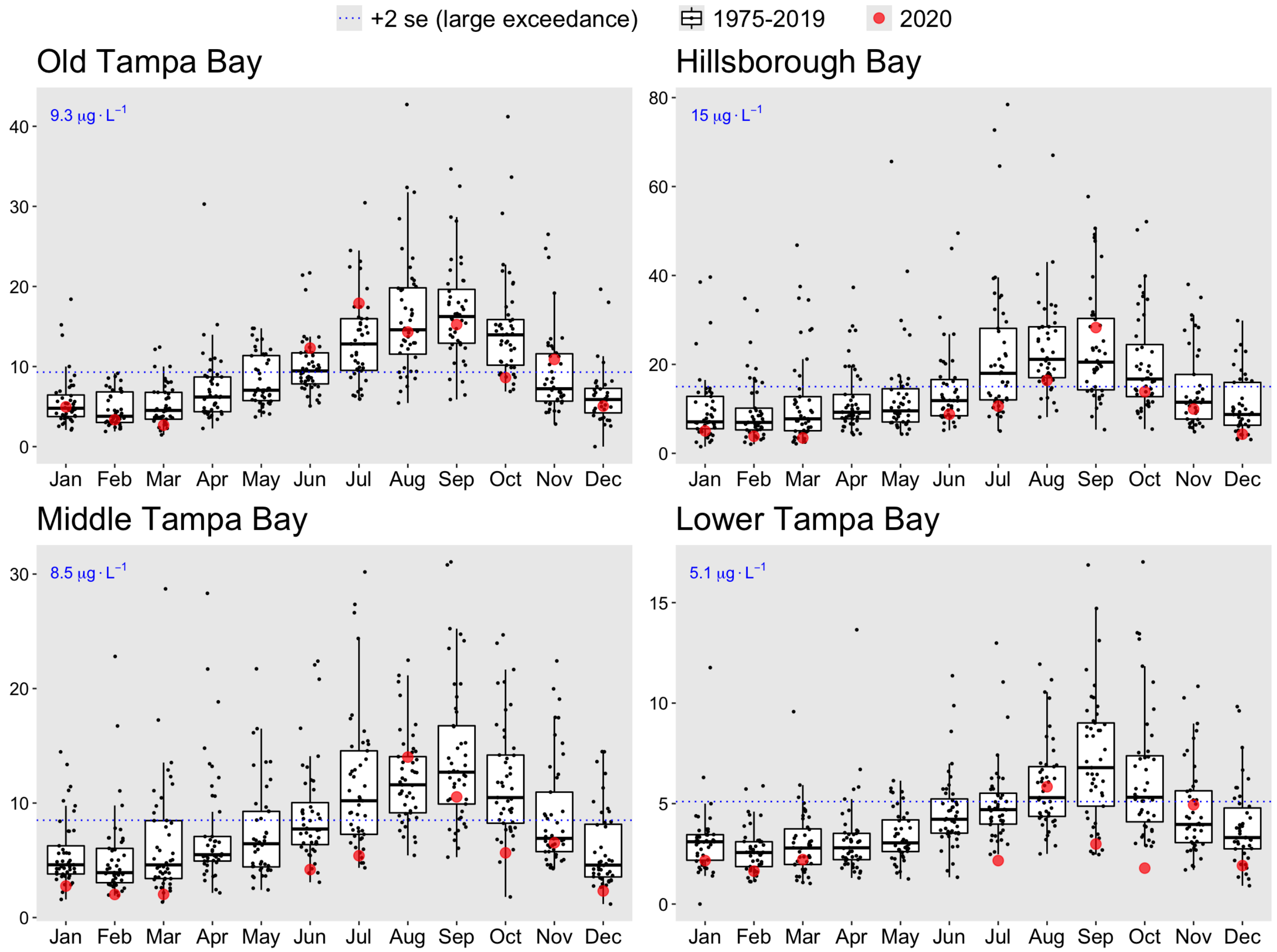


Figure 4: 2020 monthly chlorophyll-a bay segment means (red dots) compared to monthly distributions from 1972-2019 (box plots and black dots). Boxes encompass the 25th and 75th percentiles, while whiskers bound the interquartile range. Dots beyond the whiskers represent outliers throughout the 1972-2019 sample period. April, May data missing for 2020.

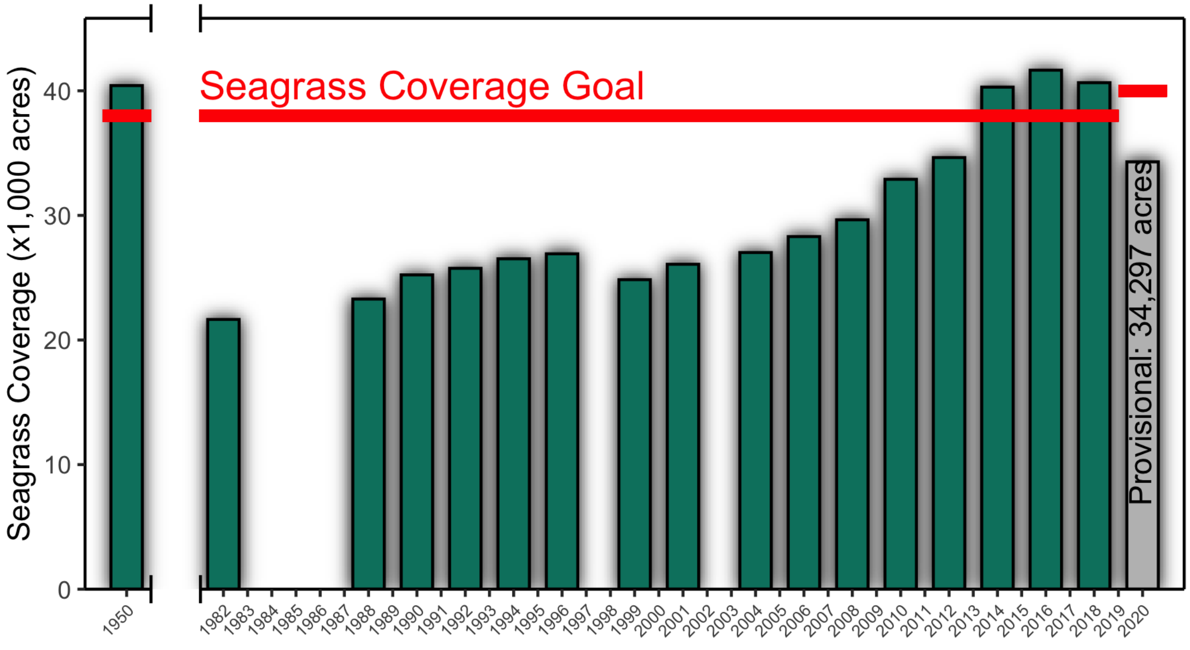
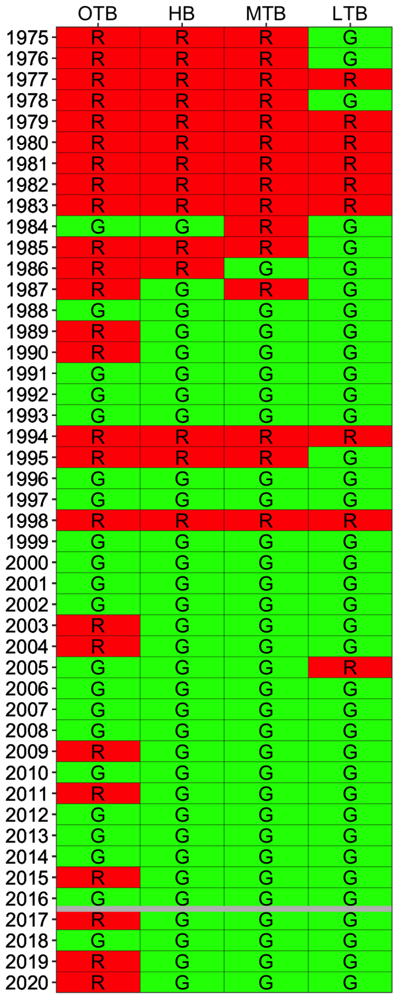


Figure 5: Historic seagrass coverage estimates for Tampa Bay. The target coverage of 38,000 acres was changed to 40,000 acres in 2020 to reflect programmatic goals in the 2020 Habitat Master Plan Update (TBEP #07-20 (https://drive.google.com/file/d/1Hp0l_qtbxp1JxKJoGatdyuANSzQrpL0I/view?usp=drivesdk)). 2020 coverage

estimate is provisional. Data source: TBEP & SWFWMD.



	OTB	HB	MTB	LTB
1975	R	R	R	G
1976	R	R	R	G
1977	R	R	R	R
1978	R	R	R	G
1979	R	R	R	R
1980	R	R	R	R
1981	R	R	R	R
1982	R	R	R	R
1983	R	R	R	R
1984	G	G	R	G
1985	R	R	R	G
1986	R	R	G	G
1987	R	G	R	G
1988	G	G	G	G
1989	R	G	G	G
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2008	G	G	G	G
2009	R	G	G	G
2010	G	G	G	G
2011	R	G	G	G
2012	G	G	G	G
2013	G	G	G	G
2014	G	G	G	G
2015	R	G	G	G
2016	G	G	G	G
2017	R	G	G	G
2018	G	G	G	G
2019	R	G	G	G
2020	R	G	G	G

Figure 6: Attainment of adopted chlorophyll-a thresholds (1974 - 2020) in the four major bay segments. Green (yes) indicates that average annual chlorophyll-a thresholds were met; red (no) indicates that threshold levels were not met. Grey line is the beginning of the Reasonable Assurance implementation period. Data source: EPCHC.

Table 2: Demonstration of reasonable assurance assessment steps for Old Tampa Bay. Green and red squares indicate outcomes of decision points outlined in the Consortium's reasonable assurance assessment framework (Figure 1).

Bay Segment Reasonable Assurance Assessment Steps	DATA USED TO ASSESS ANNUAL REASONABLE ASSURANCE					OUTCOME
	Year 1 (2017)	Year 2 (2018)	Year 3 (2019)	Year 4 (2020)	Year 5 (2021)	
NMC Action 1: Determine if observed chlorophyll-a exceeds FDEP threshold of 9.3 ug/L	9.5 (Yes)	9.2 (No)	9.8 (Yes)	9.5 (Yes)		First, third, and fourth years (2017, 2019, 2020) above threshold, necessary for NMC Actions 2-5.
NMC Action 2: Determine if any observed chlorophyll-*a* exceedences occurred for 2 consecutive years	No	No	No	Yes		Concurrent years with threshold exceedances occurred (2019, 2020), necessary for NMC actions 3-5.

NMC Action 3: Determine if observed hydrologically-normalized total load exceeds federally-recognized TMDL of 486 tons/year	N/A	N/A	N/A	Check data		Review data, check if anomalous events influenced exceedance.
NMC Actions 4-5: Determine if any entity/source/facility specific exceedences of 5-yr average allocation occurred during implementation period						Not necessary when chlorophyll-*a* threshold met

Table 3: Demonstration of reasonable assurance assessment steps for Hillsborough Bay. Green and red squares indicate outcomes of decision points outlined in the Consortium's reasonable assurance assessment framework (Figure 1).

Bay Segment Reasonable Assurance Assessment Steps	DATA USED TO ASSESS ANNUAL REASONABLE ASSURANCE					OUTCOME
	Year 1 (2017)	Year 2 (2018)	Year 3 (2019)	Year 4 (2020)	Year 5 (2021)	
NMC Action 1: Determine if observed chlorophyll-a exceeds FDEP threshold of 15 ug/L	9.7 (No)	13.9 (No)	11 (No)	10.5 (No)		All years below threshold so far, not necessary for NMC Actions 2-5
NMC Action 2: Determine if any observed chlorophyll-*a* exceedences occurred for 2 consecutive years	No	No	No	No		All years met threshold, not necessary for NMC Actions 3-5
NMC Action 3: Determine if observed hydrologically-normalized total load exceeds federally-recognized TMDL of 1451 tons/year	N/A	N/A	N/A	N/A		Not necessary due to observed water quality and seagrass conditions in the bay segment
NMC Actions 4-5: Determine if any entity/source/facility specific exceedences of 5-yr average allocation occurred during implementation period						Not necessary when chlorophyll-*a* threshold met

Table 4: Demonstration of reasonable assurance assessment steps for Middle Tampa Bay. Green and red squares indicate outcomes of decision points outlined in the Consortium's reasonable assurance assessment framework (Figure 1).

Bay Segment Reasonable Assurance Assessment Steps	DATA USED TO ASSESS ANNUAL REASONABLE ASSURANCE					OUTCOME
	Year 1 (2017)	Year 2 (2018)	Year 3 (2019)	Year 4 (2020)	Year 5 (2021)	
NMC Action 1: Determine if observed chlorophyll-a exceeds FDEP threshold of 8.5 ug/L	5.8 (No)	7 (No)	5.7 (No)	5.5 (No)		All years below threshold so far, not necessary for NMC Actions 2-5
NMC Action 2: Determine if any observed chlorophyll-*a* exceedences occurred for 2 consecutive years	No	No	No	No		All years met threshold, not necessary for NMC Actions 3-5

NMC Action 3: Determine if observed hydrologically-normalized total load exceeds federally-recognized TMDL of 799 tons/year	N/A	N/A	N/A	N/A		Not necessary due to observed water quality and seagrass conditions in the bay segment
NMC Actions 4-5: Determine if any entity/source/facility specific exceedences of 5-yr average allocation occurred during implementation period						Not necessary when chlorophyll-*a* threshold met

Table 5: Demonstration of reasonable assurance assessment steps for Lower Tampa Bay. Green and red squares indicate outcomes of decision points outlined in the Consortium's reasonable assurance assessment framework (Figure 1).

Bay Segment Reasonable Assurance Assessment Steps	DATA USED TO ASSESS ANNUAL REASONABLE ASSURANCE					OUTCOME
	Year 1 (2017)	Year 2 (2018)	Year 3 (2019)	Year 4 (2020)	Year 5 (2021)	
NMC Action 1: Determine if observed chlorophyll-a exceeds FDEP threshold of 5.1 ug/L	3.3 (No)	4.7 (No)	3.9 (No)	2.8 (No)		All years below threshold so far, not necessary for NMC Actions 2-5
NMC Action 2: Determine if any observed chlorophyll-*a* exceedences occurred for 2 consecutive years	No	No	No	No		All years met threshold, not necessary for NMC Actions 3-5
NMC Action 3: Determine if observed hydrologically-normalized total load exceeds federally-recognized TMDL of 349 tons/year	N/A	N/A	N/A	N/A		Not necessary due to observed water quality and seagrass conditions in the bay segment
NMC Actions 4-5: Determine if any entity/source/facility specific exceedences of 5-yr average allocation occurred during implementation period						Not necessary when chlorophyll-*a* threshold met

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ENH1282

The Fate of Nitrogen Applied to Florida Turfgrass[1]

T. W. Shaddox and J. B. Unruh[2]

The quality of Florida's surface and ground waters is of utmost importance to flora and fauna living in these waters. The growth of flora and fauna is directly related to the amount of available nutrients in these waters. Additionally, we use these waters as the primary source of drinking water for ourselves and our families. A wide range of compounds may be found in these waters, the most common of which may be nitrate (NO_3^-) (Pye et al. 1983). The sources of nitrogen (N) may include, but are not limited to, atmospheric deposition (National Atmospheric Deposition Program 2015), septic tanks (Katz et al. 2010), effluent water disposal (Warneke et al. 2011), agricultural fertilization (Schmidt and Clark 2012), or landscape fertilization (Erickson et al. 2008). Despite evidence to the contrary, some Floridians assume that N applied to turfgrass is a major contributor to water pollution (Shaddox et al. 2016a; Shaddox et al. 2016b; Telenko et al. 2015; Trenholm and Unruh 2005). In order to make informed decisions regarding N applications to turfgrass, it is important to understand the N cycle in the soil/turfgrass system. Therefore, the objective of this publication is to identify and describe the sources and potential fates of N applied to Florida turfgrass.

This discussion will include five paths N may take after being applied to turfgrass: conversion to atmospheric gas, turfgrass uptake, soil storage, leaching, and runoff. However, it is important to first understand turfgrass' contribution to Florida's fertilizer consumption. When discussing Florida's water quality, in particular N contamination, we must consider all the potential sources of N and their relative contributions to groundwater contamination. Florida is uniquely positioned in an environment with optimal sunlight, rainfall, and temperature, which allows for year-round plant growth and crop production. Increased plant growth is often a function of N applications. Nitrogen applications are regarded as essential to sustain the food production necessary to support our population. When all the N fertilizer applied in Florida is considered, the amount applied to turfgrass is comparatively low, contributing only 11% to the total N applied in Florida (FDACS 2017). Although that percentage is low relative to other markets, it is still crucial that we understand the paths that it may take in a turfgrass system. Understanding these fates will help to protect Florida's ecosystem and enhance decisions regarding best management practices.

Atmospheric Nitrogen

More than 99% of all N on planet earth exists in the atmosphere (Havlin et al. 1999) and is chemically and biologically unavailable to plants, except those which are capable of biological N fixation. Approximately 78% of the air we breathe is N_2 gas, which can be converted into a useable form (i.e. fertilizer) via the Haber-Bosch process or by biological N fixation. Approximately 80% of the N manufactured via the Haber-Bosch process is used for agricultural fertilizers (Galloway et al. 2008), and it is estimated that the Haber-Bosch process is responsible for supplying the dietary needs of 50% of the human population or 3 billion people (Smil 2001). Thus, second to photosynthesis, the Haber-Bosch process may be the most important process influencing human development over

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the past century (Erisman et al. 2008). Once harvested from the atmosphere, N applied to turfgrass easily coverts back to a gas either via volatilization or denitrification (Figure 1).

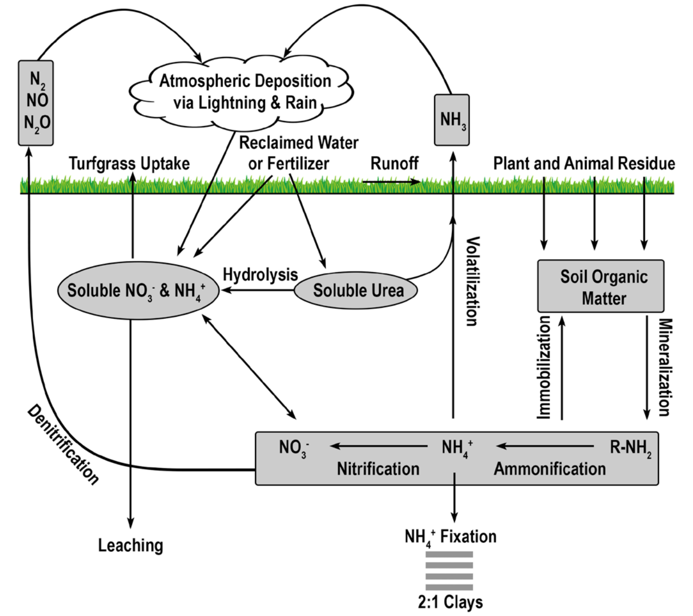

Figure 1. The nitrogen cycle in turfgrass.
Credits: Travis Shaddox, UF/IFAS

Volatilization is the conversion of N to ammonia (Figure 2). The factors influencing conversion of N to a gas include quantity of soluble N as urea or ammonium, temperature, high soil pH, low soil moisture, and low cation exchange capacity. Nitrogen converted to ammonia is lost to the atmosphere and is no longer available for turfgrass uptake. While volatilization is a distinct disadvantage to the turfgrass, the loss of N as ammonia decreases the amount of N available to move into nearby water bodies via leaching or runoff. However, N volatilization may increase the amount of N returned to the earth via rainfall and atmospheric deposition. Because N is commonly applied to turfgrass as urea, volatilization can be a major contributor to N lost from turfgrass systems, with losses ranging from <1% to as high as 60% of applied N (Goos 2011). This percentage can be reduced by using slow-release urea, urease inhibitors, or by irrigating the turf immediately after fertilization (Franzen et al. 2011). Slow-release N sources are defined as any N source that releases its N at a slower rate compared with a reference soluble N source (AAPFCO 2017). Urease inhibitors slow the conversion of urea to NH_4^+ by inhibiting urease, the enzyme necessary for urea hydrolysis to occur. In so doing, the rate of volatilization can be reduced by as much as half (Goos 2011). Urease inhibitors may be marketed as "nitrogen stabilizers". Numerous products marketed as urease inhibitors have been tested by land-grant institutions. Only the "nitrogen stabilizers" containing N-(n-butyl) thiophosphoric acid triamide (NBPT) or N-(n-propyl) thiophosphoric acid triamide (NPPT) have consistently reduced volatilization compared with urea alone (Franzen et al. 2011; Goos 2011). Slow-release N fertilizer also reduced volatilization not through urease inhibition, but by delaying the release of urea into the N cycle.

$$\underset{\textit{Urea}}{CO(NH_2)_2} + H_2O \xrightarrow{\textit{urease}} 2NH_3 + CO_2$$

Figure 2. Nitrogen volatilization converts urea into ammonia gas.
Credits: Travis Shaddox, UF/IFAS

Denitrification is the microbial conversion of NO_3^- to N_2 gas (Figure 3). The conditions that favor denitrification are wet, organic soils containing NO_3^- (Galloway et al. 2004). Similar to volatilization, denitrification converts N into one of several N species: nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O), or gaseous N (N_2), reducing the amount of plant-available N and the amount of N available to move to non-target locations. Denitrification requires N to be in the NO_3^- form, which is then reduced as oxygen is removed. Denitrification is greatly influenced by increased soil moisture, which results in an oxygen-deprived soil and hastens the removal of oxygen from NO_3^- by denitrifying bacteria. When soil oxygen levels drop below 2%, denitrification is increased. However, denitrification may still occur in aerated soils due to the saturation of internal soil microsites (Carrow et al. 2001). Turfgrass studies designed to determine denitrification rates in Florida are limited. However, in sandy, well-drained soils, denitrification is normally low and accounts for <1% to 5% of applied N, but could approach 94% when temperature exceeds 30°C (Mancino et al. 1988). Denitrification in turfgrass systems compares with other agroecosystems in which 10–40% of applied N may be denitrified (Galloway et al. 2004). Although already low in Florida turfgrass systems, denitrification may be further reduced by using nitrification inhibitors or slow-release N, which may reduce the amounts of NO_3-N in the soil. Nitrification inhibitors should contain either 2-chloro-6(trichloromethyl) pyridine (Nitrapyrin) or dicyandiamide (DCD), as these are the only two compounds that have reduced denitrification in field and laboratory studies (Janzen and Bettany 1986; Malzer 1989; Malzer et al. 1989). Similar to their effect on volatilization, slow-release N fertilizers may reduce denitrification by delaying the release of their N into the N cycle.

Additional research aimed at determining denitrification rates in Florida turfgrass systems is needed.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Figure 3. Denitrification - NO_3-N is subject to reduction by soil microbes, leading to N_2.
Credits: Travis Shaddox, UF/IFAS

Turfgrass Uptake

The objective of all N applications to turfgrass is sustainable plant uptake and the resulting increase in turfgrass growth or quality. Numerous factors may influence turfgrass uptake of N, including (but not limited to) turfgrass species, season, N type, N rate, and moisture management.

The percent of applied N recovered in turfgrass tissue can vary depending upon turfgrass species. Species that possess a greater density of roots deeper in the soil profile tend to take up greater amounts of applied N compared with turfgrasses with less dense root systems (Bowman et al. 2002). Clearly, greater uptake occurs because a turfgrass with a greater quantity of roots has an increased chance for its roots to intercept and uptake N (Sullivan et al. 2000). St. Augustinegrass and bermudagrass (two of the most common turfgrasses in Florida) have been documented to utilize greater percentages of applied N than centipedegrass, bahiagrass, and zoysiagrass (Bowman et al. 2002). Even cultivars within the same species may also differ in their ability to consume applied N (Young 2015). Although the exact cause is not fully known, it is reasonable to postulate that the differences among cultivars is due to different levels of evapotranspiration (ET), dry matter production, or root masses, which would result in different amounts of applied N being consumed.

Like most plants, the change in climatic seasons can have a dramatic influence on plant growth and nutrient uptake. During the winter in northern Florida, most warm-season turfgrasses will exhibit a decrease in growth and may enter dormancy (a natural turfgrass phase in which the plant is alive, but no cell division or elongation occurs). Even in southern Florida, reduced turfgrass growth will occur during the winter, but true dormancy has not been reported. As turfgrass growth declines, the amount of N needed by the turfgrass also declines. Thus, consumption of applied N can be lower in the winter than in the summer (Wherley et al. 2009). N applications to dormant or semi-dormant turfgrass have not resulted in N leaching unless excessive rainfall occurs (Shaddox et al. 2016a); thus, the applied N will remain in the soil until the plant consumes it or until rainfall/irrigation moves the N beyond the rootzone (Wherley et al. 2009). However, the agronomic advantages to applying N to dormant turfgrasses are low relative to the environmental risk. Thus, N applications to dormant turfgrasses in Florida are not recommended.

Nitrogen fertilizers differ in their form of N and their release characteristics. These differences can lead to different quantities of N absorbed by turfgrass. Nitrogen applied as NH_4^+ may result in less N uptake than N applied as NO_3^- due to the tendencies of NH_4^+ to volatilize and be lost from the soil/turfgrass system (Brown 2003). A larger percentage of N from slow-release N fertilizers may be taken up by the turfgrass compared with soluble N sources (Shaddox 2001). Soluble N is immediately available to follow any of the potential paths in the soil/turfgrass system, including leaching and volatilization, whereas only small portions of N from slow-release N fertilizers become soluble at any given time. To this end, slow-release N fertilizers can increase N uptake by as much as 300% compared with soluble N sources (Shaddox 2001).

A driving factor behind UF/IFAS nutrient recommendations to turfgrass is to apply the amount of N necessary to achieve a desired turfgrass response without applying more N than the turfgrass can consume at any given time. When UF/IFAS recommended N rates are followed, turfgrass uptake of applied N ranges from 40–68% (Brown 2003; Sartain 1985; Shaddox 2001; Stiegler et al. 2011), whereas research conducted outside of Florida indicates the uptake percentage may approach 80% (Bowman et al. 2002). When small quantities of N are applied, very little N has an opportunity to escape turfgrass assimilation. As rates of soluble N increase, the percentage of applied N recovered in turfgrass tissues decreases (Ashley et al. 1965). However, slow-release N sources often require higher application rates compared with soluble N sources in order to achieve the same desired turfgrass response, because only a small portion of the slow-release N will become soluble on a daily basis. Consequently, higher rates of slow-release N sources may result in greater percent uptake of applied N than lower rates (Sartain 1985). Additionally, a single application of slow-release N at a high rate may result in the same N uptake as soluble N applied as a split application (Sartain 2008). Therefore, slow-release N sources may be applied at higher rates than soluble N sources so long as the single application rate and total annual N applied do not exceed UF/IFAS recommendations.

Moisture management greatly influences plant uptake of applied N. Most N is taken up by the plant via the soil solution. Thus, when the soil water content exceeds the soil water holding capacity, N in the soil solution may be moved below the rootzone, which results in reduced plant uptake (Shaddox 2001). On the other hand, when insufficient water is applied, the turfgrass may enter a state of drought-induced dormancy in which the turfgrass reduces water and N uptake in order to survive (Ashley et al. 1965). Thus, careful consideration should be given to applying sufficient water to maintain acceptable turfgrass, but not applying more water than can be retained by the soil. Generally, rain sensor, soil water sensor, and evapotranspiration controllers apply water more effectively than automatically timed controllers (Dobbs et al. 2014).

Soil Retention, Immobilization, and NH+ Fixation

The amount of N stored in the soil is dependent upon many factors, particularly fertilizer type, fertilizer rate, time of year, soil moisture, soil pH, and rainfall. The majority of soil N exists as organic N in the form of organic matter or as N that has not been released from slow-release fertilizer granules. Technically, fertilizer granules are not a component of soil-stored N. However, the process of measuring soil N (combustion or digestion) will also measure N from any fertilizer granules that have not yet been released. The type and amount of slow-release fertilizer will directly influence this value. Once released from the slow-release form, N may remain in the soil via anion or cation exchange. The cation exchange capacity of most Florida soils is normally less than 3 milliequivalents of positive charge, and the anion exchange capacity is normally too low to measure. In Florida soils, mineralized N, N applied as urea, or N applied as NH_4^+ can rapidly convert to NO_3^- and, because NO_3^- is an anion, it is not retained by the soil. Thus, soil storage of N via cation exchange is commonly less than 10% of applied N (Shaddox 2001) and can be less than 2% (Brown 2003).

Nitrogen immobilization occurs when inorganic N is converted to organic N via microbial activity. An organic form of N is simply any form of N that is bound with carbon. Like plants, microbes require N to survive and some portion of applied N will be consumed by microbes and converted into amino acids, proteins, or some other organic form used for growth by the microbes. While in an organic form, N is not soluble and therefore is unavailable for plant uptake or loss to a water body. Organic N will remain unavailable for plant uptake until the environmental conditions change to favor N mineralization. The percentage of applied N that becomes microbially immobilized in Florida turfgrass systems will vary according to numerous factors including soil moisture, pH, and soil temperature. Little, if any, research has been conducted to determine immobilization of applied N in Florida turfgrass systems. Thus, providing an estimation is difficult. However, research conducted on turfgrass in cooler climates (Connecticut) reports that N immobilization may range from 15 to 26% of applied N (Starr and Deroo 1981). Because Florida receives more rainfall and is warmer than Connecticut, N immobilization in Florida may be lower than previous reports indicate because of increased microbial activity.

Ammonium fixation occurs when NH_4^+ enters the layer (lattice) of a 2:1 clay (Figure 4), becoming unavailable for plant uptake. Ammonium fixation in Florida soils is believed to contribute very little to the overall fate of applied N for two reasons. First, the content of 2:1 clays in Florida soils is normally very low and, second, NH_4^+ normally converts to NO_3^- very rapidly. The exact percentage of applied N to Florida turfgrasses that eventually is fixed by 2:1 clay minerals is unknown. However, evidence from other agronomic systems indicates the percentage is less than 5% (Nieder et al. 2011).

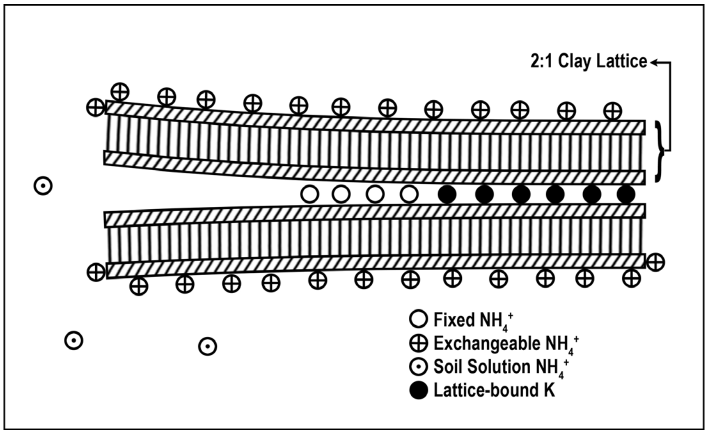

Figure 4. Ammonium may become fixed within the lattice of 2:1 clays and be rendered unavailable for turfgrass uptake.
Credits: Modified from Strand (1998)

Leaching

Leaching is the process that moves soluble N below the rooting zone. Nitrogen leaching in turfgrass systems occurs at the moment soluble N moves below the deepest root. When turfgrass is fertilized according to UF/IFAS recommendations, N leaching is normally low and comparable to, or less than, other landscape plants (Erickson et al. 2008). As with other fates of applied N, the exact amount of N that will leach is difficult to determine. However, it is possible that 0 to 55% of applied N could be leached, with the higher percentages occurring when UF/IFAS recommendations are not followed. When N leaching does occur, it is usually a factor of the turfgrass species, irrigation management, N source, N rate, or stressed turfgrass.

Direct comparisons of N lost through leaching related to turfgrass species indicate that less N leaches through 'Raleigh' St. Augustinegrass than 'Empire' zoysiagrass, 'Meyer' zoysiagrass, 'Emerald' zoysiagrass, centipedegrass, 'Tifway' bermudagrass, and common bermudagrass (Bowman et al. 2002; Telenko et al. 2015; Trenholm et al. 2012). The influence of turfgrass species on N leaching losses is largely a factor of the turfgrass root system. Deeper-rooted turfgrasses tend to reduce N leaching losses compared to shallow-rooted turfgrasses (Bowman et al. 1998). Management practices that encourage deep rooting, such as deep, infrequent irrigation, are factors that shape UF/IFAS recommendations. Increased N leaching has been documented when N is applied within the first 60 days of planting sod (Telenko et al. 2015). After the sod has been planted for 60 days, N leaching is reduced and is a result of increased root growth. Based upon these results, UF/IFAS recommends N applications to newly sodded turf commence 60 days after the sod has been planted. This recommendation allows the sod to develop a root system prior to fertilization and thus minimizes the risk of N leaching.

The movement of water through the soil has a profound influence on N leaching. Once any nutrient becomes soluble in the soil solution, that nutrient is subject to the movement of water. Therefore, it is crucial to minimize any movement of water beyond the turfgrass rootzone. Increased water movement may be a result of excessive irrigation or fluctuations in rainfall due to changing seasons, which may result in more water being applied to the soil than the soil can retain. Moisture sensor or ET-based irrigation is more effective than daily irrigation at applying the amount of water the turfgrass needs without exceeding the rootzone's water holding capacity. Throughout the year, N leaching can be highest in February–March, reduced in April–May, and the lowest in June–July (Snyder et al. 1984). The reduction in N leaching from winter to summer is largely a factor of increased plant growth and increased ET, which reduce the amount of N in the soil solution and the amount of moisture in the rootzone, respectively. In each season, sensor-based irrigation can reduce N leaching by 2–28 times that of daily irrigation. Thus, UF/IFAS recommends refraining from applying any N when the National Weather Service has issued a flood, tropical storm, or hurricane watch or warning, or if heavy rains are likely. These recommendations reduce the risk of exceeding the soil's water retention capacity and, in turn, reduce N leaching.

When applied according to UF/IFAS recommendations, soluble N may not leach more N compared with N lost naturally from unfertilized turfgrass (Shaddox et al. 2016a). Additionally, slow-release N sources further reduce N leaching losses compared with soluble N sources. Essentially, slow-release N sources delay the release of N into the N cycle (Figure 1). Over time, small portions of N are released, which increases the likelihood of plant uptake of applied N and decreases potential for N leaching losses (Guillard and Kopp 2004). Blending soluble N sources with slow-release N sources also results in reduced N leaching losses (Shaddox 2001). Generally, differences in N leaching losses among slow-release N sources are negligible assuming they are applied at the same time and rate. However, organic N sources and polymer-coated N sources may result in the least amount of N leaching losses compared with other slow-release sources (Petrovic 2004). Enhanced efficiency fertilizers, such as nitrification and urease inhibitors, do not delay the release of N into the N cycle and thus result in similar N leaching losses as other soluble N sources (Guertal and Howe 2012).

Increasing the rate of applied N beyond the rate recommended by UF/IFAS (http://edis.ifas.ufl.edu/ep353) can increase the risk of N leaching losses (Trenholm et al. 2012). UF/IFAS turfgrass nutrient recommendations take into account the turfgrass need for N and the potential impact on the environment. UF/IFAS nutrient recommendations are often 50–75% less than the amount of N necessary to increase N leaching losses above the natural environment (McGroary et al. 2017; Trenholm et al. 2012). Thus, current rates are considered conservative, and exceeding these rates is unnecessary because any further increase in turfgrass growth or quality is minimal and could come at a cost to the environment.

As previously mentioned, N applied according to UF/IFAS recommendations to healthy, growing turfgrass has a low probability of leaching. However, when turfgrass is stressed, N leaching can increase (Telenko et al. 2015). Normally, stresses manifest themselves as reductions in turfgrass density and growth, which correspond to a reduction in N uptake. These stresses are largely environmental caused by pests, late-season frosts, and changes in season. However, stresses can also be anthropogenic caused by misapplications of nutrients or pest control products. When stresses occur, further applications of N may not cure the problem and may, in fact, exacerbate the problem and increase N leaching. Further research regarding how to manage nutrient applications to stressed turf is needed.

Runoff

Runoff is defined as the lateral movement of N beyond the target location. Runoff may occur above or below the soil surface but always occurs above the deepest root. At the moment that N moves below the deepest root, further movement of N is defined as leaching. Leached N may then runoff if the leached N encounters a subsurface barrier, but the N lost from the turfgrass system is considered leached if the N moved vertically beyond the rootzone. Nitrogen lost via runoff may be influenced by topography, soil type, soil compaction, soil moisture, rainfall, and fertilizer type. Because Florida soils are predominantly sand-based and have a high water infiltration capacity, the movement of water across the soil surface is far less common than the movement of water into the soil. Thus, in Florida, runoff studies are less common than leaching studies because the few runoff studies that do exist report that little to no runoff occurs. In Florida, when N is applied on steep slopes subject to intense irrigation rates, N found in runoff has been reported to be less than 0.1% of that applied (Shaddox and Sartain 2001). This evidence does not discount the probability that runoff could occur under different conditions. However, even on less permeable soils than many soils found in Florida, N runoff from turfgrass is commonly 0% of applied N, but may approach 7% on topographies and environments that are uncommon in Florida (Brown et al. 1977; Morton et al. 1988).

Summary

The fate of N applied to Florida turfgrass may vary greatly depending upon numerous factors. Essentially all N used in turfgrass management originated from the atmosphere and will eventually return to the atmosphere. During this cycle, ranges of the potential fates of applied N to Florida turfgrasses are:

- Volatilization—<1%–60%
- Denitrification—<1%–5%
- Plant uptake —40%–68%
- Soil Storage—7%–15%
- Leaching—<1%–55%
- Runoff—<1%–7%

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Sources and mechanisms of nitrate and orthophosphate transport in urban stormwater runoff from residential catchments

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ABSTRACT

Nutrients export from residential catchments contributes to water quality impairment in urban water bodies. We investigated the concentrations, transport mechanisms, and sources of nitrate-nitrogen (NO_3–N) and orthophosphate-phosphorus (PO_4–P) in urban stormwater runoff generated in residential catchments in Tampa Bay, Florida, United States. Street runoff samples, collected over 21 storm events, were supplemented with rainfall and roof runoff samples from six representative residential catchments. Samples were analyzed for N and P forms, N and oxygen (O) isotopes of nitrate ($\delta^{18}O$–NO_3^- and $\delta^{15}N$–NO_3^-), and $\delta^{18}O$ and hydrogen (δD) isotopes of water (H_2O). We found that the main NO_3–N source in street runoff was atmospheric deposition (range: 35–64%), followed by chemical N fertilizers (range: 1–39%), and soil and organic N (range: 7–33%), whereas PO_4–P in the street runoff likely originated from erosion of soil particles and mineralization from organic materials (leaves, grass clippings). The variability in the sources and concentrations of NO_3–N and PO_4–P across catchments is attributed to different development designs and patterns, use of various fill materials during land development, and landscaping practices. This data can be useful to develop strategies to offset the impacts of urban development (e.g., designs and patterns resulting in variable impervious areas) and management (e.g., fertilizer use, landscaping practices) on NO_3–N and PO_4–P transport in urban residential catchments.

1. Introduction

Urbanization and associated land use conversion cause a range of environmental problems leading to changes in the physical and biogeochemical characteristics in ecosystems (Jacobson, 2011). The removal of vegetation and sealing of soil surfaces with pavements and buildings decrease infiltration of rainfall and increase surface runoff and incidences of urban flooding (Jacobson, 2011; Yang et al., 2011). If the current trends in population continue to increase in the world, then urban land cover will approach 1.2 million km^2 by 2030, nearly tripling the current urban land (Seto et al., 2012). This means that the planning for protection and restoration of waters will require considerably more effort in rapidly urbanizing watersheds.

Nutrients such as nitrogen (N) and phosphorus (P) are important stormwater pollutants in many coastal waters, streams, lakes, and reservoirs due to their role in eutrophication and algal blooms (Lusk and Toor, 2016a, 2016b; Badruzzaman et al., 2012). Nonpoint sources of pollution present a major challenge not only because the sources are diffuse but not all sources and transport mechanisms have been identified and quantified (Carey et al., 2013). Consequently, effective strategies are needed to control nutrients carried in stormwater runoff to water bodies.

The impact of stormwater runoff on coastal water quality is of particular concern in subtropical and tropical regions because a large amount of stormwater runoff and associated pollutants flow into the ocean during storm events (Brown et al., 1985). Further, the sources, mechanisms of transport, and potential contribution of N and P in stormwater runoff originating from residential catchments especially in subtropics have not been well studied. Understanding how urban development in subtropics causes water quality impairments may contribute to existing scientific knowledge as studies have largely taken place in different climatic regions.

In many urban residential areas, stormwater retention ponds provide temporary storage of stormwater runoff and capture a variety of pollutants before delivering water and pollutants to streams, rivers, and estuaries, which are the final destination of

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pollutants (McEnroe et al., 2013). The pollutants build-up and wash-off processes are influenced by catchment development as well as conventional factors such as land use. Thus, addressing the stormwater runoff in residential catchments may provide greater opportunities for attenuating nutrients transported in runoff before they enter the hydrological network in watersheds. Further, estimations of urban residential nutrient sources are highly uncertain and present a challenge for water quality management due to the lack of understanding of the sources and mechanisms driving the nutrient release and transport from land to water (Causse et al., 2015; Listopad et al., 2015; Yang and Toor, 2016).

Dual isotopic analysis of nitrate-nitrogen (NO_3–N) has provided evidence that NO_3–N sources and denitrification processes in estuarine systems control N transport (Wankel et al., 2009; Kaushal et al., 2011; Hale et al., 2014). Urban form and layout of impervious area are important factors that determine the magnitude of various pollutants loss in stormwater runoff (Liu et al., 2012; van der Sterren et al., 2012). For example, the impervious area layout plays an important role in directing runoff as it dictates the time of response to rainfall and therefore influences the pollutant wash-off processes (Liu et al., 2012). Increase in impervious surfaces in urban watersheds is related to increased concentrations of N in stormwater runoff (Wollheim et al., 2005; Kaushal et al., 2008) and a decline in biodiversity in streams (Paul and Meyer, 2001). However, limited information is available about the sources and mechanistic controls on N and P release and transport in residential catchments.

In our recent study conducted in a low-density urban residential catchment, we determined that atmospheric deposition (43–71%) and chemical fertilizers (<1–49%) were the main NO_3–N sources in stormwater runoff (Yang and Toor, 2016). In the present study, a broader geographical area, with six medium-to high-density urban residential catchments, was targeted to expand our understanding on N as well as P in roof and street stormwater runoff. The focus of this study is on the concentrations, transport mechanisms, and sources of nutrients in residential stormwater runoff in a subtropical region. We designed this study to address these questions: (*i*) What are the concentrations and dominant forms of N and P in stormwater runoff originating from medium- and high-density urban residential catchments? and (*ii*) Are atmospheric deposition and chemical fertilizers the important NO_3-N sources across the residential catchments within the same biophysical context? To our knowledge, this study is the first scientific investigation on the source separation of NO_3–N along with PO_4–P in residential catchments of different development patterns and ages. Study findings may be useful not only for determining sources of nutrients originating from urban residential catchments, but for devising strategies to mitigate and minimize their impacts on the receiving urban waters.

2. Materials and methods

2.1. Study sites

Six residential catchments in Tampa Bay, Florida, United States were selected for this study based on their representativeness in terms of type of neighborhoods (i.e., townhome, apartment, single family), age of the homes (1985–2007), and accessibility to storm drain outfalls (Fig. 1 and SI Table S1). Five residential catchments (A–D, F) were located in the Hillsborough County and one catchment (E) was located in the Manatee County. Median home values in the catchments ranged from ~$100,000 to $280,000. Mean home size is 100–200 m^2. Based on the visual observations, excess runoff waters in these catchments flow from roofs to other impervious areas (driveways, sideways, and roads) before entering into a stormwater gutter. The total area of the catchments varied from 0.09 to 0.62 km^2, of which 42–81% was impervious (rooftops, patios, driveways and roads), and 11–58% was pervious (lawns and tree canopies). The climate in the area is subtropical with 2014 monthly average air temperatures ranging from 14 to 27 °C, with daily extremes of 4–29 °C (FAWN, 2016). The annual rainfall in the area over the last 10 years (2004–2014) was 94–153 cm (mean 130 cm), of which 47–77% (mean 65%) occurred during the wet season (June to September). In 2014, total rainfall was 144 cm, and monthly rainfall ranged from 1.5 to 34.2 cm, of which 33% occurred during the study period (August–September).

2.2. Sample collection and nutrient analysis

Storm events from individual catchments were traced using the NOAA weather app, which showed progression of a storm event. After identifying a significant storm event, personnel were dispatched to manually collect grab street runoff samples using a small container before runoff entered into storm drains. At each catchment site, samples were collected at 5-min intervals after initiation of runoff during each storm event. A composite sample for each 5-min interval sampling was taken in 250 mL plastic bottles. Rainfall intensity in targeted storm events ranged from 0.1 to 2.2 cm/h (mean 0.57 cm/h) and total daily rainfall durations were <0.5–9 h (40% of time <0.5 h) during the study period (SI Fig. S1). We targeted sample collection during the early part of the rainfall-runoff period due to the logistics of sample collection and observations from our previous study that typical storms last only 0.5 h in the region (Yang and Toor, 2016). This resulted in collection of 1–7 street runoff samples in each of 21 individual storm events. In addition, 25 rainfall samples (23 samples were analyzed for isotopes) and 11 roof runoff samples were collected from downspout drains across the catchments. Due to the logistic surrounding roof samples collection (needed permission from homeowners, identification of places to collect samples), we limited roof runoff samples collection to catchments A and C (Fig. S2), where 11 samples were collected over 6 storm events. At these sites, roof runoff is diverted into a pipe, which then discharges runoff over the driveway and streets. The samples were collected by placing a plastic bottler below the pipe, then a composite sample (~250 mL) was taken for analysis. All the samples were stored in a refrigerator at 4 °C until analysis (<24 h).

A portion of collected water samples was vacuum-filtered (0.45 μm Pall Corporation, Ann Arbor, MI) within 24 h of collection and placed in 20 mL high-density polyethylene scintillation vials and either refrigerated (N chemistry and water isotope analysis) or frozen (N isotopic analysis). The filtered samples were analyzed for NO_3–N and PO_4–P using an AutoAnalyzer 3 (AA3, Seal Analytical, Mequon, WI, USA) with EPA methods 365.1 and 353.2, respectively (USEPA, 1993a, 1993b). The unfiltered water samples were analyzed for total N (TN) and total P (TP) using the alkaline persulfate digestion method (Ebina et al., 1983) followed by NO_3–N and PO_4–P analysis as described above. The difference between TN and NO_3–N was determined to be other–N (combination of ammonium-N and organic N). Similarly, the difference between TP and PO_4–P was other–P (combination of particulate reactive P and dissolved and particulate unreactive P). The detection limit was 0.001 mg/L for NO_3–N and TN and 0.002 mg/L for PO_4–P and TP.

2.3. Isotopic analysis

Stormwater samples were analyzed for stable isotopes of water (H_2O), that is, oxygen ($\delta^{18}O$–H_2O) and hydrogen (δD–H_2O). The detailed description of the analysis technique is given by Lis et al. (2008) In brief, for simultaneous D/H and $^{18}O/^{16}O$ ratios measurements of H_2O, an off-axis integrated cavity output spectroscopy

Fig. 1. Location maps of six residential catchments located in Tampa Bay, Florida, United States.

(OA-ICOS) water isotope analyzer (LWIA, Los Gatos Research, Mountain View, CA, USA) was coupled to a CTC LC-PAL liquid autosampler. Analysis of $\delta^{18}O{-}NO_3^-$ and $\delta^{15}N{-}NO_3^-$ was conducted using $AgNO_3$ method described by Silva et al. (2000) and Coplen et al. (2012). All stable isotope results are expressed as δ values, representing deviations in per mil (‰) from standards for O, N, and D/H such that:

$$\delta(‰) = 1000 \times \left[\left(R_{sample} \middle/ R_{standard}\right)\right] - 1$$

where R_{sample} and $R_{standard}$ are the measured isotopic ratios (e.g., D/H, $^{15}N/^{14}N$ or $^{18}O/^{16}O$) for the sample and standard, respectively. The ratio of $^{15}N/^{14}N$ reference is N_2 in air and the D/H and $^{18}O/^{16}O$ reference is Vienna Standard Mean Ocean Water.

2.4. Bayesian mixing models

The proportional contribution of the $NO_3{-}N$ sources was estimated using Bayesian stable isotope mixing models as described in Parnell et al. (2013) To estimate the contribution of different $NO_3{-}N$ sources, two isotope values of $\delta^{15}N{-}NO_3^-$ and $\delta^{18}O{-}NO_3^-$ from the four potential $NO_3{-}N$ sources (i.e., atmospheric deposition, NH_4^+ fertilizer, NO_3^- fertilizer, and soil and organic N) were used. Isotopic values of $NO_3{-}N$ source end members were defined through a combination of field- and literature-based estimates. For instance, measured $\delta^{15}N{-}NO_3^-$ (-0.9 ± 2.18‰, $n = 23$) and $\delta^{18}O{-}NO_3^-$ (56.8 ± 8.03‰, $n = 23$) values of rainfall samples, collected from the study sites during the wet season, were used as atmospheric deposition end member. Whereas, the end member literature values for NH_4^+ fertilizer ($\delta^{15}N{-}NO_3^-$: -0.2 ± 2.28‰, $\delta^{18}O{-}NO_3^-$: -2.0 ± 8.0‰), NO_3^- fertilizer ($\delta^{15}N{-}NO_3^-$: 1.1 ± 2.78‰, $\delta^{18}O{-}NO_3^-$: 21.3 ± 3.01‰), and soil and organic N ($\delta^{15}N{-}NO_3^-$: 7.5 ± 5.23‰, $\delta^{18}O{-}NO_3^-$: -2.0 ± 8.0‰) were used as described in Yang and Toor (2016). In the Bayesian mixing model, measured $\delta^{15}N{-}NO_3^-$ and $\delta^{18}O{-}NO_3^-$ values of individual street runoff samples ($n = 56$) were treated as "customers" and mean values of four $NO_3{-}N$ sources were treated as "sources". It should be acknowledged that choice of isotopic end members in the mixing model may contribute uncertainty in the estimates. Increasing $\delta^{15}N-NO_3^-$ values with decreasing NO_3-N concentrations and 2:1 ratio between $\delta^{15}N-NO_3^-$ and $\delta^{18}O-NO_3^-$ indicates denitrification in the samples (Kendall et al., 2007; Divers et al., 2014). We did not observe these relationships in any of our samples, thus, we conclude that there was no denitrification in any of our samples, therefore, the enrichment factors for denitrification were not evaluated in the Bayesian mixing model. Nitrification of soil N (expected $\delta^{18}O-NO_3^-$ values: 2.90–10.32‰) was determined using a calculation widely used in previous studies (Kendall et al., 2007). In theory, the $\delta^{18}O$ of NO_3-N produced by nitrification can be calculated using the O value (23.5‰) of the air and experimental O value of street runoff samples using the formula of $\delta^{18}O-NO_{3\text{-}nitrification} = 2/3\ \delta^{18}O-H_2O + 1/3\ \delta^{18}O-O_2$ (Kendall et al., 2007). However, some caution is required when using this formula as experimental studies have produced microbial NO_3^- with $\delta^{18}O-NO_3^-$ values both higher and lower than the expected values (Kendall et al., 2007; Casciotti et al., 2010; Snider et al., 2010). The Bayesian mixing model was run for 100,000 interactions, with a burn-in of 50,000. Chains were thinned by 50 and convergence was evaluated with the diagnostic built into the MixSIAR package (version 3.0.2) (Divers et al., 2014; Phillips et al., 2014). The 2.5, 5, 25, 95, 97.5%, and mean values for each source define the range of possible NO_3-N proportion contributions.

2.5. Statistical analysis

The one-way Analysis of Variance (ANOVA) Tukey-Kramer HSD (honest significant different) test was used to examine the significant differences ($p < 0.05$) of measured variables across the catchments and among water samples. When the data failed to meet the assumption of normality for parametric statistical analyses, the nonparametric Wilcoxon/Kruskall-Wallis test (rank sums) was used to determine the significance ($p < 0.05$) of measured variables among water samples. Pearson correlation coefficient was used to determine the degree of association between water quality variables and storm characteristics such as total rainfall and rainfall intensity. Principal component analysis (PCA) was performed to determine the correlation structure among water samples and their relative importance of different variables. Measured variables in rainfall, roof runoff, and street runoff samples in six catchments over the storm events were used for PCA. All statistical analyses were performed using the JMP statistical software package (JMP Pro 12, SAS Institute).

3. Results

3.1. Nutrient concentrations in rainfall and runoff

The concentrations and proportions of N and P forms varied widely in rainfall, roof runoff, and street runoff across residential catchments (Fig. 2 and SI Figs. S2–S4). Concentrations of N in street runoff were not significantly ($p > 0.05$) different among the catchments (SI Fig. S3). Concentrations of TN and other–N (organic N + NH_4^+) were significantly ($p < 0.05$) lower in rainfall (TN: 0.06–0.51 mg/L; other–N: 0.01–1.70 mg/L) as compared to roof runoff (TN: 0.05–1.97 mg/L; other–N: 0.01–0.35 mg/L) and street runoff (TN: 0.03–1.90 mg/L; other–N: <0.01–1.71 mg/L) (Fig. 2 and SI Fig. S2). In contrast, NO_3-N concentrations were not significantly ($p > 0.05$) different among rainfall (0.01–0.41 mg/L), roof runoff (0.05–0.15 mg/L), and street runoff (0.01–0.29 mg/L). The NO_3-N:TN was greater in the rainfall (mean 0.61) and decreased as rainfall water emerged as roof runoff (0.34) and street runoff (0.39), whereas the other–N:TN was lower in the rainfall (0.39) than roof runoff (0.66) and street runoff (0.61) (Fig. 2).

Concentrations of P varied among the catchments (SI Figs. S2–S4). Across all residential catchments, TP was significantly ($p < 0.05$) greater in street runoff (0.14–2.78 mg/L) than rainfall (0.09–0.15 mg/L) and PO_4-P was significantly greater ($p < 0.05$) in street runoff (0.05–1.52 mg/L) than both roof runoff (0.05–0.13 mg/L) and rainfall (0.02–0.11 mg/L) (SI Fig. S2). The other–P:TP was higher in rainfall (mean 0.54) and roof runoff (0.59) and lower in street runoff (0.37), whereas PO_4–P:TP was lower in rainfall (0.46) and roof runoff (0.41) and higher in street runoff (0.63) (Fig. 2).

3.2. Nitrogen and phosphorus forms in stormwater runoff: principal component analysis

To determine the correlation structure among water samples and the relative importance of different variables (N and P), PCA was used, which showed two significant components (Eigenvalue > 2) that collectively explained 54% of the variance in rainfall, roof runoff, and street runoff. The loading plot and correlation matrix resulting from the PCA showed a wide gradient in nutrient species distribution in rainfall, roof runoff, and street runoff over 21 storm events across six residential catchments (Fig. 3 and SI Table S2). Two major correlating clusters were identified, where other–P and PO_4-P in street runoff were strongly correlated to each other (group 1), while NO_3-N in street runoff, NO_3-N and other–P and other–N in roof runoff, and PO_4-P in rainfall formed a separate cluster (group 2). Both groups (1 and 2) were relatively orthogonal to each other, which suggest that they were not correlated and, thus, other–P, PO_4-P, and NO_3-N in street runoff likely originated from different sources (Fig. 3). Further, the clear separation between N and P forms in street runoff suggests that N and P originated from different sources in residential catchments.

3.3. Sources of water and nitrate-nitrogen in rainfall, roof runoff, and street runoff

In rainfall ($n = 23$), roof runoff ($n = 11$), and street runoff ($n = 56$), $\delta D-H_2O$ varied between −60.5‰ and 23.1‰ and $\delta^{18}O-H_2O$ between −7.4‰ and 3.7‰ (SI Fig. S5). Most of the $\delta D-H_2O$ and $\delta^{18}O-H_2O$ values in street runoff were closely correlated ($R^2 = 0.99$) with the global meteoric water line (GMWL, defined as $\delta D\text{-}H_2O = 8\delta^{18}O\text{-}H_2O + 10$) (Craig, 1961) with a slope of 7.03. The results of H_2O isotopes indicated that runoff water during the stormwater events originated from the local rainfall and no other sources of water (e.g., reclaimed water, municipal water, leaking sanitary sewers) contributed N and P in the street runoff; similar to our earlier finding in a low-density residential neighborhood (Yang and Toor, 2016).

The $\delta^{15}N-NO_3^-$ was −4.2‰ to 3.3‰ in rainfall ($n = 23$), −5.8‰–1.9‰ in roof runoff ($n = 11$), and −5.9‰ to 11.3‰ in street runoff ($n = 56$), whereas the $\delta^{18}O-NO_3^-$ was 41.5‰–71.7‰ in rainfall, 52.4‰–64.3‰ in roof runoff, and 2.2‰–63.0‰ in street runoff (Fig. 4). All rainfall and roof runoff samples had similar $\delta^{15}N-NO_3^-$ and $\delta^{18}O-NO_3^-$ values within the expected range from the literature (Kendall et al., 1998, 2007; Kendall and McDonnell, 1998) implying that atmospheric deposition was the sole source of NO_3-N in roof runoff (Fig. 4). In contrast, isotopic signatures of potential NO_3-N sources suggest that atmospheric deposition, NH_4^+ fertilizers, NO_3^- fertilizers, soil and organic N contributed NO_3-N in street runoff in the residential catchments. The Bayesian mixing model showed that atmospheric deposition contributed 35–64% (mean 50%) of NO_3-N to street runoff over 21 storm events across six residential catchments (Fig. 5A and SI Table S3). The second major contributing source of NO_3-N in street runoff was derived from chemical fertilizers (NO_3^- and NH_4^+ fertilizers; 1–39%, mean 33%), whereas soil and organic N contributed the least NO_3-N (7–33%, mean 18%) to

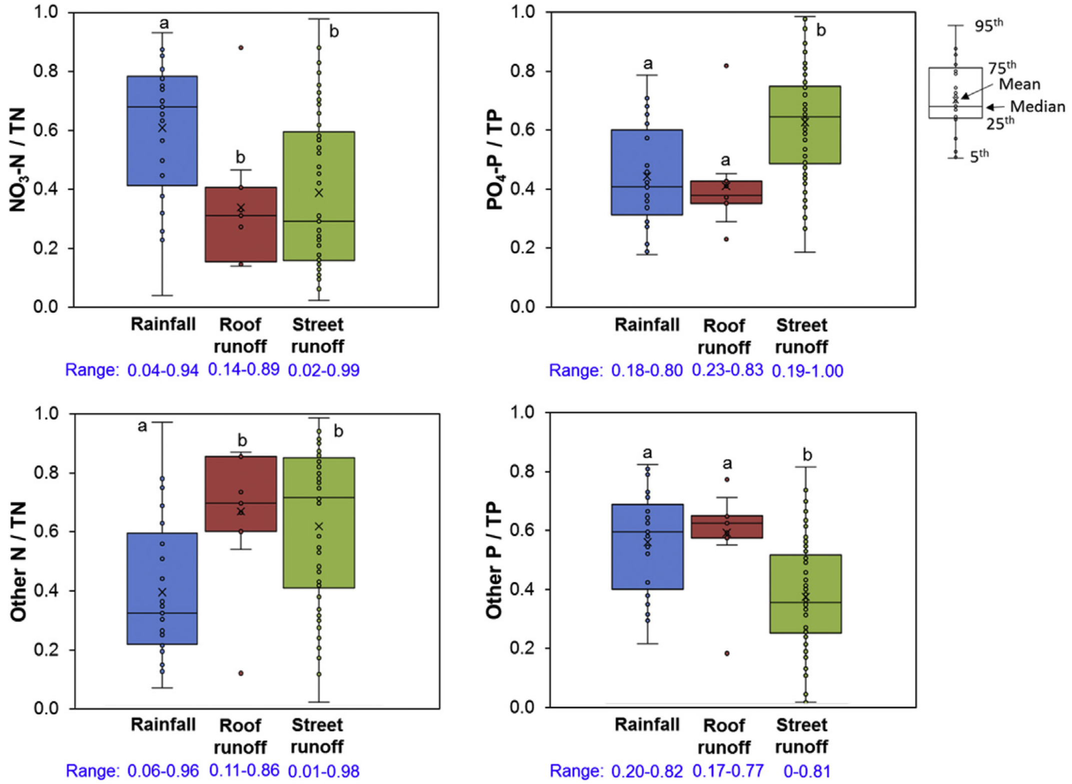

Fig. 2. Proportion of nitrogen and phosphorus forms in rainfall, roof runoff, and street runoff from 21 stormwater events across six residential catchments. The different letters indicate significant difference (ANOVA; $p < 0.05$).

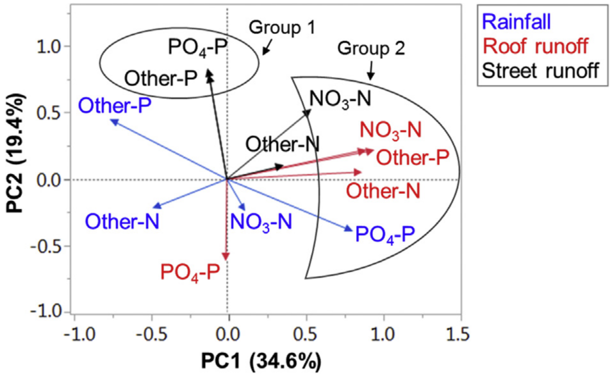

Fig. 3. Loading plot of different forms of nitrogen and phosphorus in rainfall ($n = 25$), roof runoff ($n = 11$), and street runoff ($n = 56$) across six residential catchments (A to F) based on Principal Component Analysis (PCA). Length of lines and arrows represent the strength and the direction of loading of each variable in relation to others.

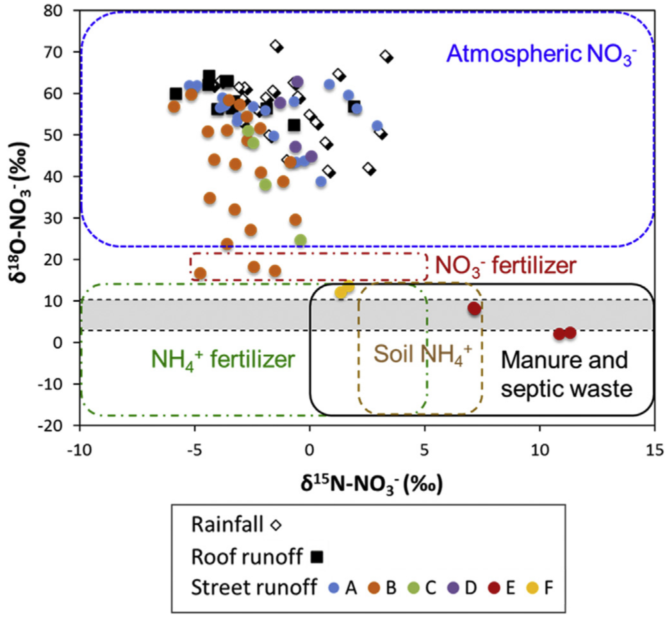

Fig. 4. Dual $\delta^{15}N-NO_3^-$ and $\delta^{18}O-NO_3^-$ in rainfall ($n = 23$), roof runoff ($n = 11$), and street runoff ($n = 56$) during August–September 2014. Area shows the range of the $\delta^{15}N-NO_3^-$ and $\delta^{18}O-NO_3^-$ values from Kendall et al. (2007). The shaded area between two horizontal dashed lines represents the $\delta^{18}O-NO_3^-$ values in the range of expected nitrification.

street runoff in residential catchments. In addition, the four catchments (A–D) had NO_3–N isotope signatures dominated by atmospheric deposition (mean range 62–78%), whereas NO_3–N was mainly derived from chemical fertilizers in catchment F (3–64%, mean 64%) and from soil and organic N in catchment E (33–81%, mean 59%). The variability in different NO_3-N sources across catchments is attributed to the urban heterogeneity due to the different development patterns such as variable impervious area and landscape management practices.

4. Discussion

In street runoff, most of the N was present as other–N, whereas P was primarily present as other–P in roof runoff and as PO_4–P in street runoff. Although storm characteristics such as rainfall intensity and rainfall amount can influence N and P in stormwater runoff, we did not observe any relationship between measured variables and rainfall amount and intensity in our study catchments

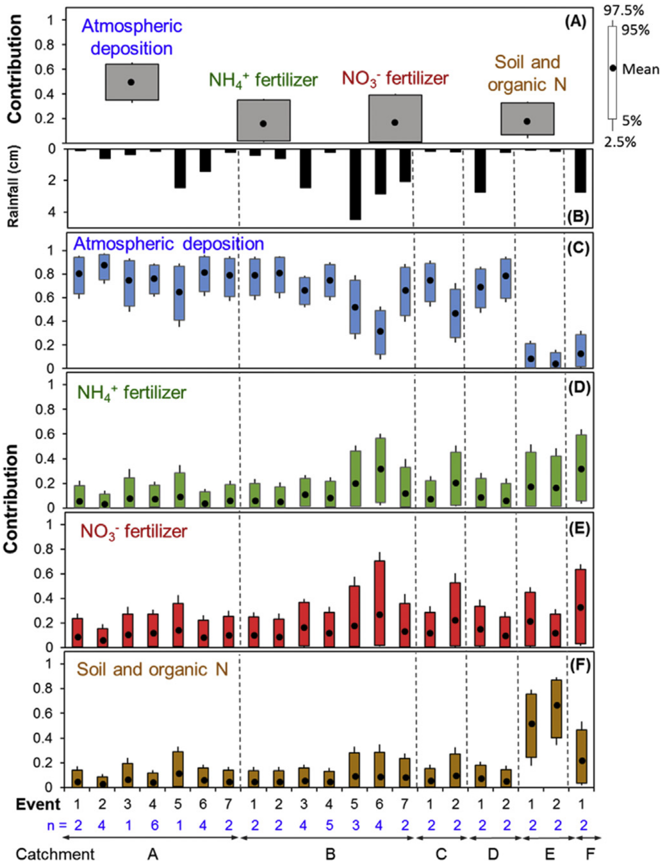

Fig. 5. (A) Fractional contribution of different NO_3–N sources to street runoff from six catchments (n = 56) based on Bayesian stable isotope mixing models, (B) daily rainfall, and Bayesian credible intervals for the probability distribution calculated for (C) atmospheric deposition, (D) NH_4^+ fertilizer, (E) NO_3^- fertilizer, and (F) soil and organic N sources. Numbers in blue on x-axis represent total number of sequential 5-min samples collected during each rainfall event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(SI Fig. S1). The results of PCA suggested that N and P originated from different sources in stormwater runoff in residential catchments. In addition, a wide variability in N and P forms and NO_3–N sources over 21 storm events across six catchments suggest that transport processes of N and P are likely different (Fig. 3), as also observed by Egodawatta et al. (2012). In the below sections, we discuss the potential sources and processes controlling N and P transport in residential stormwater runoff.

4.1. Nitrogen in stormwater runoff

Concentrations of N forms were slightly higher (mean 1.3–1.5 times) in roof runoff than street runoff, but no statistical differences ($p > 0.05$) were observed (Fig. 2 and SI Fig. S2). Roof runoff can be a potential source of nonpoint pollution as the compounds present in the roofing materials and deposition of leaves, dead insects, and bird droppings on roof surfaces will eventually leach/wash into the runoff (Chang et al., 2004; Egodawatta et al., 2012). In addition, higher roof temperatures due to the greater surface inclination to direct solar radiation may accelerate chemical reactions and decomposition of materials deposited and present in roofing materials (Chang et al., 2004). For example, variable concentrations of NO_3–N were observed in roof runoff collected from different types (aluminum, galvanized metal, thatch, and asbestos) of roof materials (Chizoruo and Onyekachi, 2016). Therefore, during storm events, rainfall can add and react with a variety of compounds present in and on the roofs and cause N to runoff.

Most of the data points of N forms from six medium-to high-density residential catchments were within similar concentration ranges of our previous study in a low-density catchment (SI Fig. S2) (Yang and Toor, 2016) and other literature (Badruzzaman et al., 2012; Listopad et al., 2015). No significant ($p > 0.05$) differences were observed in street runoff concentrations of N forms among the six residential catchments (SI Fig. S3) likely due to the similar climatic and geological factors (Polsky et al., 2014). However, the local factors such as anthropogenic inputs (fertilizer use) and socio-economic variables (homeowner management vs. professional landscapers) likely influenced the concentrations across catchments (Groffman et al., 2014). For example, mean concentration of NO_3–N in street runoff (0.10 mg/L) was similar to previous urban stormwater runoff studies conducted in Florida (0.11 mg/L) (Badruzzaman et al., 2012). However, these concentrations were lower than the mean concentration found in nationwide urban runoff studies (0.53 mg/L) in the United States (Schueler, 2003; Carey et al., 2013). The mean concentration of TN in our street runoff (0.42 mg/L) was about two-to five-times lower than other urban stormwater runoff studies conducted in Florida (1.09 mg/L) (Badruzzaman et al., 2012) and the mean concentration from nationwide studies in the United States (2.0 mg/L) (Schueler, 2003; Carey et al., 2013). Previous studies have documented that both the velocity and volume of surface runoff increase with increase in impervious area (Jacobson, 2011). All six residential catchments have medium-to high-density land use and five catchments (A–C and E–F) have greater percentage of impervious area (52–81%) than D catchment (42%; SI Table S1). As high rainfall is known to cause dilution (Vaze and Chiew, 2004; Ballo et al., 2009; Miguntanna et al., 2013), we suggest that higher rainfall in Florida during the wet season generated more stormwater runoff especially from impervious surface (e.g., roads, driveways), which then likely diluted N concentrations in stormwater runoff.

4.2. Sources and transport of nitrate-nitrogen in residential runoff

The high $\delta^{18}O$–NO_3^- values in roof runoff indicates that atmospheric deposition was the sole source of NO_3–N in roof runoff waters (Fig. 4). Kojima et al. (2011) observed high $\delta^{18}O$–NO_3^- (65.9–67.0‰) in leachate from roof dust and suggested that NO_3–N was mainly derived from atmospheric deposition. In contrast, sources of NO_3–N in street runoff changed over the storm events and varied among different residential catchments based on Bayesian mixing model results (Fig. 5 and SI Table S3 and Fig. S6). We attribute this variability in changing proportion of NO_3–N sources to the switching of N sources over the wet season such as runoff of fertilizer from turf, runoff of soil particles containing N, depletion of N present in atmospheric deposition as season progressed.

Atmospheric N includes both wet (NO_3^- and NH_4^+) and dry forms (particulate NO_3^- and gaseous nitric acid), which may be carried directly or indirectly in stormwater runoff with rainfall (Anisfeld et al., 2007; Divers et al., 2014). Using stable isotope analysis, wash-off of atmospheric NO_3–N has been found to be the main source in urban water systems during storm events in central New York (43–50%) (Anisfeld et al., 2007), Baltimore, Maryland (5–94%) (Kaushal et al., 2011), and Tampa, Florida (43–71%) (Yang and Toor, 2016). In Florida, direct deposition of N from atmosphere to Tampa Bay estuary was estimated to be 8.4 kg/ha/yr, which was equivalent to ~22% of TN loading from the Tampa Bay watershed (Poor, 2006). Our study catchments are located in Tampa Bay urban area with annual daily average traffic between 4,200 and 100,000 vehicles around the catchments. The heavy automobile traffic can serve as an additional N source as dry deposition from vehicles can deposit within hundreds of meters of roadways (Kirchner et al., 2005; Gilbert et al., 2007), which can then enter water bodies as atmospheric deposition and stormwater runoff during storm events.

Chemical fertilizers contributed on average 16–64% (mean 33%) of NO_3–N in street runoff over 21 storm events. In other words, NO_3–N that originated from chemical fertilizers contributed ~6–25% of the TN in street runoff as NO_3–N:TN was ~0.39. In urban residential areas, a large fraction of N input is from residential lawn fertilizer applications. For example, fertilizers are frequently used in Florida's urban neighborhoods due to the sandy texture of soils and subtropical climate, with typical TN application of 80–240 kg/ha/yr in residential lawns (Badruzzaman et al., 2012). The estimated annual TN inputs in our study regions are 105 kg/ha (2.5 application on average) in the Hillsborough County and 43 kg/ha (2.2 application on average) in the Manatee County, respectively (Listopad et al., 2015). In our previous study in a low-density residential catchment, we found that chemical fertilizers contributed ~42% of NO_3–N to street runoff (Yang and Toor, 2016). In this study, the contribution of NO_3–N from chemical fertilizers was determined to be ~33% (~13% of TN) in six medium-to high-density residential catchments. Although we do not know the exact reasons for slightly low (~9%) contribution from chemical fertilizers in this study, we suggest a few possible reasons. First, the area under turfgrass was greater in the low-density catchment (61% pervious area) (Yang and Toor, 2016) as compared to medium- and high-density residential catchments (11–58% pervious area; Fig. 1 and SI Table S1). Second, the median home values were >US\$450,000 in low-density compared to < US\$280,000 in medium- and high-density residential catchments (Table S1). Neighborhoods with high socio-economic status are likely to use more services of professional landscapers as compared to neighborhoods with low socio-economic status, where homeowners usually manage their yards, with former using more fertilizers (Listopad et al., 2015). A recent study reported that a residential neighborhood with the highest fertilizer N inputs also had highest percentage of professionals responsible for landscape management as compared to a neighborhood with lower fertilizer N inputs (Listopad et al., 2015). Even within the six catchments, the fractional contribution of chemical fertilizers varied. Perhaps, the differences in landscape patterns, management practices (e.g., fertilizer use), and socio-economics resulted in variable NO_3–N contribution from chemical fertilizers among low-, medium-, and high-density residential catchments highlighting the complexity of N transport and need to conduct long-term studies across residential catchments to assess the sources variability.

Across all catchments, the contribution of soil and organic N to NO_3–N in street runoff was 7–33% (mean 18%), which is equivalent to 7% of TN (Fig. 5). In two catchments (E and F) where limited storm events (≤ 2) were sampled, soil and organic N contributed ~22% (9% of TN) and 59% (23% of TN) of NO_3–N. The results of H_2O isotopes suggested that runoff waters during the rainfall events originated from the local rainfall in our six residential catchments, thus, we can exclude the possibility of household wastewater as a source of NO_3–N as all wastewater is piped and conveyed to wastewater treatment plants. Therefore, the potential source of organic N contributing NO_3–N in runoff may be soil organic matter, bird/pet waste, or organic materials such as grass and leaves. From the visual observation of catchment E, we noted presence of a construction area behind the buildings, which may have caused transport of soil NO_3–N in street runoff during the storm events. This is supported by the fact that $\delta^{18}O{-}NO_3^-$ values in street runoff samples from catchment E were in the range of expected nitrification (2.90–10.32‰; Fig. 4) based on the equation of $\delta^{18}O{-}NO_{3\text{-nitrification}} = 2/3\ \delta^{18}O{-}H_2O + 1/3\ \delta^{18}O{-}O_2$ (Kendall et al., 2007), suggesting that soil solution NO_3–N might have been transported from *in situ* soil; a similar finding to our previous study in a low-density residential catchment (Yang and Toor, 2016). We did not find any evidence of denitrification in any runoff samples, which would produce low NO_3–N concentrations with a heavier isotopic composition.

In summary, the results of mixing model are in line with our previous research in the area (Yang and Toor, 2016) and other studies (Anisfeld et al., 2007; Buda and DeWalle, 2009; Kaushal et al., 2011; Riha et al., 2014), which points out the importance of atmospheric deposition of NO_3^- in storm events. The contribution from the potential NO_3–N sources varied across the catchments during storm events, indicating that even within the same biophysical context (similar geologic and climatic conditions) in a city, managing N in residential areas may require site-specific approaches due to the variable landscape patterns, management practices, and socio-economics (Polsky et al., 2014).

4.3. Phosphorus in residential runoff

The mean concentrations of PO_4–P (0.25 mg/L) and TP (0.43 mg/L) in street runoff were similar to other urban runoff studies conducted in Florida (PO_4–P 0.2 mg/L; TP 0.35 mg/L) (Arias et al., 2013), but higher when compared to urban runoff studies conducted in the United States (PO_4–P 0.10 mg/L; TP 0.26 mg/L) (Schueler, 2003; Badruzzaman et al., 2012; Carey et al., 2013). This is likely because many Florida soils in central part of the state (where our study catchments are located) are naturally high in P due to P-rich geology (Khare et al., 2012; Arias et al., 2013); as such, any dissolved P or P attached to soil particles can be carried off site into stormwater runoff during the storm events. For example, Arias et al. (2013) reported that PO_4–P sorbed to suspended sediment particles was carried in storm runoff in an urban catchment in Florida. Concentrations of P were not statistical different ($p > 0.05$) among catchments A, B, and D, but were significantly ($p < 0.05$) different when compared to catchments C, E, and F (SI Fig. S3). In Florida, fill material for landscaping originate from local subsoils with spodic horizons that are rich source of P. Due to the differences in development patterns and age of residential catchments, the fill materials used may have been derived from different parts of the state, which then resulted in variability in soil P content and influenced P concentrations in street runoff (Clark et al., 2008; Drake et al., 2014). Further, bird droppings, insects, debris, and intercepted dry deposition from tree canopies in residential areas could be likely sources of P in residential runoff. During rainfall events, P associated with organic matter and/or fine particles is transported in stormwater runoff (Wu et al., 2015). The other–P:TP slightly increased from rainfall (mean 0.55) to roof runoff (0.59) and then decreased in street runoff (0.37) likely due to the contribution of particulates from roof and then mixing and dilution with runoff water from other places such as roads and turfgrass in the catchments. Suspended finer-sized sediment associated with transport of particulate P (which is part of the other–P) increased over a storm event due to the longer contact time of water with P-rich sources (Kennedy et al., 2016). Thus, higher TP concentrations observed in street runoff are attributed to the P release from soil (sediment) bound P by higher runoff volume in the street runoff, which is in line with a study that found that higher runoff volumes resulted in higher concentrations of TP in urban runoff (Miguntanna et al., 2013).

4.4. Potential sources and transport of orthophosphate in residential stormwater runoff

In this study, the exact source of the PO_4–P in residential runoff cannot be quantified, as methods of source identification using ^{18}O of PO_4 are not fully developed and reported in literature. Based on the H_2O isotopes results, we can exclude reclaimed water, wastewater, and leaky sanitary sewers as the sources of PO_4–P. Atmospheric deposition can be a source of P to stormwater runoff; however, the vast majority (90%) of P deposition from air is due to the wind-eroded particles (Smil, 2000) with less contribution from rainfall (Migon and Sandroni, 1999; Anderson and Downing, 2006). The results of PCA showed that PO_4–P in street runoff was not correlated with PO_4–P in rainfall, suggesting that atmospheric deposition is not likely the source of PO_4–P in street runoff (Fig. 3). Another potential source of PO_4–P can be lawn fertilizers, though these are unlikely as most Florida soil are naturally high in P and it is typically recommended that fertilizer with no more than 2% of TP should be applied (Badruzzaman et al., 2012). Further, the use of P fertilizer is prohibited without a soil test in our study region (Listopad et al., 2015). As most of the fertilizers used in the region are N based, we can exclude the possibility of P fertilizer use in our study catchments. Thus, we *hypothesize* that in most of the residential catchments, the source of PO_4–P is from (1) desorption or dissolution from natural sediment (soil) materials, which may include particles from dust and (2) mineralized P derived from the degradation of organic materials such as leaves and grass clippings (Song et al., 2015; Wu et al., 2015). This observation is largely based on the fact that a large amount of P is often bound to soil particles (Song et al., 2007; Ma et al., 2010; Arias et al., 2013) and organic materials (leaves, grass clippings) release P as they degrade. The variability in PO_4–P concentrations across residential catchments (Fig. S3) is attributed to the geologic factors such as use of fill material during construction and variable organic materials such as leaves and grass clippings due to the differential urban land development patterns and impervious areas. Research is needed to characterize the sources and release mechanisms of P in stormwater runoff originating from urban landscapes.

5. Conclusions

This study illustrates the importance of identifying NO_3–N sources in residential stormwater runoff, and of considering co-transport of N and P forms across residential catchments during the storm events. Bayesian mixing model results of $\delta^{15}N–NO_3^-$ and $\delta^{18}O–NO_3^-$ indicated that atmospheric deposition contributed ~50% of NO_3–N (~20% of TN) and chemical N fertilizers contributed ~33% of NO_3–N (~13% of TN) to urban residential stormwater runoff over 21 storm events. The source of PO_4–P is likely from desorption and/or dissolution of P from natural soil/sediments and from degradation of organic materials (leaves, grass clippings) in the catchments. Various NO_3–N sources and different PO_4–P concentrations across catchments suggest that even within the same biophysical context (similar geologic and climatic conditions), urban heterogeneity (i.e., residential development patterns) resulted in different mechanistic controls on N and P transport. Our data makes the case that efforts are urgently needed to curtail contribution of NO_3–N from atmospheric deposition and PO_4–P from landscape in Florida and other urban areas fighting to reduce nutrient loading to the water bodies to reduce algal blooms and restore seagrass beds. One approach that could facilitate NO_3–N and PO_4–P removal is by sourcing rooftop runoff through green infrastructure structures (e.g., bioswales, open protected vegetated spaces), which may provide additional opportunities for nutrient removal before these waters emerge as street runoff and enter hydrological network in urban watersheds. Further, we need a wider discussion with urban planners, landscape architects, policy makers, ecologists, and soil scientists on ways to remediate the impacts of urban residential catchment designs, urban heterogeneity and development (e.g., impervious areas), and land management (e.g., fertilizer use, management practices) on runoff of nutrients.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2017.01.039.

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δ^{15}N and δ^{18}O Reveal the Sources of Nitrate-Nitrogen in Urban Residential Stormwater Runoff

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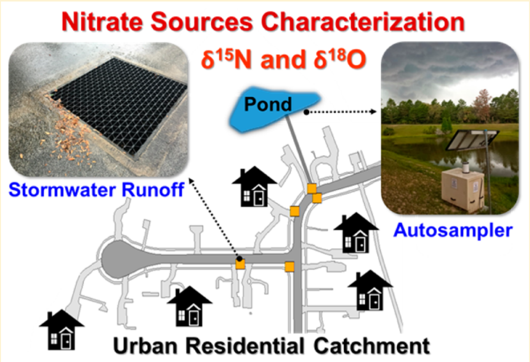
Ⓢ *Supporting Information*

ABSTRACT: Nitrogen (N) sources are widely distributed in the complex urban environment. High-resolution data elucidating N sources in the residential catchments are not available. We used stable isotopes of N and oxygen (O) of nitrate (δ^{18}O-NO_3^- and δ^{15}N-NO_3^-) along with δ^{18}O and hydrogen (δD) of water (H_2O) to understand the sources and transformations of N in residential stormwater runoff. Stormwater runoff samples were collected over 25 stormwater events at 5 min intervals using an autosampler installed at the residential catchment outlet pipe that drained 31 low-density homes with a total drainage area of 0.11 km^2. Bayesian mixing model results indicated that atmospheric deposition (range 43−71%) and chemical N fertilizers (range <1−49%) were the dominant NO_3-N sources in the stormwater runoff and that there was a continuum of source changes during the stormwater events. Further, the NO_3-N transport in the stormwater runoff from the residential catchment was driven by mixing of multiple sources and biotic (i.e., nitrification) processes. This work suggests that a better understanding of N transport and sources is needed to reduce N export and improve water quality in urban water systems.



INTRODUCTION

Sources of nitrate−nitrogen (NO_3-N) in urban waters may include a combination of atmospheric deposition, fertilizers, organic materials, and leaking sanitary sewers.[1,2] These nonpoint sources of NO_3-N are a leading contributor to water quality impairment,[3] and result in eutrophication, hypoxia, and loss of biodiversity and habitat.[4,5] To prevent and remediate eutrophication in urban coastal systems, the sources and transport mechanisms of NO_3-N in stormwater runoff need to be determined and quantified.[6,7]

Dual nitrogen (N) and oxygen (O) stable isotope ratios of nitrate (δ^{18}O-NO_3^- and δ^{15}N-NO_3^-) coupled with chemical data are a powerful tool to distinguish the NO_3-N sources and investigate N transport from land to water bodies.[8,9] In general, δ^{15}N-NO_3^- values have been used to distinguish NO_3-N derived from ammonium (NH_4^+) fertilizer, soil organic matter, and animal manure/septic waste, whereas δ^{18}O-NO_3^- values are more useful to distinguish NO_3-N derived from NO_3^- fertilizer and atmospheric deposition.[10,11] However, abiotic (e.g., volatilization) and biotic (e.g., nitrification and denitrification) processes transform N during transport from land to water bodies[2,8,12] making it difficult to distinguish the contributing N sources in urban systems.

Studies have used the dual stable isotope ratios of NO_3^- to discriminate inorganic (e.g., chemical fertilizers) and organic (e.g., human and animal waste) N sources using biweekly to monthly sampling regimes in urban streams during storm and baseflow conditions.[2,13,14] These urban studies have suggested that NO_3^- in surface waters is commonly derived from the atmospheric deposition and sewage.[2,15] Atmospheric deposition is highly variable in space and time and is a major source of NO_3-N due to the high density of automobile traffic in urban areas.[6,16,17] Divers et al.[12] in an urban stream in Pittsburgh, PA observed that atmospheric deposition contributed 34% of NO_3-N during storm events with the remainder (66%) of NO_3-N contributed by sewage-derived sources. Buda and DeWalle[18] reported that wash-off of atmospheric deposition was the main NO_3-N source during storm flow conditions in a central Pennsylvania urban watershed.

Transport of N from land to water is controlled by a complex interaction of hydrological and biogeochemical mechanisms.[2,19−21] Previous research had found that biogeochemical mechanisms are dominant in watersheds,[22,23] whereas some studies found that transport of stormwater driven N is primarily a function of hydrology, with biogeochemical processes playing a minor role.[20,24,25] The dynamics of NO_3-N transport in urban stormwater runoff from residential areas have not yet been fully investigated. Among different N forms, NO_3-N is one of the main form of concern in the stormwater runoff.[26] Stormwater runoff sampling during rain events may reveal N transport mechanisms and contributing NO_3-N sources in residential

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catchments. The objective of this study was to investigate the contributing NO_3-N sources and elucidate the processes controlling NO_3-N transport using dual stable N and O isotopes in a residential catchment. To our knowledge, this is the first study to illustrate the source identification and transport of NO_3-N in residential stormwater runoff using consecutive 5 min intervals sampling from a low-density residential catchment. This data can help develop strategies to reduce NO_3-N transport from residential catchments to downstream urban waters.

■ STUDY LOCATION AND METHODS

Site Description. The study site is a low-density residential neighborhood of 31 single-family homes, with an average lot area of 2400 m^2 and home area of 409 m^2. The site is located along Florida's Gulf Coast in Hillsborough County, Florida (latitude 27°86′63.17″ N, longitude 82°19′37.73″ W) and is part of the metropolitan area of Tampa, Florida. The total area of the catchment including stormwater pond is 0.11 km^2; of which 37% is impervious (rooftops: 15%, patios: 4%, driveways and sidewalks: 12%, roads: 6%) and 61% is pervious (lawns in and around homes: 29%, tree canopies: 32%), and 2% is occupied by pond (Supporting Information (SI) Figure S1). The dominant vegetation in the catchment is live oak (*Quercus virginiana*) and St. Augustine turfgrass (*Stenotaphrum secundatum*). Soils in the catchment are predominantly Seffner fine sand series (Sandy, siliceous, hyperthermic Aquic Humic Dystrudepts). The climate in the area is subtropical with 2014 average monthly annual air temperature of 14−27 °C and daily extremes of 4−29 °C.[27] The average annual rainfall in the area over the last 10 years (2004−2014) was 94−153 cm (mean 130 cm), of which 47−77% (mean 65%) occurred during the wet season (June to September) (SI Figure S2A). In 2014, total rainfall was 144 cm, and monthly rainfall ranged from 1.52 to 34.24 cm, of which 58% occurred during the wet season. During the study period, monthly rainfall was highest in September (34 cm), followed by July (24 cm) and August (14 cm) (SI Figure S2B).

Sample Collection and Nitrogen Analysis. An ISCO Avalanche 6712 refrigerated autosampler (Teledyne Isco, Inc., Lincoln, NE, USA) was installed at the end of the stormwater outlet pipe that delivered runoff from the residential catchment to the stormwater pond. The autosampler was equipped with 14 plastic sample bottles of 950 mL each and was programmed to collect runoff entering the pond at the onset of flow and to take samples every 5 min until end of the runoff. An ISCO 674 rain gauge (Teledyne Isco, Inc., Lincoln, NE) was installed at the site for rainfall measurements and collection. Due to the need to have sufficient flow (and water depth) in the outlet pipe for ISCO sampler to operate, it was only possible to collect runoff samples when there was a minimum of 0.25 cm rainfall occurring in 15 min (equivalent to rainfall intensity of 1 cm/h). Thus, samples could not be collected during those rainfall events when the rainfall intensity was lower than 1 cm/h. The samples were collected in airtight plastic bottles and stored in a refrigerator at 4 °C until analysis (<24 h). The range of runoff samples collected during 25 individual events (July to September 2014) varied from 1 to 13 (SI Table S1), resulting in 121 stormwater samples; this corresponds to runoff occurring from 5 to 65 min as each runoff sample was collected at 5 min intervals. Twelve rainfall samples (10 samples were analyzed for isotopes) were also collected from the catchment during the wet season.

A subsample of collected water samples was vacuum-filtered (0.45 μm Pall Corporation, Ann Arbor, MI) within 24 h of collection and placed in 20 mL HDPE scintillation vials (Fisher Scientific, PA) either refrigerated (N and water isotope analysis) or frozen (N isotopic analysis). Aliquots of the filtered water samples were quickly transferred in 2 mL GC vials (Fisher Scientific, PA), sealed without headspace to eliminate water evaporation, and refrigerated until the water isotope analysis. The filtered samples were analyzed for NO_3-N using an AutoAnalyzer 3 (AA3, Seal Analytical, Mequon, WI) with EPA method 353.2.[28] The unfiltered water samples were analyzed for total N (TN) using the alkaline persulfate digestion method[29] followed by NO_3-N analysis as described above. The detection limits for both NO_3-N and TN were 0.001 mg/L.

Isotopic Analysis. Stable isotopes of water (H_2O), that is, oxygen ($\delta^{18}O-H_2O$) and hydrogen (δD-H_2O) were conducted in the Stable Isotope Laboratory at the University of California, Davis. The detailed description of the analysis technique is given by Lis et al.[30] For simultaneous D/H and $^{18}O/^{16}O$ ratios measurements of H_2O, an off-axis integrated cavity output spectroscopy (OA-ICOS) water isotope analyzer (LWIA, Los Gatos Research, Mountain View, CA) was coupled to a CTC LC-PAL liquid autosampler. Analysis of $\delta^{18}O$-NO_3^- and $\delta^{15}N$-NO_3^- was conducted using Coplen et al.[31] at the Isotope Ratio Mass Spectrometry (IRMS) facility at University of California, Riverside. All stable isotope results are expressed as δ values, representing deviations in per mil (‰) from Vienna Standard Mean Ocean Water standards for O, N, and deuterium such that

$$\delta(‰) = 1000 \times [(R_{\text{sample}}/R_{\text{standard}})] - 1$$

where R_{sample} and R_{standard} are the measured isotopic ratios (e.g., D/H, $^{15}N/^{14}N$ or $^{18}O/^{16}O$) for the sample and standard, respectively. The ratio of $^{15}N/^{14}N$ reference is N_2 in air, the D/H and $^{18}O/^{16}O$ reference is Vienna Standard Mean Ocean Water.

Bayesian Mixing Models. The proportion of the NO_3-N source contributions was estimated using Bayesian stable isotope mixing models as described in Parnell et al.[32,33] The Stable Isotope Analysis in R (SIAR) graphical user interface package (MixSIAR version 3.0.2) incorporating sources of uncertainty, isotope fraction, and multiple NO_3-N sources was used in this study. In brief, the isotope mixing analysis was used to determine fraction of NO_3-N in stormwater runoff from four sources (i.e., atmospheric deposition, NH_4^+ fertilizer, NO_3^- fertilizer, and soil and organic N) with two isotope systems. End member isotopic compositions were defined as follows. Atmospheric deposition was estimated from measured $\delta^{15}N$-NO_3^- (2.7 ± 4.90‰, n = 10) and $\delta^{18}O$-NO_3^- (44.8 ± 18.07‰, n = 10) values of rainfall samples collected during the wet season. NH_4^+ fertilizer ($\delta^{15}N$-NO_3^-: −0.2 ± 2.28‰, $\delta^{18}O$-NO_3^-: −2.0 ± 8.0‰),[10,34−41] NO_3^- fertilizer ($\delta^{15}N$-NO_3^-: 1.1 ± 2.78‰, $\delta^{18}O$-NO_3^-: 21.3 ± 3.01‰),[10,35,36,38,39,42] and soil and organic N ($\delta^{15}N$-NO_3^-: 7.5 ± 5.23‰, $\delta^{18}O$-NO_3^-: −2.0 ± 8.0‰)[2,10,12,35,37−39,42−46] end members were based on literature values. Measured $\delta^{15}N$-NO_3^- and $\delta^{18}O$-NO_3^- values of individual stormwater runoff samples (n = 121) were treated as "customers" and mean values of four NO_3-N sources were "sources". It should be acknowledged that the use of stable isotopes for source identification is complicated when the mixing of multiple N sources with overlapping isotopic ranges occurs together with microbial processes such as assimilation,

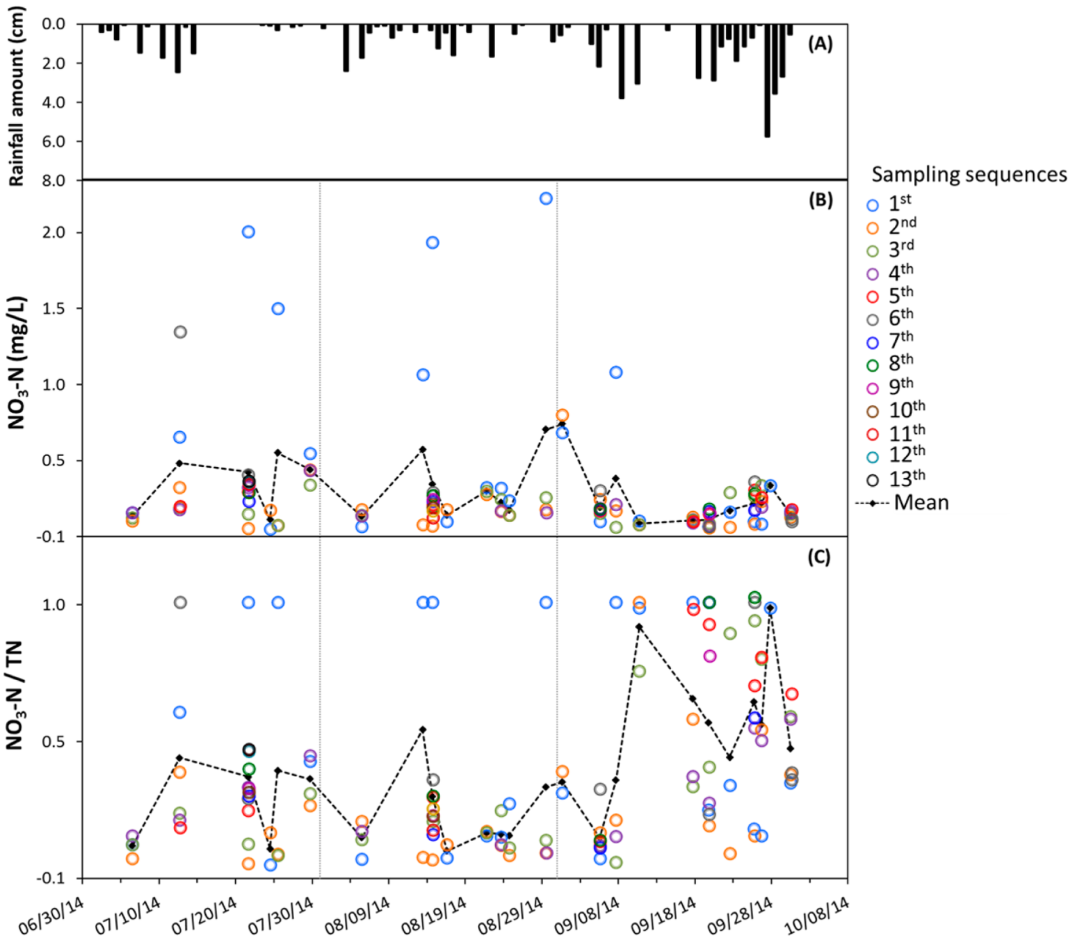

Figure 1. Temporal variability of (A) daily rainfall, (B) NO_3-N concentrations, and (C) NO_3-N/TN in stormwater runoff (n = 121) from 25 events during July−September 2014. The colors of circles and labels indicate sampling sequences. The dashed line shows change of mean values from individual events.

nitrification, and denitrification. Studies have reported that denitrification process causes increase in δ^{15}N-NO_3^- and δ^{18}O-NO_3^- in roughly 2:1 ratio.[10,12,47] The observed linear relationship between the δ^{15}N-NO_3^- and δ^{18}O-NO_3^- values of the stormwater runoff implied that no obvious denitrification occurred during the sampling events (data not shown). Further, the mean dissolved oxygen (DO) concentration in stormwater runoff during the wet season were high (>2 mg/L), suggesting that denitrification did not cause enrichment of δ^{15}N-NO_3^- and δ^{18}O-NO_3^- in the study catchment as denitrification generally occurs under the low DO concentration (<2 mg/L) condition.[10,48] Thus, the enrichment factors for denitrification were not evaluated in the mixing models. We determined the potential nitrification process using a calculation widely used in previous studies,[10,49] which is discussed in the later section. More detail on the mixing model and calculations can be found in SI.

RESULTS AND DISCUSSION

Nitrogen Concentration in Rainfall and Urban Stormwater Runoff. Concentrations of TN and NO_3-N in rainfall (n = 12) were 0.09−2.32 mg/L (mean 0.8 mg/L) and <0.001−1.15 mg/L (mean 0.18 mg/L), respectively. Mean concentrations of TN and NO_3-N in individual 25 stormwater runoff events (July−September) varied from 0.04 to 2.49 mg/L (mean 0.96 mg/L) and 0.04 to 0.69 mg/L (mean 0.24 mg/L), respectively (SI Table S1). The decrease in monthly NO_3-N concentrations from the beginning to the end of wet season could be due to the exhaustion of N sources in the residential catchment. We were not able to evaluate the relationship between N export and hydrological factors due to the lack of flow data and collection of runoff samples when the rain intensity was >1 cm/h. However, the mean concentrations of N in runoff were similar to a Tampa Bay residential stormwater runoff study (mean TN 1.25 mg/L; mean NO_3-N 0.21 mg/L)[50] but TN was lower than other urban stormwater runoff studies conducted in the United States (TN 2.0 mg/L).[6] Within individual stormwater events, the ratio of NO_3-N:TN varied between 0 and 1, with mean monthly values of 0.29 in July, 0.21 in August, and 0.47 in September, respectively (Figure 1).

Source of Water in Urban Stormwater Runoff. Stable isotopes of δ^{18}O−H_2O and δD-H_2O are ideal conservative environmental tracers that can provide essential information about the origin of the water, hydrological processes, and insights into the likely N sources.[51−53] In urban residential areas, stormwater runoff can be a combination of various water sources such as rainfall, municipal water, and reclaimed water used for lawn irrigation. Thus, we used water isotopes to determine the water source in stormwater runoff. The δ^{18}O−H_2O and δD−H_2O values in the rainfall (n = 10) ranged from −8.4‰ to −2.6‰ (mean −4.1‰) and −51.7‰ to −10.8‰

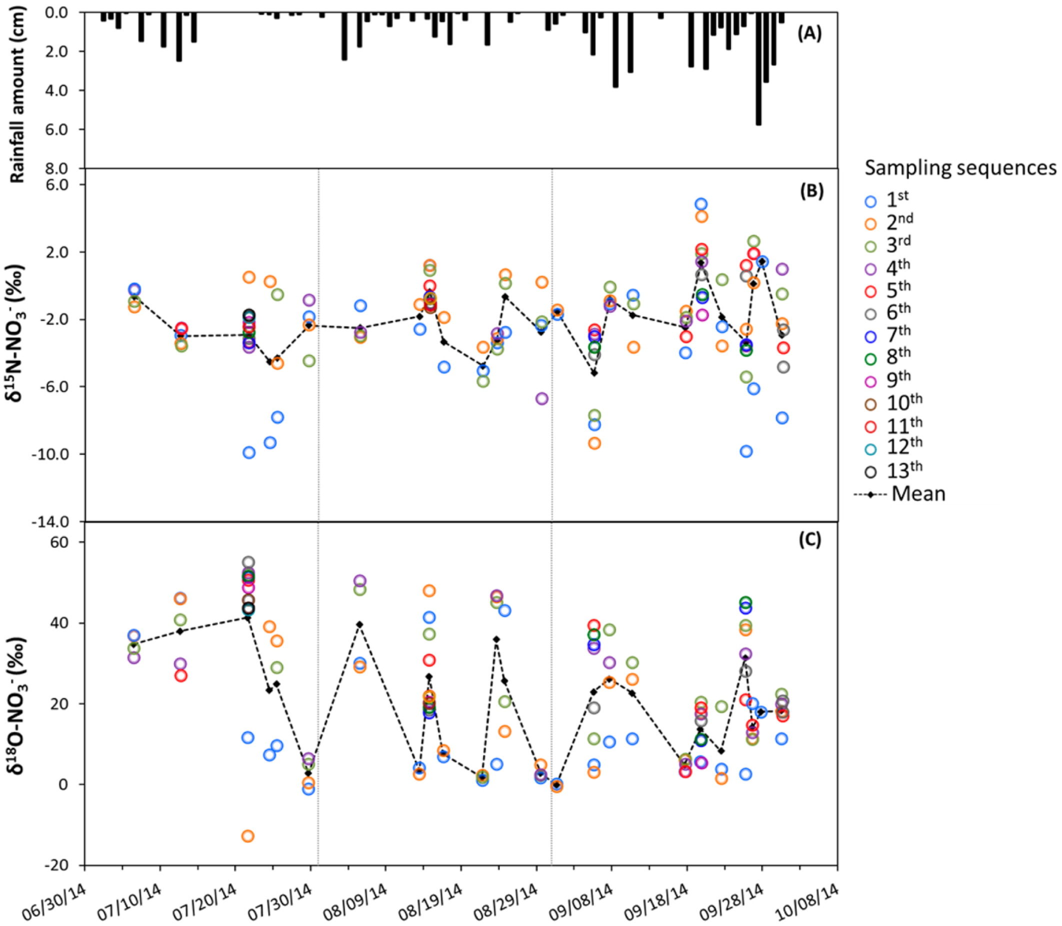

Figure 2. Temporal variability of (A) daily rainfall, (B) δ^{15}N-NO_3^-, and (C) δ^{18}O-NO_3^- in stormwater runoff (n = 121) from 25 events during July–September 2014. The colors of circles and labels indicate sampling sequences. The dashed line shows change of mean values from individual event.

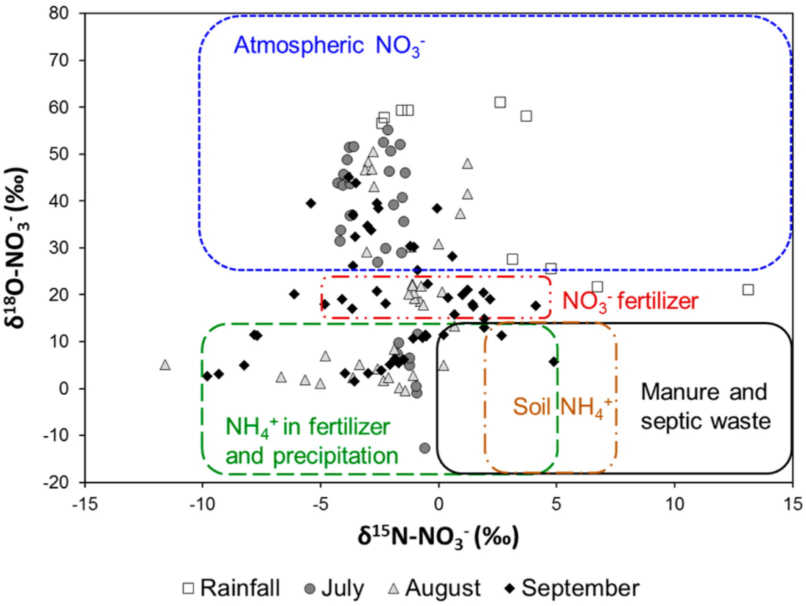

Figure 3. Dual δ^{15}N-NO_3^- and δ^{18}O-NO_3^- in rainfall and stormwater runoff during the wet season in 2014. Area shows the range of the δ^{15}N-NO_3^- and δ^{18}O-NO_3^- values from Kendall et al. (2007)[10]

(mean −24.0‰), respectively (SI Figure S3A). In the stormwater runoff samples (n = 121), δ^{18}O−H_2O and δD−H_2O varied from −8.3‰ to 0.8‰ (mean −2.6‰) and −50.1‰ to −12.1‰ (mean −12.1‰), respectively. Most of the δ^{18}O−H_2O and δD-H_2O of stormwater runoff samples (SI Figure S3A) were close to the global meteoric water line (GMWL), defined as δD−H_2O = 8δ^{18}O−H_2O + 10.[54] Further, the y-intercept (deuterium excess, d-excess = δD-H_2O−8δ^{18}O−

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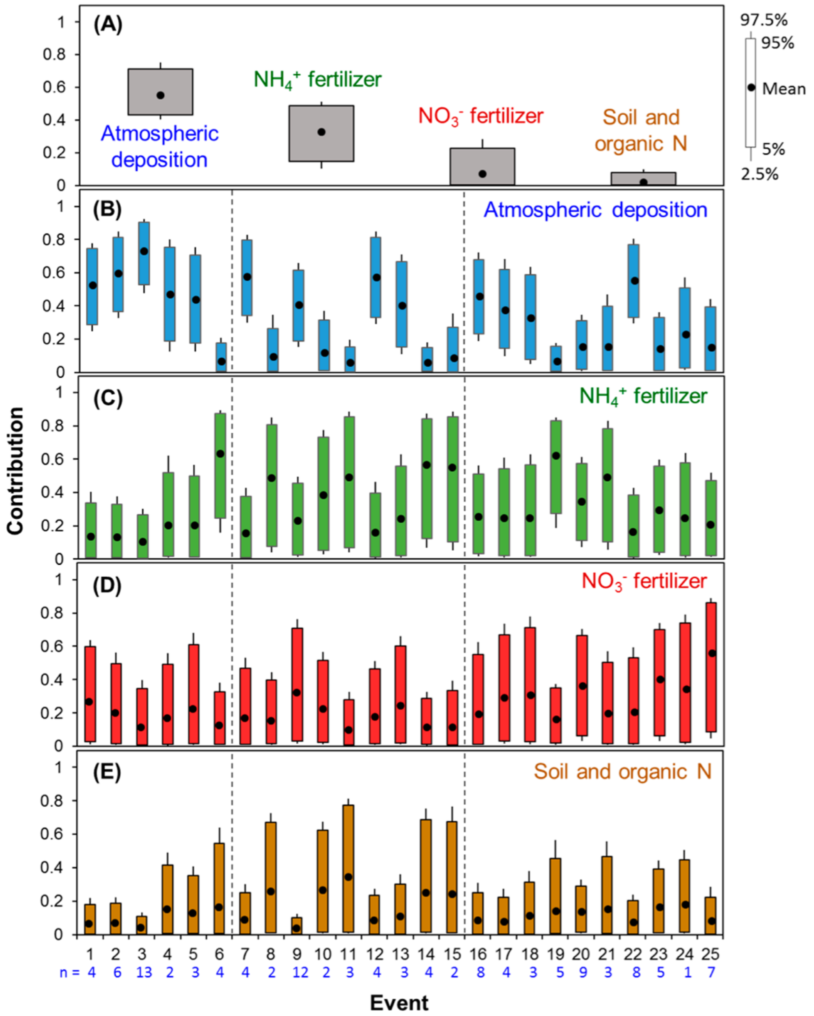

Figure 4. (A) Fractional contribution of different NO_3-N sources to stormwater runoff from 25 events ($n = 121$) based on Bayesian stable isotope mixing models, and Bayesian credible intervals for the probability distribution calculated for (B) atmospheric deposition, (C) NH_4^+ fertilizer, (D) NO_3^- fertilizer, and (E) soil and organic N sources. Events 1–6, 7–15, and 16–25 occurred in July, August, and September 2014, respectively. Numbers in blue represents total number of sequential 5 min samples collected during each event.

H_2O) was used a diagnostic tool to measure the contribution of evaporated moisture.[55] The mean *d*-excess value in our stormwater runoff samples were lower than GMWL (10‰), indicating enrichment due to the evaporation (SI Figure S3B). Some evaporation is expected in our residential catchment due to the higher temperature (23–29 °C) during study period and presence of 37% impervious area, which may have caused evaporation as water traveled over impervious areas to reach stormwater pond. Overall, our data indicated that all runoff water during 25 stormwater events originated from the local rainfall and evaporation slightly changed the isotopic composition. This suggests that no other sources of water (e.g., groundwater, municipal water, reclaimed water, leaking sanitary sewers) contributed any water and thus N in our stormwater runoff samples.

Source of Nitrate-Nitrogen in Urban Stormwater Runoff. The δ^{15}N-NO_3^- in rainfall ($n = 10$) and stormwater runoff ($n = 121$) varied from −2.4‰ to 13.1‰ (mean 2.7‰) and −11.5‰ to 4.9‰ (mean −2.2‰), respectively (Figure 2). There was a narrow range of δ^{15}N-NO_3^- in the runoff samples, with 65% of samples between −4‰ and 0‰. The δ^{18}O-NO_3^- in rainfall and stormwater runoff samples ranged from 21.0‰ to 61.0‰ (mean 44.8‰) and −12.8‰ to 55.2‰ (mean 22.6‰), respectively. Isotopic signatures of potential NO_3-N sources suggest that atmospheric deposition, chemical fertilizers, soil based N, and organic N sources contributed NO_3-N to stormwater runoff in our residential catchment (Figure 3). To estimate the potential contributions from each of these sources, we used a Bayesian mixing model to determine the different sources of NO_3-N during the wet season. The mixing model outputs revealed a high variability in contributions of the four potential NO_3-N sources over 25 stormwater events (Figure 4). In the below sections, we examine the isotopic signatures of different sources of NO_3-N in stormwater runoff based on mixing model results.

Atmospheric Deposition. The δ^{15}N-NO_3^- in the atmospheric deposition is reported to range from −15‰ to 15‰.[10,11] Atmospheric N is known to be enriched in δ^{18}O-NO_3^- due to the exchange of O atoms with ozone.[56] The pattern of δ^{18}O-NO_3^- is considered more useful than δ^{15}N-NO_3^- in identifying NO_3^- sources as there is a large variability in the δ^{18}O-NO_3^- among the different sources.[10] The highest δ^{18}O-NO_3^- values in stormwater runoff were >25‰, which indicated largest contribution from atmospheric N (Figure 3). In addition, high δ^{18}O-NO_3 values in the stormwater runoff samples with low NO_3-N concentrations were observed, suggesting the importance of atmospheric sources in stormwater runoff (SI Figure S4A). Based on the mixing model results, the contribution of NO_3-N from atmospheric deposition to stormwater runoff ranged from 43 to 71% (mean 56%) over 25 stormwater events (Figure 4 and SI Figure S5; Table S2), and observations of fractional contribution for individual samples within events ranged more widely from 1 to 90%. Overall, atmospheric deposition was an important source of NO_3-N in the stormwater runoff during the wet season. Our results are in agreement with previous studies.[2,14,18] For example, Anisfeld et al.[14] observed that atmospheric deposition contributed greater stream NO_3-N (∼50%) during stormflow in urbanized rivers of central New York. Kaushal et al.[2] reported that source contributions of NO_3-N changed with storm magnitude and atmospheric deposition accounting for ∼50% of NO_3-N during storms in Baltimore, Maryland. Earlier studies conducted by Ging et al.[57] and Silva et al.[58] in Austin, Texas also pointed out the importance of atmospheric deposition in urbanized stormflow due to the influence of runoff from impervious surfaces. In summary, these findings suggest that in urban systems, wet atmospheric deposition combined with accumulated dry atmospheric deposition and wash-off from impervious surfaces has the potential to enhance delivery of atmospheric N to waters during storm events.[2,59,60]

Inorganic Fertilizers. Research suggests that δ^{15}N-NO_3^- in the inorganic fertilizers range from −4‰ to 4‰.[10,11] The δ^{18}O-NO_3^- in NO_3^- fertilizers is 17−25‰, which overlaps with atmospheric values (ca. 23.5‰)[10] whereas NO_3^- derived from NH_4^+ fertilizers has lower δ^{18}O-NO_3^- values, usually in the range of −5 to 15‰.[10,11] The δ^{15}N-NO_3^- and δ^{18}O-NO_3^- values in our stormwater runoff samples were in the range of both NH_4^+ fertilizers and NO_3^- fertilizers. The mixing model results suggests that NH_4^+ fertilizers contributed 15−49% (mean 34%) and NO_3^- fertilizers contributed <1 to 23% (mean 8%) of NO_3-N in stormwater runoff over 25 stormwater sampling events (Figure 4 and SI Table S2). Chemical fertilizers as the sources of NO_3-N in urban watersheds have been investigated in previous studies.[2,20,61] For example, fertilizer was the main source of NO_3^- in stormwater runoff, contributing 44% NO_3^- loads in an urban watershed in Phoenix, Arizona.[20] However, a study conducted in an urban watershed in Baltimore, Maryland found fertilizer as a minor component of NO_3^- in stormwater runoff.[2] Lawn fertilizers can be an important source of N in residential catchments depending upon the frequency and quantity of fertilizer use and climatic factors such as high rainfall. Fertilizers are frequently used in Florida's urban neighborhoods due to the sandy texture of soils and subtropical climate (up to ∼60% rainfall occurs during wet season). The fertilizer N input to the residential areas in Hillsborough County (our study region) is estimated to be ∼105 kg/ha, with an average 2.5 applications in a year and 16−22% (18% on average) of fertilizer application during wet season.[50] In our study, we found that N fertilizers contributed ∼42% (on average) of NO_3-N to stormwater runoff during the wet season, which is due to the fertilizers use in the residential catchment and excess rainfall. We hypothesize that NO_3-N in the stormwater runoff might have originated due to the runoff of improper application and/or spillage of N fertilizers on the impervious areas.

Soil and Organic N. The δ^{15}N-NO_3^- values of organic sources of N such as sewage and animal waste generally have much wider range of compositions (2−30‰) than inorganic fertilizers due to their more diverse origins.[10,11] In general, the δ^{18}O-NO_3^- of NO_3-N derived from organic N sources range from −5 to 15‰ based on the literature values.[10] Our mixing model results suggested that <1 to 8% of NO_3-N in stormwater runoff originated from soil and organic N sources (Figure 4 and SI Table S2). It is important to consider the hydrologic connectivity of N sources with surface waters when estimating N sources in water bodies.[62] For example, septic systems have been suggested as major sources of NO_3^- in groundwater and connected surface waters.[6,63] Studies conducted in Baltimore, Maryland found that older leaking sewer systems were the source of NO_3^-.[2] There are no known sources of septic waste in our residential catchment due to the fact that all wastewater is piped and conveyed to a central wastewater treatment plant and there are no septic systems. Further, water isotope results showed that all stormwater runoff originated from the local rainfall, thus it is unlikely that sewer leaks contributed N in stormwater runoff. Another organic N source such as pet waste has been identified in urban catchments.[60,64] Thus, the organic N sources observed in the residential catchment may be derived from the pet waste. In addition, it is important to recognize that there can be multiple organic N sources in urban stormwater runoff as organic N is the dominant N form in urban water systems.[65,66] The estimated area of tree canopy and lawns in our residential catchment is 61% of total drainage area. Therefore, the mineralization of lawn grass clippings and tree leaves likely contribute NO_3-N in stormwater runoff. Research is needed to determine the contribution of organic N sources to NO_3-N in residential stormwater runoff.

Processes Controlling NO_3-N Transport. The isotopic composition of NO_3-N is influenced by nitrification and denitrification in soil. The values of δ^{18}O-NO_3^- can be used to identify the contribution of nitrification, as δ^{18}O-NO_3^- from −10‰ to 10‰ suggests in situ soil nitrification.[10] In theory, the δ^{18}O of NO_3-N produced by nitrification could be calculated using the O value (23.5‰) of the air and experimental O value of stormwater runoff samples using this formula: $\delta^{18}\text{O-NO}_3^- = 1/3\ \delta^{18}\text{O}-\text{O}_2 + 2/3\ \delta^{18}\text{O}-\text{H}_2\text{O}$.[10] Based on this calculation, the expected δ^{18}O-NO_3^- values in our stormwater runoff from nitrification ranged from 2.3‰ to 8.4‰, which suggests that in situ soil nitrification contributed a part of NO_3-N in stormwater runoff (SI Figure S6).

Denitrification is an important process in which bacteria utilize NO_3^- as an electron donor instead O_2 to reduce NO_3^- to N_2 or N_2O in the environment. Combined evaluation of N isotope data and NO_3-N concentrations was pursued to gain a better understanding of denitrification in our stormwater samples. If denitrification occurs, δ^{15}N-NO_3^- increase with decrease in NO_3-N concentrations and there is be 2:1 ratio between δ^{15}N-NO_3^- and δ^{18}O-NO_3^-.[10,67] None of these two conditions were present in our data, suggesting no denitrification in any of the stormwater runoff samples (see Figure 3 and SI Figure S4B).

In contrast, increasing δ^{15}N-NO_3^- values with increase in NO_3-N concentrations were observed in some stormwater runoff samples indicating mixing of NO_3-N from multiple sources (SI Figure S4B). Of 25 stormwater events, 13 events had N isotopic signatures that were dominated by atmospheric deposition (mean credible interval of feasible 33−73%), eight events were dominated by NH_4^+ fertilizer (mean 38 to 63%), and four events were dominated by NO_3-N fertilizer (mean 35 to 56%) (SI Table S2).

Fractional contribution of different NO_3-N sources to stormwater runoff during the wet season indicates that atmospheric deposition had more effect on NO_3-N in the beginning of the wet season (SI Figure S7), which decreased from July (55−88%) to August (32−65%) and September (18−55%). Meanwhile, chemical fertilizer (NH_4^+ fertilizer and NO_3-N fertilizer) showed an increasing contribution from July (1−32%) to August (1−57%) and September (1−59%). Higher contributions of atmospheric deposition in July can be due to the longer antecedent dry weather period prior to the beginning of wet season. It is not possible in this study to estimate the relative importance of wet and dry deposition due to the lack of dry deposition measurements. The increasing trend of sources of N fertilizers as season progressed could be due to the amount and duration of precipitation events as runoff of soil based N fertilizers from residential area to the stormwater runoff is more likely to occur during periods of high rainfall as compared to low rainfall where runoff will primarily occur from impervious areas. These findings are supported by previous research, which found that variation in isotope composition in urban waters is primarily result of mixing sources rather than biogeochemical processes during storm runoff events.[18,20,68]

Environmental Implications. Stormwater runoff from the residential catchments located in subtropics represents a unique scenario of N pollution in urban coastal water bodies. The different NO_3-N sources in residential catchments present a challenge for effectively mitigating N enrichment in urban waters. In this study, combining dual isotope source identification techniques with chemical analysis was used to elucidate the transport and sources of NO_3-N from a low-density residential catchment. Long-term studies in residential catchments of different landscape patterns, community stormwater systems, residential landscape, and resident behaviors are needed to better understand the contribution of urban residential catchments to N pollution in water bodies. Nevertheless, the results from the mixing model suggest that both atmospheric deposition and chemical fertilizers are important NO_3-N sources in urban stormwater runoff. Further, the transport of NO_3-N in the residential catchment was due to the mixing of sources and their changing contributions during the wet season. We are first to report and quantify the contribution of N fertilizers (average of 42%) to NO_3-N in urban stormwater runoff from a residential catchment. This data suggests that proper application of urban N fertilizers in residential areas dominated by turfgrass is important to reduce NO_3-N concentrations in stormwater runoff. This can be achieved by careful application of urban fertilizers on urban lawns and avoiding any accidental spillage on impervious areas that have the high potential for transport during stormwater events. In addition, the use of green infrastructure such as bioswales in residential neighborhoods to slow and direct runoff waters away from impervious areas may provide additional opportunities to remove NO_3-N contributed by atmospheric deposition, chemical fertilizers, and other sources before it reaches stormwater retention ponds and enters the hydrological network in urban watersheds.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b05353.

Detailed descriptions of Bayesian mixing models; Source of Water in Urban Stormwater Runoff; Table S1, S2 and Figures S1−S7 (PDF)

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Notes

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IFAS Extension

Urban Water Quality and Fertilizer Ordinances: Avoiding Unintended Consequences: A Review of the Scientific Literature[1]

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Summary

Degraded inland urban and coastal water quality is a critical concern in Florida. Nutrients released from urban land-based human activities (disturbed soil, fertilizer, pet wastes, plant debris, atmospheric deposition, septic systems, and others) are present in water bodies, resulting in eutrophication and an increase in algal blooms that impair water quality. There are many scientific publications that document the nature and scope of the water pollution problem. There are differing approaches to addressing eutrophication, including adoption of current best management practices (BMPs) for nutrients, state regulation, or local ordinances. The local ordinance, sometimes including a summer fertilizer ban, has been the chosen approach by several Florida counties and municipalities to address local water quality issues. Many components of these ordinances follow published BMPs. There is agreement in the national literature on the effectiveness of BMPs and public education programs to reduce local water quality problems. However, there has been disagreement among stakeholders over the inclusion of a summer fertilizer ban in an ordinance. Other states do not use summer fertilizer bans, rather they use BMPs to reduce the risks for nutrient losses from landscapes. There are numerous research reports that provide information about proper management of nutrients and irrigation throughout the year, especially in the summer, to optimize the benefits of turf in the landscape while protecting the environment. This paper provides a literature review of the critical eutrophication problem and the pertinent literature regarding managing urban landscapes to improve water quality with particular attention to N and P fertilization during the active plant growth period corresponding to summer fertilizer bans.

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Reasons for this publication

This publication was developed to serve the need for educational information on the urban landscape nutrient and water management issues, especially pertaining to protecting urban and coastal water quality. Eutrophication of water bodies is a major problem faced by the state, counties, and municipalities; their officials are asking for more information to assist them in making decisions about legislation for protecting water quality. Educators, county extension agents, representatives of non-governmental organizations, and leaders of the fertilizer, turf, nursery, and landscape maintenance industries also are asking IFAS for information about how to best protect the environment. This document is a review of the scientific literature addressing the major questions being asked about fertilization practices for turfgrass.

This document consists of three major sections. The first section reviews the science about the eutrophication problem for urban and coastal water bodies, and the sources of nutrients that lead to water pollution. The second section of the document presents the current state of the scientific knowledge about fertilizer and irrigation management in urban landscapes with emphasis on turfgrass health and water quality. The final section summarizes some of the approaches that are being used in the United States to deal with the nutrient problem. There are regulatory and incentive-based programs that include BMPs, educational programs, and rules that restrict fertilization. Our goal is to take the reader through the process: learning about the pollution issue, the sources of pollutants, management of nutrients in the urban landscape, and the most effective approaches being undertaken to reduce the nutrient loading problem.

Section 1. Introduction to the Issue of Urban Nutrient Pollution

Eutrophication or nutrient enrichment of fresh and coastal waters is a serious and growing concern (Diaz and Rosenberg, 2008; Heisler et al., 2008). Eutrophication is largely the result of human activities in managing land, energy, plants, nutrients, and wastes (Selman and Greenhalgh, 2009). Human impact on the land is increasing. For example, in the United States, during the decade of 1982–1992, there were 1.4 million acres converted to urban development, and there were 2.2 million acres converted during the 5-year period of 1992–1997 (USDA, NRCS, 2005). It is well documented that urbanization changes land cover and hydrology and leads to "unintended consequences" on urban ecosystems that include altered nutrient flows (Roach et al., 2008).

Human influences lead to point and non-point source nutrient pollution of water bodies causing degradation or impairment of the water bodies for their intended uses, such as recreation, fishing, drinking water, irrigation, etc. Nitrogen (N) and phosphate (P) are often involved in eutrophication because these are two limiting nutrients for algal growth in most natural water bodies. Earlier research reports therefore focused on N or P, but Paerl (2009) pointed out that today N and P must be managed together to control eutrophication in the freshwater-marine water system.

Cleanup of impaired water bodies is required under the total maximum daily load (TMDL) program (US, EPA, 2010; FDEP 2009a), which places severe economic burdens on local governments (Baker, 2007). In addition to the costs to local governments, harmful algal blooms were determined to result in significant revenue losses for local businesses on the panhandle of Florida, even more than other environmental events such as tropical storms and rains (Larkin and Adams, 2007). Nutrient enrichment of Florida waters is a serious and costly issue and must be addressed in an informed and comprehensive process. Before a comprehensive nutrient management process can be determined, however, we must understand the various sources of nutrients causing the problems in urban water bodies.

Urban land-based nutrient sources and impacts

Research has pointed to many sources of nutrients contributing to increased nutrient loads and eutrophication of surface waters throughout the world (Alcock, 2007; Baker, 2007; Gilbert et al., 2005; Heisler et al., 2008). Impairment of urban water bodies in Florida includes increases in algal growth, including those algae that produce toxins that can potentially harm aquatic wildlife and humans (Anderson, 2002; Paerl et al., 2010). The following information summarizes the many and varied sources of nutrients that should be of concern in any approach addressing the overall urban water quality problem.

Sewage-based nutrients. Water bodies can receive nutrients from several sewage sources including water treatment plant discharges and on-site septic systems. Land-based sewage sources were implicated in algal blooms off the southeast coast of Florida (Lapointe et al., 2005). Paerl et al. (2010) found that cyanobacteria (one of the bacteria associated with red tide) responds to iron, N and P from sewage outfalls, urban wastewater, urban development runoff, and nutrients from groundwater. Lapointe et al. (2006), determined that large algal blooms of *Microcystis aeruginosa* in the Caloosahatchee estuary in 2005 were likely related to sewage effluent as were red tide blooms off Sanibel Island in 2004. There are examples where the removal of sewage-based nutrient sources was related to a subsequent reduction in algal blooms (Anderson et al., 2002).

Land-based N and P discharges. Nutrients from a mixture of sources can enter the water stream moving off of land toward a water body. N discharges from Lake Okeechobee and the Caloosahatchee River following hurricanes of 2004/2005 were implicated in algal blooms in southwest Florida. Nutrient flux from bays, harbors, and rivers along the west coast of Florida can provide significant amounts of nutrients to support high-biomass blooms of red tide, *Karenia brevis* (Vargo et al., 2008). Land-based N and P sources vary from location to location, and this variability leads to a gradient of P- and N-limited phytoplankton communities (Heil et al., 2007). Although the ultimate source of nutrient enrichment may be land-based, there can be considerable cycling, transport, and mineralization of N and P from phytoplankton, and these cycled quantities can be greater than external loadings (Wang et al., 1999). These authors suggested that, while nutrient load reductions are needed at the source, time will be required before observing impacts of those reductions because cycling of already imported nutrients plays a role in algal blooms. Further, some algal species can fix nitrogen from the atmosphere, adding another level of complexity to the nutrient source picture (Havens, 2004). Finally, the impacts of eutrophication differ depending on the algal species (Anderson et al., 2002).

Distant sources. While nearby land-based sources are important, studies have also implicated long-distance transported nutrients in Florida red tides. For example, depositions of Saharan dust, containing iron, could relieve iron deficiency of certain aquatic organisms (Walsh and Steidinger, 2001). Stumpf et al., (2008) used thermal and ocean color satellite data to suggest the possible importance of nutrients from the Mississippi River that travel in a plume to the west Florida shelf, 30 to 50 miles from the coast. The connectivity of the water bodies makes it difficult to clearly distinguish among the many and varied sources of nutrients at any single locale.

Industrial emissions (e.g., smoke) and fossil fuel combustion (e.g., automobiles) adds N oxides to the air, which can be later deposited onto land or water bodies during rainfalls. For example, the Tampa Bay Estuary Program predicted in 1996 that as much as 33% of nutrients in Tampa Bay by 2010 would result from atmospheric deposition (Zarbock et al., 1996). An updated report (Janicki et al., 2001), using the methods of Zarbock et al. (1996) predicted that for 2010 conditions, atmospheric deposition would be 20% and non-point contributions of N to Tampa Bay would be 49%. The total annual N load predicted for 2010 in the latter report was 2950 tons, down from the predicted value of 3670 tons in the Zarbock et al. (1996) report. Predicted total quantities of non-point N losses in both estimates were similar. The percent loads due to non-point sources increased because material losses and atmospheric deposition were predicted to be lower in the later model. A planning and management document from the Tampa Bay Estuary Program concluded that the two largest contributors of nutrients to Tampa Bay were atmospheric deposition and storm water runoff (Tampa Bay Estuary Program, 2006).

Fertilizers. Fertilizer has been a common input for managing healthy urban turfgrass and landscape plants and gardens. Amounts of fertilizers sold and used in non-farm areas in Florida (nurseries, golf courses, athletic fields, roadsides, airfields, cemeteries, parks, and retail establishments) have declined over recent years (FDACS, 2009). For example, N use increased from 2000 to 2004, but it declined from 2004 to 2008. In 2005, the non-farm use of N fertilizer was 69,522 tons, but it declined to 36,074 tons in 2008, a 48% reduction in urban fertilizer use. The non-farm use of P fertilizer declined from 14,168 tons in 2005 to 8,034 tons in 2008--http://www.flaes.org/complimonitoring/past_fertilizer_reports.html. Although the recent negative economy may have influenced this trend toward the latter part of the period, this overall reduction in fertilizer use is significant in light of fertilizer limitations imposed by passage of the Urban Turf Fertilizer Rule in Florida and the potential positive environmental implications from adoption and training about BMPs.

Fertilizers are used in urban landscapes to increase the ability of plants to provide aesthetic, recreational, and functional benefits for residential homes, businesses, and common areas. Research has been conducted in most states to determine the most appropriate amounts, sources, and time-of-application of fertilizers for many landscape plants, especially turf. For example, fertilizer BMPs for Florida can be found at http://edis.ifas.ufl.edu, and the UF/IFAS Florida-Friendly Landscaping^{TM} Program (http://fyn.ifas.ufl.edu/). Selected examples of Florida Extension publications dealing with turf and landscape plants include Sartain (2007) and Knox et al. (2002). Best management practices have been developed in many states including Florida (FDEP, 2008; FDEP, 2009a) to help homeowners minimize the chances that nutrients will be lost from the urban landscape at times when the root system is not actively growing.

Research shows that fertilizer-derived nutrients can be lost from the urban landscape under certain circumstances. Losses are most likely when fertilizer is applied just before or during heavy rainfall (Soldat and Petrovic, 2008), when fertilizer is applied before the turf root system is established (Erickson et al., 2010; Trenholm et al., 2011), or when fertilizer is applied in excess of research-based recommendations (Trenholm et al., 2011). Studies in Florida using isotopes have documented the presence of fertilizer-derived nutrients in water bodies (Jones et al., 1996; Pinellas County DEP, 2004; TBEP, 2008a; 2008b). While these studies show fertilizer is being found in urban water bodies, they do not conclude whether the nutrients were lost predominantly from landscapes fertilized properly according to BMPs or from improperly fertilized landscapes.

Animal wastes. The U.S. Environmental Protection Agency (2009) has stated that "Decaying pet waste consumes oxygen and sometimes releases ammonia. Low oxygen levels and ammonia can damage the health of fish and other aquatic life. Pet waste carries bacteria, viruses, and parasites that can threaten the health of humans and wildlife. Pet waste also contains nutrients that promote weed and algae growth (eutrophication)." A 45-pound dog can excrete approximately 9 pounds of N and 2 pounds of P per year, while a human produces 13 pounds of N and 1.5 pounds of P (Baker, 2007). Most of the pet N would be in urine and the P in the solids so that "pooper scooper" ordinances can be effective in P control but less so for N (Wood et al., 2004). Groffman and colleagues (2004) suggested that approximately 15 lb/acre/year of N could be added to the Glyndon (Baltimore, Maryland) watershed from pet waste.

Plant litter and debris. In urban communities, nutrients can come from the native and introduced landscape plants, such as tree leaf fall and grass clippings (Cowen et al., 1973; Dorney, 1986; Strynchuk et al., 2004). From a time-series analysis of decomposition of leaf and grass clippings in Brevard County, Florida, Strymchuck et al. (2004) determined that quick removal of street organic debris is needed to avoid the rapid impacts of pollutants from the debris on water quality. Leaf litter in Milwaukee, Wisconsin, was determined to be a major source of P and the amount of leachable P per whole leaf varied by tree species, but not by tree diameter (Dorney, 1986). Up to 9% of the total leaf-P could be leached from leaves in 2 hours. In an early paper on leaf-P, Cowen et al. (1973) calculated concentrations of P in oak and poplar leaves in Madison, Wisconsin. Leaves that were in the literal zone of Lake Mendota had less P than leaves collected from the ground surface near the shore. In heavily canopied communities, leaves can be greater sources of P than lawns (Baker, 2007).

These studies on the subject of nutrients from plant debris point to two conclusions: First, there is considerable potential nutrient load from plant debris in the urban environment that can add significant amounts of nutrients to the storm water. Second, plant debris should be removed from impervious surfaces (street sweeping, blowing) or mulched and put back into the lawn with mulching mowers as soon as possible because water (rain) can easily and rapidly extract nutrients from the leaf debris.

Urban watersheds. In a Baltimore, Maryland study, Groffman et al. (2004) measured increased nitrate losses from urban and suburban watersheds (approx. 2 to 7 lb per acre per year of N) compared with a forested watershed (less than 1 lb per acre per year of N). These researchers also noted high retention (75%) of N inputs in the urban watersheds mostly consisting of fertilizer and atmospheric deposition. In other studies of urban turf and forested landscapes in Baltimore, researchers noted that grasslands exported more N than forests, but the urban grasslands (turf) had significant ability to retain N (Groffman et al., 2009). The authors found that, in some instances, unfertilized urban turfgrass lands had more leaching losses than fertilized grasslands. The authors emphasized that changing from agricultural land to urban grasslands would have N-load benefit for reducing N losses to the Chesapeake Bay watershed. In a study of urbanization impacts on water quality in small coastal watersheds, Tuffurd et al. (2003) found that dissolved organic nitrogen (DON) and P-containing particulates were the dominant sources of these nutrients and there was variation in location and season. For instance, in the summer, DON from forested wetland creeks and P from urban ponds dominated. These authors concluded that broad land-use or land cover classes should not be used to predict nutrient concentrations in streams of small watersheds. Baker et al. (2001) calculated an N balance for the central Arizona-Phoenix ecosystem. They determined that humans controlled as much as 88% of the N inputs; half of the total N was imported by humans as food and fertilizer. Another third of the N came in as combustion products. 20% of the N accumulated in the watershed and the main avenue for N loss was atmospheric with only 3% of the N leaving in the surface water. The Arizona study identified several topics in need of research including dry deposition processes, soil N dynamics, and denitrification losses.

Take-home message for nutrient sources and impacts

The brief literature review above clearly documents the complexity of eutrophication of inland and coastal water bodies. Land-based nutrient (N and P) sources are important in the nutrient loads to the water bodies, and there are many distinct nutrient sources. These sources undergo changes and interact with the environment in route to a water body. Once in the water body nutrients play a role in complex nutrient cycling that maintains nutrients in forms suitable for algal growth. Controlling nutrients at the source is a sound approach to reducing nutrient loading to water bodies, but nutrient sources and fates are complex processes (Alcock, 2007). Due to the myriad of sources and their complex interactions, source reduction requires a comprehensive and careful approach.

Section 2. Relationship of lawn fertilization to leaching and runoff from landscapes

In this section we examine several important issues relative to fertilization, leaching, rainfall, irrigation, soil, and runoff. We present the information from national research studies on several questions:

- What role does healthy turfgrass play in the urban environment? Will unhealthy turfgrass lead to increased nutrient losses and when?

- How might various urban soil types and qualities impact the effectiveness of landscape fertilizer management?

- How might rainfall patterns and amounts affect fertilizer nutrient leaching and runoff before, during, or after the summer growth period?

- What role does irrigation management play in the leaching and runoff of nutrients?

- What role does reclaimed water play in nutrient runoff and leaching before, during, and after the summer growth period?

Issue #1. What role does healthy turfgrass play in the urban environment? Will unhealthy turfgrass lead to increased nutrient losses and when?

Published books (Beard and Green, 1994; Beard and Kenna, 2008; Nett et al., 2008) have summarized the research literature on turfgrass systems and their care with attention to environmental impacts. Turfgrass benefits (Beard and Green, 1994) can be grouped into *functional* (e.g., preventing erosion, preventing weeds), *recreational* (sports fields), and *aesthetic* (beauty and value-added homes and properties). Healthy turfgrass systems absorb the majority of nutrients when applied at recommended rates, thus minimizing leaching and runoff from landscape surfaces (Brown et al., 1977; Easton and Petrovic, 2004; Frank 2008; Hull and Liu, 2005; Shuman, 2001). Eighty to 90% of N was assimilated in the transition fall and spring months for Bermuda turfgrass in North Carolina (Wherley et al., 2009). The following description of healthy turfgrass that meets its many roles in the landscape is summarized from these citations above. *Healthy turfgrass* means turfgrass that maintains a complete and dense cover over the soil to reduce erosion and weed growth. Healthy turfgrass has an expansive root system that fills the soil and absorbs nutrients and water. Healthy turfgrass is reflected in the medium-green color that is desired for aesthetic purposes and to add value to the home and community. Healthy turfgrass consists of strong plants that stand up to the wear and tear of athletic use.

Scientific data shows that healthy turfgrass has a positive impact on the environment by reducing leaching and runoff. Petrovic and Easton (2005), reviewed the literature on the relationship of healthy turfgrass and urban water quality. Numerous, research studies show that turfgrass has a lower impact on groundwater N levels than other land uses. Raciti et al. (2008) outlined N flows in an urban environment where lawns, under low to moderate management, can be nutrient sinks rather than sources. These authors found high retention of atmospheric N in the soil organic matter pools of urban lawns.

Beard and Green (1994) have described the functional and nonfunctional benefits of properly maintained lawns and landscapes to be:

- excellent soil erosion control and dust stabilization,

- improved recharge and quality protection of groundwater,

- enhanced entrapment and biodegradation of synthetic and organic compounds,

- soil quality improvement that includes CO_2 conversion,

- accelerated restoration of disturbed soils,

- substantial heat reduction,

- reduced noise, glare, and visual pollution problems,

- decreased noxious weed pests and allergy-related pollens,

- safety in vehicle operation on roadsides and engine longevity on airfields,

- lowered fire hazard via open, green-grassed firebreaks,

- improved security of sensitive installations provided by high-visibility zones.

- low-cost surface for outdoor sport and leisure activities,

- enhanced physical health for participants, and a low-cost cushion against personal injuries.

- enhanced beauty and attractiveness;

- a complementary relationship to the total landscape ecosystem of flowers, shrubs and trees;

- improved mental health with a positive therapeutic impact, social harmony and stability;
- improved work productivity;
- and an overall better quality of life, especially in densely populated urban areas.

Studies demonstrating the importance of healthy turfgrass for controlling nutrient losses from lawns

The literature on the fate and transport of P in turfgrass systems was reviewed by Soldat and Petrovic (2008). They found that soil properties had great impacts on P runoff, sometimes more than plant growth. Greatest P runoff and leaching occurred when P was applied close to heavy rainfall. P inputs slightly exceeded the P uptake in grass clippings. Rate, timing, and source for P fertilization were critical factors for P losses. In an early review of the fate of N in turfgrass systems, Petrovic (1990) analyzed the literature on N uptake, leaching, runoff, atmospheric losses (volatilization and denitrification), and immobilization. The research showed that proper fertilizer management was important for minimizing impacts to the environment. These strategies would include proper irrigation management, using slow-release fertilizers (at least 15% slow-release fertilizer), and modifying sandy soils for better nutrient and water-holding capacities.

Several of the environmental benefits have been addressed in research from various sites around the country and in Florida. In a study in Minnesota with Kentucky bluegrass, zero, low, and high P (and a zero control) fertilization programs were imposed during the year (Bierman et al., 2010). The researchers measured runoff volume and P loads moving off the research site plots. Where N and K were supplied (better growth), P in the runoff increased as the P rate increased. P runoff from the unfertilized plots (no N and K and lower growth) was greater than from fertilized turf. The researchers attributed the increased P runoff to poorer growth of the turfgrass in the unfertilized plots. P runoff was greater when P was applied in the fall, when plant growth slows and plants enter dormancy. These researchers concluded that P should not be applied in the fall or when soils already are high in P content, and that P runoff was reduced in healthy, fertilized (N and K) turf. Authors of the Minnesota study noted their results were consistent with other studies showing runoff was reduced by dense turf (Easton and Petrovic, 2002; Gross et al., 1990; 1991).

The same result has been found for Florida. Properly maintained lawns include attention to proper fertilization. For example, there are times when fertilization should not be practiced. Phosphorus fertilization is not needed when the soil already is high in P content as determined by a soil test (Sartain, 2007).

In a 6-year study in Wisconsin, Kussow (2008) evaluated management practices that affect N and P losses from upper Midwest lawns. Annual nitrate-N leachate concentrations were typically between 2 and 4 ppm and the quantity of N leached was about 3 pounds per acre, which is intermediate between losses from agricultural and natural areas in the upper Midwest. The most important factor for increasing runoff loss of N and P was runoff depth. Next in importance was failure to fertilize.

Leaching and runoff will increase as fertilizer rates are increased above the rates recommended by UF/IFAS and established in the Florida Department of Agriculture and Consumer Services (FDACS) Fertilizer Rule (Trenholm et al., 2011). However, even though leaching of N increased with fertilizer rates above those recommended, the total mass leached was minimal in studies with healthy St. Augustinegrass. Fertilization practices must maintain strong photosynthetic activity and movement of metabolites from the leaves to roots, thus maintaining an actively growing root system for maximum nutrient absorption.

The most active growth period for warm-season grasses is during the long, warm days of late spring and summer (Figure 1). This is the time of greatest growth and nutrient requirements for these grasses. Bermuda grass captured more N during the active growing season (Wherley et al., 2009) and large amounts of N also were captured in a summer Kentucky bluegrass system (Frank, 2008).

Leached N averaged 0.23% of the total N applied over two years for Kentucky bluegrass (Miltner et al., 1996). Total recovery of N was 64 and 81% for Spring and Fall, pointing to potential gaseous losses of N. Research shows that the active growth period is the time when the grasses have the greatest ability to take up nutrients, due to larger, denser, and more actively growing root and shoot systems. Following recommended fertilization practices helps maintain healthy turfgrass with a strong, expansive root system to absorb nutrients, especially during periods of active growth in the summer. Recommended fertilization rates lead to dense turf growth that prevents erosion and slows overland transport of water and nutrients (Easton and Petrovic, 2004). Nitrate leaching was three times greater from turfgrass that had been killed than when Kentucky bluegrass turfgrass was living (Jiang et al., 2000). The latter authors stressed the importance of living turf roots in stabilizing nitrate-N in the turf-soil ecosystem.

Root biomass of warm-season grasses declines in the fall (Figure 2). Bushoven and Hull (2001) showed that the nitrate assimilative capacity of roots correlates with greater dry matter allocation to root mass by the whole plant. This greater nitrate assimilative capacity was correlated with increased N uptake efficiency in one of the two grass species studied. Bermudagrass roots were more competitive than the soil microbial population for assimilating nutrients (Wherley et al., 2009). Grass (annual bluegrass and bentgrass) with greater above-ground biomass also had greater root biomass that, in turn, led to more N uptake (Pare et al., 2006). Bowman et al. (1998) showed that deep-rooted turf resulted in less nitrate-N leaching losses than a shallow-rooted turf. Nitrogen uptake efficiency was greater with increased amounts of finer, fibrous roots, while amounts of thick roots had little impact on N uptake rate (Sullivan et al., 2000). Increased rhizome length had a negative relationship with N uptake efficiency. These studies showed that management practices that lead to better root development, especially deeper root expansion and more fibrous roots can be important in controlling fertilizer N leaching.

Management of turf clippings is important for N management in the turfgrass system. Turfgrass clippings are a large repository of assimilated N and P. Turf scientists recommend returning grass clippings to the lawn so the nutrients can be recycled. Fertilizer N was rapidly converted to non-mineral forms within 3 weeks of application and the loss of N was mostly due to volatilization and denitrification (Starr and DeRoo, 1981). Fertilizer N, accounted for by direct measurement, was 76% where clippings were returned and 64% where clippings were not returned. Clippings management affected N fertilization, turf growth, and quality in a study in Connecticut by Kopp and Guillard (2002). These scientists found that returning grass clippings did not decrease turf quality, but did result in an increase in N uptake and recovery. These research reports show that returning clippings to the lawn is an important aspect of good N and P management in the turfgrass system.

Fertilizers can be supplied in soluble (fast) or slow- or controlled-release forms. Controlled-release fertilizers have been shown to be effective for producing healthy turfgrass (Sartain, 1981; 2008; Petrovic, 1990) and reducing the potential for nutrient losses (Saha et al., 2007; Snyder et al., 1984) from lawn grasses. Similarly, research also shows that properly managed soluble N sources can result in low leaching losses. This result was observed by Sartain (2008) and Quiroga-Garza et al. (2001). The latter authors found that highly insoluble N sources reduced N leaching losses but had negative impacts on turf growth and health. These authors, however, pointed out that a trade-off between turf color and N leaching may be important, i. e., lighter green turf color is associated with reduced N leaching losses, which may be an important consideration in the turfgrass system. They determined that proper N fertilization and irrigation practices, even with soluble N sources, can avoid risks of N leaching losses. These latter two conclusions suggest the importance of a rigorous homeowner education program about fertilizer sources and application in the overall management of fertilizer in the urban environment.

UF/IFAS research showed that leaching was negligible during the summer months from St. Augustinegrass grown with a commercial fertilizer containing 62% soluble/38% controlled-release N at a 1.0 lb N/1000 sq. ft. rate (Erickson et al., 2001). The current (2011) N recommendations for turf limit a single application to 1.0 lb per 1000 sq ft. of N under the FDACS' Fertilizer Rule (FDACS, 2007). Therefore, under a summer fertilizer ban the turfgrass manager will be limited to this 1.0 lb application for the entire 4-month summer growing period. Studies are underway to determine if there are fertilizer materials that will maintain healthy turf for this 4-month period when applied at the recommended rate at the beginning of the period.

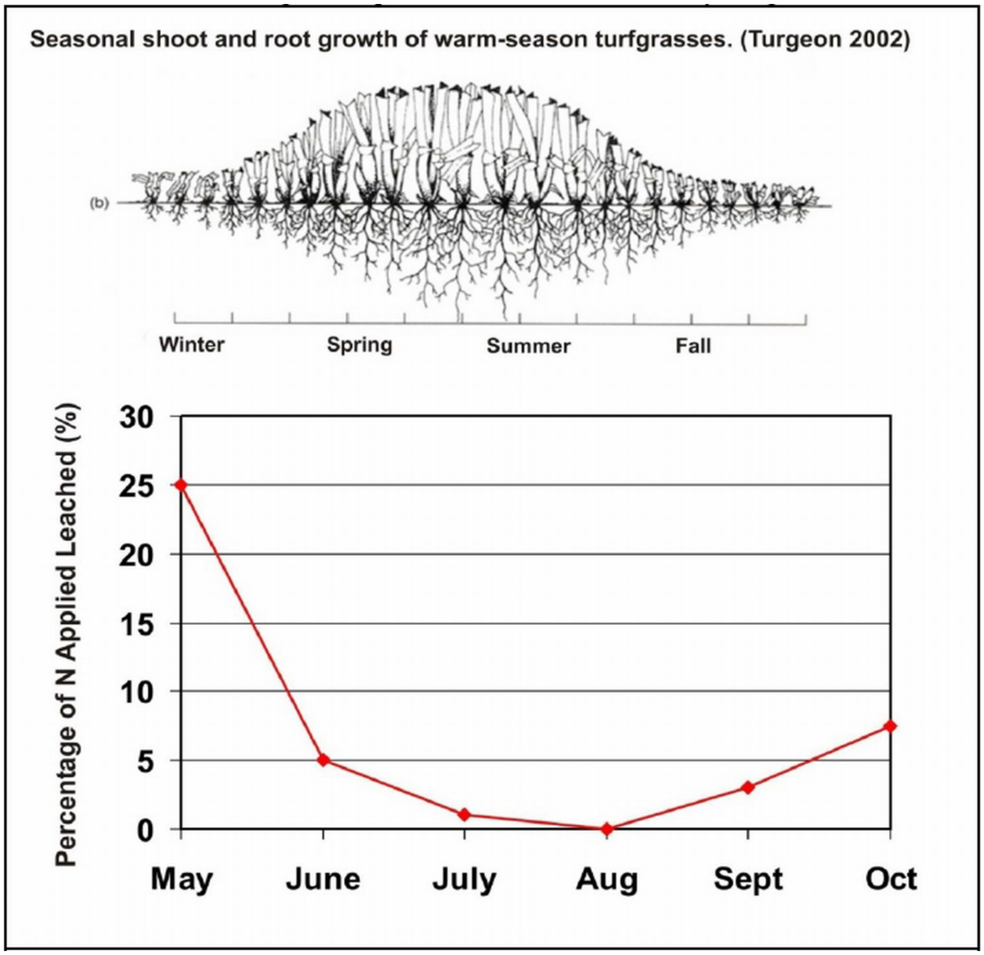

Figure 1. Diagrammatic (textbook) presentation of growth of warm-season turfgrass (top drawing) and actual N leaching during season (bottom figure-after Sartain, 2010).

The UF/IFAS Extension fertilizer recommendations for turfgrass, summarized by Sartain (2007), emphasize applications of slow-release (controlled-release) N in the summer. The use of controlled-release fertilizer in the summer helps minimize the losses of N because only very small amounts of N are released from the fertilizer at any one time (typically based on temperature and moisture). These release schedules are in relationship with the plant growth rate. Recent research in Florida shows that leaching was dependent on fertilizer rates and turfgrass type (Trenholm et al., 2011). Leaching was greater from zoysiagrass than from St. Augustinegrass (Trenholm et al., 2011). Similar results for these two species were found in a North Carolina study by Bowman et al. (2002), and leaching was greater just after planting than after the establishment phase. In well-established and maintained St. Augustinegrass turf, inorganic N leaching was lower with concentrations of NH_4-N and NO_3-N in drainage generally less than that reported for rain water in southern Florida. This experiment was conducted over a three-year period encompassing wet and dry season cycles that bracket proposed black-out periods when the turf was fertilized at 1 lb N/1000 sq. ft. bimonthly with a 62%/38% soluble/controlled-release commercially available fertilizer (Erickson et al., 2008).

New research at UF/IFAS (accepted for scientific peer-reviewed publication) has shown that leaching from turfgrass is greater in the spring and fall than in the summer. In a Florida DEP-funded project, Trenholm et al. (2011) found that more fertilizer is lost from fertilizer applications made during the time of year when the turfgrass is not actively growing and that the lowest leaching levels were during the period of active growth (summer) . The following are some results from the multi-year study:

1. As St. Augustinegrass matured after the first establishment year, NO_3-N leaching in the summer was minimal, even at very excessive application rates. No significant correlation with N rate and NO_3-N leaching was found.
2. Zoysiagrass was more prone to leaching at high N rates. Less N was needed for zoysiagrass health and quality than for St. Augustinegrass.
3. Greater disease pressure leads to less healthy turf and more NO_3-N leaching.
4. There was greater NO_3-N leaching in spring and fall.
5. All cultural practices, including fertilization and irrigation, are important to reduce nutrient losses from turfgrass.
6. Even at high application rates imposed in this study, NO_3-N leaching did not exceed 1.3% of the applied N in St. Augustinegrass.
7. Turfgrass quality and health were adequate with the current UF/IFAS fertilizer recommendations.

Effectiveness of healthy turfgrass in preventing soil and nutrient losses by erosion

Erosion in urban landscapes can be a serious problem resulting in loss of topsoil and the associated nutrients. Reducing the velocity of runoff water with dense, healthy turfgrass will increase infiltration and result in groundwater recharge (Blanco-Canqui et al., 2004; 2006; Easton and Petrovic, 2004). Healthy turfgrass captured runoff that contained nutrients and displaced soil from a 10% slope. Capturing the runoff allowed time for nutrient uptake by the turfgrass, reducing the N concentration in the runoff to the concentration in the rain water (Erickson et al., 2001). Bare-soil areas are most prone to soil erosion that carries nutrients with the displaced soil.

Buffer strips consisting of healthy turf grass are used to capture, filter, and reduce nutrient runoff (Cole et al., 1997; Steinke et al., 2007). Buffer strips as small as 2 feet wide have reduced runoff, compared with no buffer strips. Dense turf vegetation reduces runoff by creating "tortuous pathways" that reduce runoff rate thus enhancing infiltration. Water can be filtered of its sediment and nutrient load by turf shoots and roots. For example, doubling the number of turfgrass shoots in a lawn reduced the amount of runoff by 67% (Easton and Petrovic, 2004). Weedy, unhealthy lawns had three times more N runoff than a healthy, dense turf (Easton, 2004; Easton, 2006).

Research summarized above shows that healthy turfgrass plays a major role in absorbing nutrients, especially in the periods of active growth. Further, research shows that nutrient-deficient turfgrass is less effective than healthy turfgrass at reducing runoff volume and nutrient losses. The research shows that the mass of a healthy turfgrass root system plays a large role in removing nutrients from the soil, and that a healthy plant is required to produce a healthy root system.

Iron and N are two essential nutrients for plants (Barber, 1984; Epstein and Bloom, 2005). Deficiency of either nutrient shows up as yellowing of the turfgrass. Fe is involved in the synthesis of chlorophyll and N is part of the chlorophyll molecule, which gives plants their green color (Marschner, 1995). Iron can be rendered unavailable to turfgrass in high-pH (>7.2) soil at certain times in the year (Carrow et al., 2001; Turgeon, 2008). Reduced availability of Fe occurs in spring when the high-pH soils are cool and the root system is not very active in absorbing Fe, as it is recovering from winter dormancy (Carrow et al., 2001). Iron yellowing ("iron chlorosis") also can occur in the summer when turfgrass is growing rapidly (possibly just after a nitrogen application). In this situation not enough iron is available from the soil to meet the rapid

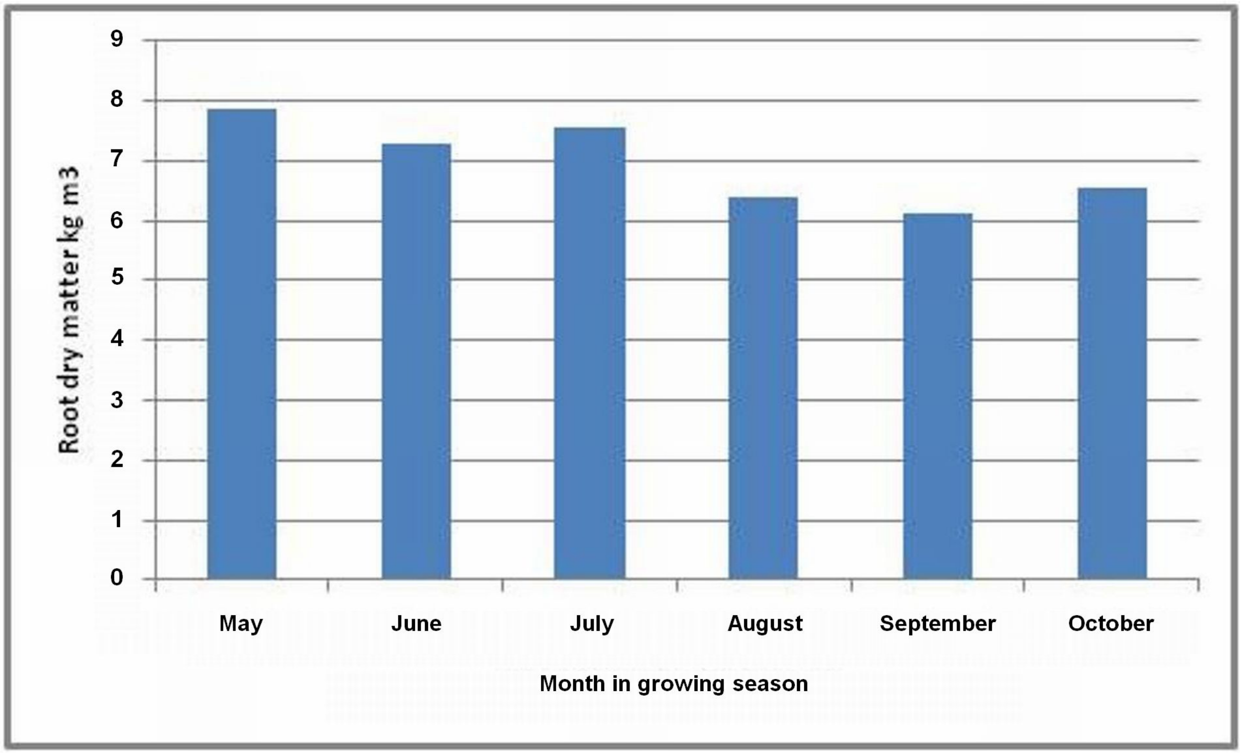

Figure 2. Root mass of warm-season turfgrass (bermudagrass) across the growing season in Florida (after Sartain, 2002). There was a significant difference between the mean of dry matter for May-July and that for August-October.

growth and micronutrient demand. In the summer, frequent irrigations with high-pH (aquifer or reclaimed) water causes the soil pH to rise, rendering Fe unavailable. Other conditions leading to Fe deficiencies include saturated soils and compacted soils (Carrow et al., 2001), which restrict root growth. Foliar iron will help green-up the yellow areas in the lawn caused by iron deficiency (Carrow et al., 2001). The greening results from correcting the underlying iron deficiency so that the turfgrass can synthesize more chlorophyll leading to better greener color (Barker and Pilbeam, 2007; Marschner, 1995).

Yellowing of turfgrass also can result from N deficiency. N deficiency is typically more general in scope in the lawn while Fe deficiency is in spots or patches. N deficiency results in significantly reduced clipping yields while Fe deficiency typically does not (Carrow et al., 2001). Wording in the Florida Yards and Neighborhoods Handbook (UF IFAS, 2009): "*Apply an iron source instead of a nitrogen fertilizer. To green the lawn without increasing growth in the summer, use chelated iron or iron sulfate*" may lead to misinterpretation. While both Fe and N deficiencies result in yellowing, they are distinctly different deficiencies. Applying iron will not cure yellowing of turfgrass due to an N deficiency, and iron fertilizer is not a substitute for N fertilizer.

Issue #2. How might various urban soil types and qualities impact the effectiveness of landscape fertilizer management?

Probably no other factor is more important to nutrient management and water quality in urban environments than the soil in the landscape. There may be no definition for a "typical" urban soil (Pouyat et al., 2010) since there are so many soil types, many types of urban fill-soils, and many ways to impact soils during construction and landscape installation. Soils can have *direct* effects on ecosystems, such as soil disturbance, and they can have an *indirect* impact, such as pollution resulting from soil management practices. Pouyat et al. (2010) showed how these direct and indirect effects can contribute to a "mosaic" of soil conditions in their study in Baltimore, Maryland. They found that urban soils, even though disturbed, can have a high capacity to deliver positive effects on the ecosystems relative to the native soils they replaced. McKinney (2008) also noted a particularly high degree of plant species diversity or richness in urban areas. These studies suggest that urban soils offer potential for using the diversity for the development of sustainable management practices for improving the capacity of the urban landscape to deliver environmental benefits.

Urban soils can be highly disturbed due to the excavation, grading, soil moving, and construction processes, and fill-soils can take many forms (USDA-NRCS, 2005). Urban soils can be highly compacted during the construction period and the water infiltration rate is reduced in these compacted soils (Gregory et al., 2006). These authors found that construction activity reduced infiltration rates 70 to 99% and infiltration rates were typically lower than design storm infiltration rate (10 inches per hour) used in northern Florida. Understanding these soil formation and transformation processes is important for developing (after construction) and maintaining landscapes that achieve the desired aesthetic properties yet also do not result in degradation of nearby water bodies. Paving and compacted soils can be facilitators of urban runoff and pollution. In a meta-analysis of research studies on the relationship between impervious surface and stream water quality, Schueler et al. (2009), found the *impervious cover model* was supported; stream water quality can be predicted from impervious cover percentage. Relative proportion of open urban turf and landscape areas and impervious areas should be considered to minimize runoff impacts on stream water quality (USDA-NRCS, 2005). However, municipalities considering regulations regarding limits to impervious cover should first conduct a comprehensive evaluation of receiving water bodies and environmental assessments such as sources and mitigation because limits may lead to increased environmental problems (Jones et al., 2005).

Plant growth and health are related to soil properties (USDA-NRCS, 2005). For example, soils that are high in organic matter (>3%) may require less N than soils with low organic matter (1% or less) because significant amounts of N can be made available from the organic matter in these soils. Urban soils that test high in P content would be unlikely to require additional P fertilization for at least several years, and then a well-calibrated soil test could predict when P fertilization could resume. The majority of soils in a North Carolina study did not need P fertilizer (Osmond and Hardy, 2004).

Urban soil systems can be responsible for significant N losses due to denitrification (Groffman and Crawford, 2003). Their studies in an urban riparian zone in Baltimore, Maryland, showed strong positive relationships between soil moisture and organic matter and denitrification. These authors suggested taking advantage of these soil properties in storm water treatment in urban environments.

The potential for nutrient retention can be great for urban soils, especially for lawns. This is because lawns are typically managed with irrigation and fertilizer to encourage plant growth and development (Pouyat et al., 2010). Plant biomass is converted to soil organic matter, especially in lawns, and this organic matter retains nutrients and water. Unfertilized lawns would reduce their productivity and reduce their nutrient retention capacity. The key will be to balance the amount of nutrient inputs during the summer with the need to maintain nutrient-assimilation capacity and organic matter building capacity with reductions in nutrient losses to water bodies.

In summary, research shows that urban soils can be highly disturbed yet maintain a high degree of capacity to benefit the environment. Urban soils are highly variable in nutrient-supplying and retention capacities. Urban landscape management, especially for soil disturbance, fertilization, and irrigation, is a critical factor determining whether a soil/landscape system will be a nutrient sink or a nutrient source and the degree to which it will either retain or release nutrients. Research shows the most effective approach to reducing nutrient losses will not be a one-size-fits-all approach, such as a fertilizer ban across all landscapes. Proper fertilization is needed to maintain healthy turfgrass that retains nutrients and water.

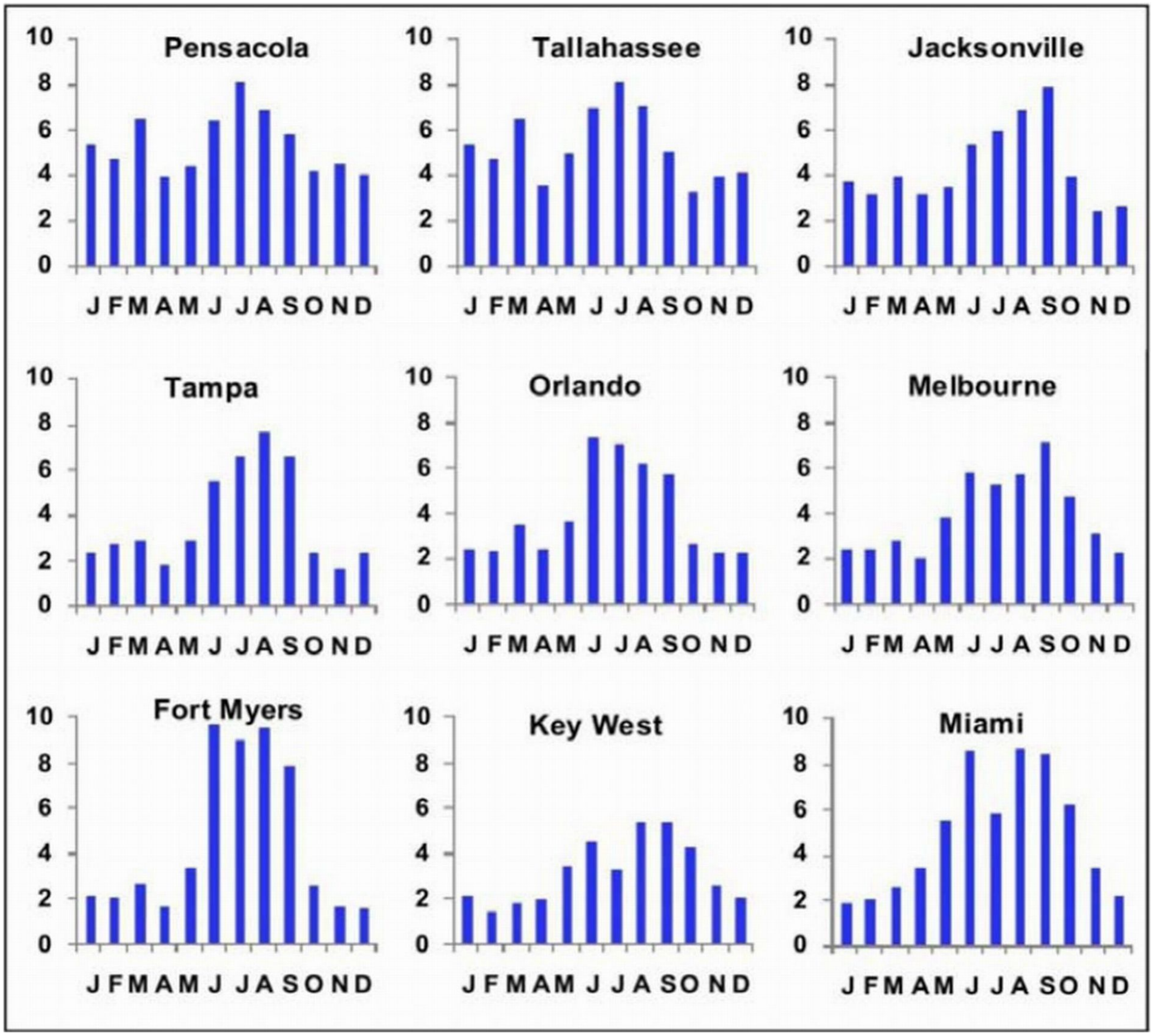

Figure 3. Mean monthly rainfall totals (inches) at select stations across Florida from 1971–2000 (CLIM20, 2004).

Issue #3. How might rainfall patterns and amounts affect fertilizer nutrient leaching and runoff before, during, or after the summer growth period?

Florida receives more rain than nearly all other states, but the rain sometimes falls in large amounts over short periods (Purdum, 2007). Erosion may occur where soils are on slopes and where groundcover is poor. Florida may receive significant rainfall at any time of the year but particularly in the summer months from thunderstorms or tropical systems (Figure 3). There are times in the year when heavy rainfall occurs before and after the summer period (Figure 3). As recommended in the UF/IFAS Florida-Friendly Landscaping^{TM} Program, fertilizer applications during the summer result in less leaching than applications at other times of the year (Trenholm et al., 2011).

Potential for fertilizer leaching and runoff increase when the soil becomes saturated following a heavy rain or several successive heavy rains. The World Meteorological Society and National Weather Service have established a two-inch rainfall as a "heavy rain"— when soil saturation is most likely to occur for most soils in Florida. However, there are several factors that affect how fast the soil will become saturated leading to leaching or runoff (Brady and Weil, 2002; Zotarelli et al., 2010). These factors include the soil texture, natural soil bulk density, compaction, and how much of the

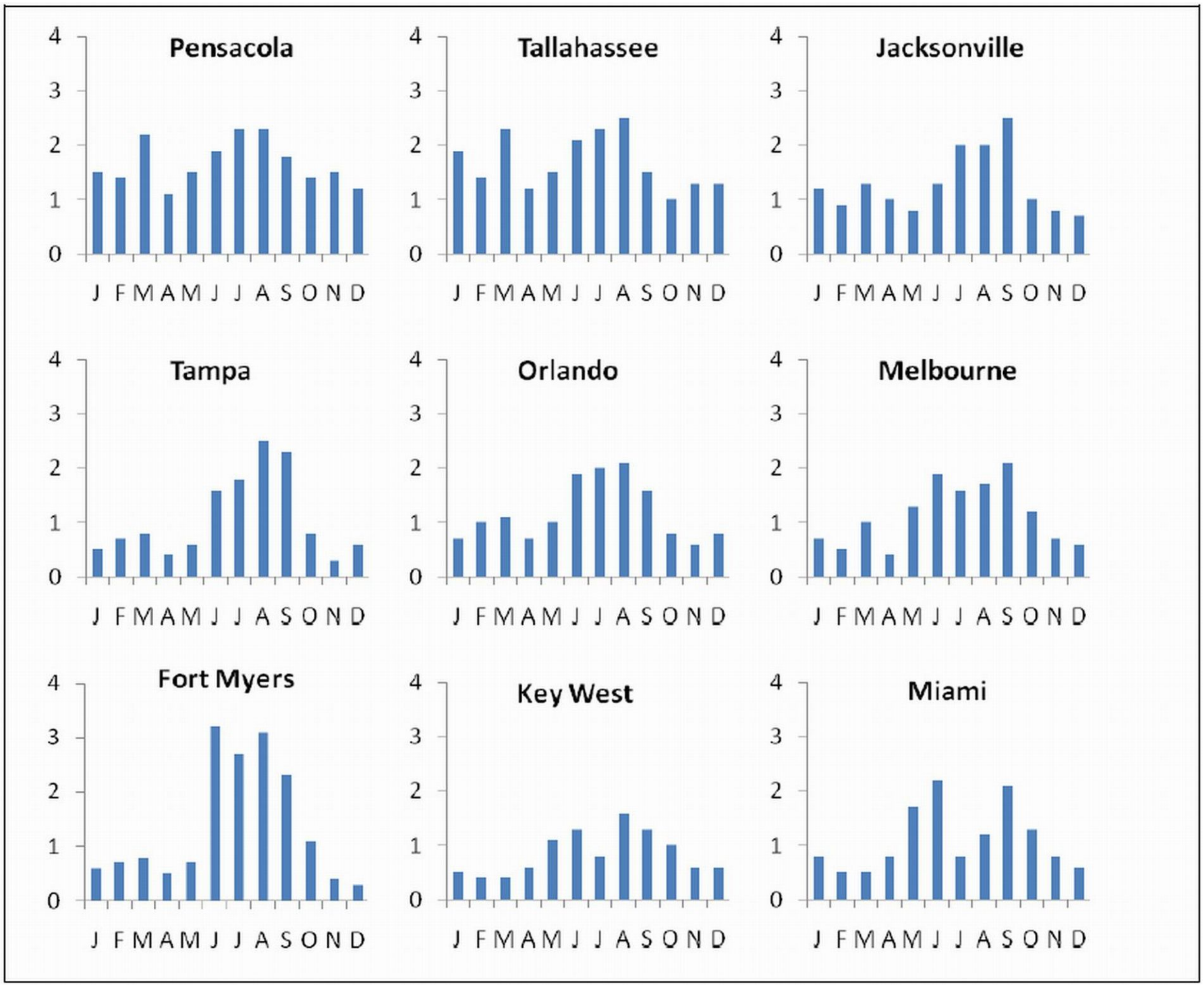

Figure 4. Mean number of rainfall events greater than 1 inch (CLIM20, 2004).

water-holding capacity is already filled by prior rain or irrigation. Sandy soils that are present in most urban areas in Florida only hold from 0.7 to 1.0 inches of water per foot of soil. Up to 25% of P fertilizer was lost in runoff and leaching when applied to saturated soils (Linde and Watschke, 1997). This illustrates the importance of careful irrigating so as not to keep the soil saturated. Following irrigation BMPs throughout the year helps minimize the negative impacts of these natural leaching rain events.

During the year there are rarely more than 2 or 3 rainfall events of more than 1 inch, considered to be a significant rainfall in any month at any location (Figure 4). Only about 10–15% of rainfall events in Florida are 1 inch or more (i.e., those most likely to result in nutrient leaching or runoff) (Figure 5). Additionally, leaching or runoff occurs not simply because of "heavy" rainfall but because the rainfall is in excess of the soil's water-holding capacity. Homeowners should be educated more about not fertilizing immediately before a heavy rainfall event. Education should also focus on not irrigating when the soil already is at its water-holding capacity.

Issue #4 What role does irrigation management play in the leaching and runoff of nutrients?

Irrigation accounts for nearly one-third of residential water use in the United States and this amount is greater in warmer climates (Mayer et al., 1999). Romero and Dukes (2010) studied irrigation water use in southwest Florida. While the average irrigation closely matched the calculated irrigation need, they found over-irrigation was commonplace in some cities. On average 53% of the irrigating households accounted for nearly all of the

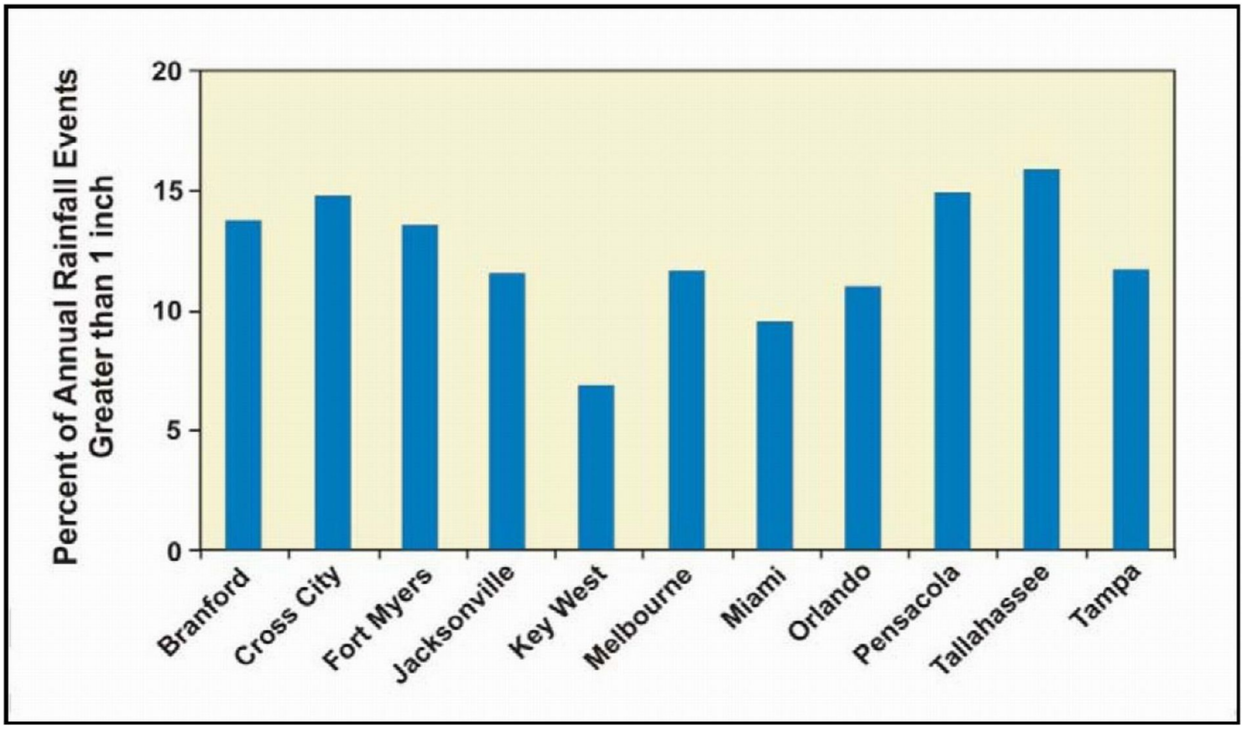

Figure 5. Percentage of annual rainfall events greater than 1 inch at selected locations in Florida. Rain events separated by less than 6 hours are considered to be a single event. Period of record used: 1942–2005. The data sets analyzed contained between 28 and 64 complete years of data (Harper and Baker, 2007).

over-irrigation showing that some homeowners greatly exceeded irrigation requirements.

Any attempt to minimize N and P pollution from the urban landscape will be for naught if irrigation management practices are not included in fertilizer guidelines. Barton and Colmer (2004) reviewed the literature regarding irrigation and N management. These authors concluded that N losses are low (<5% of applied N) from any established turfgrass when irrigation is not excessive, and with moderate (not excessive) rates of N fertilizers. Irrigation scheduling that does not result in water moving below the root zone helps keep N in the root zone minimizing N losses. Sometimes this approach even resulted in improved turfgrass growth and quality.

In an early benchmark study in Florida by Snyder et al. (1984) on irrigation management and N leaching, scheduling irrigation was done by a moisture sensor device that canceled irrigation when the soil contained adequate moisture. Controlled irrigation led to more efficient irrigation and to negligible loss of the soluble N applied (ammonium nitrate) (Snyder et al., 1984). Irrigation at 125% of evapotranspiration (ET) + rainfall resulted in loss of 50% of the applied soluble N (Snyder et al., 1984). Proper irrigation management is critical to preventing nutrient losses.

New technology is available in the irrigation arena known as "Smart Irrigation." New controllers typically monitor soil moisture status and void or permit irrigation based on soil moisture levels. These irrigation controllers use inputs of information (sensors) from the irrigated area to determine or regulate irrigation. Research in Florida on soil moisture sensor controllers has shown that irrigation savings can exceed 70% of automatic, clock-scheduled irrigations with a variety of controllers under normal rainfall conditions (Cardenas-Lailhacar et al., 2008; McCready et al., 2009). Savings during dry periods were less dramatic but were as much as 30 to 40% (McCready et al., 2009). Finally, evapo-transpiration controllers have also been shown to result in savings of 43% during dry conditions (Davis et al., 2009). It should be noted that scheduling irrigation with soil sensors may not be consistent with current rules on irrigation of Florida landscapes. The reader is referred to the local water management authorities for pertinent rules on irrigation water availability.

In a study in North Carolina, Osmond and Hardy (2004) found that residents with movable sprinklers used about one-half the water as residents with fixed systems. Automatic systems that irrigate during rainfall or when the soil is saturated, or that simply over-irrigate all intensify leaching and runoff potential (Hull and Liu, 2005). Irrigation and fertilization practices go hand-in-hand. Properly fertilized and irrigated turf results in minimal nutrient losses to the environment (Beard and Green, 1994).

Morton et al. (1988) studied N losses from Kentucky bluegrass in Rhode Island. N mass losses due to leaching were 2 lb/acre with the managed-irrigation treatment (tensiometer) and 30 lb/acre with the over-watered treatment. The N loss with the managed irrigation treatment was the same as the N loss with the non-irrigated control treatment. Leaching, not runoff, was the main avenue of loss of N. Runoff occurred only on two occasions, once when rain fell on frozen ground and once when rain fell on an already saturated soil.

Runoff volume from bermudagrass was related to simulated rainfall amounts and soil moisture level prior to rain (Shuman, 2002). Runoff was 24 to 44% of an applied 50 mm rain and 3 to 27% for the 25 mm rainfall. The greatest mass loss of P was from the first 4 hours after the first rainfall. The P loss decreased after 24 hours and for later rain events. Loss of N increased with rate of N. The author suggested that runoff losses of N and P could be minimized with small applications of irrigation after fertilizer application and by not applying fertilizer before heavy rainfall or when the soil is saturated.

Current trends in Florida point to greater mandated water restrictions, even during non-drought periods, to help conserve potable water supplies. Homeowners should be educated about refraining from excessive irrigation on "your day," which could result in saturated soils, nutrient leaching, and runoff. For irrigation recommendations to have maximum benefit, other recommended practices must be followed. For example, the irrigation system should be properly designed and installed to achieve a high degree of uniformity of water application (Baum et al., 2005).

Nutrient and water management go together for maintaining healthy turfgrass (Dukes, 2008; Dukes et al., 2009). Proper irrigation management is needed for healthy turf and to prevent nutrient losses. An urban irrigation scheduler tool is available on the Florida Automated Weather Network (FAWN) at http://fawn.ifas.ufl.edu/tools/urban_irrigation/. This tool allows a user to determine irrigation controller runtime estimates with three clicks of the computer mouse. Research has shown that using guidelines such as this tool can reduce irrigation by as much as 30% (Haley et al., 2007). Careful attention to irrigation helps keep the water and nutrients in the root zone where nutrients will be used to grow healthy turfgrass and not be lost to the environment.

In summary, proper irrigation management is critical for achieving minimal nutrient losses for the urban landscape, irrespective of time of year. The research shows that timing of fertilizer in relation to rain or irrigation is important for minimizing leaching of nutrients. There are websites containing assistance in scheduling irrigation and there are "smart irrigation" systems that help take the guesswork out of irrigation management.

Issue #5 What role does reclaimed water play in nutrient runoff and leaching before, during, and after the summer growth period?

Reclaimed water contains nutrients such as N and P. Where reclaimed water is used for irrigation, these nutrients could be leached if nutrient levels are high and if irrigation is excessive. The information below is presented to make several points about managing reclaimed water and cautions for relying on reclaimed water as a total substitute for fertilizers during a restricted period. A history of reclaimed water use in Florida, by Toor and Rainey (2009), can be found at http://edis.ifas.ufl.edu/ss520. Information on Florida's reclaimed water program was summarized by Martinez and Clark (2009a).

Reclaimed water can be a valuable resource for urban landscapes (Martinez and Clark, 2009b; Parsons, 2009). Many new residential developments have made reclaimed water available for irrigating lawns and landscapes as a means to reserve potable water for direct human use (drinking and food preparation, etc.). In addition to the water for irrigation, reclaimed water is sometimes viewed as a source of nutrients (Martinez et al., 2010) and these nutrients may be beneficial for plants. Florida is a leading state for the use of reclaimed water (Assoc. Calif. Water Agencies, 2009; FDEP, 2009c). There is a new concern that the proposed EPA numeric nutrient criteria may lead to unintended consequences that constrain the beneficial use of reclaimed water in Florida, for example as irrigation for landscapes (Arrington and Melton, 2010).

There are challenges to using reclaimed water in the landscape, especially if reclaimed water is seen as a way to replace fertilizers during a restricted period. The data presented in Tables 1 and 2 are for illustration purposes only and are not meant to be used for estimating reductions in fertilizer, for reasons discussed below.

Thomas et al. (2006) used reclaimed water from San Antonio, Texas, to irrigate bermudagrass and zoysiagrass. The reclaimed water contained 12.6 ppm nitrate-N. Irrigation was managed to only replace evapotranspiration. Concentrations of nitrate-N in leachate exceeded 10 ppm on only 6 out of 27 sampling dates and most of those events were when the turf growth was inactive.

FDEP provides regulation of reclaimed water utilities in Florida. Reclaimed water from advanced wastewater treatment (AWT) facilities is limited to no more than 3.0 ppm N and to 1.0 ppm total P. Using these maximum limits, the mass balance indicates that excessive amounts of water (more than 100 inches) would be required to deliver even the lowest recommended amounts of N for most lawn grasses. This is due to the low concentration of N in AWT reclaimed water (Table 1). Reclaimed water users should know the concentrations of nutrients in their water before determining an irrigation schedule. Concentrations of total N can be greater from facilities with only secondary waste water treatment (the 20 and 30 ppm rows of data in Table 1). These are the calculated amounts of total N that may be in the reclaimed water, but the quantity of specific species of N in the reclaimed water that is immediately available will depend on the wastewater treatment methods used. Research has not been completed to address the unknowns about N losses from reclaimed water during transport; therefore, it is not clear that there is a 1:1 substitution of reclaimed water N for fertilizer N.

Reclaimed water is a nutrient solution (water plus nutrients) and should be managed to keep the solution in the root zone. Proper irrigation management with reclaimed water is required to prevent N leaching from over-application of reclaimed water. Rates of reclaimed water used in irrigation should be based primarily on the water needs of the turfgrass. Excessive irrigation with reclaimed water may result in leaching of the N contained in the reclaimed water as well as fertilizer-N previously applied to the turfgrass. Irrigation with reclaimed water should be practiced with careful attention to avoid overirrigation, as described above in the section on irrigation.

Proper irrigation management with reclaimed water can also reduce the overapplication of P. For example in Table 2, using 30 inches of reclaimed water with 0.5 ppm P would result in the application of 0.179 lbs of P_2O_5 per 1,000 ft^2 for the year. The amount of P from the reclaimed water can influence the amount of fertilizer-P needed as indicated by appropriate soil testing. Many of the combinations of reclaimed water P concentrations and irrigation amounts in Table 2 would exceed the FDACS "Urban Turf Fertilizer Rule" (FDACS, 2007), especially where the soil tests show high levels of P already in the soil. This rule, which currently pertains only to bagged fertilizer and not reclaimed water, places a limit of 0.25 lb P_2O_5 per 1,000 ft^2 per application and no more than 0.50 lb P_2O_5 per 1,000 ft^2 per year.

Accumulation of salts contained in the reclaimed water might become a problem for certain turfgrasses during periods of drought and could result in an unhealthy turfgrass with a reduced root system. This may lead to an increase in leaching of applied fertilizer nutrients later on due to the damaged root system's inability to take up the nutrients (more information on salinity in reclaimed water can be found at Martinez and Clark, 2009b; http://edis.ifas.ufl.edu/ae449). Evanylo et al. (2010)

found that problems with certain ions in reclaimed water can result even in the humid eastern U. S., especially with newly established sod. Turfgrass, however, was able to remove the N from reclaimed water precluding groundwater impairment even under a wide variety of irrigation practices.

Application of reclaimed irrigation water to impervious surfaces such as driveways, sidewalks, or roads will result in losses of nutrients to the storm water system and in potential pollution. Irrigation systems should be designed to ensure on-target application of all reclaimed water used for irrigation.

Irrigation systems set to automatically irrigate with reclaimed water year-round would contribute N, P, and other nutrients during the slow-growing or dormant period of turfgrass and landscape plants when these nutrients are not needed by the plants. For example, in most areas of the state, fertilization of turfgrass is not recommended in the winter (Sartain, 2007).

The specific N and P concentrations in reclaimed water are not always optimal for turfgrass requirements. For example, a homeowner may have a soil that tests high in P and therefore does not require the P from the reclaimed water. In this case, it might not be wise to use reclaimed water if there is a nearby water body that would be harmed by increased P concentrations. The actual availability to the turfgrass of the added P in reclaimed water is governed by the soil chemical properties, which may render the P unavailable to the turfgrass. This may occur if the soil pH is too high or the soil contains high levels of iron and/or aluminum.

Issue #6 Does the scientific literature say anything about homeowners' willingness to adopt best management practices?

There are only a few reports in the scientific literature on the relationship between human behavior and urban water quality. However history does indicate that homeowners may be willing to change practices. For example we are recycling one-third of municipal waste today, an increase from 7% in the 1970s (USEPA, 2005; 2007). Zhou et al. (2009) studied lifestyle as a predictor of lawn care expenditures. While the relationship between socio-economic status and lawn greenness was statistically significant, the correlation was weak. Law et al. (2004) surveyed homeowner lawn fertilization practices in two watersheds in Baltimore County, Maryland. Fertilizer amount in the Glyndon watershed averaged 110 lb/acre/year N, but the standard deviation was 100 lb/acre N, meaning that the application rates were extremely variable in the watershed. The rate varied from 2 to 4 lb/1000 square feet per year. Rates used were more related to the soil type than to socio-economic variables. More fertilizer was applied to turf on nutritionally poorer soils. These findings pointed to more "hot-spots" for nutrient losses and suggested the need for more soil-based testing to predict fertilizer needs. The authors above and others (Grove et al., 2006), point to the importance of comprehensive and detailed environmental testing and education programs, rather than "one-size-fits-all" approaches. Baker (2007) studied literature on the question of whether fertilizer laws would work and concluded that programs most likely to result in behavioral change include a mix of components including education, incentives (subsidies), disincentives, and marketing. Further, programs may need to be spatially and socially targeted.

Section 3. Some approaches to controlling nutrient losses in the urban environment

Local Ordinances as an Approach to Reduce Fertilizer Losses to the Environment

The research presented above points to potential losses of nutrients from various lands and land use practices. The research points to potential differences in nutrient losses among various landscapes and various nutrient management practices, which leads to the question, "*How can we best address water quality issues, nutrient sources, and losses to the environment?*" State and federal rules and guidelines and research-based University recommendations have been developed to encourage improved nutrient management practices in the urban environment that have source reduction as their goals. However, some counties and municipalities have instituted rules more stringent than the IFAS and FDEP BMPs. In some cases, some states and counties have chosen the local ordinance approach as a means to locally control urban fertilizer application (Florida Department of Agriculture and Consumer Services, 2007; Hartman et al., 2008). In particular, the severe Florida red tide blooms in 2005 and 2006 precipitated local governmental action in Florida (Hartman et al., 2008).

Examples of other states with fertilizer ordinances

Minnesota enacted in 2002 the first state regulation on P in urban fertilizers. This regulation prohibited P application to soils already high in P content. The Minnesota Department of Agriculture reported to the Minnesota Legislature on the effectiveness of the Minnesota Phosphorus Lawn Fertilizer Law over the first years (Minnesota Dept. Agriculture, 2007). The findings included: P-free fertilizer had become widely available in Minnesota; amount of P applied was reduced 48%; and the law created a "teachable" moment for fertilizer management. Also, the report pointed out that additional research was needed to ensure avoidance of "un-intended" negative consequences of P-free fertilizers on turf health and water quality.

Ann Arbor, Michigan, enacted a fertilizer ordinance controlling P fertilization (Ann Arbor, 2011). The ordinance was in conjunction with a statewide EPA Total Maximum Daily Load (TMDL)-driven P fertilizer reduction effort. The ordinance went into effect in 2007. Manufactured fertilizers cannot be applied prior to April 1 or after November 15, coinciding to the colder part of the year when the turf is not growing. P fertilizer cannot be used except where establishing new turfgrass or where a soil test indicates a deficiency in soil-P.

Researchers established water quality sampling stations in the Huron River watershed in southeastern Michigan (Lehman et al., 2009). Sampling was conducted under the jurisdiction of the Ann Arbor, Michigan, fertilizer ordinance and upstream in a geographic area not under the city ordinance. P concentrations in the water were compared for 2008 data against older data collected before the ordinance was enacted. P concentrations in the river water were lower in 2008 compared to the period prior to the ordinance and lower for the Ann Arbor sampling sites compared to upstream sites. The ordinance not only controlled P fertilization but also included strong education programs about proper fertilizer management. The study showed a positive relationship between P reduction in the water with the implementation of the ordinance BMPs, but the authors acknowledged that it was impossible to determine if the controls on fertilizer solely led to the reductions in P. Other components of the overall program, such as fertilizer-management education, may have also played a role.

The Ann Arbor ordinance and the Minnesota law are similar to the Florida Green Industries Best Management Practices (BMPs) (FDEP, 2008) and the Florida-Friendly Landscaping^{TM} Program (FFL) approaches (FDEP, 2009b). These best-management approaches control fertilizer applications through research-based turfgrass management decisions. These ordinances do not have across-the-board blackouts of fertilizer use during the active growing period. Wisconsin is seeking to manage P fertilizer in a similar manner to Minnesota. It is interesting to note that Dane County (Madison) is the only county allowed to pass fertilizer ordinances (http://www.wisconsinlakes.org/press1-12-09.html). While other counties cannot use the ordinance approach, the municipalities can do this. Madison, Wisconsin, has a P ordinance addressing P loads to Lake Mendota. Apparently Wisconsin counties and municipalities are interested in a statewide fertilizer rule.

These programs in Minnesota, Wisconsin, and Michigan demonstrate the potential improvements in water quality by following the BMPs in the ordinance and implementing a strong public education program.

Other municipalities in the country have enacted ordinances controlling fertilizer, most often P fertilizer. A brief summary is presented below:

- Municipalities in New Jersey--http://www.lakehopatcong.org/ordinances.htm --ban P fertilizer in the winter when the ground is frozen and have set-backs from water bodies. They do not prevent P fertilization of newly established turf.

- Several municipalities in Michigan use an ordinance to control P applications--http://www.michigan.gov/documents/mda/mda_Michigan_Local_Fertilizer_Ordinance_List_297174_7.pdf. Most of these ordinances contain the following parts:

  P application is not allowed in the winter. P fertilizers should contain 0 P except when fertilizing newly planted sod or when a soil test indicates a need for P. Some ordinances include set-backs and reference to keeping fertilizer from impervious surfaces.

- New York has similar rules for not allowing P application in the winter, controlling P-content of fertilizers, involving a soil test in the decision to apply P, and limiting the per-application amount of N.

- Annapolis, Maryland, has an ordinance similar to those above, banning P fertilizer in the winter and allowing P use of soils testing low in P or for newly planted turfgrass--http://www.ci.annapolis.md.us/Government/Headlines/Arhives/OctDec2008.aspx.

While probably not exhaustive, the survey above found no laws or ordinances that banned fertilizer in the summer period of active turfgrass growth. The rules in these states typically control fertilizer application based on BMPs, including the use of a soil test to predict P needs, the use of set-backs from water bodies, advice on keeping fertilizer off impermeable surfaces, controls on total amounts of fertilizer per application and for the season, bans on fertilization in the winter when the ground is frozen or when the turfgrass is not actively growing, and allowing fertilization of newly planted turf seeds or sod. The ordinances in other states are much like Florida DEP's Green Industries Best Management Practices, DEP's state model ordinance, the state's Urban Fertilizer Turf Rule, and the UF/IFAS Florida-Friendly Landscaping™ Educational program for homeowners, commercial fertilizer applicators, and builders and developers.

The Florida situation with fertilizer ordinances

Many counties and municipalities in Florida, like other states and municipalities, have chosen the ordinance as a means to control fertilizer use, however, some have included a fertilizer ban in the summer active growing season. Most Florida ordinances contain guidelines that are supported by research and are consistent with the University of Florida, IFAS, and FDEP nutrient BMPs. These practices include following recommended fertilizer application methods and keeping grass clippings and fertilizer from impervious surfaces. These materials can be moved into water bodies via the storm water. Fertilizer management is important because studies (North Carolina) have shown only one-half of residents remove fertilizer from impervious surfaces (Osmond and Hardy, 2004). This result shows that lack of knowledge about how to avoid misapplication of fertilizer may be a contributing factor to nutrient losses, and a more serious one than properly fertilized lawns where lawn maintenance activities are consistent with BMPs.

Certain ordinances in Florida contain a ban on fertilizer sale and application during the summer months of June 1 through September 30. The rationale is that heavy rainfall events are common in the summer months and the likelihood of leaching and runoff of fertilizer is therefore greater during the summer. However, the summer months also are the months when landscape plants such as turfgrass grow the most actively and require nutrients for healthy development. National research shows that this is the time of the year when turfgrass is most active in taking up nutrients and nutrient loss is negligible. The ban was part of a recommendation of a workgroup for a model ordinance from the Tampa Bay Estuary Program (TBEP, 2008a; TBEP, 2008b). This workgroup was composed of members from most of the important stakeholders (public, private, turf and fertilizer industry, and non-governmental organizations) in the urban water quality issue for the Tampa Bay area. The ban or restricted period, or "blackout" part of the model ordinance was not supported by all stakeholders but was included in the final model ordinance (TBEP, 2008). The model ordinance including the summer ban was proposed as a model for counties and municipalities in Florida, especially around Tampa Bay to follow in their own ordinances.

In 2007 the FDACS created the Urban Turf Fertilizer Rule (FDACS, 2007) to help protect water quality in Florida by restricting the application of N and P fertilizers for urban turf and lawns. The rule requires that all fertilizers less than 50 lbs. sold for urban turf use are labeled with only the amount of N and P needed to sustain healthy turf. The rule requires the directions on any turf fertilizer label to limit the amount of N and P that can be applied in a single application and per year. This rule was designed to help guide Florida's citizens to apply fertilizers in the urban environment at rates that sustain healthy turfgrass and minimize potential nonpoint source pollution from nutrient movement. After reviewing urban landscape leaching and runoff literature reports, the Urban Fertilizer Task Force, established by the Florida Legislature in 2008, decided not include a restricted period (ban) in their report to the Florida Legislature (FDACS, 2008). Evans et al. (no date) from the Conservation Clinic of the University of Florida, College of Law, summarized the arguments for and against BMPs or fertilizer bans. These authors suggested that bans should be considered after mandated or voluntary BMPs have been tried and found ineffective.

Center for Landscape Conservation and Ecology/Florida-Friendly Landscaping™ Program

Education programs and timely communication of new research results to the stakeholders is extremely important in addressing urban water quality issues (Heisler et al., 2008). The Florida-Friendly Landscaping™ (FFL) Program is a UF/IFAS Cooperative Extension program that educates Florida's citizens about protecting the state's water resources and environment through sustainable landscaping practices. In conjunction with the Florida Department of Environmental Protection (FDEP), the FFL Program operates out of Extension offices in all 67 counties. The three-part educational program is composed of the GI-BMP program, which trains commercial horticulture professionals in BMPs; the FYN Homeowner program, which targets the education of homeowners; and the FYN Builder & Developer program, which does outreach to Florida's many builders and developers. The FFL Program educates each of these groups with print and online materials, in-person workshops and trainings, Florida-Friendly Yard Recognitions, and continuous outreach.

The FFL Program has come increasingly into the spotlight since the July 2009 passage of SB494, which determined that all commercial fertilizer applicators in Florida must be certified in the Florida Green Industries Best Management Practices for Protection of Water Resources in Florida by January 1, 2014; and of SB2080, which prevents homeowner associations from interfering with residents' implementation of Florida-Friendly Landscaping™ practices. The FFL Program is the UF/IFAS vehicle for delivering sound scientific information to the public for educational purposes, including scientifically based fertilization practices. More information on the FFL Program can be found at: http://fyn.ifas.ufl.edu.

Take-home lesson: Will fertilizer restricted periods result in an improvement of urban water quality?

The literature reviewed in sections 2 and 3 regarding urban nutrient management and water quality, and the experiences of other states shows that:

- Nutrient losses are negligible during the active growth period for healthy turf being fertilized according to BMPs.
- Increased runoff and increased nutrient loss may result when turfgrass is over-fertilized or when fertilizer is applied to unhealthy turfgrass.
- Properly fertilized turfgrass helps prevent soil erosion which moves soil and nutrients off-site.
- There are no scientific reports relating summer fertilizer bans with improved water quality, but fertilizer control by science-based BMPs has been shown to be effective in reducing water pollution.

- The literature documents the importance of using BMPs and education programs together to maximize the improvement of nutrient management and its impact on water quality.

- Some other states and municipalities in the country are using local ordinances based on BMPs as a means to control fertilizer use in residential areas, but none could be found that included a blackout of fertilizer application in the summer growing period.

Continued research needed:

Considerable research has been completed on nutrient and water management in urban landscapes addressing water quality. There is an increasing amount of research-based information for nutrient management in urban environments, but there are still areas in need of further work as identified in the national research reports. Some of these areas are described below.

There is an inadequate level of understanding about the nutrient sources and fates in the urban environment. Some of these sources have been described in this paper. While the Tampa Bay Estuary Program (2006) attributed a large portion of storm water runoff to residential sources, no information was presented on the portion due to fertilizer use. Before specific control measures can be determined, more information is needed about the particular nutrient sources, their relative amounts, and how they potentially could contribute to a problem in water quality. This nutrient mass balance is needed for N and P.

Fertilizer recommendations should be continually evaluated for turfgrass health and for impacts on water quality from leaching or runoff. These studies should include the relationship of healthy or unhealthy turfgrass and landscape plants with nutrient losses from the landscape.

Human behavior plays a large role in the success of programs, voluntary or regulatory. For example, misinterpretation or lack of good understanding of fertilizer, fertilizer ordinances, and landscape maintenance practices may result in misapplied fertilizer before and after the restricted period and throughout the year. More research is needed in the social sciences to determine what individuals understand about water quality and the relationship their landscape management activities may have on water quality.

Research also is needed on appropriate and most effective educational programs. The University of Florida provides the Florida-Friendly Landscaping^{TM} program (FFL, 2009) through the Green Industries Best Management Practices for the Protection of Water Resources (GI-BMPs) professional training program and the Florida Yards & Neighborhoods (FYN, 2009) homeowner program. The Florida-Friendly Landscaping^{TM} program (FFL, 2009; Hansen et al., 2009) has been developed to educate the public about conserving water and protecting water quality through sustainable landscaping practices.

More research is needed on the interaction of irrigation and nitrogen fertilization to determine the optimum fertilizer and irrigation combinations for various turfgrasses and landscape plants.

More information is needed on the specific nutrient and water requirements of common and new landscape plants. This research should include native and non-native plants.

Research is needed on optimum construction site management for best soil preparation for landscape installation, with attention to minimizing negative environmental impacts.

Research is needed on reclaimed water use in urban environments for supplying water and nutrients. Questions include, "Is there a fertilizer offset when using reclaimed water?"

Overall Summary/Concluding Comments

From this literature review and analysis, the following conclusions can be made:

- Coastal and urban eutrophication is an increasing problem and is, at least in part, related to urban land-based activities. Sources of nutrients involved with eutrophication are numerous and the interactions with harmful algal blooms are complex.

- Based on an analysis of national research, unfertilized turf will lead to increased runoff and nutrient losses as turfgrass health and density declines over time due to insufficient nutrient supply.
- BMPs, whether voluntary or embodied in a fertilizer ordinance, have been shown to be effective in reducing pollution of water bodies.
- Developing nutrient BMPs involves an iterative process based on science and must be sustained to develop continually advancing knowledge.
- The BMP solution avoids the "one-size-fits-all" approach because BMPs, by definition, provide for adjustments in the practices depending on local conditions and science-based recommendations.
- All published scientific research should be part of a comprehensive and complete discussion of approaches to reduce urban nutrient losses. All stakeholders should actively engage in this process.
- Research publications point to the importance of a continued education effort to inform homeowners about how their landscape practices impact water quality. UF/IFAS conducts public education for the consumer and the landscape management professional. Continuing the effort to educate the public about the BMPs, as determined by scientific research, is of the utmost importance.

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Table 1. Amounts of total N applied depend on the concentration of N in the reclaimed water and the amount of reclaimed water applied during irrigation. Highlighted columns represent the approximate average annual irrigation needs for turf in Florida.

N conc. in reclaimed water (ppm total N)	1.0 inch irrig. water	5.0 inches irrig. water	10 inches irrig. water	20 inches irrig. water	30 inches irrig. water	50 inches irrig. water	100 inches irrig. water	150 inches irrig. water
	Resulting lbs N per 1,000 ft^2							
1.0	0.005	0.026	0.052	0.104	0.155	0.259	0.518	0.777
2.0	0.010	0.052	0.104	0.207	0.311	0.518	1.036	1.554
3.0	0.016	0.078	0.155	0.311	0.466	0.777	1.554	2.331
5.0	0.026	0.130	0.259	0.518	0.777	1.295	2.590	3.885
10.0	0.052	0.259	0.518	1.036	1.554	2.590	5.180	7.770
20.0	0.104	0.520	1.041	2.081	3.121	5.202	10.41	15.61
30.0	0.156	0.780	1.561	3.121	4.682	7.804	15.61	23.41

Table 2. Amount of P_2O_5 applied as a function of the concentration of P (as P) in reclaimed water and the quantity of reclaimed water applied. Highlighted columns represent the approximate average annual irrigation needs for turf in Florida

P conc. in reclaimed water (ppm)	1.0 inches irrig. water	5.0 inches irrig. water	10 inches irrig. water	20 inches irrig. water	30 inches irrig. water	50 inches irrig. water	100 inches irrig. water	150 inches irrig. water
	Resulting lbs P_2O_5 per 1,000 ft^2							
0.1	0.001	0.006	0.012	0.024	0.036	0.060	0.119	0.179
0.25	0.003	0.015	0.030	0.060	0.089	0.149	0.298	0.447
0.5	0.006	0.030	0.060	0.119	0.179	0.298	0.596	0.894
0.75	0.009	0.045	0.089	0.179	0.268	0.447	0.894	1.340
1.0	0.012	0.060	0.119	0.238	0.357	0.596	1.191	1.787
2.0	0.024	0.119	0.238	0.477	0.715	1.192	2.383	3.575
5.0	0.060	0.298	0.596	1.192	1.787	2.979	5.957	8.936