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Diffuse Nutrient Pollution from Residential Catchments

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Diffuse Nutrient Pollution from Residential Catchments

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
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DEDICATION

To all those who have loved and encouraged me, I dedicate my academic pursuit of engineering and this thesis. Mom, Dad, Michael and James, I owe a part of my success to each of you. Thank you for supporting me in all the various ways you have over the years. I appreciate every time you listened, let me cry on your shoulder and, most importantly, for believing in me the entire way. Michael, you made the journey so much easier than it would have been. Thank you for all the times you went out of your way to make my life less stressful; you are an amazing partner. Thank you for putting me on a pedestal and believing in me when I had trouble doing it for myself. James, you have been the best friend I could ask for through ups and downs. Thank you for listening, having faith in me and being so generous. Mom and Dad, thank you for your love and support; your patience and love is always a huge prop up. I will continue to strive to make you all proud and to be the best companion, friend and daughter I can be.

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ABSTRACT

Nonpoint source nutrient pollution is diffuse pollution lacking discrete origin and conveyance. This thesis synthesizes and critically reviews research on residential nitrogen and phosphorus loss to stormwater runoff and leaching. The evaluation pulls from research covering influential socio-demographic indicators, such as use of lawn maintenance services and homeowner fertilizer practices. The extent to which such social and economic factors may influence the prevalence and fate of diffuse nutrients in stormwater runoff from residential areas has not been adequately established. Understanding the source and influencing factors of diffuse nutrient pollution is important in order to effectively protect surface and groundwater resources.

Research based on sampling campaigns of catchments, sampling of controlled turf systems and models of residential catchments were compiled for this review. Based on the compilation reviewed for this thesis, there are wide differences in approaches researchers have taken to attempt to quantify and understand diffuse nutrient pollution from residential and urban areas. There is not consistency in the chemical nitrogen or phosphorus species evaluated or in reported measurements (i.e. concentration vs. loading vs. yield).

This review revealed several important knowledge gaps. Determination of correlation between residential system nutrient loss to the environment and social factors, demographic characteristics, local fertilizer ordinances or nutrient management education programs has not been substantiated. More exploration of nutrient leaching from different soil types and turf grass species is needed to develop a complete understanding of nutrient loss from turf grass systems. Further, other specific management practices such as leaving grass clippings on lawns has not been studied in depth for a variety of soil types and grass species. There is room for improvement in future research and additional studies are needed to guide future policy and implementation of best management practices. Based on these and other findings, I recommend a concerted effort to standardize a portion of the reporting details of future stormwater research and for reevaluation of nutrient/fertilizer education efforts.

CHAPTER 1: INTRODUCTION

Water issues currently faced by society are many in number and varied in scope and complexity. Researchers and water managers continue to face quantity and quality issues amidst new challenges, such as emerging pollutants. Combined, these challenges emphasize the importance of recognizing that no water should be polluted and cast aside; the entire hydrologic cycle is connected and all water resources are important. The obstacle addressed in this research is that of stormwater quality from residential areas, with a particular focus on nonpoint source nutrient pollution. Nutrients (nitrogen and phosphorus specifically) arise from multiple sources. One of the most potent nonpoint nutrient pollution sources is fertilizer, considered a nonpoint source due to its lack of discrete origin and conveyance. This is an important environmental topic to address because of the 67 million pounds of fertilizer applied by homeowners annually in the US, 40 to 60% of the fertilizer nitrogen ends up in surface and groundwater, while homeowners are attempting to achieve the look of the idealized highly manicured monoculture turf lawn (Welker & Green, 2004 [EPA], values from Congressional Hearings). Current water quality experts recognize historic and potential future impacts of these practices, which include the potential of acute water quality degradation.

1.1 Nitrogen and Phosphorus as Nutrients in the Environment

Nitrogen, in various biochemical forms, is a key building block to both protein and enzymes; it can drive certain metabolic processes in living organisms, and it is a component of plant chlorophyll (Sutton et al., 2011). It can be limited in terrestrial systems as a result of poor soil quality found in high sand content soil, which negatively impacts nitrogen retention and ion exchange. Nitrogen is often the limiting nutrient in estuarine systems; this has resulted in a comparative lack of studies on phosphorus export from coastal watersheds (Tufford, Samarghitan, Mckellar, Porter, & Hussey, 2003).

Atmospheric nitrogen (N_2 gas) makes up approximately 78% of the earth's atmosphere. Though abundant in this form, N_2 gas is not bioavailable to organisms for use in metabolic or other processes. However, the amount of nitrogen now circulating in bio-geochemical cycles has effectively doubled in the past century, meaning that anthropogenic production nitrogen via fertilizer, crop cultivation and combustion processes approximately matches natural production (Elser et al., 2007). Prior to industrial times, the primary avenue for conversion of N_2 to a terrestrial based form was by way of living organisms that could use carbohydrate energy to reduce gaseous N_2 to produce ammonia (NH_4). Extreme changes in the nitrogen nutrient cycle are a result of industrial processes, population growth and technological advances, such as the Haber-Bosch process and combustion engines' consumption of fossil fuels (Collins et al., 2010). The reaction of the Haber-Bosch process allowed the production of ammonia fertilizer, breaking the triple molecular bond of N_2 and adding four hydrogen atoms to form ammonia as follows.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Equation 1

The Haber-Bosch process provided a breakthrough in fertilizer production, and concurrent ability to significantly increase food production, which directly contributed to population increase. The process was developed in the early 19th century, at which time internal combustion engines became further refined and more widespread (Alvord, 2000). However, combustion processes release unprecedented amounts of NO_x into the atmosphere (Sutton et al., 2011). According to the EPA Science Advisory Board (2011), humans have introduced 29 teragrams (Tg) of N into US terrestrial and water environments via the Haber Bosch process used in fertilizer manufacture, other industrial reactive nitrogen (N_r) production and biological nitrogen fixation through cultivation and combustion. In addition, due to anthropogenic influence on the bio-geochemical cycle and its resultant harmful effects, the National Academy of Engineers named “Management of the Nitrogen Cycle” as one of the “Grand Challenges for Engineering” in 2008 (National Academy of Engineering, 2008).

Figure 1 depicts the major sources of nitrogen introduced to the US. The term reactive nitrogen (N_r) refers to characteristically mobile species and encompasses biologically active, chemically reactive and radiatively active nitrogenous species in the atmosphere and biosphere (EPA Science Advisory Board, 2011). Movement of nitrogen in human created ecosystems is inherently inefficient, with leakage at every step (Baker, Hope, Xu, Edmonds, & Lauver, 2001). Amplified releases to the environment means increased nitrogen inputs to aquatic ecosystems. Nutrient excess in aquatic systems can lead to algal blooms; as algae decays, it depletes the dissolved oxygen (DO) that other aquatic organisms need to survive. Collectively, such damaging impacts are referred to as eutrophication; eutrophication limits water resources usability for industry, recreation and municipal purposes (King, Balogh, Agrawal, Tritabaugh, & Ryan, 2012). Additional effects of nutrient increases can include water body acidification and loss of biodiversity.

For phosphorus, mining phosphate has altered the phosphorus cycle by unearthing and processing reserves that took millions of years to form (Filippelli, 2011). Furthermore, 95% of mined phosphorus is used to produce fertilizer for the agricultural sector (Vaccari, 2011). Much like fossil fuels, phosphorus sedimentary deposits are not renewable on the human time scale. The global phosphorus input to the biosphere has been amplified by approximately four fold compared to preindustrial times (Falkowski et al., 2000). As an important nutrient for both animals and plant biota, this significant alteration to the bio-geochemical cycle has not occurred without environmental consequence.

Nutrients in stormwater from residential areas can be generated as a result of fertilizer application to lawn turf, animal waste (such as pet bio-waste), leaky on-site wastewater systems (e.g. septic systems), and atmospheric deposition (Carey et al., 2013). Stormwater runoff eventually flows to surface water such as streams, lakes, rivers, estuaries and oceans. High nutrient loading in stormwater can cause eutrophication and severe impairment to water bodies causing adverse impacts to healthy ecosystems. For example, the National Estuary Program Coastal Condition Report (EPA, 2007a), which evaluated the United States and its territories, rated two regions, Puerto Rico and Northeast Coast, at a “poor” overall condition and two large regions, Gulf Coast and West Coast estuaries, below fair. These assessments comprise evaluation of water quality, sediment quality, benthic index and fish tissue contaminant index. The overall US estuary condition was declared below fair. Specifically, approximately 62% of the nation’s National Estuary Program estuaries were experiencing moderate to high degrees of eutrophication. As coastal waters become eutrophied, sea grasses are killed off, which eliminates important nursery and feeding ground for multiple aquatic species, including various crustaceans, fish and manatees (McClelland & Valiela, 1998).

Increases in nitrogen and phosphorus inputs into groundwater have caused environmental problems as well, including induced methemoglobinemia, a form of blue baby syndrome resulting from high nitrate concentrations in water (EPA, 2007) National Center for Environmental Health 2012). Methemoglobinemia may also occur in livestock, where the condition interferes with both the blood’s ability to carry oxygen and fetal viability (Carpenter et al., 1998). In humans, nitrates can be reduced to nitrite; nitrite oxidizes iron in blood hemoglobin converting it to methemoglobin, which cannot carry oxygen (Weiner, 2013). Other societal threats of nutrient pollution include: decreased air quality, greenhouse gas imbalance, ecosystems damage, loss of biodiversity, and soil quality degradation (Sutton et al., 2011). While degradation of water bodies can be measured in terms of lost species or amenities, we simultaneously recognize that poor water quality is linked to increased cost of treating water for both potable and non-potable use (Carpenter et al., 1998).

Recent decades have seen a reduction of nutrient inputs to surface waters, in great part, as a result of reduction in nutrient point discharges from centralized wastewater treatment effluent. As the point source contribution of nutrients to stormwater and surface water has decreased, the overall percentage of nonpoint contribution of nutrients has increased (Davies, 1995). Diffuse nutrient pollution sources are, however, many and varied. This thesis attempts to elucidate factors that impact concentration and loading of the nutrients, nitrogen and phosphorus, from residential areas and lawns. This should be helpful to guide future research on understanding and reducing diffuse nutrient loading to water bodies.

1.2 Motivation

The word “urbanization” is generally understood to mean an expansion of urban area along with a growth in the number of people living in and around urban regions. Today, it is accepted as a trend in globalization (Pickett et al., 2007). Almost half of the world population and 80% of the US population reside in urban areas; it is expected that 60% of the world population will live in an urban area by 2030 (Burns et al., 2005). Such growth necessitates housing development, which may come in the form of high-density residential areas near urban centers, low-density, primarily single-family housing further away from urban centers or any number of variations in between. Currently, there is not a US or global standard for categorizing urban or residential land use based on housing, population or vegetation density (Hitt, 1994). While proposed classification systems are available (e.g. Anderson, Hardy, Roach, & Witner, 1976), none of the research reviewed in this work showed consist utilization of any particular classification tool (Cadenasso, Pickett, & Schwarz, 2007).

As precipitation occurs on impervious surfaces and rainfall exceeds the capacity of soils to absorb (whether due to exceeding storage capacity or intensity of the rainfall event), runoff occurs. Combined with impervious surfaces, in urban and residential areas stormwater is produced. Impervious surface decreases infiltration, increases runoff and shortens the time for which runoff does occur (Brezonik & Stadelmann, 2002). Runoff from urban and residential areas carries nonpoint source nutrient pollution. The extent of potential anthropogenic contribution to nutrient pollution is emphasized in figure 2; these charts enunciate urban impacts to the Chesapeake Bay. Although, it is not currently known what portion of urban anthropogenic nutrient pollution is made up of residential nonpoint sources, lawn fertilizer has the potential to be a major contributor.

The US Department of Agriculture has conducted land use pattern change analyses to account for the primary uses of public and private lands in the US (Nickerson, Ebel, Borchers, & Carriazo, 2011). The 2007 report showed that urban land acreage quadrupled from 1945 to 2007. The total urban area estimated for 2007 was 61 million acres, up nearly 2 percent since 2002 (as cited by Nickerson et al., 2011). Such increases in impervious area necessitate a corresponding development of stormwater management and treatment. Implications for growth in urban and residential areas remain. Residential development and urbanization converts regions previously undisturbed (forests, shrublands and deserts) into an entirely different ecosystem with high impervious surface and complicated networks of storm, sanitary and water supply pipes, sometimes referred to as “urban karst” (Janke et al., 2013). Urban and residential development modifies hydrology by the implementation of “urban karst”, entombment of streams and further hydrologic alteration as a result of aging, leaky infrastructure (Janke et al., 2013). Residential areas make up a large component of urban space; its associated water infrastructure (and the various conditions and ages different regions have) play a significant role in watersheds’ hydrologic behaviors (Hammer, Stewart, Winkler, Radeloff, & Voss, 2004). Compared to pre-development, it is widely acknowledged that urban and residential development influence stormwater runoff characteristics in many ways, such as (Burns et al., 2005):

- Decreased groundwater recharge
- Increased surface water runoff
- Greater magnitude of peak runoff
- Shorter lag time between rainfall onset and runoff response

Rainfall intensity and timing can also influence the amount of nutrients that are released by lawns, dislodged from impervious surfaces and carried away via overland flow and stormwater. Nutrients carried by these storm events can have important implications for nearby aquatic health. Table 1 shows various concentrations at which some nutrients begin to disrupt aquatic ecosystems.

Due to high percentage of impervious surface coverage, stormwater management is essential to flood management. In the context of residential areas in the US, storm drains are a common community feature. Results from surface stormwater runoff research vary considerably, however, most show surface stormwater runoff to contain high concentrations of nutrients from nonpoint sources (Janke et al., 2013). As such, stormwater control measures often target nutrient removal (Janke et al., 2013). The need to estimate nonpoint source loading for effective watershed management has driven a variety of research efforts in stormwater monitoring and modeling (Brezonik & Stadelmann, 2002). Some researchers have evaluated households as systems with flux of nutrients coming in and out. Such modeling efforts in the US upper Midwest revealed that approximately 25% of household nitrogen flux occurs through the lawn (Fissore, Baker, et al., 2011).

In 1997, the USDA stated that if lawns were classified as a crop, they would rank as the country's 5th largest crop on the basis of acreage covered (Nielson & Smith, 2005). Nitrogen and phosphorus are the main constituents of commercial fertilizers at risk for leaching into stormwater runoff and causing water quality problems (EPA Science Advisory Board, 2011). This phenomenon can be more pronounced as a result of over-fertilization or fertilizer applied during the incorrect season for optimal absorption. This research focuses on nutrients associated with residential lawn management such as fertilizer application, factors affecting fertilizer application, and subsequent impacts. Nitrogen concentrations in stormwater from urban areas can also be highly variable, but researchers have found that loadings are always greater from urban areas, compared to undisturbed natural regions (Collins et al., 2010). Evaluation of associated best management practices are merited as a result of such nutrient concentrations entering open water bodies.

Approximately 50% of turfgrass is estimated to not be fertilized, while the remainder is fertilized at different intensities (EPA Science Advisory Board, 2011). However, in some regions of the United States, fertilization of lawns can be a dominant source of nitrogen (EPA Science Advisory Board, 2011). Turfgrass, generally referring to a group of grass species used for lawns and golf courses, typically requires concerted management in both fertilization and intense watering (King, Balogh, & Harmel, 2007; Shore, Delgado, Totten, & O'Leary, 2014). King et al.

(2007) found that nitrate and dissolved reactive phosphorus exiting a managed turfgrass area to be significantly greater than those entering. This implies that current turf management practices are not successful in nutrient management.

Despite protection offered by the Clean Water Act, eutrophication due at least in part to excessive nutrient loading, is one of the most pervasive causes of water quality impairment in the US (EPA, 2012b). If adequate light is available, N and P are the limiting factors for growth of phytoplankton in aquatic environments; in coastal areas, nitrogen is often the limiting nutrient while phosphorus is often the limiting nutrient in fresh water (Florida LAKEWATCH, 2000; Howarth et al., 2000). Noted eutrophication impacts include: phytoplankton growth, macrophyte growth, benthic and epiphytic algae growth, gelatinous zooplankton growth, toxin release (from harmful algal blooms [HAB]), reduced carbon availability to food webs, loss of habitats, loss of coral reefs, loss of sport fisheries, odor problems and loss of recreational and aesthetic water use. (Badruzzaman, Pinzon, Oppenheimer, & Jacangelo, 2012)

Eutrophication in salt waters causes algal blooms, which can hinder light penetration over large regions of water (Bricker et al., 2007). This results in the inability of aquatic plants to thrive, destroying both habitat for small marine animals and eliminating the food source of other animals. Eutrophication in freshwater bodies can result in impaired fisheries, inability to use water for recreational purposes, and induced oxygen shortage (Bricker et al., 2007). Further, some algae growth can induce formation of carcinogens when impaired water is processed through conventional drinking water treatment processes (Sharpley, Mcdowell, & Kleinman, 2001).

The EPA has instigated multiple initiatives in attempt to prevent nutrients from ending up in stormwater runoff. Federal Water Pollution Control Act and the Clean Water Act have effectively reduced pollution from point sources from both industrial and municipal discharges (Davies, 1995). Nonprofit organizations, such as the Chesapeake Bay Program and the Tampa Bay Estuary Program, serve both to further research on watershed protection and act as advocates for sound water protection policy.

1.3 Objectives

The overall objective of this thesis is to synthesize existing literature and available data to evaluate concentration or loading of nitrogen and phosphorus associated with stormwater that originates from residential lawn management. Towards that overall objective, I specifically aim to: (1) explore and assess current practices in the evaluation of stormwater nutrient water quality, (2) identify key knowledge gaps in the existing literature, (3) propose specific objectives for future research that could contribute to alleviation of impacts from diffuse nutrient pollution, and (4) determine if any research has successfully linked nutrient loading to specific nonpoint source influences at a fine scale (i.e. at the scale of an individual household, versus an overly broad group of behaviors, such as "residential activities").

The results of this thesis should aid in assessing impacts of nutrients in stormwater runoff from residential areas. Results of this thesis will also elucidate how factors such as geography or the socio-demographics characteristics of homeowners may affect nutrient concentrations and/or loadings to stormwater from residential locations. Moreover, it is important to have an understanding of limitations to current residential lawn management practices in order to successfully implement or change best management practices (BMPs).

1.4 Organizational Overview of Thesis

This introductory chapter is followed by two chapters. Chapter 2 provides the literature review, analysis, results and discussion. That chapter explores nutrient cycles, aquatic nutrient policies and regulations, characterization of urban and residential stormwater, socio-demographic factors influencing lawn management practices and concentrations/loadings of nutrient and phosphorus from residential regions. Through the critical literature and review of existing research, I attempt to connect and analyze nitrogen and phosphorus concentrations/ loadings in stormwater from residential or primarily residential areas to potential specific socio-economic influences. Further, the review allowed for identification of factors that may improve or decrease the success of fertilizer and lawn management practices. It contributes to the current body of scientific knowledge by addressing the initial need to develop understanding of diffuse nutrient sources such that truly sustainable BMPs of residential stormwater controls for nutrient treatment use may be advanced.

Chapter 3 entails major findings, conclusions, recommendations for future research and additional considerations. In the final chapter, I explore important implications of this research, recommendations for BMPs in urban and residential areas and I present a set of guideline recommendations for future researchers to use when pursuing sampling campaigns and evaluations of nutrients from such regions.

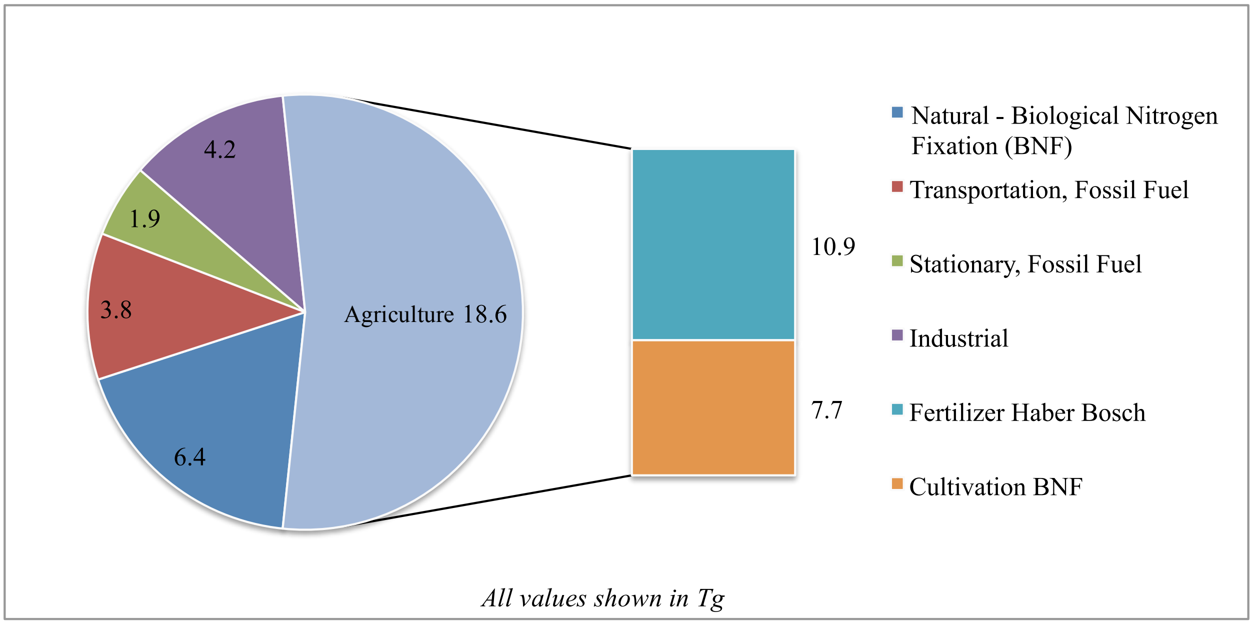

Figure 1 Reactive Nitrogen Sources by Sector in the US, 2002 (Adapted from EPA Science Advisory Board, 2011)

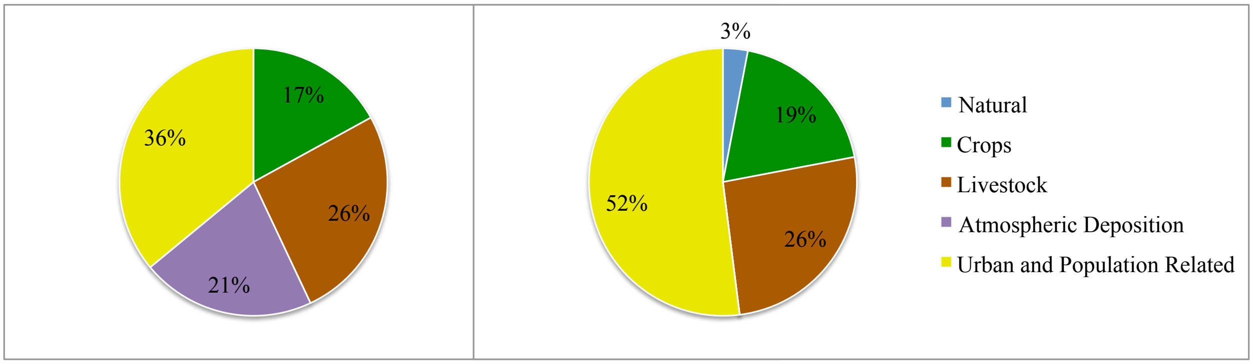

Figure 2 Sources of Nutrient Pollution (Nitrogen on Left, Phosphorus on Right) Entering the Chesapeake Bay (adapted from EPA, 2010)

Table 1 Concentrations of Nutrient Species' Aquatic Impact

Nutrient Species	**Aquatic Level**	**Reason for concern**
NH_4^+/NH_3	> 0.5 NH3-N mg/L	Significant toxicity to fish (Weiner, 2013)
NO_3^-	> 400 mg/L	Impacts begin to occur on growth and feeding activities of fish (Burton & Pitt, 2002)
NO_2^-	> 0.7 mg/L	Fish mortality begins **Nitrite is usually oxidized to nitrate, but if aquatic conditions favor formation of nitrite, it can severely impact aquatic species at low concentrations*. (Burton & Pitt, 2002)
TP	> 0.1 mg/L	Accelerated eutrophication begins at concentrations higher than 0.1 mg/L (Weiner, 2013)

CHAPTER 2: LITERATURE REVIEW, ANALYSIS, RESULTS, DISCUSSION

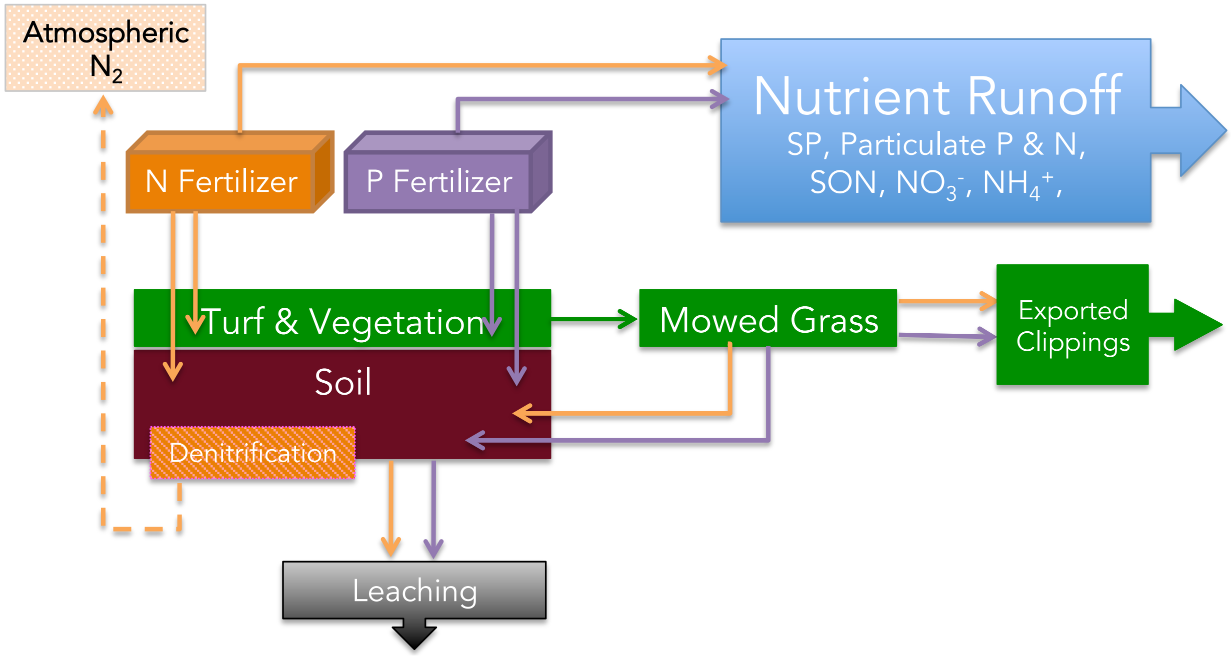

Figure 3 Selected Nutrient Cycles in a Turf Grass Ecosystem (adapted from Baker, Wilson, Fulton, & Horgan, 2008)

2.1 Literature Review

Increasing amounts of impervious surface from population growth and associated urbanization has been linked with indicators such as fish species loss, changes in channel morphology, loss of benthic organisms and increased stream baseflow. Although researchers have used different measurement techniques in the past, most agree that there is a definite relationship between impervious surface and stream health; several have found the threshold of degradation value to be at approximately 10% impervious surface cover (Dietz & Clausen, 2008). Through review of research published over the past several decades that address lawns as complex ecosystems, homeowner management trends and stormwater sampling campaigns, we can begin to weave narrative for understanding a temporally and biologically complex system. The basic nutrient cycle of the ecosystem reviewed in this thesis, the residential lawn, is depicted in Figure 3. Importantly, Figure 3 highlights three pathways for nutrient losses from the turf lawn system: atmospheric, leaching and stormwater. Within residential and urban areas, nutrient pollution in leaching groundwater and stormwater will be the focus of this review.

2.1.1 Nutrient Species

There are multiple species of organic and inorganic nitrogen that can enter the environment. The relationship among these nutrients is complex and influenced by numerous external factors such as medium, temperature and pH. Nitrogen in chemical fertilizer can be composed of multiple nitrogenous species and may include ammonia, various ammonium species, such as diammonium phosphate ($(NH_4)_2HPO_4$), ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(NH_4)_2SO_4$), nitrate species such as calcium nitrate ($Ca(NO_3)_2$) and sodium nitrate ($NaNO_3$) and urea (N_2H_4CO) (Shakhashiri, n.d.).

Four commonly used water quality measures of nitrogen are total nitrogen (TN), total Kjeldahl nitrogen (TKN), nitrite+nitrate–nitrogen ($NO_3^- + NO_2^-$ as N) and ammonia-nitrogen (NH_4^+/NH_3-N) (Aryal et al., 2010). TKN is the sum of organic nitrogen plus ammonia; organic nitrogen can be converted into ammonia through ammonification (Atasoy, Palmquist, & Phaneuf, 2006). Ammonia can be converted into nitrite via oxidation, however, nitrite is unstable and is converted quickly to nitrate (Weiner, 2013). Nitrite (NO_2^-) and nitrate (NO_3^-) anions are extremely soluble and, therefore, able to move through soil at approximately the same rate as water; furthermore, they are nonvolatile species, meaning they are likely to persist in water until uptaked by plants or other organisms (Weiner, 2012). Nitrate is also more likely to leach during cool, wet seasons (Burton & Pitt, 2002). Equation 1 summarizes these possible transformations of nitrogen species in the natural environment.

$$Organic\ N \xrightarrow{biodegradation} NH_3 \underset{reduction}{\overset{oxidation}{\longleftrightarrow}} NO_2{}^- \underset{reduction}{\overset{oxidation}{\longleftrightarrow}} NO_3{}^-$$

Equation 2
(adapted from Weiner, 2013)

The prevalence of a given nutrient species varies depending on a variety of factors influencing the soil profile: land use, water column characteristics and a watershed's hydrologic characteristics. The primary sources of inorganic nitrogen are potassium nitrate and ammonium nitrate; these salts are used primarily in fertilizer (Weiner, 2013). Organic sources of nitrates typically discharged to the environment include domestic wastewater and livestock manure (Weiner, 2013). Fertilizer, wastewater and livestock manure all have the potential to end up in stormwater via runoff or can leach from leaky pipes if not properly managed. When stormwater ends up in stormwater control devices, N can be altered or removed in three ways: assimilation/uptake, adsorption and denitrification. Assimilation is usually accomplished by bacteria or plants, where the pollutant becomes part of the organism's biomass (Collins et al., 2010).

Nitrogen is most commonly the limiting component to plant growth. In soil, many microorganisms are capable of denitrification, but few are capable of nitrogen fixation. When the natural carbon to nitrogen ratio of soil is altered, such as by fertilization or plant uptake, soil microorganism restore a balance through carbon oxidation, nitrogen fixation or denitrification. In well-aerated soils with adequate moisture, ammonium and urea are converted to nitrate. Groundwater contamination as a result of over-fertilization is highly pronounced during heavy rain seasons, heavy irrigation and when plants are seasonally inactive (Bohn, Myer, & O'Connor, 2001).

Nitrogen losses from ecosystems can occur from forest fires and leaching through the ground (Sutton et al., 2011). Due to its mobile nature, nitrate fertilizer application that exceeds the needs of plant uptake will leach through the soil profile to groundwater sources. Subsequent losses can be influenced by rainfall, cultivation and soil management techniques. Reactive nitrogen flux in terrestrial ecosystems is influenced by soil moisture content, temperature and properties such as clay content, organic carbon content, pH and the types of vegetation growing. This is important to understand because such conditions can influence transport of nutrient species from fertilized ground. Ammonium ion (NH_4^+) can adsorb to soil particles as a result of a cation exchange processes, therefore, yielding lower concentration values in seepage water (Sutton et al., 2011).

Like nitrogenous species, phosphorus can be found in both organic and inorganic (phosphates, orthophosphates, polyphosphates) forms. Phosphorus in chemical fertilizer is generally comprised of multiple phosphate species, which can include diammonium phosphate ($(NH_4)_2HPO_4$) and dihydrogen phosphate ($Ca(H_2PO_4)_2$) (Shakhashiri, n.d.). Common water quality measurements include total phosphorus (TP), soluble reactive phosphorus (SRP) and biologically available phosphorus (Aryal, Vigneswaran, Kandasamy, & Naidu, 2010). Total phosphorus is the sum of particulate and dissolved phosphorus (DP). SRP is the fraction of TP available for organisms to grow (Michaud, 1991). Particulate phosphorus is of concern for other specific types of environmental research, such a limnology (Mitchell & Prepas, 1990).

In general, soil has a relatively good capacity to retain a significant amount of various phosphorus species. Researchers have attempted to devise methods for releasing unavailable phosphorus in soils or methods to prevent fixation, but have, thus far, been unsuccessful (Bohn et al., 2001). Phosphorus immobilization (fixation) is influenced by multiple factors: (1) aluminum and iron oxides influence P retention in acidic soils (2) calcium compounds influence solubility of P in calcerous soils and (3) organic matter aids P adsorption (Novotny, 2003). Plant growth accelerates as adsorbed P levels in soil increase from 0 to approximately 25 mg/kg soil; however this phenomenon has not been well studied for cool season turf (Baker et al., 2008). Residential lawns may, in fact, have much higher concentrations than this threshold of 25 mg/kg as a result of repeated and excessive application of fertilizer (Baker et al., 2008).

Phosphorus in nature, including that which is mined to produce fertilizer, is found in a bound phosphate form. In water, phosphate exists as phosphoric acid at low pH levels and dissociates into different species as a function of pH (Figure 4). The various phosphate species that commonly occur near neutral pH readily absorb to positively charged surfaces and ions to form stable components. In fact, it has been reported that at typical soil pH levels of 5.0 to 8.0, soil components can bind more P than can be used by plants (Thomason, 2002). As soil becomes more acidic, phosphate becomes increasingly bio-unavailable; under these conditions, phosphate binds to aluminum and iron (Bohn et al., 2001).

It is generally understood that pollutants bound to particulates may be found in higher concentrations during high intensity storms that mobilize particulates, as opposed to highly soluble species, such as nitrate, which are mobile during all rainfall events (Francey, Fletcher, Deletic, & Duncan, 2010).

Figure 5 illustrates different pathways by which nitrogen and phosphorus may be released and move through the environment. Although phosphorus is not known to be dry or wet deposited in large concentrations as nitrogen species are via atmospheric pathways, most other avenues for nutrients to end up in aquatic systems are similar for N and P. Figure 5 illustrates how various nitrogen and phosphorus species can end up in runoff from fertilized crop land, animal agriculture waste, industrial processes, urban runoff and residential runoff, particularly associated with lawn fertilization. Various N and P species originate from fertilizer and animal excrement, meaning that these pollutants can end up in runoff from agricultural areas (e.g. crop fertilizer, bovine bio-solids, swine-biosolids) and from residential areas (e.g. lawn fertilizer, pet excrement).

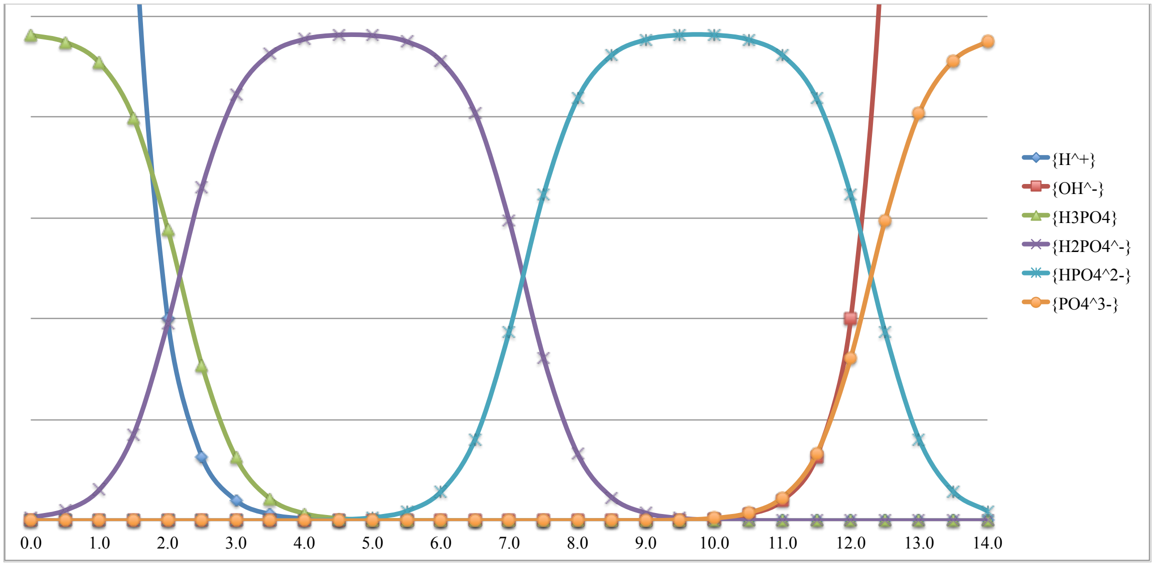

Figure 4 Distribution of Phosphate Species as a Function of pH

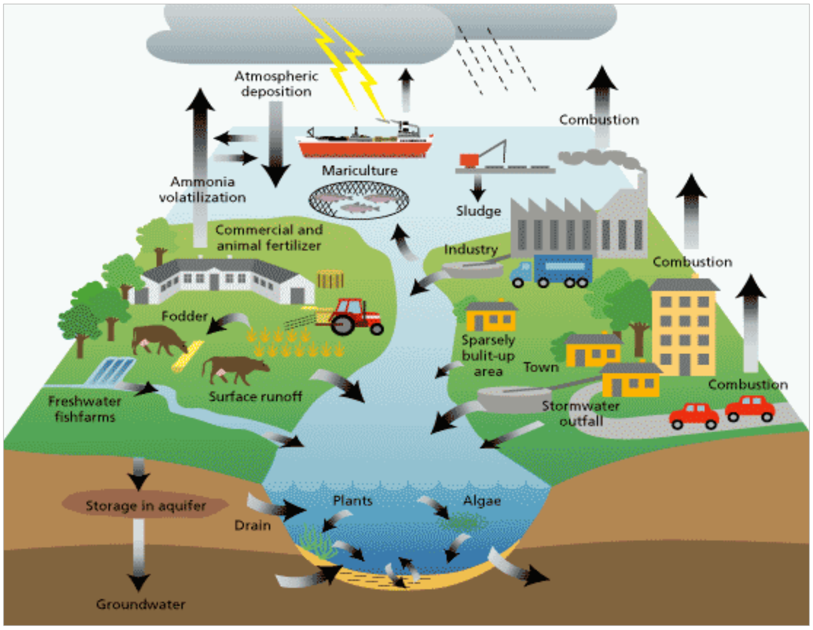

Figure 5 Hypothetical Water Cycle Showing Potential Pathways for Nutrients to Enter Surface Waters and Groundwater (Ærtebjerg, Andersen, & Schou Hansen, 2003)

2.1.2 Stormwater Nutrient Policies and Regulations

At the Federal level in the United States, there are portions of the Clean Water Act that address both point and nonpoint source pollution. The National Pollution Discharge Elimination System (NPDES) was instigated as part of the Clean Water Act in 1972 to address point source pollution (EPA, 2013). Point sources permitted and regulated under NPDES include pipe or ditch conveyance, and municipal or industrial discharges (EPA, 2009). The approach of attempting to control the amount of pollution entering the environment is sometimes referred to as an end-of-pipe approach (Harwell, 1998). The NPDES stormwater program requires that states regulate discharge runoff by employing separate municipal stormwater collection systems (Collins et al., 2010). State environmental management agencies, such as the Florida Department of Environmental Protection (FDEP), use the NPDES as a way to control water pollution by regulating point source discharges.

In 1987, nonpoint source management program was amended to the Clean Water Act to encourage states to assess nonpoint source problems in their jurisdictions and to develop protocol for mitigation and management. EPA regulations require cities to test and determine the magnitude of urban nonpoint source problems and to develop plans to capture and treat stormwater runoff (40 Code of Federal Regulations §§122, 123, 124, 504, 1988). These nonpoint source rules dictate that nonpoint sources of pollution be considered point sources after entering storm sewers (Marsh, 1993). Section 208 of the Clean Water Act requires states to plan and implement watershed-wide plans to address point and nonpoint source abatement. Section 303 explains solutions for such watersheds for situations where point source controls will not achieve goals set forth by the act (Novotny, 2003).

In 2001, the EPA implemented the Total Maximum Daily Loads (TMDL), which are provisions added to the Clean Water Act meant to address nonpoint source nonpoint source pollution. The provisions are based on best management practices (BMPs) for watersheds. Targeting nonpoint sources in residential areas, however, requires working with and obtaining collaboration from many individual private landowners (Nielson & Smith, 2005). Several social scientists have attempted to identify specific factors that influence lawn maintenance behaviors, but suggest these factors vary among economic class and geographic region, which is discussed in section 2.1.4.2 (Dietz, Clausen, & Filchak, 2004; Grove, Cadenasso, et al., 2006; Nielson & Smith, 2005). An understanding of nutrient source release and transport is necessary in order to implement BMPs that will be capable of meeting TMDLs.

2.1.3 Urban and Residential Land Use

Activities and atmospheric deposition taking place within an urban area can contribute to nutrient inputs of aquatic systems. For example, in a study conducted in Miami (Florida), researchers found that in an area where directly connected impervious area accounted for 44% of the watershed, it accounted for 72% of the total runoff volume (Carey et al., 2013). A high amount of impervious cover has also been shown to increase runoff volumes, which enhances nutrient transport because of decreased infiltration. Notably, transportation areas such as parking areas and gas stations all contribute to nutrients in stormwater systems; this is thought to be a result of high automobile use and the resultant atmospheric pollution deposition in these areas (Carey et al., 2013). Accordingly, street traffic density can influence nutrient loads in stormwater.

Also highly relevant to urban and residential areas is new residential construction, such as for a subdivision or apartment complex. New construction can produce increased levels of pollution in runoff, particularly from sediments, which can contribute to phosphorus loadings

(Carey et al., 2013). In Fort Leavenworth, KS, average concentrations of total suspended solids (TSS) in stormwater runoff were over 24 times greater than those in low-flow samples from a watershed with construction sites (Brezonki & Stadelmann, 2002).

Measuring and modeling precisely where loadings originate is difficult because the specific activities and weather patterns continually change spatially and temporally. Additionally, drawing clear, linear connections between eutrophication and nonpoint source pollution has been reported as difficult (Carpenter et al., 1998). Diffuse sources of pollutants also prove difficult to monitor and regulate. Nutrient loadings that result from fertilizer application are highly variable and can depend on rate of application, season, chemical form of fertilizer, application method, rainfall frequency and vegetative cover (Carpenter et al., 1998).

2.1.3.1 Residential Stormwater

Land use changes and spreading urbanization have also contributed to the altered nitrogen cycle. US citizens spent $8.9 billion on lawn-care inputs and equipment in 1999 (Robbins & Sharp, 2009). The public often views lawn management as a status symbol and a duty to their neighborhood. Extensive use of turfgrass and ornamentals has definitively increased the use of chemical fertilizers and other lawn management practices. Collins et al. (2010) note in particular that residential fertilizer use, pet wastes and septic systems to be major nonpoint source contributors to nitrogen pollution. Due to the characteristics of residential areas, such as altered terrain, impervious roads, roofs and compacted grounds, the characteristics of stormwater flow vary greatly from that of an undeveloped area. Compared to undeveloped land and watersheds, researchers expect residential areas to exhibit respectively larger runoff volumes, greater peak flows, steeper hydrographs and to experience higher pollutant loading (Collins et al., 2010).

Urban vegetation serves a variety of positive purposes as well. It has the ability to create microclimates (offsetting urban heat island effects), sorb pollutants including particulate matter and radiation impacts can also be attenuated by vegetation. Vegetation can stabilize slopes, such as for swales and streams, while simultaneously contributing to stormwater management (Grove, Troy, et al., 2006).

2.1.3.2 Unique Challenges

Urban ecosystems are a heterogeneous land mix of roads, buildings, homes, vegetation, water infrastructure, agriculture, and natural and semi-natural ecosystems (Groffman, Law, Belt, Band, & Fisher, 2004). Combined, urban and residential regions are their own ecosystem with production, consumption, decomposition and nutrient flux. This diversity in use and impervious surface makes it difficult to assess the structure as an ecosystem (Groffman et al., 2004). Groffman et al. (2004) stated that, “there is a great need to quantify pollutant delivery better from urban ecosystems to receiving waters and to understand the factors (for example, altered hydraulics, population density, physical setting, and social factors) that influence this delivery.” In this quote, Grove et al. highlight some of the many complexities one encounters when trying to connect diffuse pollution to sources within the urban-residential setting.

Many municipalities throughout the US, especially the West and Southeast, have implemented reclaimed water systems. For reclaimed water, wastewater is treated to a slightly lower water quality standard than would otherwise be required for traditional discharge and can then be piped back out to the public and other customers via a non-potable pipe network for use in lawn irrigation. This reclaimed water is valuable because it also contains varying levels of nutrients. Use of reclaimed water for irrigation is now a well-established practice, particularly in arid regions. However, in this review, no studies were identified that addressed the long-term implication of potential nutrient pollution caused by reclaimed water irrigation; this could be of particular concern to areas with high water tables, including Florida.

The authors explained that phosphorus deposition should also be a concern in Florida, as approximately 70% of Florida's lakes are seepage lakes, which do not have inlets and outlets (Badruzzaman et al., 2012). Flux of atmospheric phosphorus deposition in Florida has been measured to range from 6 to 16 mg m^{-2} yr^{-1}. Using the Florida total water area estimate of 3.05×10^{10} m^2, total P deposition to Florida water bodies was estimated to range from 1.8×10^8 to 4.8×10^8 g-P yr^{-1} (Badruzzaman et al., 2012).

In 2009, reclaim water production in Florida was estimated at 2.1×10^{11} L yr^{-1}. This reclaimed water is being used to irrigate home lawns, golf courses, parks and schools (Badruzzaman et al., 2012). A study conducted by the Southwest Florida Water Management District (SWFWMD) showed that a single family residence with metered reclaim water will use 2,020 L day^{-1}, but an unmetered household will use 3,710 L day^{-1} (Badruzzaman et al., 2012). Reclaimed water is desirable for irrigation because it provides some level of nutrient contribution to a lawn, offsetting a portion of fertilizer needs. However, nutrients in reclaimed water fluctuate and it is too cost and technologically prohibitive to find out the nutrient content of reclaimed water each time you wish to irrigate a lawn. Therefore, there is a continued risk of users over-fertilizing beyond the dose that the lawn requires.

The wide variation among homeowners' lawn management techniques provides further difficulties in modeling and pollution assessment. If fertilizer is applied in excess or before a significant precipitation event, nutrient export can occur from managed lawns. Fertilizer restrictions are intended to aid in reducing nutrient export from residential areas and therefore improve local water quality. However, understanding how fertilizer restriction impacts nutrient loadings may not be readily transferable across varied geographic regions. This is because the rate of application, type of fertilizer (i.e. regular or slow release), timing of fertilization, type of vegetation fertilized and soil properties may all impact uptake and potential nutrient exportation (Carey et al., 2013).

Another important issue impacting the amount of nutrients that may runoff from a residential lawn is the fact that vegetative nutrient uptake is strongly influenced by the current growth rate of the plant in question. Recent agronomy research has focused on the nuances of vegetative utilization and demand of nutrients. Kussow et al. (2011) listed the following characteristics of nutrient demand that drive plant growth: (1) Nutrient uptake and plant tissue content are more closely related to plant growth rates than external nutrient supply. (2) Nutrient uptake at a given level of external nutrient supply varies substantially in response to variable nutrient demand. (3) Plant tissue nutrient content tends to remain constant once external nutrient supplies allow plants to satisfy their demand. Based on this information, it can be noted that adding additional nutrients to the system does not necessarily lead to more or healthier vegetative growth. It is also extremely important to apply highly mobile nutrient sources (such as nitrate) at the time the plant is able to absorb the nutrient to meet its need. Mulching, laying down fibrous material (i.e. straw, wood fiber, bark fabric) before vegetation develops, has been suggested as a method for erosion control and pollutant reduction; however, the research reviewed in this thesis did not evaluate mulching in terms of nutrient pollution runoff (Novotny, 2003).

In addition, leaving grass clippings and leaf litter on lawns functions as a natural fertilizer (through the natural decay of organic matter), but also has the potential to facilitate nutrients in runoff, similar to the application of regular fertilizer. Some homeowners bag and throw away lawn clippings rather than composting or reapplying it to their lawn. Thus during summer months, up to 20% of residential waste may be composed of yard waste that contains a large proportion of grass clippings. Legislation has passed in some areas of the US to eliminate lawn clippings from being disposed of with residential solid waste; the successfulness and extent of restriction enforcement was not addressed in the research reviewed for this thesis. Removing clippings and leaf detritus may, therefore, waste a product that could be natural fertilizer for lawns (Guillard & Kopp, 2004).

2.1.4 Diffuse Nutrients from Residential and Urban Catchments

This section contains three subsections. The first subsection reviews research on turfgrass and the lawn as an ecosystem. This section highlights the complexity of lawn systems and reports on the significance of nutrient loss from such systems. The second subsection reviews studies that elucidate various social and psychological impetuses for lawn management practices, such as fertilization, irrigation or cultivation of particular vegetative species. Lastly, the third subsection summarizes multiple studies that have attempted to quantity nutrient pollution exiting residential lawns, turfgrass plots or residential watersheds.

2.1.4.1 Lawns and Turfgrass

Turf generally refers to a small number of vegetative species commonly used as lawn cover by homeowners and at golf courses. The turfgrass research reviewed in this study tended to focus on either leaching or runoff, rather than both simultaneously. Leaching refers to the loss of dissolved nutrients as water moves through the soil profile beyond the vegetative root layer; it is important to note in the context of a nutrient balance, as it can be a very important avenue for export or loss from a residential lawn system. Runoff refers to overland flow generated after precipitation saturates the ground, which is typically conveyed to streets or other stormwater system pathways in residential areas. The amount of nutrients found in fertilizer that can leach from a turfgrass system is influenced by irrigation regime, precipitation patterns, fertilizer practices, the growth phase the grass is in at the time of evaluation and soil chemistry such as organic carbon content. The establishment period of turfgrass may be the most problematic time for nutrient loss. A low amount of ground cover coupled with frequent fertilization and heavy irrigation in an attempt to foster a quicker establishment of the grass creates a situation prone for water quality degradation via nutrient contamination (Easton & Petrovic, 2004).

Nutrient cycles within the residential lawn are subject to disturbance from a variety of influences including: soil organic carbon content, precipitation frequency and intensity, fertilizer frequency and loading, irrigation frequency and intensity, pH and temperature. For example, soil carbon content influences nitrogen mineralization (decomposition of organic matter into plant available substances), thereby impacting vegetative accessibility to nutrient uptake (Barton & Colmer, 2006). In addition, sandy soils have been shown to readily leach phosphorus (Easton & Petrovic, 2004). Though specific values are not reported in this manuscript, the authors stated that prolonged rainy periods following fertilizer application can induce significant nutrient loss, even on established turf (Easton & Petrovic, 2004). Barton and Colmer (2006) stated that landscape management practices, such as removing grass clippings, that increase carbon sequestration could have the potential to increase nitrogen storage in soil, thus potentially reducing nitrogen leaching.

Compared to other nutrients, nitrogen is applied in the largest quantity, but it is also generally the most mobile nutrient applied (Easton & Petrovic, 2004). Nitrogen losses can be as low as 5% per year from established turfgrass if it is neither over-irrigated or over-fertilized; however, current research suggests that up to 30% of applied nitrogen fertilizer is lost to leaching to subsurface (Barton & Colmer, 2006). An effective nitrogen management strategy must take into account the needs of the specific vegetation, and the biological, chemical and physical attributes of the soil. Consider that a plant's ability to take up nutrients will, in part, be influenced by the rate at which the nutrient penetrates the soil. Application of fertilizer at the time of active plant growth will thus minimize loss (Barton & Colmer, 2006).

Petrovic (1990) conducted a review of turf and fertilization research completed in the 1980's; these studies evaluated both residential lawns and putting greens. He found that fertilizer nitrogen taken up by turf is highly variable, between 5 to 74%. In addition, losses can occur by volatilization and denitrification and these losses varied anywhere from 0 to 93% of total amount applied, with the atmospheric gaseous loss (volatilization of NH_4^+ and denitrification) portion comprising 0 to 36%. This work also showed that denitrification was most significant (93%) on a particular soil type: fine textured, saturated, warm soils. Tracking nitrogen from fertilizer to determine where it ends up (i.e. as soil organic matter, as turfgrass biomass, volatilized, leached, etc.) is difficult and requires use of a tracer. ^{15}N is an isotope label that can be used for such purposes (Petrovic, 1990). The work reviewed by Petrovic employing the isotope labeling method found that 15 to 26% of N applied would become part of the soil organic content. Petrovic also noted a highly specific type of research in this field that does not receive widespread attention: measuring of the ability to recover nutrients from clippings of different species under different management scenarios.

It stands to reason that highly soluble nitrate dissolved in irrigation water has a potential to leach below the root system if over-irrigation is occurring. Several such studies examined this issue. Researchers conducted sampling on five controlled turf plots. The 6×6 m^2 experimental sections were located in a field and divided by 1.5 m wide buffer (Exner, Burbach, Watts, Shearman, & Spalding, 1991). They applied various pre-determined fertilizers to each plot, with one control receiving no fertilizer. After 34 days of each receiving the same irrigation regime (1, 1.5, 2 or 2.4 kg N 100 m^{-2}, respectively), the researchers collected 6-meter deep continuous core samples for each plot and analyzed them for nitrate, which should indicate leaching patterns. They found that as much as 95% of the applied nitrogen in the fertilizer could leach below the turfgrass root system, compared to 5 to 74% reported by Petrovic (1990). This means it was possible in this sandy loam under these particular fertilizer and irrigation regimes, the majority of applied fertilizer could pass beyond the reach of the turf's root system to utilize. No matter the rate of fertilization used in the study, for each plot that received fertilization, a portion of nitrate leached below the turf root system. In this particular study, the authors also noted an inherent presence of nitrate in the control plot, meaning that nitrate in irrigation water could be the culprit for a portion of deep nitrate movement (Exner et al., 1991).

Schueler (2000) reviewed five studies on nitrate leaching from turfgrass. This review conveyed that, like other reports have concluded, crop plots export more nitrate than lawn turfgrass. Schueler (2000) also concluded there was a strong seasonal variation in nitrate export associated with the growing cycle of turfgrass itself; essentially exports are lowest at the onset of growing season and increase as the season progresses, peaking at the non-growth season. The best time to fertilize thus depends on the type of grass. Warm season grasses should be fertilized at the onset of the warm season and cool season grasses are best fertilized in early spring or fall. The growing and dormancy periods of grasses are dependent on the particular species and local climate where the species has been cultivated; that is to say that cool and warm season refer to the regional locations/temperature where the species thrives, rather than the time of year (Sod Solutions, 2013). Cool and warm season turfgrass characteristics for several species are summarized in Table 2.

Table 2 Turfgrass Characteristics and Common Species (Sod Solutions, 2013)

Characteristic	**Warm Season Turf Grass**	**Cool Season Turf Grass**
Ideal temperature range	80-95° F	65-75° F
Best region for growth	South, Southwest	Midwest, Pacific Northwest
Active growing season	Spring & Summer	Spring & Fall
Common Varieties	Zoysia St. Augustine Bahiagrass Centipedegrass Bermudagrass (arid)	Bluegrass Tall fescue Fine fescue Rye grass
Additional characteristics	Goes dormant (turns brown) below approximately 65° F	Does not have dormant period (except below freezing)

Easton and Petrovic (2004) conducted a mass balance of study of plots near Ithaca, NY, that were fertilized in different ways. They attempted to measure both nutrient leaching and runoff exports. Experimental plots were selected in an area with sandy loam soil. The researchers stripped the sod and seeded the area with 80% Kentucky blue grass and 20% perennial rye grass. Treatment consisting of five different fertilizer types at two different loadings was applied in triplicate with additional plots left untreated as controls, for a total of 33 plots. The two application rates were a low treatment amount at 50 kg ha^{-1} for each application and the other test plots received 100 kg ha^{-1}. Plots also received different fertilizers: natural (swine compost, dairy compost, municipal biosolid) or synthetic (readily available NPK and controlled release NPK) nutrient sources. Rainfall depth and runoff were measured for the selected storm events; the first event (with the least established turf) produced the highest non-snowmelt runoff depth, the highest runoff as percentage of precipitation and some of the highest nutrient concentrations.

Overall, Easton and Petrovic (2004) found nitrate losses to be 2 to 5 times higher during the non-establishment period compared to post turf establishment, creating a direct correlation between nutrient loss and turfgrass density. The unfertilized plot had, at times, higher runoff and higher pollution concentrations (specifically NO_3^--N and NH_4^+-N) in the runoff compared to the fertilized plots, due in part to its low infiltration rates. The authors also observed that as turfgrass became more established, NH_4^+-N concentrations decreased in runoff. Table 3 shows mass losses of phosphate and nitrate from all plots during the development stage (year one) and established stage (year two). They further pointed out that the root turnover and organic matter reduced the bulk density of the soil. This means that the soil porosity increased, allowing for faster stormwater infiltration and increased water storage.

Table 3 Mass Loss of Phosphate and Nitrate from Fertilized Plots Over Two Years (Easton & Petrovic, 2004)

Fertilizer source	**Fertilizer Rate (kg-N ha^{-1})**	**Year**	**PO_4^{3-}-P Loss (kg ha^{-1})**	**NO_3^--N Loss**
Swine compost	50	1	0.8	8.2
Swine compost	50	2	1	2.9
Swine compost	100	1	1.2	6
Swine compost	100	2	1.2	3
Dairy compost	50	1	0.4	2.6
Dairy compost	50	2	0.7	2.9
Dairy compost	100	1	0.4	4.1
Dairy compost	100	2	0.7	2.5
Biosolid	50	1	0.4	8.7
Biosolid	50	2	1	4.4
Biosolid	100	1	0.2	8.5
Biosolid	100	2	0.6	2.5
Readily available	50	1	0.2	11.2
Readily available	50	2	0.6	3.1
Readily available	100	1	0.3	15.9
Readily available	100	2	0.6	4.1
Controlled-release	50	1	0.5	7.6
Controlled-release	50	2	0.6	4.3
Controlled-release	100	1	0.6	10.5
Controlled-release	100	2	0.7	2.8
Control	0	1	0.2	5.6
Control	0	2	0.3	3.8

Urea application at the highest rate (100 kg ha^{-1}) to one plot was the only plot that yielded higher amounts of nitrate in runoff than the unfertilized control. The results of this experiment showed that nitrogen loss tended to follow solubility trends, meaning that synthetic fertilizers with more soluble N also produced higher N losses. In addition, experimental plots receiving swine waste produced the highest concentrations of P in runoff. Among all systems, P was most likely to be lost in the form of clippings while N was most likely to be lost via leaching. The authors reported mass balance losses for phosphorus and nitrogen as percentage of total amount applied (see Figure 6). Phosphorus leached the most from plots that received swine and dairy fertilizer treatment. Leaching was found to be a function of fertilizer source, timing, infiltration rate, shoot density and antecedent soil moisture. Despite reductions in nitrogen loss over time as turf plots became more established, the concentrations found in the experiment were high enough to be problematic for aquatic organisms.

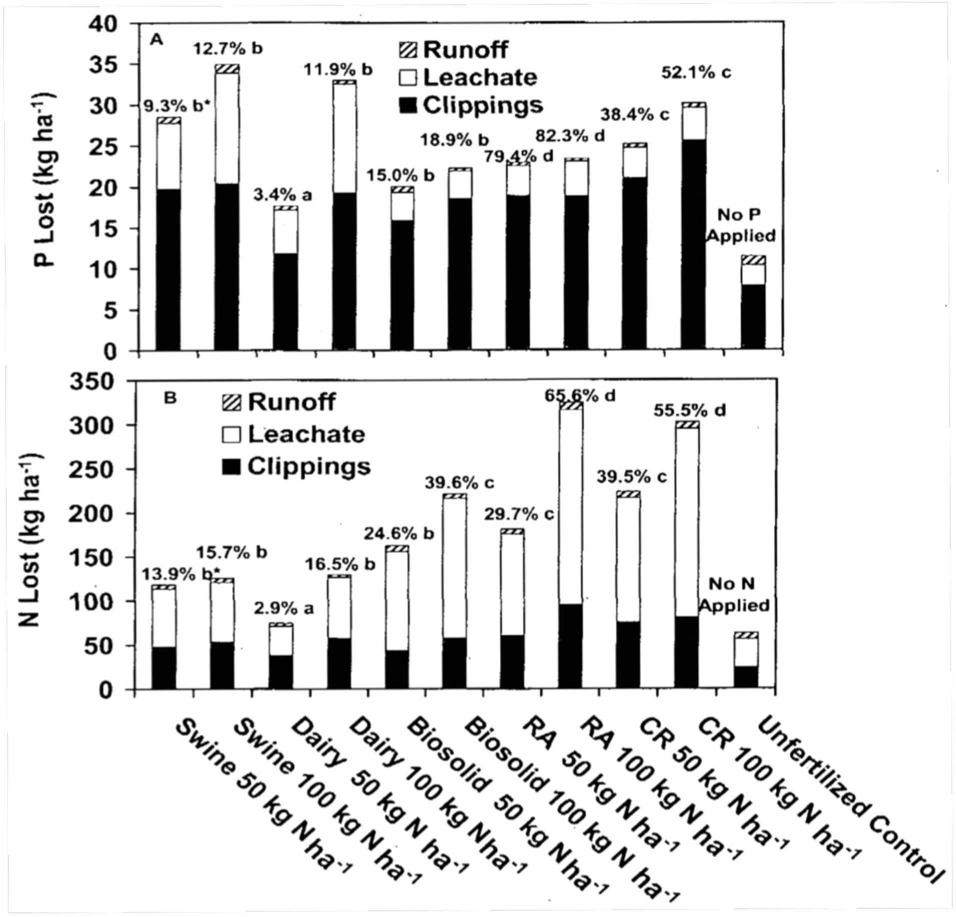

Figure 6 Mass Balance for (a) Phosphorus and (b) Nitrogen. Percent shown above each bar represents nutrient recovered rate in runoff, leachate and clippings as percent of applied after correcting for looses from the unfertilized control. (from Easton & Petrovic, 2004)

Another group of researchers conducted similar studies on phosphorus runoff from turfgrass as impacted by fertilization (Bierman, Horgan, Rosen, Hollman, & Pagliari, 2010). They carried out phosphorus runoff sampling on a series of 24 controlled plots in St. Paul, MN, of which the prior land use was pasture. They tested different application levels of fertilizer with different nutrient ratios: none, fertilizer with N and K only, and then two different levels of P with N and K. Their results showed that when soil was frozen, a higher percentage of precipitation was lost as runoff: 1% precipitation on non-frozen soil converted to runoff while 5 to 27% of precipitation lost as runoff on frozen soil. Runoff depths and P loss in runoff for all years were impacted by fertilizer application and season. A summary of total P and reactive P runoff for the test plots is shown in Table 4.

The authors reported that for all years, plots receiving no fertilizer had lower quality turf, based on a visual rating scale. The fertilized plots, regardless of amount received, essentially all produced the same quality of grass. Clipping application improved turfgrass quality two years and had no effect the third year; clipping removal or application in whole did not produce consistent P runoff effects. All three years of the study showed significant linear increases of flow-weighted P concentrations. Phosphorus losses in runoff from turfgrass were most affected by fertilizer application, frozen versus non-frozen soil conditions, runoff depth, and turf quality/growth. The authors reported an overall correlation of increased P when fertilizer applications were high and precipitation (leading to higher runoff) was high (Bierman et al., 2010). Bierman et al. (2010) found that in climates that have harsher winters, runoff during seasons when the soil is frozen can produce significant amounts of volumetric runoff along with P loading.

Table 4 Effects of Fertilizer Application, Clipping Management on Mean Annual Flow-Weighted P Concentrations in Runoff for 2005 to 2007 (from Bierman et al., 2010)

Fertilizer application	**Annual fertilizer rate of P**	**Year**	**Annual runoff depth total (mm)**	**TP annual runoff total (kg ha^{-1})**	**Reactive P annual runoff total (kg ha^{-1})**
No fertilizer	0	2005	32.6	0.49	0.33
No fertilizer	0	2006	18.9	0.22	0.17
No fertilizer	0	2007	10.4	0.11	0.9
0×P, N+K	0	2005	36.9	0.51	0.31
0×P, N+K	0	2006	9.4	0.1	0.06
0×P, N+K	0	2007	7.3	0.6	0.5
1×P, N+K	21.3 kg ha^{-1}	2005	31.6	0.68	0.49
1×P, N+K	21.3 kg ha^{-1}	2006	11.5	0.16	0.1
1×P, N+K	21.3 kg ha^{-1}	2007	8.3	0.10	0.9
3×P, N+K	63.9 kg ha^{-1}	2005	33.4	1.47	1.15
3×P, N+K	63.9 kg ha^{-1}	2006	8.1	0.15	0.11
3×P, N+K	63.9 kg ha^{-1}	2007	6.5	0.16	0.10
Clipping management					
Removed	-	2005	33.9	0.77	0.56
Removed	-	2006	14.4	0.19	0.13
Removed	-	2007	8.0	0.10	0.8
Returned	-	2005	33.4	0.81	0.58
Returned	-	2006	9.5	0.12	0.08
Returned	-	2007	8.2	0.13	0.9

King et al. (2012) conducted an eight-year experiment to analyze phosphorus export from golf turfs at a country club in Duluth (Minnesota). During the first testing period (2003-2006), the turfs received traditional, commercially available synthetic fertilizer. During the second period (2007-2010), the turf plots received a reduced rate of an organic fertilizer formulation. The researchers concluded that switching to an organic P fertilizer and reducing application amounts resulted in a reduction of flow-weighted export of phosphorus compared to the period 1 regimen. The authors reported that 21% of the dissolved reactive phosphorus (DRP) samples and

37% total phosphorus (TP) exceeded the 0.05 mg L^{-1} EPA threshold recommendation during the first study period compared to 4% and 20%, respectively, in period 2 (see Table 5).

Table 5 Summary of Annual Application of Phosphorus and Annual Loading of Dissolved Reactive Phosphorus and Total Phosphorus at Northland Country Club (King et al., 2012)

	Year	**Total aerial weighted P applied (kg ha^{-1})**	**Percent of total P applied in organic form**	**Annual loading DRP (kg ha^{-1})**	**Annual loading TP (kg ha^{-1})***
Period 1	2003	8.8	1.0	0.11	NA
	2004	6.5	2.0	0.17	0.29
	2005	6.9	0.8	0.25	0.36
	2006	4.4	2.9	0.07	0.09
Period 2	2007	3.1	6.9	0.11	0.18
	2008	0.006	83.4	0.13	0.33
	2009	0.09	99.3	0.02	0.08
	2010	0.84	100.0	0.09	0.2

**From country club site only*

2.1.4.2 Socio-Demographic Implications on Lawn Vegetation and Management Practices

Giner et al. (2006) described the importance of understanding influences for lawn care because urban and suburban areas in the US are projected to increase from 5% to 10% of the US land area by 2025. The ability to predict how these changes to land vegetation and hydrology affect water quality management is thus critical (Grove, Cadenasso, et al., 2006). A prominent managed lawn feature associated with recent residential growth in the US was described as “weed-free, mono-species, lush-green lawn” (Giner, Polsky, Pontius, & Runfola, 2013). From a sociological perspective, lawns represent social status, property ownership, good citizenship and/or a pride in one’s possessions (Giner et al., 2013). For all these reasons combined, it is critical to have a comprehensive understanding of vegetation and fertilizer management in residential lawns to come closer to better predicting transport and fate of nutrient pollution from a particular residential area.

Researchers are only just beginning to tap into high-resolution GIS capabilities in attempt to analyze what socio-demographic factors are attributable to lawn management practices such as specific vegetative cultivation patterns and fertilizer use. GIS allows users to overlay spatial datasets and develop meaningful correlations between them. For example, some of the research reviewed here employed GIS to draw correlations between vegetative and socio-demographic factors, such as average income level and ethnicity (Grove, Troy, et al., 2006). As resolution of aerial images becomes finer, so to will the statistical analyses that employs it.

The lawn monoculture generally necessitates augmented fertilizer and irrigation, which can contribute to polluted runoff or nutrient leaching through the soil layers. One question researchers should ask is: how can we enhance the important aspects of lawns - carbon sequestration, water infiltration, and heat island mitigation - while lessening the negative impacts (stormwater pollution, burdens on domestic/potable water supply, release of nitrous oxide, acidification of soil, etc.)?

Osmond and Platt (2000) conducted household surveys regarding fertilizer and irrigation practices in Cary (North Carolina), an area primarily established with tall fescue turf (*Festuca arundinacea*). This household survey asked about fertilizer application frequency, but did not collect information about amount of fertilizer applied or type of fertilizer applied (i.e. synthetic vs. organic or N-P-K ratio). At the time of survey, approximately 50% of homeowners in Cary employed lawn management services, which is close to the national average (EPA, 2012c; Osmond & Platt, 2000). As anticipated, homes with higher tax valuation were more likely to be sustained by private lawn management.

Osmond and Hardy (2004) expanded on the Osmond and Platt work (2000). They conducted door-to-door surveys of 300 households regarding fertilizer and irrigation practices in five North Carolina communities in the Neuse River basin (Cary, Goldsboro, Kinston, New Bern and Greenville). Approximately double the percent homeowners in Cary employed lawn management services compared to the other areas in this study; this was expected due to Cary's relatively higher median income level (Osmond & Hardy, 2004). The authors reported that in all five basins combined, approximately half of residents fertilize; of those who fertilize, only about 20% based their fertilizer management on soil test results. Approximately half of residents leave lawn clippings on site versus bagging them. Osmond and Hardy (2004) reported that the recommended fertilization rates for tall fescue and centipedegrass are 122 kg N ha^{-1} and 24 kg N ha^{-1}, respectively. In the community of Cary, it was reported that lawn care services applied approximate 50 kg N ha^{-1} more than recommended for the grass species there. A summary of their findings is presented in Table 6.

Table 6 Geographic Characteristics and Lawn Management of Five Communities in the Neuse River Basin, North Carolina (Osmond & Hardy, 2004)

	Cary	**Goldsboro**	**Kinston**	**New Bern**	**Greenville**
Population	86,613	47,814	24,974	22,048	56,853
Sample size	300	86	130	66	130
Median Income Per annum	$67,250	$43,200	$36,200	$30,410	$25,527
Mean lawn size (m^2)	445	1899	810	1168	873
Primary grass type	Tall fescue	-	centipedegrass *(or mix)*	centipedegrass *(or mix)*	centipedegrass *(or mix)*
Fertilizing	83%	66%	54%	72%	73%
Use lawn care service	43%	16%	16%	18%	26%
Average fertilizer application by homeowner	151 kg N ha^{-1}	-	29 kg N ha^{-1}	24 kg N ha^{-1}	73 kg N ha^{-1}
Soil testing	23%	20%	16%	35%	18%
Bag grass clippings	-	50%	43%	40%	57%

As part of the Baltimore Ecosystem Study, a group of researchers conducted an analysis of nitrogen-based fertilization in Baltimore County (Maryland) to find social and geographic correlations with fertilizer application and rates (Law, Band, & Grove, 2004). They found a wide range of application rates; the median application rate was 97.6 kg N ha^{-1} yr^{-1} with a standard deviation of 88.3 N ha^{-1} yr^{-1}. They conducted door-to-door surveys regarding lawn management practices and, if homeowner permission was given, also collected soil samples for bulk density and soil chemistry analysis. In addition, follow-up surveys were conducted with lawn maintenance companies to document management practice details. Homeowners doing their own lawn work typically fertilized one or two times a year; lawn maintenance companies fertilized up to six times per year. However, increased frequency was not necessarily an indicator of higher overall annual application.

Table 7 Geographic and Lawn Management Characteristics of Two Watersheds in Maryland (Law et al., 2004)

	Glyndon Watershed	**Baisman Run Watershed**
Received survey, Response rate	60, 68%	40, 80%
Watershed area (km^2)	0.8	3.7
Residential area	27%	34%
Forest & open space area	20%	66%
Commercial area	32%	0%
Lawn Area	15%	25.5%
Population Density (pers. ha^{-1})	9.4	1
Housing density (house ha^{-1})	3.9	0.3
Apply fertilizers to their lawns	68%	56%
Average application rate of fertilizer*	12.5 kg N ha^{-1} yr^{-1}	9.5 kg N ha^{-1} yr^{-1}
Self Apply / Professionals Apply	71% / 29%	44% / 56%

*Based on the most frequently used (56% of households) fertilizer 29N-3P-4K and percentage of homeowners who use a lawn care service or fertilize their own lawn was used to provide a weighted average application rate.

A summary of this study's findings are shown in Table 7. Law et al. (2004) wrote that high application rates were associated with newer, single-family home developments and townhouse developments. Based on the correlation with younger homes, Law et al. (2004) suggested two possibilities for which application rate could be a function of: (1) higher socio-economic class related to newer homes having higher taxable value or (2) attempt to establish quality lawn because the development is new and recently under construction.

Nielson and Smith (2005) undertook an evaluation of a watershed the Tualatin watershed (Oregon), which was the first in the state to implement Total Maximum Daily Load (TMDL) provisions. This watershed is in the vicinity of the Portland metropolitan area (Oregon). They surveyed three different neighborhoods with distinctly different average home value ranges ($100,000 to $149,999, $150,000 to $199,999 and $200,000 to $299,999). The Tualatin area was already known by local officials to be a relatively high contributor of nutrient pollution to waterways compared to other local watersheds. Local farmers who were asked to alter their practices pointed to the residential lawn care problems as culprits for blame. In attempt to understand factors influencing residents' lawn care, lawns were observed, surveys were conducted of homeowners and a subset of these homeowners were interviewed (Nielson & Smith, 2005).

Direct observation of yard maintenance practices in this watershed suggested that residents' habits were potentially harmful to water quality. Mail surveys contained questions on lawn management practices, water quality knowledge, factors influencing lawn management, environmental values and demographics. Follow up interviews of a small sample group (22) focused on lawn care priorities, factors influencing maintenance and yard management knowledge sources. Fifty-six percent (98 of 176) of the surveys mailed were returned; demographics such as age, education level, career type, and household income were collected. There was a slightly higher response rate from those with college degrees, compared to the region's overall percentage of college graduates, and a slightly higher response from those with incomes higher than the percentage of persons with this income level in the region. Nielson and Smith (2005) noted that in general, homeowners tend to have higher levels of education and income compared to renters. Whether because of personal preference, societal pressure, or perceived neighbor peer pressure, residential homeowners with the resources to access and purchase lawn care products, were found to over-fertilize and overwater in attempt to obtain the year-round monoculture green lawn. Table 8 shows a summary of Nielson et al.'s (2005) findings.

Nielson et al. (2005) did not survey the amount of fertilizers or the type of fertilizer (i.e. synthetic or organic, N-P-K ratios, etc.) being applied. The survey results revealed citizen knowledge gaps, which could hinder optimal decision-making with respect to water quality. For example, despite Oregon's education initiative to cultivate understanding that "fish live downstream", only fifteen percent of the survey respondents correctly identified that stormwater goes directly into the nearest stream (Nielson & Smith, 2005). Eighty-two percent of respondents applied fertilizer to their lawn at least one time per year, compared to 68% and 56% in the two watersheds in Baltimore or an average of 70% in North Carolina (Law et al., 2004; Osmond & Hardy, 2004). Sixty-six percent of respondents who fertilized answered that they used weed and feed products; the remaining 44% used time-release fertilizer. Furthermore, most respondents (60%) claimed to conduct their own lawn maintenance, versus hiring a service (Nielson & Smith, 2005). Partially based on the fact that the majority of respondents misunderstood or were ignorant about the fate of stormwater and/or did not understand best management practices (such as flushing pet waste), the authors concluded that there were persistent practices that could decrease water quality and retard conservation efforts. Also based on their findings, Nielson and

Smith (2005) concluded that this was in large part due to lack of concern about environmental impacts individual lawn practice and higher priority placed on what neighbors might think of them. Thus, the authors opined that TMDL targets could be quite challenging to meet.

Table 8 Geographic, Social and Fertilizer Management Characteristics of a Watershed in Oregon (Nielson & Smith, 2005)

	Tualatin River Watershed
Area (km^2)	1,844
Urban / Farm / Forest	15% / 35% / 50%
Households	169,000
Surveys sent / Surveys completed	176 / 98 (56%)
Respondents' ages	80% between 35-75
Respondents w/college education County residents w/college education	59% 42%
Median household income of respondents	72% between $25,000-$150,000
Fertilizer application % of Respondents / times per year	26% / 3 38% / 2 18% / 1 17% / 0
Responses to question: What happens to water when it goes down a storm drain?	57% I don't know 19% goes to a treatment plant 6% goes to nearby filtration system 3% goes to groundwater table 15% goes to nearest stream (*correct*)

This study also identified an association between fertilizing and watering practices with green monoculture lawns; however, demographics such as age, income, education, occupation, length of residence and house/land values were found to not correlate well with lawn management (Nielson & Smith, 2005). Statistical analysis showed that motivation for yard maintenance practices were heavily influenced by the personal importance priority of neighborhood appearance, while economics, environmental values, and demographics were not correlated to homeowner practices (see Table 10 for comparison with other studies). The strong concern for perceived neighbor approval could thus lead to overwatering and over fertilization (Nielson & Smith, 2005). Based on this study, the majority of the citizenry in the study area are either unaware or unconcerned with the environmental impacts of their individual lawn management decisions.

Researchers of the Baltimore Ecosystem Study executed a geo-spatial study of vegetative land cover in Maryland. Their goals included finding possible correlations between vegetative land cover with population, lifestyle behavior or social stratification. Social characteristics such as age, household size, household income, race, ethnicity, etc. facilitate a wide range of audiences for which managers must communicate to (Grove, Troy, et al., 2006). Grove, Troy et al. (2006) examined distribution of grass and tree cover in residential areas; they further distinguished residential land areas by riparian, private land or public right of way. Typically, population increase has been thought to have an almost linear relationship to decreasing vegetation as displacement by impervious surfaces, buildings and houses occurs (Grove, Troy, et al., 2006). Social scientists recognize that specifically selected vegetation, such as grass, shrub and tree type, are also avenues for expressing social status (Giner et al., 2013; Grove, Troy, et al., 2006).

The area in Maryland studied contained various types of residential homes including single-family detached housing, multi-family units, and townhomes. Urban sprawl in this region has caused one of the highest rates of deforestation in the US Census block data, Claritas Inc.’s potential rating index for zip code markets (PRIZM) and GIS data were aggregated to evaluate the potential influences of vegetative cover. PRIZM is a set of demographic information developed by Claritas Inc. (New York City, NY) and was originally developed as a marketing tool to aid in discerning consumer preferences (Troy, Grove, O’Neil-Dunne, Pickett, &

Cadenasso, 2007). Two important designations in PRIZM are termed social stratification and lifestyle behavior. Social stratification refers to characteristics used to define social class such as income and education. Lifestyle behavior is described as consumption or expenditures motivated by group identity.

Using logistical regression, lifestyle behavior and housing age were shown to best explain grass cover in public right of ways, private land tree cover and private land grass (Grove, Troy, et al., 2006). Homeowner lifestyle choices were the best predictor for vegetation cover on private property. Housing age can serve as a predictor only up to a certain age, approximately 40 to 50 years, after which the correlation declines with age (Grove, Troy, et al., 2006). Social stratification, or social class indicators such as income and education level, was not the best indicator of vegetation in these areas. The authors found lifestyle behavior was a better predictor for these. Population density was not correlate-able to vegetation cover in riparian areas, suggesting alternative theories and research are needed. The results of this study are included in Table 10 compared with other studies at the end of this section.

Troy et al. (2007), also part of the Baltimore Ecosystem Study, built on the previous Baltimore work by Grove, Troy, et al. (2006) and published another study using the PRIZM tool to attempt to correlate socio-demographic characteristics with realized stewardship (kept lawn) and possible stewardship (pervious area that could become realized stewardship) (Troy et al., 2007). This is important because authors of another study reviewed in this thesis concluded that unkempt, bare land contributes more pollution via runoff than pervious area with maintained vegetation (Spence, Osmond, Childres, Heitman, & Robarge, 2012). They found that realized stewardship positively correlated with average household size, percent married, percent single-family detached housing units, median home value, education and population decrease per unit area. Realized stewardship was negatively correlated with population density and housing vacancy. Troy et al. (2007) found no correlation between lawn properties and median income or crime rate.

Based on a national survey (a phone survey of 594 households across the US) Robbins and Sharp (2009) concluded that homeowners who learned about lawn management from a family member were more likely to use fertilizer at regular intervals compared to individuals who learned lawn management from another source (e.g. retail salespeople, books/magazines, packaging materials instructions included with product); long-term implications of this are unclear (Robbins & Sharp, 2009). Ironically, consumers who were most likely to report strong willingness to pay a higher cost for clean water were also the most likely to be applying the higher amounts of lawn chemicals. It is also unclear precisely why this disparity between knowledge and behavior existed for the citizenry polled. Robbins and Sharp (2009) also reported that, "our investigation yields a clearer understanding of the continual and increased use of lawn chemicals by affluent Americans despite widespread knowledge of their possible negative environmental impacts." It is unclear exactly what the authors mean by widespread knowledge; this seems to contradict the findings of Nielson and Smith (2005), which showed that only 15% of survey respondents could correctly identify that storm pipes terminated at nearby streams.

In Boston, Massachusetts, an in depth spatial analysis was conducted of a small area of the city to assess how and what social drivers might impact vegetation cover (Giner et al., 2013). Giner et al. (2013) focused strictly on land vegetation. Parameters evaluated included percent lawn cover and percent lawn realized stewardship (with tree and grass vegetation). These parameters were compared to US census block groups, which are less detailed than previously mentioned PRIZM segments. This work combined mapping and theory with conceptual strengths

– focus on lawns, household observation at parcel level and actual lawn alongside potential lawn. They used spatial regression to analyze how population density, social stratification, and lifestyle behavior may predict lawn cover distribution at a neighborhood scale. Results of the Giner et al. (2013) study showed that income, home value, education, ethnicity and housing age were not significant indicators of landscaping practices for the area studied. Important predictors were population density, percent single family detached home, average household size, and the percent of land in the census block group that is protected. Important implications of Giner et al.'s work are included in Table 10.

The Center for Watershed Protection (1999) reported on two separate surveys. The first survey questioned Chesapeake bay residents from Maryland, Pennsylvania and Virginia about specific nutrient management related behaviors (e.g. lawn care, fertilizer application, septic system maintenance and pet waste disposal) and it was completed by a contracted to a third party provider with expertise in conducting phone surveys. They contacted a representative sample of residents who responded to a five minute long survey on their profile, lawn care practices, septic system maintenance and pet waste habits. The second survey was conducted by Center for Watershed Protection staff who facilitated mail surveys of nutrient management programs across the US (conservation districts, cooperative extensions, municipal stormwater NPDES permittees, Natural Resource Conservation Service offices, watershed organizations). The latter contained program related questions on topics such as annual program budget, staffing capability, outreach techniques and estimation of community engagement. Comparison of the demographics of both surveys is located in Appendix A.

The household surveys were conducted in such as way as to have representation from rural and urban households. Of those surveyed that had a lawn, the majority maintained their own lawn (91%). Of the 7% of respondents who employed a lawn maintenance company, only one selected the company based on eco-friendliness. Respondents with higher education and higher income were more likely to seek and use advice for lawn care management and more likely to use fertilizer. The survey results also showed that older, higher income homeowners were more likely to fertilize more than once per year. In fact, the average fertilization rate for the area was 1.73 times per year. Eighty-four percent of respondents had not conducted soil nutrient testing in the past three years and most respondents elected to consult the fertilizer label to determine how much to apply to their lawn. In addition, although it was reported that fertilization is recommended in the fall, most homeowners preferred to fertilize in the spring (Center for Watershed Protection, 1999). Finally, only 48% of dog owners indicated that while walking their dog, they picked up the pet waste consistently. The Center for Watershed Protection created a compilation of other region's homeowner surveys; this information is recreated in Appendix A.

Table 9 Selected Chesapeake Bay Homeowner Lawn Management Survey Results (Center for Watershed Protection, 1999)

	Resident Survey Results
Completed interviews for households with lawns	652
Fertilize their lawn	50%
Have tested soils for nutrients	16%
Lawn maintained by homeowner Lawn maintained by lawn care company Lawn maintained by other	91% 7% 2%
Selected lawn company based on being contacted by company Selected lawn company based on recommendation Selected lawn company based on reputation for quality lawns Selected lawn company based on cheap rates Selected lawn company based on being eco-friendly	24% 18% 16% 4% 2%
Own a dog Of those who own dog, percent who do not or rarely pick up dog waste (or refused to answer)	41% 34%

The Center for Watershed Protection reported that nutrient education programs across the country are generally underfunded and understaffed. The programs were mostly new, having been developed within the last five years. In addition, many programs were formed to meet the educational requirements of NPDES stormwater permit regulations. Program managers tended to rank workshops as a highly effective method for educating the public; however, they simultaneously noted that these outlets generally gained very poor attendance. A summary of selected survey results regarding lawn management practices in the Chesapeake Bay area are shown in Table 9.

The lawn management practices correlated with various socio-demographic factors from the studies reviewed for this research that conducted statistical analysis are summarized in Table 10. Multiple studies' results for general comparison of law management practices (i.e. percent who fertilize, percent who use a lawn management service, etc.) are summarized in Table 11. Through surveys and interviews, researchers consistently found that citizens were most concerned with the "look" of their yard and were simultaneously influenced by their perceptions that their neighbors would disapprove of a lawn that did not fit the perceived ideal of green monoculture turf. The interview results indicate that yard maintenance and accepted appearance is closely tied to culture and often guided by perceived feelings of neighbors (Nielson & Smith, 2005).

Tables 10 and 11 summarize a wide range of factors analyzed by researchers; a reader can see that some similar criteria in different geographic regions yielded conflicting results. For example Troy et al., (2007) (Baltimore, MD) found that vegetative cover was positively correlated with a decrease in population per unit area; this is the opposite of what Giner et al. (2013) found in Boston, MA. Osmond and Platt (2000) found no correlation in rate of fertilization to the average year of houses constructed in North Carolina, but Law et al. (2004) found that fertilizer rates were positively correlated with newly developed subdivisions in Minnesota. Studies by Nielson et al. (2005), Grove et al. (2006) and Troy et al. (2007) and Giner et al. (2013) corroborated that income did not correlate well with any of the lawn management specifics they analyzed. Different social criteria not explored in these papers could, theoretically, be evaluated for any given geographic region in order to better understand landscaping choices. We are faced, however, with a litany of temporal and topographical variations available for analysis.

2.1.4.3 Nutrients Measurements and Loadings in Stormwater

Multiple approaches have been taken in attempt to evaluate nutrient export from residential areas. One can look at the microscale of an individual lawn or the macroscale of an entire watershed. Each way has its own advantages and disadvantages. If evaluating an individual lawn, researchers must consider it a snapshot, not necessarily representative of the geographic region as a whole or even of the homeowner's closest neighbors. Each individual homeowner has their own regimen that involves nutrient inputs, accumulation and outputs; the individual household's management system can include different frequency and amount of fertilization, different frequency and duration of irrigation, cultivation of different turf or vegetative species, complete outsourcing of lawn maintenance to a third party, or lack of lawn maintenance practices all together.

If approaching research from the macroscale, it is important to assess the watershed's land use as a whole. Entire watersheds are rarely comprised of one singular, specific land use. Urban ecosystems are heterogeneous, containing a variety of land covers and uses such as roads,

Table 10 Summary of Socio-Demographic Research of Nutrient Management of Residential Lawns (multiple sources)

Source Citation	Location	Factor Analyzed	Correlated with	No correlation found
Osmond & Platt, 2000	Cary, NC	Rate of fertilizer application	-	Average tax valuation, average lot size, and average year that the houses were built
		Use of fertilizer	Positive correlation: high home tax valuation	Average lot size, and average year that the houses were built
		Lawn watering	Positively correlated: Summer season (drought time), during turf establishment (usually fall) Installed Lawn Irrigation was positively correlated with higher tax value and more recently constructed properties	-
Law et al., 2004	Baltimore, MD	Fertilization rates	Positively correlated: Recently developed single-family homes, townhouse developments	-
Nielson & Smith, 2005	Tualatin, OR	Green monoculture lawn	Irrigation, fertilization, herbicide application	Age, income, education, occupation, length of residence, and house & land values
Grove et al. 2006	Baltimore, MD	Private-land trees	Positively correlated: Lifestyle behavior#, Median housing age	Household population, Social stratification*
		Private-land grass	Positively correlated: Lifestyle behavior#, quadratically to Median Housing age	Household population, Social stratification*
		Public right of way trees	Positively correlated: Lifestyle behavior#	Household population, Social stratification*, Median housing age
		Public right of way grass	Positively correlated: Lifestyle behavior#, Median Housing age	Household population, Social stratification*
Troy et al. 2007	Baltimore, MD	Realized Stewardship (Vegetative cover)	Positively correlated: Avg. household size, % married, % single-family detached homes, Median home value, % high school graduation rate, Pop. decrease (per unit area) Negatively correlated: Population density, vacancy	Median income, crime
Giner et al. 2013	Boston, MA	Vegetative cover	Positively correlated: Population Increase (per unit area)	Income, Home value, Education level, Ethnicity, Housing age

**Class, including income level*

#Includes Urbanization, Housing, Social Rank, Ethnicity, Household composition, Mobility

Table 11 Summary of Lawn Maintenance Practices from Four US Reports (multiple sources)

Location	Cary, NC	Goldsboro,NC	Kinston, NC	New Bern, NC	Greenville, NC	Glyndon, MD	Baisman Run, MD	Tualatin, OR	Chesapeake Bay
Sample Size	300	86	130	66	130	41	32	98	652
% who fertilize	83%	66%	54%	72%	73%	68%	56%	82%	50%
% employ lawn maintenance service	43%	16%	16%	18%	26%	29%	56%	*40%*	7%
Tested nutrients in soil	23%	20%	16%	35%	18%	NA	NA	NA	16%
Bag grass clippings	NA	50%	43%	40%	57%	NA	NA	NA	NA
Median Annual Income	$67,250	$43,200	$36,200	$30,410	$25,527	NA	NA	NA	NA

Value shown in italics: Text reported that 60% maintained their own lawns; 40% may include households who do not maintain their lawns.

(Center for Watershed Protection, 1999; Law et al., 2004; Nielson & Smith, 2005; Osmond & Hardy, 2004) buildings, lawns, water infrastructure, and possibly agriculture, natural and semi-natural ecosystems. Accordingly, these regions can be difficult to assess in terms of ecosystem function and pollution fluxes. Furthermore, urbanization and expansion of suburbs are not planned according to watershed delineation. Therefore stormwater assessment in a watershed should take into account other potential diffuse nutrient sources present in the watershed. Outside of the establishment of the scale of evaluation, researchers have approached nutrient pollution by testing nutrient concentrations in runoff (mass liquid-volume^{-1}), loading in stormwater runoff (mass time^{-1}), yield from a lawn or catchment (mass time^{-1} area^{-1}), leaching through soil profiles, or by modeling nutrient imports and exports from a predefined system as flux. With the latter approach, modeling, we recognize that inputs which exceed the system's capacity to accumulate in it have the potential to enter the surrounding environment in various forms (Fissore, Hobbie, et al., 2011). For both N and P species, it is important to consider the limitations and strengths of short and long timescale evaluations. For instance, valuation of annual loading has the potential to conceal seasonal variations, which can be significant (Nedwell, Dong, Sage, & Underwood, 2002).

It is recognized that lawns may retain nitrogen, however, this ability diminishes with land development over time and the mechanisms for this in the urban setting are not well understood (Fissore, Hobbie, et al., 2011). Similarly, other components of homeowner decisions on management of pet and yard waste can impact biogeochemical cycles, but to unknown degrees (Fissore, Hobbie, et al., 2011). Household characteristics such as number of trees per household, irrigation practices, leaf/clipping removal and fertilization rates can vary considerably. With current technology, it may be difficult to estimate and model fluctuations of nutrients through these practices to a relatively small degree of error (Fissore, Hobbie, et al., 2011).

2.1.4.3.1 Model Studies

As described in Section 2.1.3.2, modeling nutrient fate from a residential lawn system is a complex feat. Baker et al. (2007) explained that, “the boundary of a household is conceptual rather than strictly physical. The boundary includes the property line in the horizontal plane, the soil to the bottom of the root zone and the atmosphere above the height of the tallest vegetation in the vertical direction.” Capturing everything within to develop a representative model requires many inputs. Arguably, residential watershed scale models will be even more intricate.

Fissore et al. (2011) modeled fluxes of N and P in households of the St. Paul-Minneapolis, (Minnesota) region. The approach employed household surveys regarding lawn management and vegetation measurements with allometric and biogeochemical models to estimate flux and accumulation within single-family household functioning as the system. Survey results were integrated with field measurements, available data and computational tools. Survey questions targeted lawn maintenance practices (results shown in Table 12 and Figure 7), such as fertilizer application and irrigation in addition to household specific situations such as pet ownership. Direct vegetation information was measured on site (number of trees, growth rate, etc.).

Table 12 Survey Results from Randomized Sampling of Owner-Occupied, Single-Family Houses in Minnesota (Fissore, Hobbie, et al., 2011)

	Anoka and Ramsey Counties, Minnesota	
Number Surveyed	360 randomly selected from 1,517 respondents	
Average lawn size	1457 m^2	
Average tree density	205 trees ha^{-1}	
Households who leave lawn clippings	85%	
Households who leave leaves on site	42%	
Remove both clippings & leaves	11%	
Percent of households who fertilize	72%	
	Leave lawn clippings	*29%*
Households with a dog	30%	
	Do not pick up dog waste	*40%**

**(Swann, 1999 as cited by Fissore, Hobbie, et al., 2011)*

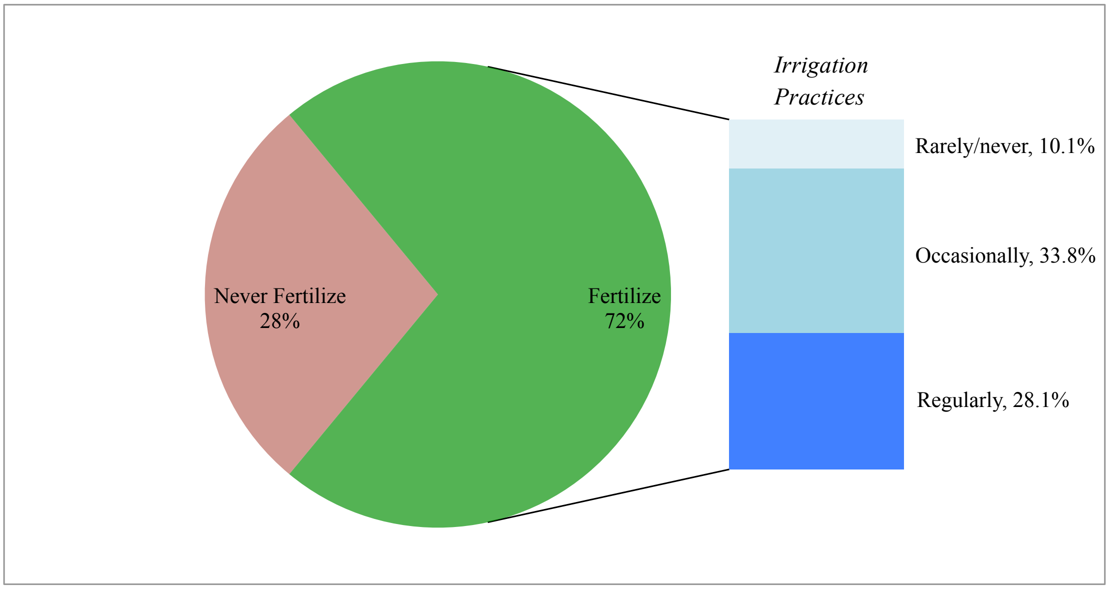

Figure 7 Summary of Fertilization and Irrigation Practices in Minneapolis-St. Paul, MN (Data from Fissore, Hobbie et al., 2011)

Multiple factors were considered for the lawn nutrient cycle in this study. Possible inputs included: net primary production of tree leaves, tree wood, and turfgrass; atmospheric deposition (N and P); fertilizer application (N only, as Minnesota law restricts P fertilizer use on lawns); dog excreta (C, N, and P). Fluxes leaving the household landscape include grass clipping, leaf litter removal (C, N, and P) and dog feces disposal (C, N, and P).

The survey administered in the St.-Paul Minneapolis study included questions regarding fertilizer application, however for modeling purposes, application rate and amounts were assumed to match the recommendation on the bag and to have been evenly distributed across the lawn. Similar assumptions, based on the practices of the most commonly used company, were made for households employing lawn maintenance services. Leaf litterfall was assumed to be in equilibrium with leaf decomposition, unless leaf litter was completely removed from the site.

For Fissore, Hobbie et al.'s (2011) model, nitrogen fertilizer application rates were assumed to be 48.9 kg N ha^{-1} at each application with the number of applications per year based on survey results; 159 kg N ha^{-1} $year^{-1}$ was used for those who employed lawn care services (though a figure was not reported for percentage of households employing lawn care companies). Nitrogen input fluxes for households were estimated to average 14.4 kg N household^{-1} year^{-1}. Figure 8 shows nitrogen inputs were dominated by fertilizer application (approximately 80%) and followed by atmospheric deposition and pet waste. On average, N fertilizer application exceeded exports summed with accumulation in wood and soil, meaning that there was some loss to the surrounding environment. In addition for the households that left both lawn clippings and leaves on site and that also fertilized (29%), all showed N to be in excess of modeled ecosystem's demand. Regardless, solely landscape management practices evaluated alone could not predict where N losses would occur. This was illustrated with the example of households that did not fertilize; even though they did not fertilize, they were shown to have a net excess of N for the lawn system's demand. Almost all households that their model showed to have a net excess of nitrogen left clippings on site.

Low retention of soil N has been linked to excessive landscape irrigation. In this model, nitrogen losses due to extreme irrigation or storm events were not accounted for. Biological N fixation was also not accounted for. Because of the phosphorus fertilizer restriction in Minnesota, Fissore, Hobbie et al. (2011) assumed homeowners fertilized with phosphorus-free fertilizers. As a result, P inputs were dominated by pet waste. Approximately 30% of the households evaluated owned at least one dog. For this region, dog excreta represented 93% of total household P input fluxes, illustrated in Figure 9.

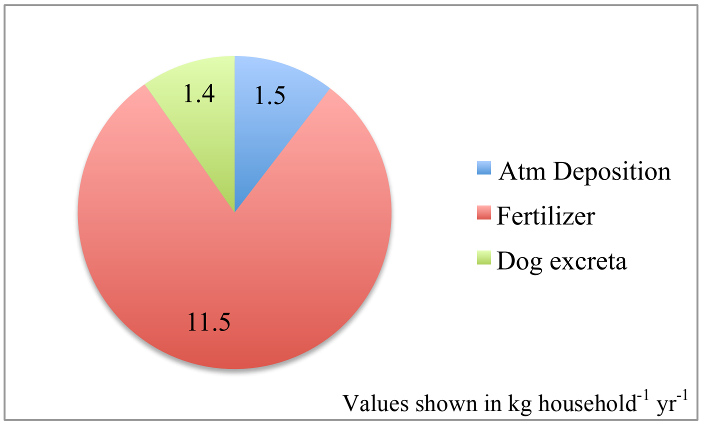

Figure 8 Average N Inputs into Modeled Households (Minnesota) (Fissore, Hobbie, et al., 2011)

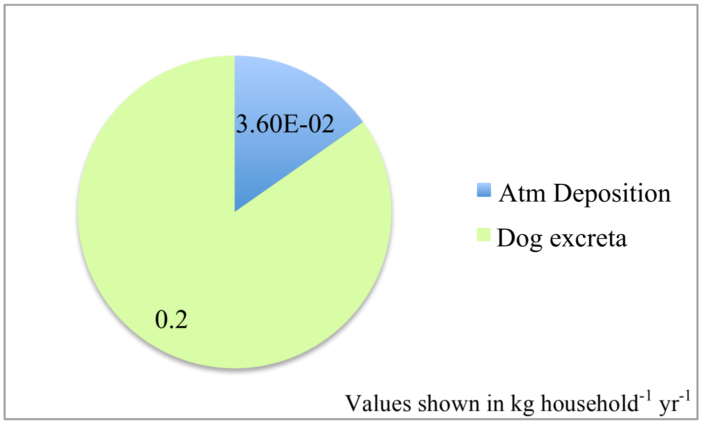

Figure 9 Average P Inputs into Modeled Households (Minnesota) (Fissore, Hobbie, et al., 2011)

The largest output flux of N from the landscape was “inferred” fluxes. The authors defined this as unpartitioned flux of N in excess (or shortage) of ecosystem demand [i.e., the N required to stoichiometrically match C accumulation in wood and soil (Fissore, Baker, et al., 2011)]. N inputs exceeded ecosystem demand on average. Fissore, Hobbie et al. (2011) explained that this meant if this N was not retained in the soil, it was lost via gaseous losses occurring from nitrification/denitrification processes, via runoff to surface waters or leaching to groundwater.

Models serve as a good starting point for evaluating the nutrient cycles of a region, but variables that were not possible to include in Fissore et al.’s (2001) approach could influence the nitrogen and phosphorus cycle of lawns. This study found a large skew in input flux varying by household, suggesting that altering specific household activities could largely influence the biogeochemistry of the landscape. Overall, nitrogen fluxes across households were highly variable and heavily influenced by fertilizer application or lack thereof. A small number of households contributed a disproportionately high amount of nitrogen while another small number of households reported that they did not use fertilizer at all (Fissore, Hobbie, et al., 2011).

This research did not have a primary focus on stormwater, however, it is understood that excess nutrients will exit the system and has the potential to harm the environment through multiple pathways, including stormwater. Though Wollheim (as cited in Fissore, Hobbie, et al., 2011) and Groffman (2009) have suggested that turfgrass can be a net sink for N, landscape, biogeochemistry and nutrient cycles within are complex and strongly influenced by lawn management techniques. In the Minnesota study 15,000 households received a survey, 1,517 responded and 360 of those who responded were randomly selected to develop the model. Consider that of those 360, the number of trees per household, irrigation practices, leaf/clipping removal practices and fertilization rates varied (see Table 12). It thus stands to reason that researchers should expect a relatively wide range of lawn management techniques (or lack there of) when evaluating large watersheds or residential regions. Therefore, it is possible that some households will contribute more to nutrient imports to the system, while others possibly even in the same neighborhood contribute little. Overall, this work reiterates the importance of understanding nutrient cycling in residential landscapes in the context of biogeochemistry. The cycling and fate of nitrogen and phosphorus in the environment is necessary in order to inform sound policy and engineering practices.

Robinson and Melack (2013) developed export coefficient models for nitrate and phosphate for watersheds in the Santa Barbara, CA area. They applied two approaches. The first was based on nutrient flux measured in streams from specific land use classes; this method uses nutrient flux from a single land use to extrapolate by amount of area in the basin. Essentially the predicted nutrient load (L) was the product of a specific land use area (A) multiplied by the developed export coefficient (E) for a given pollutant (Equation 3, where β represents a function of independent variables such as rainfall and runoff). The second used anthropogenic loading based on land use (I) coupled with atmosphere deposition (D) to calculate nutrient loading (Equation 4). Export coefficients were based on a predicted percent of the total nutrient input lost by the catchment.

$$L = \beta \sum EA$$

Equation 3
(adapted from Robinson & Melack, 2013)

$$L = \beta \sum EA\,(I + D)$$

Equation 4
(adapted from Robinson & Melack, 2013)

Both models showed the potential for predicting stormwater loads within approximately 20% of measured loads under certain conditions. Method one's approach, area times export coefficient, was not accurate for predicting dry and wet season export. However, method one was reported to provide the best event based export prediction (nitrate $r^2 = 0.93$ and phosphate $r^2 = 0.9816$, Figure 10). As the coefficient of determination, r^2, gets closer to 1, the more closely the modeled curve fits the data set, indicating a stronger statistical correlation (Kaw & Kalu, 2011). The second approach was not able to predict storm flow and baseflow export, but performed better predicting season totals for nitrate export. However, the results of method two showed consistent over-prediction of phosphate (Figure 11).

The high-frequency flux data and antecedent dry conditions employed to develop method one proved to be the better of the two methods for nutrient export predictions in for the watersheds evaluated, which were described as having a Mediterranean climate with sporadic storms and runoff (Robinson & Melack, 2013). The authors applied these models to other nearby watersheds with slightly different land use and geology, but they did not produce results consistent with measurements; therefore the authors concluded that the model in its current form was not portable. Robinson and Melack (2013) concluded that for any watershed, increased anthropogenic influences have the potential to complicate simulation of nutrient export.

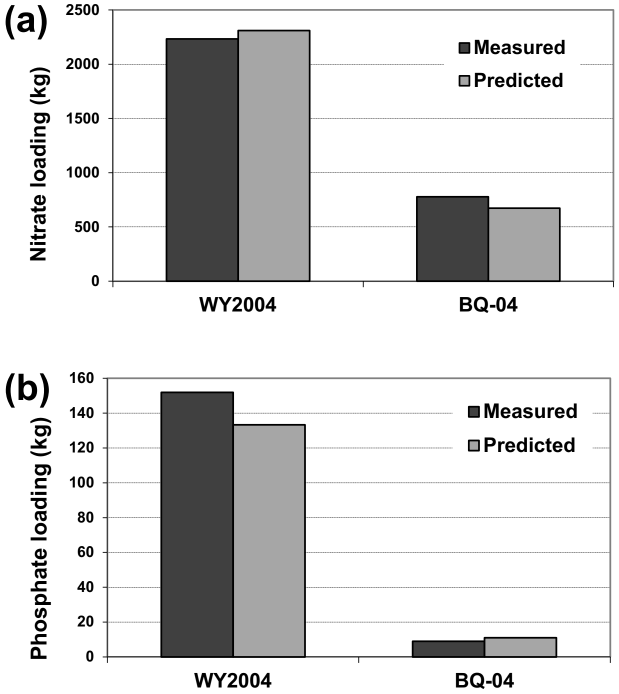

Figure 10 Model Method One for Carpinteria Creek Watershed for (a) Nitrate and (b) Phosphate in 2004. (from Robinson & Melack, 2013)

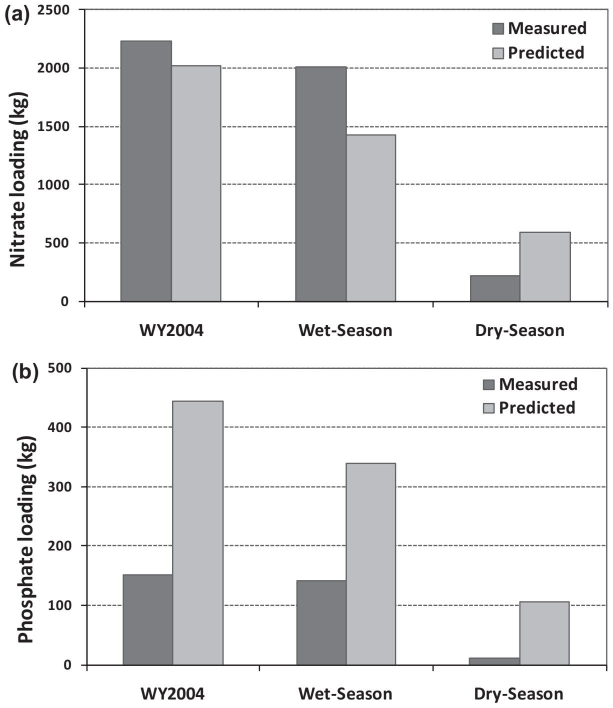

Figure 11 Measured vs. Predicted Annual, Wet-Season & Dry-Season Model Method Two (a) Nitrate and (b) Phosphate Loading for Carpinteria Creek Watershed in 2004 (from Robinson & Melack, 2013)

2.1.4.3.2 Sampling Campaign Studies

Researchers in South Carolina conducted a study that encompassed the evaluation of nutrient loadings from streams in ten small watersheds that drain into two high salinity coastal estuaries in: Hobcaw Barony and Murells Inlet (Tufford et al., 2003). The watersheds had varying percentages of residential areas; a summary is shown in Table 13. The estuaries are similar to other estuaries found along the coasts of North Carolina and Florida. Because these estuaries are not at the mouth of large rivers, they do not sustain regular flushing and are therefore susceptible to biota disruption from damaged natural processes. As with other aquatic systems, local populations are dependent on these systems remaining healthy for aesthetics, research, recreation, and ultimately their economy.

Table 13 Creeks Sampled in Hobcaw Barony (HB) and Murrells Inlet (MI) (Tufford et al., 2003)

Watershed Name	Oyster Creek (HB)	Bly Creek (HB)	South Creek (MI)	Brookwood Pond (MI)	Dog Creek (MI)	Harrelsons Creek (MI)	Bullfeathers Pond (MI)	Plantation Kitchen Pond (MI)	Ghost Ship Pond (MI)	Gasque Pond (MI)
Area km^2	0.39	3.62	1.37	0.45	1.29	0.59	0.21	0.59	0.39	1.1
Percent Residential	-	-	31.8	81.9	65	63.4	48.9	57.1	67.3	40.9
Percent Forest	<1	21	28.7	8.5	9.5	0.9	46.2	22	21	11.1
Percent Wetland	99.7	79	31.5	1	10.1	23.2	0.8	11.4	1	21.2
Percent Commercial	-	-	1	2.8	8.6	3.1	1	1.5	6.2	14.8

Tufford et al. (2003) noted that urbanized watersheds offer less opportunity for nutrient recycle and removal due to high percentage of impervious surface coverage and concurrent lack of vegetation. The two inlets evaluated had some great differences at the time their research was conducted. Murells Inlet had been severely altered from its natural state, with anthropogenic reduction of the wetland to 13% of its original size. The Murells Inlet area has mostly fine sand soil, with multiple different land uses present in the developed areas, including widespread use of residential turfgrass and landscaping. This inlet was also impacted by boat traffic and dredging. By contrast, Hobcaw Barony sustained much of its original land and pre-development characteristics including its sands and fine sands with forested wetland.

Grab samples were drawn monthly from the ten different streams at base flow period and laboratory analyzed for both inorganic and organic nitrogen and phosphorus (Tufford et al., 2003). This is in contrast to other research, which may focus on sampling during storm events only. Samples were taken each month in 1999 for a total of 120 samples. The nitrogen and phosphorus species analyzed include: TN, total dissolved nitrogen (TDN), NO_2+NO_3, NH_4, dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), TP, total dissolved phosphorus (TDP), orthophosphate (DIP) and dissolved organic phosphorus (DOP). Sampling stream locations were described as urban stream, urban pond, or forested creek, however other details such as percent residential, forested and wetland were also noted for the contributing watershed. Raw data concentration numbers were not reported; box-and-whisker plots produced by the authors are located in Appendix B.

Tufford et al. (2003) performed an analysis of variance on log nutrient concentrations to aid in identifying differences among monitoring site and seasonality. Monitoring sites were characterized by percentage of various land use and land cover (LULC) descriptors. Hobcaw Barony had no residential or industrially developed land, while Murrells Inlet contained basins with residential land coverage ranging from 31.8 to 81.8%. The regression models for this study yielded no relationship between nutrient fractions and LULC classes. General land use and seasonality alone were not enough to predict any in-stream nutrient relationship in this study. This contrasts the findings of some other studies, which showed statistically significant differences in nutrient pollution from various land use classes (Poor & McDonnell, 2007; Graves et al. 2004 WQ; Groffman et al., 2004 N fluxes). Dissolved inorganic and organic nitrogen (DIN and DON) made up 62% of TN from urban ponds (sources of other 38% not reported by authors) compared to 100% of TN from forested wetlands. Similarly, dissolved inorganic and organic phosphorus (DIP and DOP) made up 50% of TP from urban ponds compared to 100% of TP from forested wetlands. These results are indicative of the wetlands' and forested wetlands' ability to remove aqueous particulates. Results showed correlation between seasonality in both DIN fractions; NH_4 peaked in summer, while NO_3 peaked in winter. The authors suggested that this correlation might be related to microbial activity influenced by temperature.

There were large differences in concentration results seasonally. TN, DON, NH_4 and TP were greatest during the summer; this could be a result of evapotranspiration causing these particular species to be more concentrated, accelerated decay of detritus, or increased tourist activity (auto exhaust, etc.) (Tufford et al., 2003). TP seasonality, with a summer peak, was expressed in all creek types; Tufford et al. (2003) expected it to be higher in summer due to increased rainfall and resulting increased particulate mobility. Urban creeks and ponds had higher concentrations compared to forested wetlands. These results indicate that developed watershed areas may provide a source of phosphorus, a sink for nitrogen, or both. The authors highlighted the importance of evaluating the range of nutrients. This study did not evaluate loads, however, the authors believed that concentrations should provide a relatively accurate view of load proportions. Tufford et al.'s (2003) results also indicated that urbanized areas may alter estuarine nutrient ratios.

Florida is a unique environment for evaluating water routes due to the extensive karst environment and high seasonal rainfall, which all contribute to complexity in modeling nutrient pathways. Florida water quality is of great concern to locals because 38% of its drinking water comes from surface water (Badruzzaman et al., 2012). Badruzzaman et al. (2012) reported: "several studies showed evidence that nitrate-nitrite concentrations in many spring discharges have increased from 10 to 350 fold over the past 50 years, with the level of increase closely correlated with the anthropogenic activity and land use changes within the springshed".

One study in Florida evaluated two close proximity estuarine systems on the south central coast of Florida (Graves, Wan, & Fike, 2004). The Indian River Lagoon is a diverse ecosystem and the St. Lucie Estuary is its largest tributary. The St. Lucie Estuary was a freshwater estuary until construction of the St. Lucie Inlet. Graves et al. reported that the estuary had many years of nutrient concentrations higher than pre-development condition years in the time prior to this publication. They explained that increased nutrient loads caused multiple algal blooms during high runoff years (Graves et al., 2004). The Florida Legislature designated this a Surface Water Improvement (SWIM) priority water body.

The South Florida Water Management District (SFWMD), and the US Army Corps of Engineers collaborated on this ecosystem restoration plan, in part through the Everglades Restoration Plan. The effort's objective is to reestablish optimal salinity concentrations and repair water quality. In support of SWIM efforts, this research included collecting runoff samples following storm events for a period of 30 months. Criteria for defining rainfall events and guidelines for dictating when to take samples were outlined; rules included: a requirement that no rain has occurred in the area for the past 72 hours and then the rain in inches was between the 25th and 75th percentile of the region's historic rainfall amounts (Graves et al., 2004). For the Indian River Lagoon and St. Lucie Estuary region, the corresponding rain events deliver between 18 and 38 mm of rain in a widespread pattern across the basin.

The Indian River Lagoon and St. Lucie Estuary watershed has nine basins. Graves et al. (2004) evaluated land use in the basins and found that predominant uses included citrus agriculture (at 25%), cattle pasture (at 23%), urban (at 16%), and isolated wetland (13%). Of the total urban area, 74% was classified as residential. Sites for sample collection were selected in such a way that upstream land use reflected one single type. Water samples were evaluated for concentrations of nitrogen, phosphorus and a series of other pollutants, selected results of which are shown in Table 14.

Table 14 Mean Nutrient Concentrations in Storm Water Runoff from Eight Land Use Types (Graves et al., 2004)

Land Use	**No. of Samples**	**Mean Total P (mg L^{-1})**	**Mean Total N (mg L^{-1})**	**Mean Organic N (mg L^{-1})**	**Mean Inorganic N (mg L^{-1})**	**Mean NH_3-N (mg L^{-1})**	**Mean NO_x-N (mg L^{-1})**
Wetland	30	0.02	1.18	1.10	0.14	0.14	0.00
Urban	115	0.22	1.07	0.92	0.13	0.06	0.07
Golf Course	28	0.24	1.62	1.27	0.32	0.20	0.12
Citrus	127	0.29	1.37	1.11	0.26	0.13	0.14
Row Crop	20	0.63	1.88	1.14	0.77	0.20	0.57
Residual	21	0.26	1.09	0.87	0.21	0.09	0.11
Dairy	8	12.54	38.9	9.98	28.9	28.5	0.39
Pasture	53	0.29	1.46	1.32	0.15	0.11	0.03

One of the major stressors of the St. Lucie Estuary system was low dissolved oxygen (DO) concentration, found in multiple samples. Sampling results for DO could not be correlated with BOD_5, which suggested other influencing factors. The authors explained that there was a strong correlation between DO and TP, and DO and TN. Turbidity and TSS were also significantly correlated with nutrient species. Similar to the Tufford et al. study (2003), the wetland runoff had significantly lower sediment content compared to all other land use types. Results also indicated that an increasing scale exists in different land uses correlated to their propensity to discharge soluble nitrogen. Urban areas are expected to contribute more nitrogen and phosphorus to stormwater runoff because of anthropogenic activities, including lawn fertilization; agricultural regions have the capacity to contribute even more due to frequent fertilization and irrigation practices associated with raising crops. The authors noted that this may have important implications for nitrogen-limited receiving water bodies.

As part of the Baltimore Ecosystem Study, Groffman et al. (2004) consolidated three years of data on nitrogen losses from eight watersheds: one forested, six urban/suburban and one agricultural (near Baltimore, Maryland). The authors argued that many studies focus on short term (e.g. individual storm events), but long-term flux and budget analyses are necessary for comparing different urban ecosystems. Evaluation of a watershed employs a scale approach relevant to protection of managed water bodies, which can bridge the gap between basic and applied science (Groffman et al. 2004). Long-term nutrient studies are necessary to develop the capability for authentic comparison of different urban and residential ecosystems.

Groffman et al.'s (2004) objectives were to quantify variations in N yields in urban and suburban catchments, evaluate inputs, outputs and retention of N, and compare the urban and suburban watersheds with less modified systems in the Baltimore region (Maryland). At the time of study, the watershed in Baltimore had a population of approximately 356,000. There was also a noted shift in population location, with many moving from the lower part of the watershed toward middle and upper Baltimore County. With this shift in population location came commensurate development, involving conversion of areas previously natural to residential and commercially developed. The authors explained that municipal wastewater treatment was not considered in their analysis because there were no wastewater discharges or septic systems in the areas analyzed; however, they recognize that unintentional leakage from wastewater is an important contributor of N to some streams. They estimated daily mass loads from average stream concentration values for a given interval of runoff data. They estimated loads exported, "based on runoff versus concentration relationships derived from the weekly chemistry data by using flow-interval method as described by Law and others (2004)" (Groffman et al., 2004).

Table 15 shows a summary of the catchments' characteristics with the mean nitrate and mean TN annual yields estimated by Groffman et al. between 1999 and 2001 (2004). In the suburban watersheds studied, 75% of the nitrogen inputs were identified to come from home lawn fertilization and atmospheric deposition (compared to approximately 82% in the Fissore, Hobbie et al., 2011 study). The Groffman et al. (2004) study found that average nitrogen yield for the suburban (and urban) watersheds was over 10 times higher (6.7 kg N ha^{-1} y^{-1}) than that of the completely forested watershed (0.52 kg N ha^{-1} y^{-1}).

Groffman et al. (2004) estimated input and output budgets with a series of assumptions on atmospheric deposition rates (11.2 kg N ha^{-1} y^{-1}), fertilizer application rates (14.4 kg N ha^{-1} y^{-1}) based on Law et al. (2004), agricultural fertilizer application based on a local extension service (120 kg N ha^{-1} y^{-1}) and estimations of N fixation by crops growing in agricultural areas. They used a retention of estimation based on the watersheds land use classification: 95% for forested, 77% for agricultural, and 75% for suburbs (Groffman et al., 2004). They conveyed that most of the exports from the suburban watersheds were in the form of NO_3^-.

Table 15 Baltimore Catchment Characteristics and Estimated Annual Nitrate Yields (Groffman et al., 2004)

Station	**Land Use**	**Reach Drainage Area (ha)**	**Pop. Density (per ha)**	**Res. Land Use (%)**	**Imper -vious (%)**	**Avg. annual Nitrate yield (kg N ha^{-1} y^{-1})**	**Avg. annual TN yield (kg N ha^{-1} y^{-1})**
Glyndon	Suburban	81	9.4	47	22	5.5	6.5
Gwynn-brook	Suburban	985	16.4	68	17	6.5	7.4
Villa Nova	Suburban / Urban	7282	12.2	50	19	5.2	6.0
Baisman Run	Suburban / Forest	381	1	34	1	5.5	5.9
Carroll Park	Urban	1414	12.6	43	41	5.0	8.6
Dead Run	Urban	1414	12.6	43	41	3.0	5.5
McDonough	Ag.	7.8	0	0	0	26.3	NA
Pond Branch	Forested (100%)	32.3	0	0	0	0.123	0.523

Average yield figures based on yields reported for 1999, 2000 and 2001

Further stormwater analyses showed that runoff patterns were strongly influenced by percent impervious surface, which is consistent with the findings of past research (Groffman et al., 2004). Based on their analysis, Groffman et al. (2004) concluded that the majority of N export occurred during high frequency, low-flow storm events. Low variability in base flow coupled with the high contribution of low flow yields, the authors suggested that urban and suburban catchments are not entirely dominated by stormwater flows and that natural hydrologic pathways and processes continue to play an important role in the management and regulation of nutrients and water in these systems (Groffman et al., 2004).

Francey et al. (2010) explained that most urban stormwater quality studies are limited in scope spatially and temporally, containing either few data sets or few sampled events. Their research encompassed a large scale monitoring campaign of stormwater pollutants found in urban discharge during both wet and dry weather from six different urban watersheds and one large roof catchment in southeastern Australia (near Melbourne). Although this study did not have a socio-demographic analysis component, it is important because it evaluates nutrient concentrations in stormwater and baseflow from several different types of residential catchments.

Based on their results, Francey et al. (2010) concluded that concentrations of some pollutants, but not all, are higher during storm discharge versus dry weather flow (baseflow). According to these researchers, land use (they specifically noted industrial and residential) does not have a major influence on TP or TN event mean concentrations (EMC), the flow weighted pollution concentration over the duration of the entire precipitation event. Table 16 shows EMC concentrations and baseflow concentrations in the six catchments evaluated for TSS, TP and TN.

Francey et al. (2010) conducted multiple statistical analyses on their data such as checking for correlations of TSS, TN and TP concentrations with rainfall intensity and runoff rate. General hydrological descriptors such as total event rainfall or event average rainfall intensity were poor predictors of EMCs for each pollutant tested. Based on their statistical analysis, the authors found that TP and TN correlated with rainfall intensity in only four of the 19 cases. The authors found a significant negative correlation between TP and the total event rainfall in the Narre Warren catchment; they concluded that this was most likely the high amount of septic tanks leaking into drainage fields. The authors also noted the high TN concentration in baseflow of the Burwood East residential area; they concluded that based on it being a typical suburban catchment, the high baseflow concentration may be indicative of some other contaminant source.

Table 16 Catchment Characteristics and Stormwater Nutrient Concentration Results for Dry and Wet Weather (from Melbourne, Australia by Francey et al., 2010)

Site	Land Use	Drainage Area (ha)	Impervious (%)	Parameter	Wet weather EMC (mg/L)	Dry weather mean (mg/L)
Mt. Waverly	Commercial	28.2	80	TSS	71.6	7.65
				TP	0.17	0.22
				TN	1.17	1.13
Burwood East	Residential & Commericial	186	46	TSS	84.1	7.27
				TP	0.15	0.63
				TN	1.54	3.41
Richmond	High-density Residential	89.1	74	TSS	125.1	12.6
				TP	0.42	0.42
				TN	2.29	11.6
Glen Waverly	Med-density Residential	38	45	TSS	94.8	20.6
				TP	0.24	0.23
				TN	1.74	2.34
Doncaster	Med-density Residential	105.6	51	TSS	77.0	16.0
				TP	-	0.24
				TN	-	2.39
Narre Warren	Rural Residential	10.5	20	TSS	91.9	10.0
				TP	0.75	9.01
				TN	3.51	32.6

Francey et al. (2010) explained that correlation between pollutants could be a useful tool, allowing a researcher to employ “surrogate prediction”. Surrogate prediction means that one species can be used as a surrogate indicator for other species in the sample, much the same way that fecal-coliform count is used as an indicator for bacterial contamination. TSS and TP concentrations are often highly correlated; the r^2 was determined to range between 0.55 – 0.89

for TSS and TP. TSS and TP average concentrations from the five sites evaluated by Francey et al. (2010) (minus the large roof) are shown in Figure 12. According to the author’s evaluation, TN did not correlate with other pollutants.

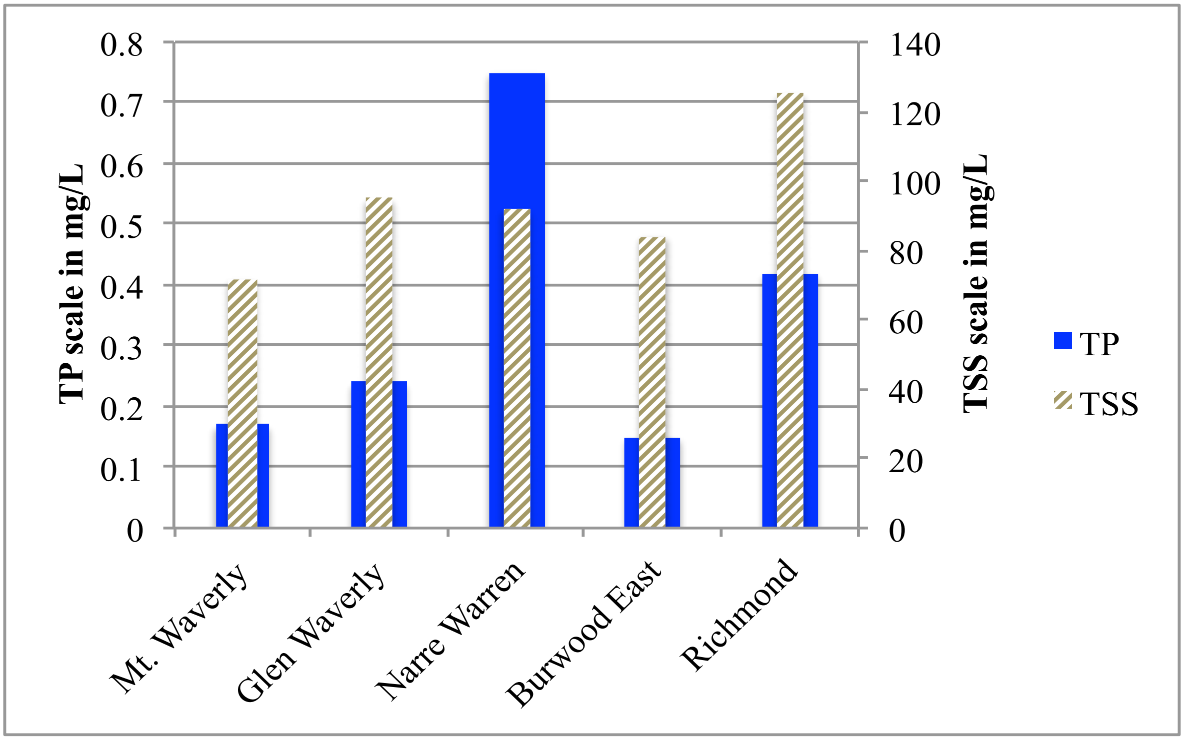

Figure 12 Average TP vs. TSS Concentrations for Five Residential Sites in Melbourne, Australia (data from Francey et al., 2010)

Francey et al. (2010) found that strong first flush phenomena (for TSS, TP and TN) were not exhibited by any of the catchments evaluated. Therefore, Francey et al. (2010) recommended that current assumptions for first flush influences should be reevaluated and revision of treatment technologies should be reconsidered. Many methodologies focus on treating first flush nutrient pollution, while essentially ignoring pollution from the rest of the storm flow; these methods are outdated and effectively contradicted by the findings of their campaign and analyses. Finally, Francey et al. (2010) found that a rainfall-intensity function based on an integration of rainfall, to a power, at each time step, produced correlations with event loads. They concluded that this necessitates further investigation for stormwater pollutant modeling, as an alternative to EMC-based models.

A two-year study, analyzing nitrogen (as an indicator of lawn chemical use) from stormwater pipe discharge was undertaken in the Wissahickon Valley Watershed, a suburb of the Philadelphia region (Toran & Grandstaff, 2007). This study did not evaluate any phosphorus species; the researchers looked at potassium and pesticides, but this is not included in this review. A prior assessment of the region conducted by the Philadelphia Water Department yielded designations of impaired or severely impaired water quality for all fifteen locations evaluated. Toran and Grandstaff (2007) selected neighborhoods to capture a range in both number of homes and lot sizes. Storm pipes in these neighborhoods collected runoff from both streets and lawns before carrying it to a discharge point. A sixth control pipe was selected for analysis; it received drainage from a small, undeveloped field. Automatic samplers were installed at each point of stormwater pipe discharge. Pre-calibrated sensors triggered once stormwater flow in the pipe reached a designated level. Two samples were obtained at each site for each storm event: one sample filled immediately to represent the first flush, and the second filled gradually over the course of the storm to be analyzed as a composite snapshot of the stormwater for each event. Storms in this region averaged four hours in duration; the composite sample, therefore, was programmed to fill 500 ml every 30 minutes. Not all storms reflect the average precisely, so the composite is not an exact likeness of the average.

Toran and Grandstaff (2007) articulated their reasoning for evaluating concentrations rather than pollutant loading. Their reasoning was that if concentration in the first flush and composite are not beyond levels that cause degradation, then there are unlikely spikes high above these measurements that will significantly harm the receiving water body. Nitrate (NO_3-N), ammonium (NH_4-N), and phosphate (PO_4-P) were selected as indicator water quality constituents. Average nitrate concentrations (0.7 – 1.7 mg NO_3-N L^{-1}) from this sampling campaign were only slightly higher than the background concentration of 0.6 mg NO_3-N mg L^{-1} reported by the USGS (as cited in Toran & Grandstaff, 2007). No particular storm exhibited higher nitrate concentrations than another, however, summer concentrations were slightly higher (4 mg NO_3-N L^{-1}). Highest concentrations of NO_3-N also alternated between first flush, composite, and pipe samples; lack of first flush is corroborated by Francey et al.'s (2010) findings discussed previously. The intended control sample site produced nitrate concentrations similar to that of the non-control basins; the authors concluded that flow from nearby yards was captured in the control basin.

Through the first year of sampling, Toran and Gradstaff (2007) did not test ammonium because it was believed that it would oxidize to nitrate either in the soil or in the storm pipe. However, because detectable levels were found, NH_4-N was added to the sampling campaign throughout the second year. Ammonium had a variable range of concentration results, from non-detect to 7.5 mg NH_4-N l^{-1}. The authors noted that circumstances such as several homeowners applying fertilizer at the same time followed by a storm event or the particular location and topography (slope) of a fertilized plot could be enough to induce a high concentration outlier. However, resident activities were not surveyed in this study. Overall, intermittent concentration spikes at an individual discharge point, but not at others for the same storm event, suggests that local circumstances, such as fertilizer application timing vary and influence discharge concentration.

Spence et al. (2012) conducted a microscale study by selecting three different residential lawns in Cary (North Carolina), in which landscape and maintenance practices were very different. One lawn was called high maintenance fescue lawn (HMFL), the second - low maintenance fescue lawn (LMFL) and the third - forested residential landscape (FRL). Each provided a snap shot of lawns with highly varying vegetation and reception of fertilizer treatment. The HMFL and LMFL lawns had been established for at least 35 years, the FRL for 15 years. Each was a privately owned and managed residential lawn, approximately 2000 m^2. Prior to the 20-month sampling campaign, each lawn's manager was provided a survey to establish what inputs and maintenance were practiced (Spence et al., 2012).

Overland flow from events was monitored continuously for 20 months using an overland flow sampling system located in delineated area in each lawn. It was designed so that 100% of runoff followed a flow path to the outlet ports for collection in sterile Nalgene® Thermo Fisher Scientific B3 media bags. Metal landscape edging (placed 50.8 mm into ground) was used to confine runoff to the delineated areas. Efforts were executed to measure rainfall on the sites (including rainfall through tree canopy) and compare the measurements with local NOAA data. Still further effort was taken to analyze the top 10 cm of soil from each lawn to determine cation exchange capacity, soil pH, and pre-existing soil phosphorus levels. Capturing rainfall onsite with the addition of collection underneath tree canopy allowed for some capture of potential influence from nitrogen deposition in tree canopy.

The three residential lawns in the Spence et al. (2012) study varied widely in maintenance, including irrigation. The HMFL was a dense, uniform, manicured lawn fertilized approximately five times per year and irrigated once per day for 20 minutes, unless a 13-mm minimum depth rainfall event occurred. The HMFL owner removed grass clippings from the site. The LMFL contained a heterogeneous mixture of vegetation, including open soil surfaces, was fertilized three times per year and, but not irrigated regularly. Grass clippings from the LMFL lawn were returned to the surface. The FRL was a forested system that was neither fertilized for irrigated. A summary of each lawn’s maintenance characteristics is shown in Table 17.

High infiltration rates coupled with inability to measure and record real time rainfall intensity at the study sites, made it unclear whether the flow generated resulted from infiltration excess or quick flow from variably saturated areas (Spence et al., 2012). The authors noted that the highly divergent methods of lawn management had substantial influence on turfgrass density, the ground cover’s ability to intercept rainfall and, therefore, overland flow generation. Furthermore, they suggested that atmospheric deposition and lawn management practices influence the interaction between rainfall, vegetation and soil.

Analytical results of nutrient export showed that less than 1% of applied fertilizer on both the HMFL and LMFL exited the lawn in overland flow, suggesting that other mechanisms for nutrient loss for well-structured soils are more important and merit investigation. The authors reported results as mass lost per unit area per year (shown in Table 17); they did not include raw data for stormwater nutrient concentrations. TDN measured in overland flow from all three sites was lower than the measured inputs. The authors opined that all three sites were sequestering atmospheric N deposition, which was consistent with previous findings in Baltimore by Raciti et al. (2008). The authors recognized that nitrogen was being removed by an unaccounted for pathway. Due to limitations set by the landowners, Spence et al. (2012) were unable to quantify nitrogen percolation to depths beneath the landscape. Based on the results they found from these three lawn systems, the authors concluded that the results demonstrated that nutrients in overland flows are greater from “poorly maintained residential lawns”.

Brezonik and Stadelmann (2002) characterized stormwater runoff loading of N and P from a database of information in Minneapolis-St. Paul (Minnesota). Using a database of stormwater loads, EMCs and runoff details from mixed land use (including suburban) catchments in the Minneapolis-St.Paul area for hundreds of storm events, Brezonik and Stadelmann (2002) set out to statistically find correlations relating nutrient pollution loads or EMCs to easily measureable physical watershed and climatic characteristics. The database contained information on hundreds of storm events that occurred between 1980 and 1998; catchment areas ranged from 6.9 to 214 ha and land uses included residential, public, open space, commercial/industrial, grassland, woods and wetlands. Rainfall depth ranged from 0.25 to 74 mm; intensity and antecedent rainfall details were also documented. The authors noted that in this region, snowmelt tends to contribute a large percentage of total annual runoff volumes and that the pollutant loading of snowmelt can be rather different than rainfall runoff. According to Brezonik and Stadelmann (2002), “during thawing and freezing cycles, soluble pollutants are flushed through the snowpack and concentrated at the bottom where they are available for transport in snowmelt.”

From several hundred events in the database, event loads and EMCs ranged over multiple orders of magnitude. Event mean concentration of nutrients was high compared to local lake water concentrations. Using descriptive statistics and linear regression, their results showed that the most relevant criteria for predicting pollutant loading were drainage area, total precipitation and rainfall intensity. Median TP was highest during the fall and winter seasons. Large disparities were found in snowmelt runoff volumes among the different sites. For sites with larger snowmelt runoff, median pollution loads were also higher, which led the authors to conclude that loadings were more a function of runoff volume than runoff source. Correlation between the evaluated explanatory variables (such as watershed characteristics) and nutrient pollution were weak (Brezonik & Stadelmann, 2002). However, pollutant EMCs in general were

Table 17 Lawn Descriptions, Management Techniques and Annual Mass Nutrient Exports from Three Lawns in North Carolina (Spence et al., 2012)

	HMFL		**LMFL**		**FRL**	
Lawn care provider	Homeowner		Contractor		NA	
Lawn size	2000m2		2000m3		2000m4	
Delineated area	33.5m2		27.9m2		26.2m2	
% Slope	10		11		3	
Vegetation	Tall fescue and hardwood		Tall fescue and hardwood		Hardwoods	
Basis for lawn management	Grass appearance		Grass appearance		No grass	
Basis for fertilizer application amount	Grass area & type		Desire for green lawn		NA	
Fertilizer formulation	Varied seasonally		Varied seasonally		NA	
Fertilize times per year	3		1 or 2		NA	
Fertilizer application Rate	10.5 g N m^{-2} yr^{-1} 2.8 g P m^{-2} yr^{-1}		8.6 g N m^{-2} yr^{-1} 5.7 g P m^{-2} yr^{-1}		NA	
Clipping management	Remove		Return		NA	
Total runoff depth	2.2mm		5.2mm		1.7mm	
Mean % Rainfall as Runoff	0.4 ± 0.1		0.6 ± 0.1		0.5 ± 0.2	
Total Runoff events	15		29		8	
Annual mass loss of nutrients per unit area (mg m^{-2} yr^{-1})	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
TKN	-	5.28	-	13.6	-	1.61
NO3-N	0.55	0.90	3.17	1.08	0.26	0.40
TDN	1.07	1.94	15.8	3.37	0.94	0.97
NH4-N	0.32	0.10	4.51	0.52	0.13	0.05
TP	-	0.74	-	2.38	-	0.34
PO4-P	0.83	0.38	5.78	1.04	0.31	0.27
TSS	133.9	148.2	907.8	669.2	33.6	36.7

correlated with the number of days since the previous event, substantiating theory of pollution buildup and the importance of antecedent dry days. Brezonik and Stadelmann (2002) found that rainfall depth, rainfall intensity and the catchment area were the strongest variables for predicting pollutant loads. A summary of monitored event nutrient load is shown in Table 18 and median seasonal event mean concentration of nutrients is shown in Table 19.

Table 18 Monitored Event Load Data (kg/event) in Minnesota (Brezonik & Stadelmann, 2002)

	TP	**DP**	**SRP**	**TKN**	**NN**	**TN**
n	360	147	85	222	213	294
Minimum	0.005	0.01	0.001	0.043	0.015	0.06
Maximum	30.1	24.8	23.7	125	85	210
Median	0.36	0.17	0.06	2.27	0.52	2.17
Mean	1.06	0.74	0.66	6.6	1.8	6.7
SD	2.85	2.50	2.85	15.5	6.5	18.2

All values except n shown in kg/event

Table 19 Median Seasonal Nutrient EMCs in Minnesota (Brezonik & Stadelmann, 2002)

EMCs (mg/L)	**TP**	**DP**	**SRP**	**TKN**	**NN**	**TN**
Winter	0.55	0.23	0.40	2.01	0.71	3.40
Spring	0.38	0.19	0.05	2.40	0.37	2.50
Summer	0.32	0.14	0.06	1.80	0.43	2.20
Fall	0.57	0.14	0.26	1.50	0.32	2.37

Poor and McDonnell (2007) measured the nitrate concentration in streams from three catchments near the Corvallis (Oregon). They selected catchments of similar size, geology, meteorology and atmospheric deposition rates; all lie within the Oak Creek Watershed. The three watersheds differed distinctly in land use; a summary of details is shown in Table 20.

This study and strategic selection of catchments allowed for a meaningful direct comparison among the sub-watersheds. As expected, baseflow and storm flow nitrate mass exports from the forested watershed were quite low (exports shown in Table 20). A clear spike and gradual fall of nitrate export was seen in the agricultural watershed not seen in the other watersheds; this suggested a representation of impact post-fertilization. The agricultural catchment also sustained a faster time to peak, suspected to be a result of lower tree cover and therefore lower interception compared to the other catchments. The agricultural catchment expressed a “dilution” pattern of nitrogen export, meaning that after the spike observed as a result of fertilization, the export diluted over time until the next spike of fertilizer application. The residential catchment’s main source of nitrogen was fertilizer application. The authors believed that the high total amount exported from the residential catchment in the fall was driven more by high baseflow versus high nitrate concentration (exports shown in Figure 13).

The residential and forested watersheds expressed a “concentration” pattern, meaning that water came into contact with soil nitrogen sources prior to reaching the stream; the pollutant concentration patterns essentially follow the hydrograph. Overall, export rates in this study increased as development increased. Poor and McDonnell (2007) explained that while we know that land use impacts nutrient exports over all, nutrient dynamics and concentrations with respect to storm events is still not well understood.

Table 20 Comparison of Three Catchments in Oregon with Nitrate Mass Export from Three Storm Events (Poor & McDonnell, 2007)

	Forested Watershed			**Agricultural Watershed**			**Residential Watershed**		
Area (ha)	49.50%			52.20%			42.9%		
Tree Cover	98.10%			52.80%			83.10%		
Impervious	negligible			negligible			15%		
	Storm 1	**Storm 2**	**Storm 3**	**Storm 1**	**Storm 2**	**Storm 3**	**Storm 1**	**Storm 2**	**Storm 3**
Nitrate Export kg NO_3-N ha^{-1} $storm^{-1}$	0.012	0.005	0.010	0.121	0.04	0.021	0.131	0.108	0.131
				Baseflow concentration NO_3-N mg L^{-1}			0.15	0.15	0.13
				Peak concentration NO_3-N mg L_{-1}			0.27	0.23	0.25

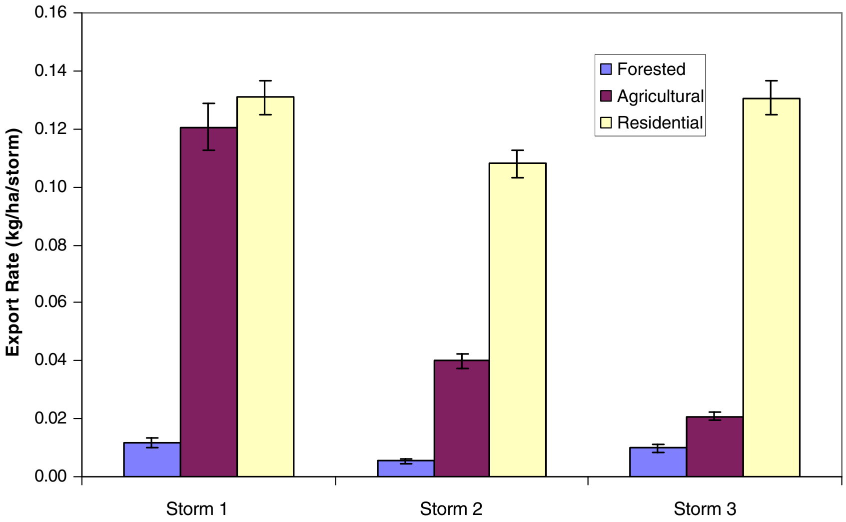

Figure 13 Nitrate Export Rates (kg ha^{-1} $storm^{-1}$) for Three Storms in Three Study Catchments, Oregon (from Poor & McDonnell, 2007)

Dietz and Clausen (2008) performed a unique microscale sampling and analysis to compare a traditionally developed subdivision with a Low Impact Development (LID) designed subdivision in Waterford (Connecticut). The primary goal of an area designed with LID techniques is for the area to maintain pre-development hydrology characteristics. Stormwater and baseflow samples were collected throughout the duration of construction and for a period of time post construction. Activities that could potentially influence pollutant loads, such as driveway and road installation, were also documented.

The results of the Dietz and Clausen (2008) were poignant. In the traditionally developed watershed, as impervious surface increased from 1 to 32%, there was a 49,000% increase in stormwater runoff volume, which indicated an exponential increase in stormwater volume as impervious surface increased in the catchment. This increase is above what other studies have found (compared to 100% and 500% increases) and this may be due to the extremely small size of the catchment studied compared to other studies (Jennings & Jarnagin, 2002 as cited by Dietz & Clausen, 2008). Dunne and Leopold (as cited in Dietz & Clausen, 2008) explained that the stormwater response per unit area is dampened as watersheds increase in size. By comparison, the LID catchment impervious surface percentage increased from zero to 21%, but had no corresponding increase in stormwater volume exported.

Nutrient export in the traditional and LID watersheds were commiserate with increases in stormwater volume. According to the authors, nitrate and ammonium export increased logarithmically in the traditional catchment, but no export changes were shown in the LID catchment. Ammonium export from the LID watershed actually decreased post development. TN export for the traditional subdivision was approximately 10 kg ha^{-1} yr^{-1}, compared to 8.6 kg ha^{-1} yr^{-1} found in a 27% impervious surface urban watershed in Maryland by Groffman et al. (2004). In contrast, the LID catchment averaged export of 2 kg ha^{-1} yr^{-1} of TN, similar to the export of forested watersheds (Dietz & Clausen, 2008). Dietz and Clausen (2008) reported that the LID watershed showed no significant increase of P export post development (0.4 kg ha^{-1} yr^{-1}), however, TP export by the traditional watershed showed a significant increase corresponding to impervious surface increase (2 kg ha^{-1} yr^{-1}). A summary of the subdivisions characteristics, including construction notations are shown in Table 21. Statistical analysis of nitrogen and phosphorus export from the LID subdivision is shown in Figure 14.

Table 21 Characteristics and Nitrate Mass Export from Two Subdivisions (Dietz & Clausen, 2008)

<table>
<tr><td rowspan="2">Common for Region</td><td colspan="2">Climate: Influenced by continental polar and maritime tropical air masses</td></tr>
<tr><td>Annual precipitation: 1237 mm</td><td>Soil infiltration rate: 33 cm h^{-1}</td></tr>
<tr><td></td><td>Traditional Site</td><td>LID Site</td></tr>
<tr><td>Area</td><td>2 ha</td><td>1.7 ha</td></tr>
<tr><td>Lots</td><td>17</td><td>12</td></tr>
<tr><td>Stormwater mgmt.</td><td>Curb & gutter stormwater collection</td><td>Bio-retention cul-de-sac</td></tr>
<tr><td>Roads</td><td>8.5 m wide asphalt</td><td>6.1 m wide eco-stone pavers</td></tr>
<tr><td>Landscape</td><td>Traditional landscape & turf</td><td>Rain gardens in each lot</td></tr>
<tr><td>Techniques used during construction</td><td>Constructed with typical practices</td><td>located & seeded stockpiles to prevent sediment loss, hay bales, silt fence, earthen berms</td></tr>
<tr><td>Impervious</td><td>32%</td><td>21%</td></tr>
<tr><td>Avg. annual TN export</td><td>10 kg ha^{-1} yr $^{-1}$</td><td>2 kg ha^{-1} yr^{-1}</td></tr>
</table>

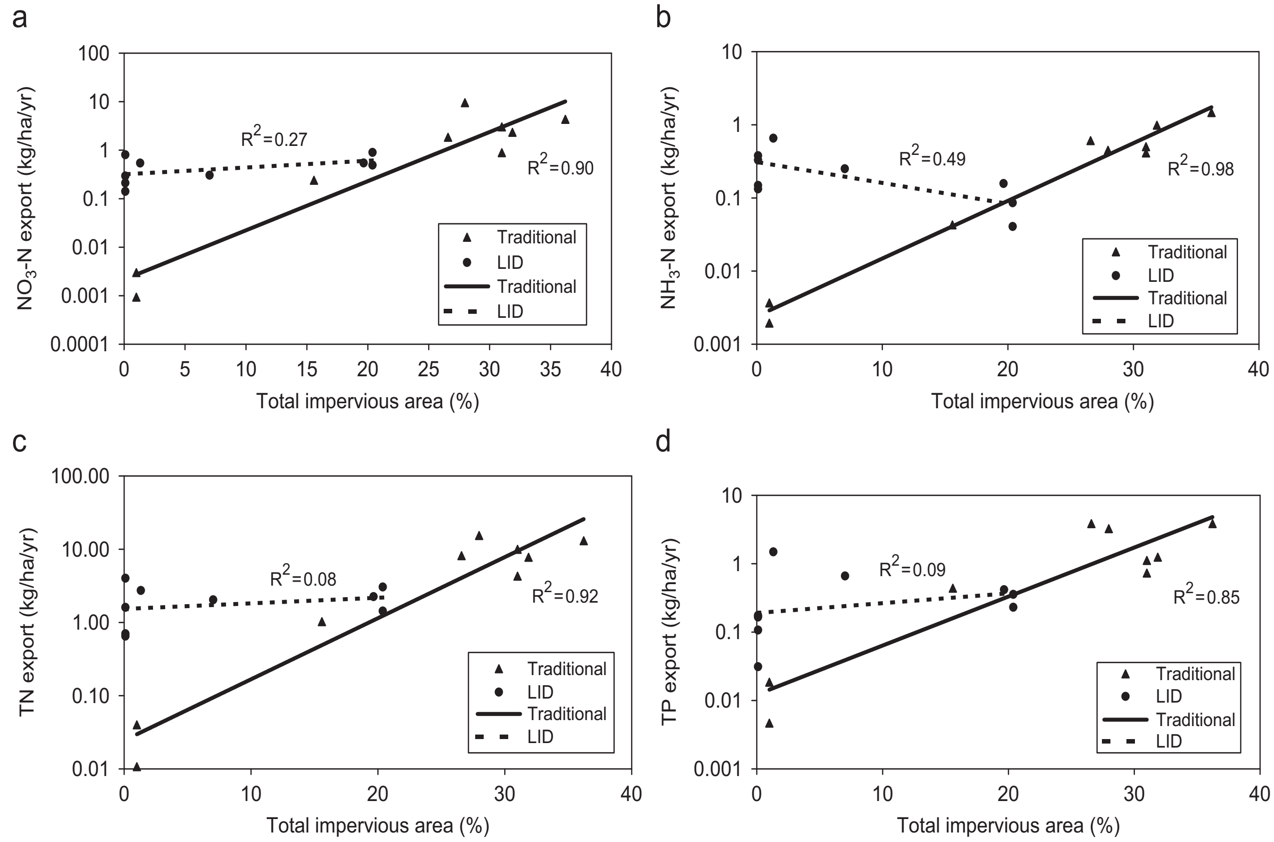

Figure 14 Nutrient Export (1996-2004) from Traditional and LID Subdivisions. (a) NO$_3$-N, (b) NH$_3$-N, (c) TN, and (d) TP (from Dietz & Clausen, 2008)

A recent review conducted in Florida by Badruzzaman et al. (2012) was motivated by numeric nutrient criteria, which the authors noted might require resource allocation to control N and P sources. They reported that environmental impacts of compounding stormwater nutrient pollution with that of heavy metals, pesticides, pharmaceuticals and hormones is not fully understood, but has been shown to increase ecological hazard (Badruzzaman et al., 2012). By 2012, Florida Department of Environmental Protection (FDEP) had identified 425 nutrient impaired water bodies (27% estuary, 39% lake, 33% stream). In July of 2011, Florida Administrative Code was updated to contain the language “in no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in natural populations of aquatic flora or fauna”. Therefore, Badruzzaman et al. (2012) recommended a review of nutrient source load release ranges and hydraulic pathway models. In their review, Badruzzaman et al. (2012) summarized the occurrence and movement of N and P in Florida with an emphasis on loading rates, hydrogeologic influences, attenuation and nutrient tracking techniques.

There are three Clean Air Status and Trends Network (CASTNET) monitoring stations in Florida run by the EPA; they monitor both wet and dry atmospheric deposition of NO_x. In Florida, the rate of deposition ranges from 195 - 308 mg-N m^{-2} yr^{-1}. Florida water body area was estimated as 3.05 x 10^{10} m^2, therefore total NO_x deposition to Florida water bodies was estimated at 5.9 x 10^9 to 9.4 x 10^9 g-N yr^{-1} (Badruzzaman et al., 2012). The Tampa Bay region does not have a CASTNET monitoring site, however, another studied measured nitrogen deposition in this region and found it to range from 648-840 mg-N m^{-2} yr^{-1} (Badruzzaman et al., 2012). There is more room for research in this area, particularly in understanding the role of indirect deposition, which also ends up in surface runoff.

Numeric nutrient criteria will also impact septic system performance requirements. FDOH (2009) reported that approximately 2.5 million such onsite systems (or 39% of the state's population) were in use at time of writing; this equates to approximately 1 x 10^{11} L yr^{-1} of effluent (as cited in Badruzzaman et al., 2012). The authors reported past research showed that, due to lack of proper maintenance or other reasons, substantial amounts of nutrients may exit the onsite wastewater treatment system before wastewater treatment is complete. Conventional septic systems can obtain a raw sewage treatment removal of TN by 10-25%, while a performance based septic system is capable of achieving 50-60% removal (Badruzzaman et al., 2012). Another study in Marion County, Florida showed that the majority of nitrate discharged was from septic systems, not the local wastewater treatment facility (Badruzzaman et al., 2012).

The most important pathways for vegetative uptake of nitrogen and phosphorus are via mass flow and diffusion at the roots (Badruzzaman et al., 2012). Nitrogen uptake occurs mostly by mass flow and phosphorus, primarily by diffusion. In Florida, nitrogen is the limiting nutrient; this influences fertilizer application behavior. According to Badruzzaman et al. (2012), there are few "field-scale" studies that have monitored and estimated groundwater nutrient loads resultant from residential fertilizer application in Florida.

The FDEP reported in 2011 that about 37% of biosolids production in the state is used for land application (as cited in Badruzzaman et al., 2012). Nutrient release from biosolids compared to synthetic fertilizer is yet another area where further research is. A study by Fouad et al. (2004) evaluated effects of fertilizer and alternative soil amendments, such as food compost and biosolids, on nitrogen transport in Florida; results showed TN released and leaching from composting was comparable to that released by synthetic fertilizer application (as cited in Badruzzaman et al., 2012).

In the Loxahatchee River Environmental Control District, researchers conducted a 20-year study evaluating wells near where reclaimed water was also applied to multiple locations, including golf courses, schools, parks, and residential areas (Arrington & Dent, 2008 as cited in Badruzzaman et al., 2012) (as cited in Badruzzaman et al., 2012). Arrington and Dent (2008) reported that consistent or seasonal increase in nitrate over time was found, suggesting denitrification took place in shallow soils. Denitrification may also occur in groundwater. Badruzzaman et al. (2012) reported that most Florida soils have been reported as over saturated with phosphorus. Any additional applied will most likely not be able to attenuate in the soil and will end up in groundwater. However, phosphorus in groundwater can adsorb or co-precipitate with calcium in carbonate aquifers, for example (Denver, Cravotta III, Ator, & Lindsey, 2010).

Soils high in calcium content also have some potential for precipitating phosphate and slowing its transport through a soil profile.

2.2 Analysis

In 1999, the US public was spending an average of $222 each on lawn care equipment and chemicals (Robbins & Birkenholtz, 2003). The ability to determine what factors influence higher spending and application of fertilizer products will lead to significant improvement of nutrient pollution models and possibly better strategy for nutrient management. Nutrient pollution from residential areas can be evaluated from a variety of perspectives. Some researchers have approached it by measuring nutrient concentrations in stormwater runoff, estimating nutrient loading export, measuring nutrients leaching to soil subsurface and others have modeled residential homes as a system with imports and exports. Each approach has the potential to provide different useful insights. Sampling campaigns can help engineers and scientists make informed decisions regarding nutrient exports in the form of runoff or leaching from other similar systems.

The variation of vegetative structure and dissimilarities of lawn management practices among households and neighborhoods are not well understood (Grove, Cadenasso, et al., 2006). Previous studies also could have been limited by less advanced geospatial technology capabilities. For accurate evaluation of both vegetation and social groups, high-resolution data is needed (Grove, Cadenasso, et al., 2006). No studies were identified to review in this thesis that attempted to quantify the success of seasonal fertilizer sales bans or local fertilizer education with measured nutrients in stormwater runoff. However, a group of researchers (Applied Ecology Inc., University of Central Florida Stormwater Management Academy and University of Florida Program for Resources Efficient Communities) are currently performing such a study with the support of the Tampa Bay Estuary Program. Their objective is to compare household nutrient dynamics among four different counties (Pinellas, Hillsborough, Sarasota and Manatee Counties) at different stages in fertilizer ordinance adoption. They are going to conduct surveys in each community to determine level of awareness of fertilizer ordinances and collect data on household lawn management practices. They are collecting soil and irrigation water samples from the yards of participating homeowners along with runoff samples from storm drain inlets. Laboratory results and collected data will be used to, “estimate the contribution of lawn fertilization to the community nutrient budget” and to “define residential fertilizer inputs as parameters for hydrological models” (Applied Ecology, 2011). Results are expected to be published in late 2014.

Caution should be taken when using approximations of nutrient export based on a broadly classified land use. For example, Carey et al. (2013) reports average values of 2.0 mg N L^{-1} for TN and 0.26 mg P L^{-1} for TP as typical values for stormwater concentration from urban areas in the United States. Upon further investigation, one can find that the previously quoted figures were referenced to Schueler (2003), who referenced these numbers from a 1998 update by Smullen & Cave and an EPA report from 1983. Both of the original sources compiled sampling information from over 1000 events, however, it is not clear how they defined “urban” land use at the time the origin studies were conducted. Nor was it clear if the same pollution problems, such as similar nitrogen deposition rates, were occurring at the time of these early stormwater sampling campaigns. In my opinion, based on increased automobiles on the road today (possibly increasing nitrogen deposition, particularly near urban areas) and that the ill-defined term ‘urban’ could have been applied to multiple different levels of land use (i.e. impervious surface, tree coverage, lawn coverage), it may not be accurate to declare that such median concentration values should be applied in current nutrient cycle modeling, BMP designs or policy decision-making.

Obtaining a true average of the concentration from a given storm can be estimated in different ways, but most likely requires multiple samples, each being taken in short time intervals throughout the duration of the event; a composite can be made on a volumetric basis to compare with the storm event's hydrograph or flow pattern. A statistically accurate composite sample can be difficult to obtain if samples must be taken in the field by hand. If using an automatic sampler, the composite can also be constrained by the maximum volume the apparatus is able to store. For example, in the study conducted by Toran and Gradstaff (2007), the automatic sampler capacity was utilized based on the region's average storm duration of four hours. The sampler was programmed to collect a sample every 30 minutes for four hours. Therefore, in this instance if the storm lasted longer than the average of four hours, a true composite could not be obtained because the latter part of the storm event could not be captured. Furthermore, intermittent sampling leaves open the possibility that one could miss "spikes" of pollution in the stream.

In evaluation of urban and residential watersheds, total impervious area has been used as an indicator for local aquatic health. As little as 5 to 10% total impervious area in a watershed can impair water quality, with significant degradation generally associated with 10 to 20% (Carey et al., 2013). A different metric that could be used is directly connected impervious area. This distinguishes total impervious area from impervious area, which is directly connected to the stormwater system. For example, directly connected impervious area includes streets, driveways and roofs that directly drain onto driveways or roads. Runoff from a roof that flows onto nearby pervious area that does not directly flow toward the storm system would not be included in directly connected impervious area. Although no studies reviewed for this thesis employed this metric, directly connected impervious area could be useful for fine-tuning fate and transport of nutrient in stormwater models.

Recent reviewers have focused efforts on nutrients in urban areas and its relationship to water quality and land use (Carey et al., 2013). They pointed out that the long-term nutrient cycles of a turf lawn, particularly when irrigating with reclaimed water, are not known. Currently, there are also some limitations in laboratory testing for the purposes of distinguishing nutrient origins (whether from wastewater, fertilizer, etc.). Although this expensive technology can be a useful tool to identify some nutrients' origins, there are limitations due to overlap in isotopic ranges (Carey et al., 2013).

The Baltimore Ecosystem Study was the most comprehensive, multi-faceted source for urban and residential ecosystem nutrient research reviewed for this thesis. The Baltimore Ecosystem Study, as part of the Long Term Ecological Research network, sought to contribute to the Water and Watersheds program by: applying an ecosystem approach (typically used in natural areas) to the urban setting, understanding links and feedbacks among social and biophysical constituents of the ecosystem and providing socio-ecological landscape knowledge for the betterment of Chesapeake Bay water quality (Pickett et al., 2007). This conglomerate of work produced studies evaluating multiple facets of nutrients and water quality including long-term stream monitoring (Groffman et al., 2004), social studies on determinants of lawn management practices (Law et al., 2004) and residential models of nutrient import and export (Fissore, Hobbie, et al., 2011). Additional works published by researchers of the Baltimore Ecosystem study relevant to residential nutrient pollution research include: Characterization of Households and its Implications for the Vegetation of Urban Ecosystems (Grove et al., 2006); Down by the riverside: urban riparian ecology (Groffman et al., 2003); Spatial heterogeneity in urban ecosystems: reconceptualizing land cover and a framework for classification (Cadenasso et al., 2007); Nitrogen Retention in Urban Lawns and Forests (Raciti et al., 2008); and Nitrate Leaching and Nitrous Oxide Flux in Urban Forests and Grasslands (Groffman et al., 2009).

2.3 Discussion

A compilation of nutrient concentrations in residential and urban-residential stormwater runoff compiled through this literature review are shown below in Figures 15 and 16. These figures depict average event concentrations of TN and TP, respectively, from different sites and studies. Bars shown in orange represent averages calculated for more than one location (i.e. the US). Appendix C provides a compilation of study details from multiple nutrient related research papers reviewed organized for comparison.

With the compilation figures, we can see that the highest concentrations found among these studies for TN and TP both came from the Spence et al. (2012) study. This study sampled individual lawns. These higher concentrations from individual lawns could be a result of: (1) the individual lawn care practices of the test sites, (2) geological characteristics of the study sites or (3) it could suggest that there is a diminution effect as stormwater collects and is tested at larger scales (i.e. neighborhood or watershed scale). The ranges we see of nutrient concentration from compiling, 0.33 to 6.67 mg TN L^{-1} and 0.02 to 0.92 mg TP L^{-1} show us how different various residential and urban catchments can be in terms of nutrients in runoff. This substantiates that a one-size-fits all approach for mitigating nutrient pollution in residential areas is not sensible. In addition to nutrient losses via runoff, leaching can also be a major avenue for loss. Based on Petrovic's 1990 review, which compiled information from multiple studies, nitrogen losses via leaching in turfgrass systems can range from 0 to 84%. Easton and Petrovic (2004) also reviewed previous studies and found among these studies NO_3^--N leachate concentration levels ranging from <10 to over 300 mg L^{-1}, which is influenced by fertilizer type, timing of application and the stage of turf establishment. In their sampling of turf plots treated with different types of fertilizer, Easton and Petrovic (2004) found a wide range of combined NO_3^--N and NH_4^+-N (12% to 79.7%) and PO_4^{3-}-P (9.7% to 59.8%) lost via leaching. Bierman et al. (2010) reported that 80-100% of phosphorus could leach from Kentucky bluegrass turf systems as a result of the drying and freeze-thaw cycles. For further information on nitrogen leaching loses, readers are referred to Barton and Colmer, 2006. These research findings further substantiate that depending on the soil type and grass species receiving fertilizer, there is the potential for the majority of nutrient fertilizer applied to be lost if the plot is not managed with the growth phase and irrigation recommendations correctly accounted for.

Table 1 in section 1.4 showed concentrations at which different nutrient species would begin to cause harm to various aquatic life; TN measurement does not allow us to know the different nitrogen species present. This might suggest that future research should consistently include nitrate and ammonia testing, in order to better assess an area's potential impact to water bodies from stormwater runoff. This is site specific, as some of the research previously discussed showed that the proportion of nutrient species leaving an area via stormwater are different depending on land use (forested versus residential).

As mentioned previously, for this review I was not able to locate any studies that researched linkage of fertilizer education or fertilizer ordinances directly with nutrient concentrations or loadings in residential stormwater. Fissore et al. (2011) modeled nutrient fluctuation from households using data based partly on household surveys in Minnesota. The model results indicated that phosphorus inputs could be heavily influenced by pet excreta, while fertilizer dominated nitrogen inputs. This model highlights pet waste as a potential phosphorus pollution source that may merit more investigation, but it did not have a sampling component and could not, therefore, link stormwater pollution directly to any particular behavior. Although several of the researchers (Tufford et al., 2003; Graves et al., 2004; Francey et al., 2010) employed different types of sampling techniques or sampling data to evaluate nutrient impacts from various residential areas, none of them based their research on or tied their results back to specific household/community lawn management practices, local fertilizer education or local seasonal fertilizer ordinances (though Groffman et al. used fertilizer application rates in their calculations based on a previous study's household surveys of the region).

Collins et al. (2010) evaluated current issues with nitrogen in stormwater and reviewed stormwater control measures and typical nitrogen pollution sources or causes. Importantly, they pointed out that if regulatory officials do not have a high level of concern about urban levels of a particular nutrient, it is unlikely regulatory enforcement will focus efforts in their region on ways to reduce or eliminate culpable pollution vectors. Collins et al. (2010) reviewed surveys of watershed managers from across the US who were, at the time of writing, directly involved with NPDES programs; the surveys were targeted to gauge industry workers concern about various pollutants. The poll results showed that despite the extensive problem associated with nitrogen pollution, respondents were more concerned with TSS, pathogens/bacteria and TP. Less than 4% of respondents ranked nitrate as being of highest concern among pollutants. Further, the survey revealed that although respondents acknowledged that technologies such as bioretention ponds were better at pollutant removal, they remain hesitant to recommend or implement them. Reasons for hesitation included developer lack of knowledge, unfamiliarity to local officials, local regulations and lack of confidence in long-term efficiency or maintenance. Based on the results of these surveys, there appears to also be a lack of understanding among nutrient managers as to where stormwater pollution mitigation efforts should be focused.

There are two main types of stormwater control devices commonly used for flood prevention and pollution treatment in urban and residential areas: dry detention ponds and wet retention ponds. Dry ponds are basins with outlets designed to detain stormwater runoff for some minimum amount of time; wet ponds retain a pool of water where storm water is “treated” before being displaced by additional runoff (EPA, 1999, 2006). It has been shown that dry stormwater ponds are successful at removing a large portion of solids loading, but are poor at removing nitrogen compounds. Wet ponds have shown ability to successfully remove both solids and nitrogen, depending on the setup, residence time and vegetation of the pond (Collins et al., 2010). Collins et al. (2010) briefly discussed green roofs and permeable pavements as possible means for nitrogen removal or stormwater control, however, the EPA (2008) reports that current research on green roofs’ ability to remove pollutants, particularly nitrogenous species, have yielded conflicting results and more work is needed in this area. Use of rain gardens or bioswales has proven effective for nitrogen removal, contingent on the rain garden size, residence time, infiltration media and vegetation (Collins et al., 2010). Further, grass and dry swales are able to attenuate some (approximately 45%) nitrogen for small rain events. Nitrogen removal in wetlands varies widely. EPA figures for removal rates via different types of stormwater treatment are shown in Table 22.

The analysis conducted by the Center for Watershed Protection discussed in section 2.1.4.2 attempted to use surveys to determine what avenue the public perceived as ideal for reaching them with nutrient management information; their consensus was media in the form of television and newspapers. They also surveyed program managers to find out what they thought was the best way for reaching the public and their response was educational workshops (Center for Watershed Protection, 1999). Preferences aside, neither response provides us insight into what actually works to facilitate widespread behavior change.

Table 22 Treatment Efficiencies of Stormwater Control Devices

Treatment Technology	Nitrogen Removal	TP Removal	TSS Removal
Dry detention basin/pond (Schueler, 1997 as cited by EPA, 2006)	TN: 31% NO_3-N: 9%	19%	61%
Wet retention basin/pond (EPA, 2012e)	TN: 6 to 62% NO_3-N: 7 to 97%	12 to 91%	32 to 99%
Bioretention (Rain Garden) (EPA, 2012a)	TN: 49% NO_3: 15 to 16%	65 to 87%	-
Shallow Marsh (EPA, 2012d)	TN: 26 to 49%	40 to 43%	51 to 83%
Extended Detention Wetland (EPA, 2012d)	TN: 56%	39%	69%
Submerged Gravel Wetland (EPA, 2012d)	TN: 19%	64%	83%

Of those who conducted surveys seeking details on household lawn maintenance practices, not all of them collected details on homeowners education level. Nielson and Smith (2005) noted that in their survey campaign, people with a higher education level were more likely to respond; they received responses from a higher percentage of college educated than the percent of college educated in the overall watershed. The survey results from Nielson and Smith (2005) were not able to correlate education level with fertilization practices. Also, Grove et al. (2006 and Giner et al. (2013) did not find a correlation between education level and vegetative cover. Troy et al. (2007) completed the only analyses reviewed for this thesis that showed a positive correlation between education (high school graduation rate) and a lawn maintenance characteristic (realized stewardship).

Urban and residential watersheds are often a heterogeneous mixture of land uses, regularly contain some combination of single-family residential, multi-family residential, commercial or industrial land uses. Residential landscape features, vegetative species and vegetation densities are highly variable. In US residential areas there is a significant variation among tree canopy coverage, from as low as 0.4% in Lancaster, CA, to as high as 83% in Corvallis, OR (Poor & McDonnell, 2007; Troy et al., 2007). While aggregating similar and pertinent studies, I found that it is a substantial stretch to attempt to directly compare among stormwater nutrient pollution studies because there is currently no consistency or uniformity in: sampling techniques, laboratory testing, selection of nutrient species for analysis, or in the recording of pertinent, potentially influential geological, meteorological and land use characteristics of the study area. Each watershed has its own unique topography including impervious surface, soil characteristics (such as depth of permeable layer), vegetation, evapotranspiration rates, lawn management habits, and weather patterns such as antecedent dry period, all of which can impact stormwater quality and quantity. Due to the site specificity of nutrient pollution impacts from residential and urban areas, prediction of pollutant loading and recommendation of control measures can prove difficult (Brezonik & Stadelmann, 2002).

For many studies evaluating nutrients, TN and TP were the primary focus. The reasoning for not testing specific species could have been motivated by budget constraints or to avoid the complexities associated with nutrient cycling (Robinson & Melack, 2013). TN and TP were considered favorable for modeling because they have exhibited less seasonal variation than specific N and P species (Robinson & Melack, 2013). Nitrate and soluble reactive phosphorus may be better indicators for potential stream health due to their bio-availability, but there is not consensus in the community on taking this approach.

It has been suggested by multiple researchers that intensity and duration of a precipitation event can impact the amount of nutrients exported from the catchment. These scenarios can be highly dependent on antecedent dry days, which allow for extended accumulation of nitrogen deposition and other pollutants on impervious surfaces that can then be dislodged and carried away by a precipitation event. Marsh (1993) explained that a storm that takes a longer amount of time to deposit an equal amount of rain will allow time for more infiltration, storage and evaporation, which has subtle implications for the movement and fate of nutrients. Accounting for subtle potential influences such as this requires a more detailed view compared to solely an import, accumulation and export view. Intense storms are capable of dislodging more pollutants from surfaces, but such storms also create greater runoff volume. It is highly situation dependent, but the runoff volume can be commiserate with the input of pollutants into the receiving waters (Marsh, 1993). Understanding and having access to the details of these conditions is crucial for the correct interpretation of nutrient concentration or loading data. For instance, smaller than expected nitrogen concentrations in a sample can be related to increased frequency of rainfall events, indicating more frequent washing away of nutrients (Spence et al., 2012).

Season of evaluation can be extremely important from two different angles. Homeowners in different geographic regions may have a propensity to fertilize their lawns at particular times of year. Several of the studies which conducted household surveys reviewed asked homeowners about how many times they fertilized per year, but neglected to ask about timing of fertilization. However, the Center for Watershed Protection (1999) found that homeowners in the Chesapeake Bay region preferred to fertilize in the spring, with the second most popular time to fertilize being fall. If researchers sample stormwater in such a region around the season of common fertilization or during the season when fertilizer application is rare, they will likely sustain very different results. This temporal, social consideration is critically important to place in the correct context. Second, different geographic regions have their own set of common meteorological patterns for rainfall, intensity, rainy versus dry seasons, etc. This is also crucial for researchers to capture in their work as a long dry season could mean high accumulation of atmospherically deposited nutrients or rainfall patterns and intensities could have other implications for the washing away of the nutrients under evaluation.

Not all lawns are managed the same way in terms of fertilization and irrigation; lawn characteristics also diverge in vegetation densities, ages and types of vegetation. This is a multi-layered, complex system and variations of such systems can have implications for nitrogen and phosphorus exports. Different types of lawn cover, such as trees, have been shown to have varying capacities at intercepting nutrients (Poor & McDonnell, 2007). Researchers have also explained that topography (slope) and geology also play important roles in the transport of nutrients and sediments to streams (Basnyat, Teeter, Flynn, & Lockaby, 1999). Soil characteristics could explain some differences in reactive phosphorus attenuation. Allophanic soils (a type of volcanic ash) in a New Zealand study area tested by Williamson (1986) had higher phosphorus retention than the dominant soils in other nearby catchments. Such a scenario could account for lower phosphorus levels in receiving water bodies. Based on other research, the age of establishment of lawn turf has also been show to have correlations with export of fertilizer nutrients (Schuchman, 2001). Still another area for fluctuation is the homeowner's decision to dispose or keep lawn clippings and leaf litter on site. This is a source of natural fertilizer, but also a potential source of nutrient pollution from decaying detritus.

Extensive impervious areas disrupt the hydrological cycle in urban watersheds, possibly contributing to enhanced nutrient transport (Carey et al., 2013). Highly developed residential catchments or urbanized residential areas demand special considerations in stormwater research. Historic burial of streams can influence groundwater movement and patterns, which has implications for nutrient leaching. Also, consideration should be given to the type, age and state of stormwater controls in place. Storm flow in storm sewer systems may contain infiltration from groundwater sources (leaky pipes) or surface water from lakes, ponds or wetlands that makes its way into the system (Janke et al., 2013). There is a gap in knowledge regarding the interface of surface water and the water table or about the processes and implications of surface and subsurface residence time on nutrient transformations (Tufford et al., 2003). A good example of this is the use of reclaimed water, which may have implications for watershed nutrient exports (Carey et al., 2013). Movement of nutrients originating from reclaimed water irrigation is not yet entirely understood. Like with fertilizer, turf and vegetative nutrient uptake could be improved by having detailed knowledge of the nutrient content in the water and the nutritional requirements of the landscape at hand (Carey et al., 2013).

Different sampling frequencies were selected for different reasons. Some studies only sampled storm flow or baseflow; some pulled samples from both. Those who looked at storm flow may have evaluated the first flush, taken multiple samples throughout the entire event, formed composite (average, blurs spikes) samples or facilitated some type of conglomeration of these. Further, researchers in different studies employed different rules to dictate what constituted a legitimate event from which to pull samples. Some rules were based on the length and magnitude of the event compared to the regions average precipitation events, while others were based on the flow of the stormwater generated in the pipe or stream in question (Janke et al., 2013). As mentioned, the findings of Toran and Grandstaff (2007) and Francey et al. (2010) suggested that evaluation of first flush samples may not be appropriate for all catchments;

therefore, caution should be taken when initially studying an area, not to assume that nutrient pollutions from the area will necessarily display a first flush exit pattern.

Researchers can be limited by funding or time. This could be, in part, why available storm water nutrient research varies widely in length of sampling campaigns, number of sites evaluated, types of sites investigated, sampling methodologies, etc. Some have sampled multiple locations, but were limited with time and not able to capture a full year to evaluate all seasons. Some have sampled fewer sites, but for longer periods of time, potentially lending to a better understanding of seasonality and meteorological impacts in the watershed at hand. Other funding limitations might have dictated methodology in the sampling process. Some researchers were able to employ automatic samplers pre-programmed to activate for their own definition of an event. Others conducted sampling by hand. Scrutiny of specific laboratory methods and statistical methods used by each individual research paper was beyond the scope of this work.

This thesis synthesized literature that addressed social implications on lawn management, modeled nitrogen and phosphorus movements within residential areas and conducted and analyzed samples for nutrients in stormwater from residential and urban areas. Through this review, I have identified some of the limitations of current residential lawn management practices and nutrient management education programs' room for enhancement. I have found stormwater nutrient management knowledge gaps and also areas where there is room for improvement in how future researchers, who wish to approach topics similar to those discussed, can improve upon past research methods. I describe these findings and recommendations in Chapter 3.

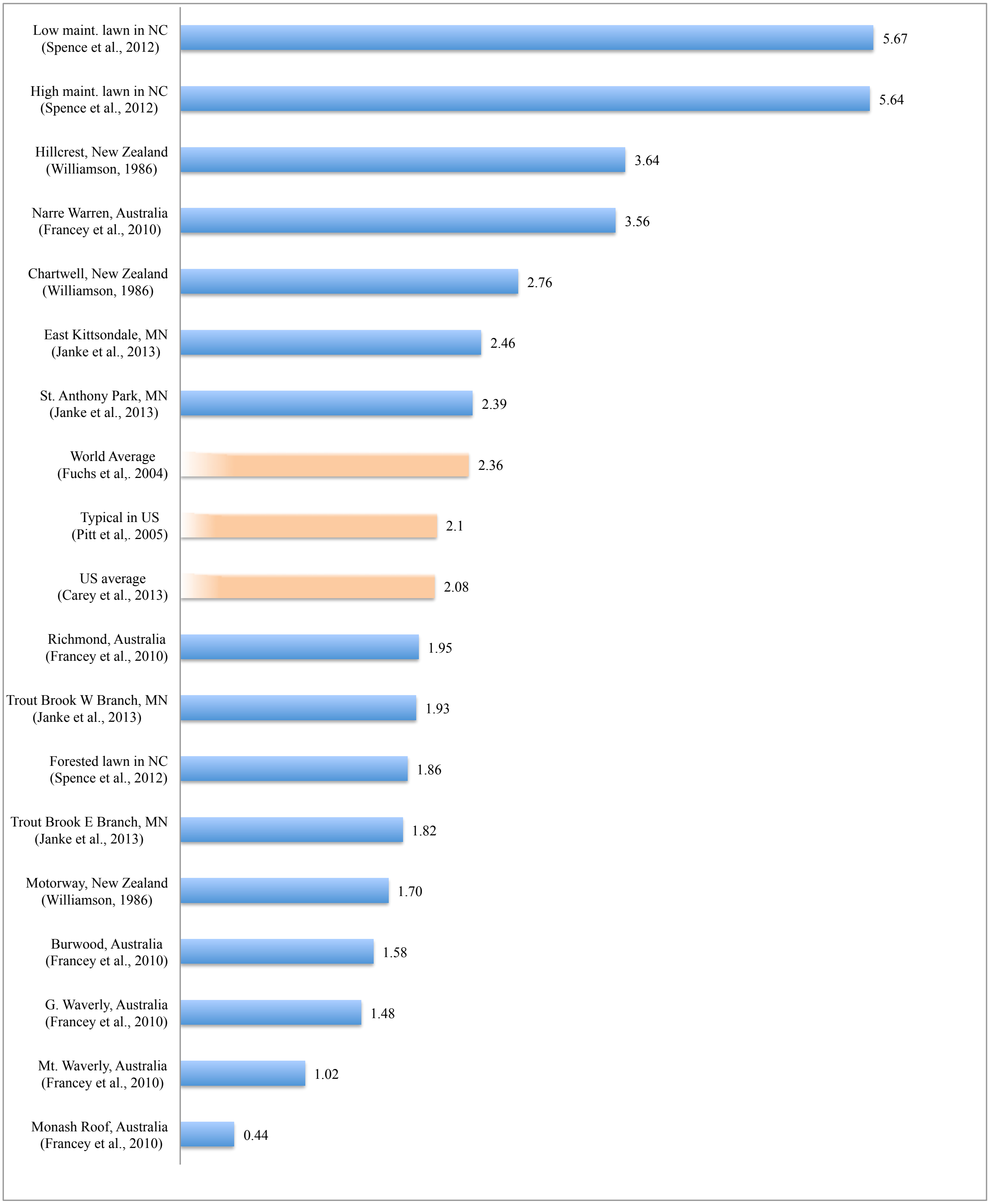

Figure 15 Compilation of Average TN Concentrations (TN mg/L) Measured in Stormwater Runoff from Multiple Locations (averaged over multiple storm events)

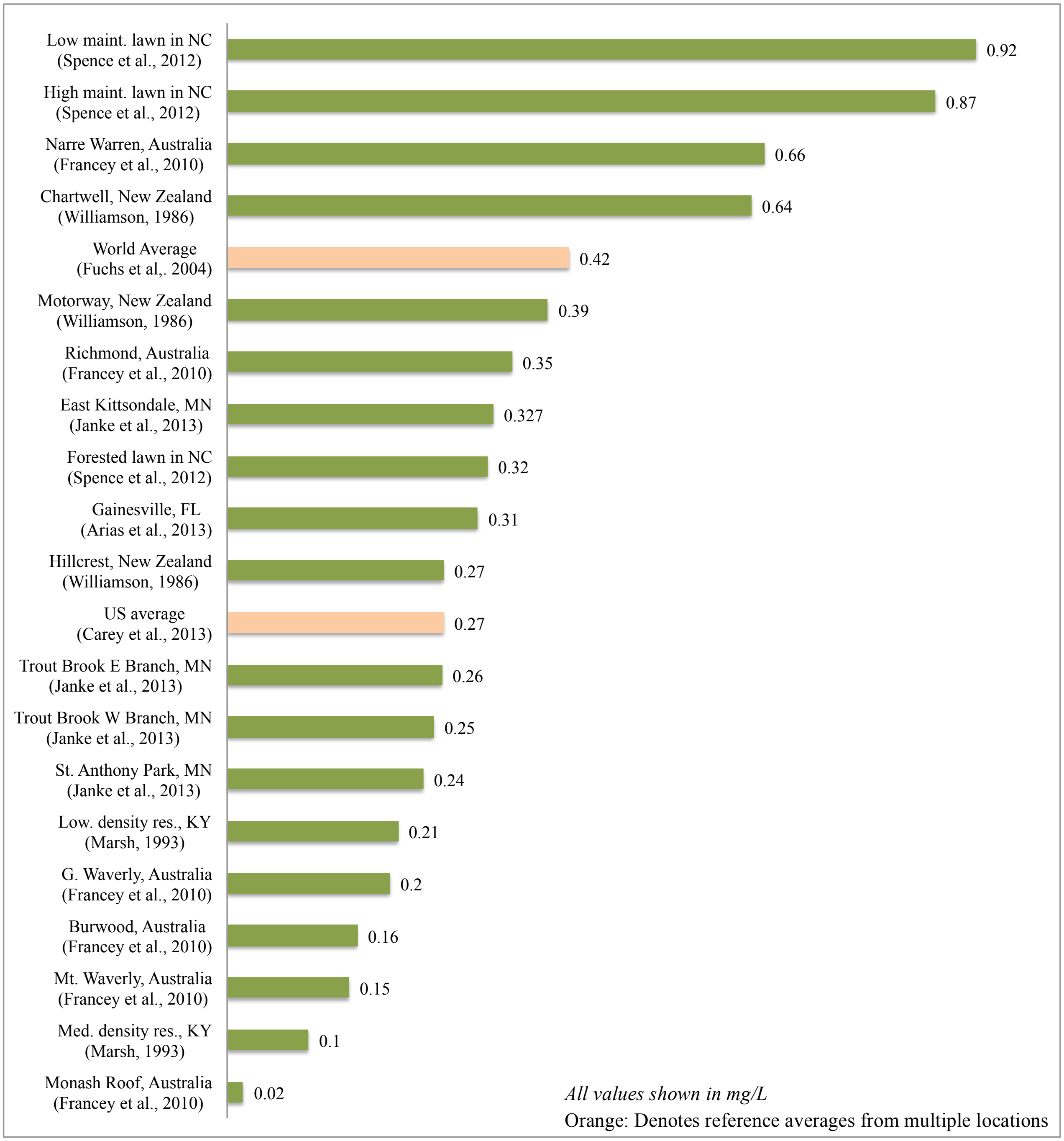

Figure 16 Compilation of Average TP Concentrations (TP mg/L) Measured in Stormwater Runoff from Multiple Locations (averaged over multiple storm events)

CHAPTER 3: CONCLUSIONS AND FUTURE RECOMMENDATIONS

The objective of this critical literature review was to synthesize existing literature and data to evaluate concentration or loading of nitrogen and phosphorus associated with stormwater originating from residential areas. I learned that the circumstances under which nutrients end up in stormwater runoff are many and varied. More importantly, the temporal and spatial context (to include meteorology, geology and anthropogenic influences) of the system is highly impressionable upon the fate and transport of the nutrients in question. Therefore, even identical residential areas with identical fertilization practices would produce different nutrient concentrations in runoff if located in two different places with dissimilar climate and geology. Due to high variability in stormwater characteristics by location, I emphasize the need for a thorough evaluation of local data to execute successful watershed management (Brezonik & Stadelmann, 2002).

Through compilation of research and studies conducted on turfgrass, I found that leaching through the soil profile is an extremely important avenue for nitrogen loss (and sometimes phosphorus loss), which should be considered when evaluating fate of applied fertilizer; this pathway cannot be ignored when modeling nitrate in a turfgrass system. Based on the work by Easton and Petrovic (2004), phosphorus leaching may also be a very important nutrient loss pathway when using natural (biosolid) fertilizer. Fertilized turfgrass does not necessarily always pose a severe environmental threat if managed precisely, with understanding of fertilization and irrigation practices on nutrient cycles. However, based on survey results, this is not the level of understanding that most US homeowners possess (Center for Watershed

Protection, 1999). There is some conflicting information regarding the magnitude of the role that lawns play in P runoff. Shaprit and Pfannkuch (1973) concluded street sweeping would reduce P load more than removing P from local lawn fertilizer, however exact percent reductions were not provided (as cited by Bierman et al., 2010).

Turfgrass and lawn leaching can have water quality implications outside of stormwater runoff. Nutrients can leach from the upper soil layer beyond the point that roots have access to absorb it and eventually end up in groundwater. Management practices that maximize contact time between applied nutrients and upper rooted layers of soil should increase vegetation uptake; this should decrease both leaching and runoff potential (Barton & Colmer, 2006). Any new recommendations, however, must be presented with evidence showing that the practice will not deteriorate the quality of the managed turf, otherwise lawn managers are not likely to adopt such measures enthusiastically (Barton & Colmer, 2006).

3.1 Current Stormwater Evaluation Practices

Based on compilation of social and demographic surveys and studies on lawn management practices, there appears to be a lack of attention given to determining what municipality (or non-profit) strategies are actually successful at facilitating behavioral changes that can mitigate environmental problems. Based on the survey conducted by the Center for Watershed Protection, which obtained practitioner responses from 35 states, it appears that managers at the ground level have misdirected priorities in terms of stormwater nutrients, however, this phenomenon would require more investigation (as cited by Collins et al., 2010).

When employing models, it is important to remember that they are only as good as the accuracy of their assumptions. Depending on the detail level of a stormwater model for a watershed or lawn assumptions must be made for: rainfall abstraction, infiltration (based on soil type, rainfall intensity, etc.), health and density of lawn turf and vegetative cover, deposition estimates, impervious or effective impervious surface cover, lawn clipping/leaf litter degradation rate, and the intensity and ubiquity of fertilizer application (Baker et al., 2008). These are just a few of the basic factors that should be taken into consideration, but as with any assumption in a model, there is an associated inherent degree of error.

Watershed managers need tools that allow them to estimate nonpoint source loads entering lakes and streams; this need has helped drive interest in predictive modeling based on previous events. Stormwater characteristics (such as rainfall intensity, storm duration, frequency, etc.) in addition to pollutants (often nitrate and ammonium) already present in rainfall can potentially influence nutrient runoff (Brezonik & Stadelmann, 2002). Land use, land cover, and land management can each cause significant effects on a watershed and its hydrologic behavior. The affects of land use on nutrient dynamics and concentration patterns during storm events are not well understood (Poor & McDonnell, 2007). Land management practices can be highly variable among different homeowners. When evaluating nutrient loading in watersheds at a macroscale, most researchers are forced to assume some amount of heterogeneity for the purposes of analysis. Such assumptions, can hinder or undermine the efficacy of regression analyses (Tufford et al., 2003). A widely used classification system for describing different types of residential and urban land uses is needed in order to effectively connect land use patterns to nutrient loading in stormwater.

Through compilation of models evaluating nutrient cycles in urban and residential watersheds with sampling campaigns targeting nutrients in stormwater, I found that the mass balance modeling approach is unwieldy for stormwater pollution fate analysis. Such models can, however, allow for the identification of inputs that need to be reduced or require more in depth investigation (for example, dog excreta identified in the Fissore, Hobbie et al., 2011, study). As such, these models can be important mitigation tools. However, they are not currently able to predict at a fine scale the fate of nutrients, whether it be in vegetation, runoff or leaching. Research that employed statistical methods for finding correlation among different pollution influences could prove useful for identifying specific sources or behaviors that require alteration. These methods might also be successful at developing relationships between pollution loads and characteristics that can later be used for their predictive capability (Francey et al., 2010). There are practical advantages in the ability to predict pollutant loads using widely available indicators such as rainfall. Research has shown, however, using a metric such as rainfall intensity does not always correlate with nutrient export, indicating that there are other causal factors for specific pollutants, which do not lend to simple prediction capabilities (Francey et al., 2010).

There is consensus among researchers that forested and undeveloped areas are better at retaining nutrients than developed residential, urban and commercial catchments (Carey et al., 2013). Basnyat et al. (1999) wrote that previous researchers in the 1970’s and 80’s attempted to establish a link between land use/land class with water quality, but were unsuccessful; regional characteristics may have prevented these researchers from finding the necessary links.

Due to the wide variety of deleterious environmental impacts of nutrients and known limitations of phosphorus supply and its impacts on food production, developing nutrient recovery methods and technologies is crucial. Current phosphorus mining and the phosphorus cycle within agriculture is extremely inefficient, with only about one fifth ending up in food that makes it to consumers (Cordell, Rosemarin, Schröder, & Smit, 2011). Like other technological ventures, achieving true sustainability must take into account life cycle analyses, embedded energy and the technology’s accessibility to those who need it.

At the time of writing, it appears as though there is a gap between clear understanding of nutrient export from urban and residential areas to water supply. An enhanced understanding of modern nutrient movement in urban and residential areas is necessary to successfully drive regulation and policy for protecting water bodies from polluted stormwater and to protect groundwater from pollution leaching. Based on the Dietz and Clausen (2008) study comparing a LID housing development to a traditional development, LID construction practices and designs may hold great promise for curbing stormwater pollution and protecting water bodies. As such, policy makers should collaborate with managers and municipalities to produce incentives for development with LID techniques. More research of similar subdivision or watershed comparison studies may be necessary to determine if the LID systems are truly able to retain nutrients (such as in plant biomass) or if the low stormwater nutrient concentrations in such catchments are, in part, a result of excess nutrients lost to leaching.

3.2 Key Knowledge Gaps in Existing Literature

Areas requiring additional research were identified by Carey et al. (2013) as: quantifying nutrient sources and sinks in urban watersheds, substantiating optimal management strategies, further develop understanding of atmospheric deposition, identification of attenuation factors for septic system discharge, and continuous in situ monitoring in areas to investigate multiple ecosystem processes and impacts simultaneously. To this I add that the success of researchers who hope to correlate a residential land use classification to a particular pollutant impact will hinge on employing a more fine scale classification tool for land use. I recommend the tool proposed by Cadenasso et al. (2007), which is described in section 3.3.1.

Currently, there is a gap in research that combines the social characteristics of a watershed with nutrients in stormwater runoff or nutrient leaching. It could serve the scientific community and policy makers if studies in different regions addressed this gap in order to better understand what social factors influence nutrient pollution and what behaviors might be important to target in different communities. Pollution prevention and source reduction should be preferred over alternative management techniques. Reaching and changing influencing factors of high contributing households is an important aspect of effective watershed pollution management. If specific social or demographic factors that tend to be correlated with high nutrient pollution could be identified, more targeted efforts could be taken by nutrient management programs, which are often operating with small budgets.

Investigation that combines nutrient pollution monitoring with implementation of different educational campaigns to determine which programs are truly effective at altering consumer behavior. Future research should be geared toward concerted research efforts that amalgamate socio-demographic behavior effects on diffuse nutrient pollution and quantifying successful programs for altering consumer behavior (with fertilizer practices and other impactful actions). The Center for Watershed Protection (1999) surveys touched on what outreach citizens and managers believe to be most effective, however, no research was identified in this review that attempted to quantify or verify the effectiveness of particular educational or nutrient management programs in residential areas.

There is a gap in research for models developed to predict nutrient lost to runoff and leaching from different soil types and turf grass species. This research should be pursued with consideration for the region’s climate, vegetation species’ growth periods and other impactful factors factors (e.g. runoff during freezing periods, water table characteristics, meteorological details such as antecedent dry days before storm events). Studies that monitor an entire residential system by measuring losses to leaching, runoff and volatilization should contribute greatly to the understanding of nutrient cycling and nutrient loss from turf grass and other traditionally managed residential systems.

3.3 Recommendations for Objectives of Future Research

In this review, I have synthesized information from different approaches to diffuse nutrient pollution research, namely: socio-demographic influences on impactful decisions, quantification based on modeling approaches and quantification based on various sampling approaches. Urban ecology research is shifting focus to, "the fine-grain heterogeneity of human behavior and ecological patterns and processes in densely settled areas" (Grove, Cadenasso, et al., 2006). Significant attention should be given to the design and implementation of stormwater nutrient sampling and monitoring in order to begin collecting watershed status reports that can be compared among watersheds. Using automatic sampling equipment that can take small samples of flow at short intervals allows for creation of a time continuous representation of various nutrients juxtaposed with the storm event hyetographs and hydrographs. This should allow for more in depth evaluation of the various nutrients contributing to baseflow versus storm flow for the catchment in question. In addition, measurements of vegetation structure and biodiversity, climate, water quality and soil quality data should be assessed and recorded for a comprehensive view of the system; these details will provide a better understanding of the nutrient cycle within the watershed at hand.

3.3.1 Land Classification

Cadenasso et al. (2007) developed a new classification system for urban and residential areas that accounts for natural features (vegetation structure) and anthropogenic components (buildings, pavement, and bare surfaces). Vegetation, surfaces, and buildings vary in ways that affect hydrology and nutrient cycles. The land classification system they developed permits modeled capture of integration among anthropogenic and natural features. I believe that if this classification is employed extensively in urban/residential stormwater studies, it could accelerate our understanding of nutrient import, attenuation and export by delineating heterogeneous urban landscapes. This land use delineation should result in more specific correlation findings between a given land use or characteristic and specific nutrient impact. In turn, new discoveries will guide better decision-making for implementation of management practices.

Residential areas differ extensively in more ways than just building density. It would be ideal if a classification were adopted for wide use in such studies to allow easy comparison among the research community. The best proposal I found in this review was the High Ecological Resolution Classification for Urban Landscapes and Environmental Systems (HERCULES) tool presented by Cadenasso et al. (2007); their work was a result of one of the Baltimore Ecosystem Study initiatives. The classification tool entails six classification "dimensions": coarse vegetation, fine vegetation, bare soil, pavement, building proportion and building type. To illustrate, Figure 17 shows four areas that would be classified as residential, but have obvious characteristics that have implications for stormwater behavior, such as impervious area, housing density, tree density and turf coverage. Arguably, 17a could even be lumped in with urban classification as a suburb. These distinct residential areas are, however, readily distinguishable using the HERCULES tool. Cadenasso et al. (2007) explained that, "(a) and (b) are differentiated by building density, although coarse vegetation density is the same; (c) and (d) are differentiated by density of coarse vegetation, but building density is the same in the two panels."

Even so, I must reiterate that not every watershed will have only one type of land use. A watershed can have some combination of highly urbanized, residential, agriculture or undeveloped land, as alluded to by some studies that record characteristics like percent residential and percent forested. Some past studies did not distinguish urban from residential, but considered residential to be a component within the urban classification. Catchments with multiple land uses necessitate further investigation of the seasonality of pollutant dynamics during storm events to accurately interpret the behavior of solutes (Poor & McDonnell, 2007). Baker et al. (2001) suggested that the most effective nutrient management strategies should be purposely tailored to individual ecosystems; this means the watershed manager must have an understanding of the area's soil characteristics, climatic factors and other catchment characteristics that influence nutrient fate.

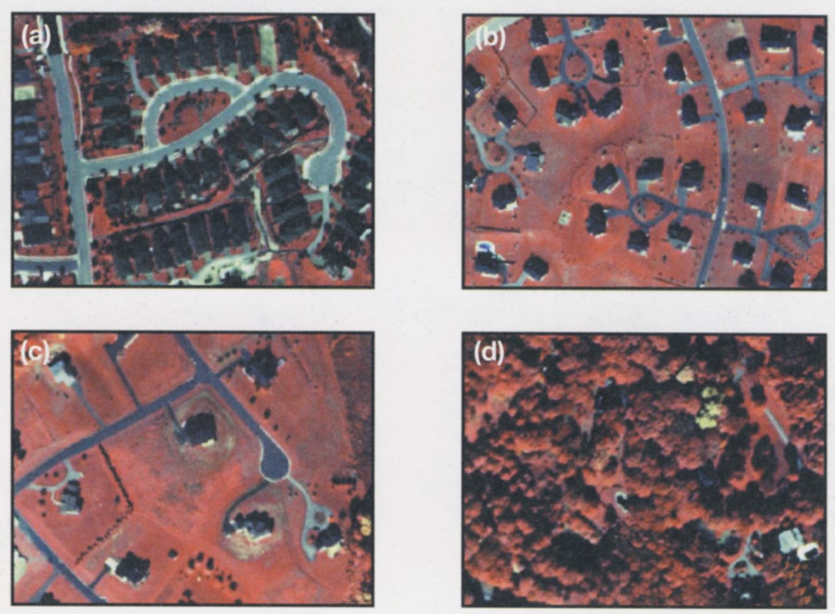

Figure 17 Residential Areas Distinguished by HERCULES (from Cadenasso et al., 2007)

If our ultimate goal is to control diffuse nutrient pollution exiting from residential lawns and ending up in a water supply, there must also be an accounting for losses by soil leaching. More research is needed on turfgrass species commonly cultivated in residential lawns along with other lawn vegetation species to determine potential for nutrient leaching in different soil types (Barton & Colmer, 2006). Different turf species grown in different soil types throughout the different phases of life establishment and season should be carefully evaluated for fertilizer loss potential. After this, better recommendations can be made for fertilizer and irrigation practices catered to specific regions and situations.

Barton and Colmer (2006) concluded that, “the main strategies for minimizing N leaching from turfgrass are (i) optimize irrigation regimes, and (ii) ensure N is applied at rates and frequencies that match turfgrass demand.” This puts a burden on the success of nutrient education programs and outreach campaigns, which are currently managed primarily by local municipalities with annual budgets between $1,000 and $25,000 (Center for Watershed Protection, 1999). With such a limited budget, program managers should be executing education efforts that are lean and most effective at reaching the public.

Districts with limited budgets attempting to address nonpoint source pollution may consider different types of campaigns to reach their public. I recommend that any program manager wishing to implement a highly successful fertilizer behavioral change in a community ignore surveys that focus on emotional responses such as how the public *believes* they want to receive nutrient management information or questions directed at program managers querying what they *think* is the most effective approach for reaching the public. Such information does not address the more important we should be asking – what nutrient management public campaigns have successfully brought awareness and facilitated behavioral change to a large number of people in a given area? To answer this, I am suggesting that the best approach is to turn to similar campaigns that have been successfully implemented and are thriving. Marketing strategists, who have already been researching the psychology behind behavioral modification, are likely to have studied and published case studies on such efforts and the reasoning behind their success. Nick Laurell presented a comparable case study; Los Angeles Rainwater

Harvesting executed a campaign to compel community residents to install rain barrels. It was so successful that they exceeded their signup goal of 600 residents by 500% and ran out of rain barrels. They accomplished this by employing techniques of “social-norm” marketing, which operates on the theory that what the public perceives as “normal” is more likely to change their behavior than personal priorities or preferences (Laurell, 2014). I believe this is substantiated by the surveys reviewed in this study, finding that homeowners are heavily swayed by the look of their lawn and how they think their neighbors perceive it. If they perceive their neighbors as endorsing rain gardens and other effective nutrient management strategies, implementation of community change should be easier. This highlights the possibility that environmental managers may have been taking the wrong approach and asking the wrong questions when trying to instill widespread behavioral modifications for environmental improvement. I am advocating that rather than asking “how do residents *want* to be reached,” we should instead ask, “what techniques have been successfully demonstrated to instill behavioral change for environmental improvement?” and proceed by employing techniques uncovered by the latter.

Robbins and Sharp (2009) pointed out that those behind fertilizer marketing see great sales opportunity in knowing that 30% of Americans are not yet conducting any type of lawn maintenance. I propose that watershed managers also view this as an opportunity. This is a large number of households that can be targeted for education before residents establish habits based on fertilizer company marketing. Without such a movement, watershed managers should anticipate that the public eye will first be captured by fertilizer companies with biased motivations for recommending frequent fertilization. It does not take long to find one major fertilizer company’s recommended fertilization webpage (The Scotts Company LLC, 2014), which endorses lawn owners to fertilize intermittently throughout every season of the year. In the interest of environmental and water protection, it would be better for policy makers and environmental managers to educate the public prior to homeowners finding such recommendations.

A potential cost saving measure for watershed managers could be to focus on the most probable culprits of poor lawn management practices with high nutrient export potential (Baker et al., 2008; Nowak, Bowen, & Cabot, 2006). A targeted approach may save money in the short term, however, long-term implications have not been studied. It would be worth evaluating whether such an approach sacrifices the opportunity to educate and change behaviors of many, leading to greater improvement impacts for years to come.

Osmond and Platt (2000) suggested that non-turf vegetation should be grown near impervious areas because non-turf pervious areas were rarely fertilized. This could decrease the possibility of fertilizer landing on impervious surfaces at the time of application and also provide a type of buffer area that may act as a nutrient sink between fertilized turf and an unfertilized area. This method could be explored in future research and could be a component of recommendations made to the public through nutrient management outreach programs.

Another important aspect of nutrient management was emphasized in a review by Hassett, Palmer and Bernhardt (2005). The authors reported that river restoration has increased in the United States in an attempt to repair degraded streams and improve coastal water quality. Healthy streams are an important component of the nitrogen cycle, potentially facilitating various avenues of treatment and removal. Large amounts of money (in excess of $400 million since 1990) have been spent, specifically in the Chesapeake Bay region, to restore stream and riverine water quality. These efforts have included implementation of riparian buffer zones and other strategies thought to provide protection against nutrient pollution impacts on water quality.

Only a small percentage of these projects, less than 10%, recorded performance-monitoring efforts. Improvements can be difficult to quantify; the effects of some restoration efforts may not be measurable until a decade or more past implementation. This is further complicated by the fact that during that time, urban development does not stop. Hassett et al. (2005) proposed that budget for tracking efforts should always be included in mitigation efforts. Hassett et al. (2005) suggested three components to critical record keeping to this end: (1) cataloging project location data; (2) implementing consistent project performance evaluations; and (3) analyzing data from individual project monitoring. Quantifying the success of mitigation measures is important to verify that efforts are carrying out their intended purpose and to allow for future engineers and scientist to improve upon past efforts.

3.3.2 Best Management Practices

Researchers have concluded that there are a number of technologies, land use practices and conservation efforts that can decrease nitrogen and phosphorus movement to surface waters (Carpenter et al., 1998). Techniques as simple as leaving grass cut to higher lengths has been shown to reduce nutrient loss from turf systems (Toran & Grandstaff, 2007). When developing strategies to reduce overall nutrient transport to water bodies, analysis of the relative contribution of various sources should be conducted (Carey et al., 2013). Best Management Practices must include sufficient management of point and nonpoint sources alike to protect the integrity of groundwater, which may heavily impact baseflow (Janke et al., 2013). To achieve optimal reduction of nutrient pollution, some combination of source reduction and management structures/technology may be necessary. For effective stormwater treatment, structural BMPs must be able to tolerate fluctuation in both volume of influent and concentration of various pollutants. At the city or county level, planners and decision-makers should evaluate all options for passive stormwater treatment such as stormwater ponds, and constructed wetlands. Constructed wetlands differ from stormwater ponds in that they often incorporate selected vegetation for water treatment and removal of multiple pollutants (Lee, Scholz, & Horn, 2006).

Successfully employed natural stormwater treatment systems include fiber filters, deep bed filters and biofilters. These natural technologies can achieve a relatively high pollutant removal, which is necessary for typical infrastructure (Aryal et al., 2010). Collins et al. (2010) recommended future research focus on the development of design criteria for those technologies, which have proven more capable in terms of stormwater treatment, such as bioretention, filters and constructed wetlands. The wide range of N removal efficiencies of the various treatment and control technologies indicate that additional research is needed. Future research should test other disciplinary design approaches, such as onsite wastewater treatment, incorporation of hydrologically connected floodplain/wetland denitrification hot spots into stream restoration, and denitrification barriers to mitigate edge of field nutrient releases in agricultural settings (Collins et al., 2010). Also a nutrient removal performance analysis of manufactured treatment devices, which are used in conjunction with traditional stormwater treatment, was completed by Sample et al., (2012). The effectiveness and cost benefit analysis of such technologies should be executed to determine the nutrient removal value and potential scalability for use in residential areas.

Local governments should encourage their local citizens to leave lawn clippings and leaf litter on lawns while simultaneously enforcing bans on blowing leaves and litter down storm drains. This should be done in conjunction with education on how lawn clippings act as a natural fertilizer, and therefore synthetic fertilizer application can be reduced. An ordinance alone is not enough, it must be enforced at some level. Leaving lawn clippings on the lawn is one of the simplest ways to provide vegetation with a natural fertilizer and reduce landfill input (Guillard & Kopp, 2004). Layers of detritus on lawn can reduce the volume of runoff by intercepting a fraction if rainfall, which could also decrease loads (Spence et al., 2012). Further, Kopp and Guillard (2001) conducted a field study (near Hartford, Connecticut) on turfgrass that showed that returning clippings to a lawn reduced the need for nitrogenous fertilizer by as much as 50% and often improved (never deteriorated) the quality of the turf growing. More research is needed, though, on the amount of phosphorus and nitrogen pollution that may exit different types of residential areas that leave grass clippings or leaf litter on lawns.

Based on the study by Dietz and Clausen in 2008, low impact development techniques might prove to be some of the most exceptional tools for curbing stormwater impacts to local water bodies, particularly in new single-family housing developments. This review did not encompass an analysis of the feasibility of employing LID in already developed regions or in various other types of residential settings. Managers seeking to employ LID techniques should seek guidance from previously conducted research and resources such as the EPA, county extension programs and programs such as the Florida-Friendly Landscaping Program. Because stormwater management and treatment can improve quality of life for a community, such as by creating aesthetically pleasing green space, managers should guide a shift in view of stormwater management to where it is viewed as a component of ecosystem restoration in urban environments that can improve the aesthetic value of infrastructure. Obtaining community buy-in may become more important as weather pattern changes and sea level rise associate with climate change intensify, the importance of pollutant loading from residential catchments may change or intensify (Collins et al., 2010).

The ability of green roofs to serve as a way to reduce nutrient pollution is not entirely understood; research results have varied. In some regions that receive high amounts of rainfall, green roofs have been shown to have a higher net export of nutrients (Carey et al., 2013). Other research, by Czemiel Berndtsson et al. (2006, 2009) reported that green roofs in Sweden and Japan were net sinks for most N species (as cited by Collins et al., 2010). If green roofs are found to effectively management nutrients, this may be a design feature to regularly employ in future residential development projects.

Permeable pavement is being explored now for possible utilization on a wider urban scale. It is generally constructed of paver blocks infiltration can occur between the blocks. High infiltration rates are achieved due to coarse aggregate underneath. Issues associated with the use of permeable pavement can include polluting soil by deterring contaminated storm water to lower soil layers, pavement clogging by particulates and decreased durability compared to traditional pavements. Analysis of pervious pavement applications are available by Jayasuriya et al. (2007), Kadurupokune and Jayasuriya (2009) and Newcomer et al. (2014). As a component of Low Impact Development Design, this technology can be an effective component of residential nutrient management.

3.3.3 Facilitating Consistency

Specific recommendations on which nutrient species are ideal indicators to test for in stormwater are not yet widely agreed upon in the scientific community (Toran & Grandstaff, 2007). The research reviewed in this study also calculated and reported nutrient export in a variety of ways (concentration, loading, yield). The current lack of consistency in research approaches evaluating nutrients pollution from residential stormwater runoff makes interpretation and practical application burdensome, particularly when trying to make comparisons among multiple study efforts. Therefore, I recommend adoption of standard details that should be recorded for future stormwater nutrient research (Table 23). Consistency will aid not only for comparative purposes, but it will also provide a more complete view of the setting's characteristics that may be impacting the system's nutrient cycle. Column two in Table 23 outlines additional recommendations that should be considered, time and budget permitting.

Table 23 Suggested Documentation and Analysis Criteria for Future Research

Critical characteristics to record in future residential stormwater nutrient research	**Additional recommendations**
• Coordinates of sampling site • Season and date of sampling • Sampling site's soil type • Vegetative species in catchment/lawn • Street canopy fraction • Percent impervious surface in catchment • Percent of catchment under construction during time of sampling • Number of homes on septic in catchment • Site specific meteorological data o Antecedent dry days (prior to sampling) o Average annual rainfall o Specific storm event characteristics (e.g. duration, intensity) o Description of any outlier storm events • Conduct sampling and analysis of the storm event's rainwater to capture background pollution present prior to formation of stormwater runoff. • Automobile traffic density of the area	• Record current details specific to the study catchment: percentage of households employing lawn service, fertilizer frequency practices, the time of year residents/lawn companies are fertilizing, local fertilizer education programs and local fertilizer ordinances. • Use automatic samplers. Calibrate sampling based on your region's typical storm characteristics and consider your region's storm characteristics when deciding on the size of sampler to acquire. • Include details on recent illicit storm sewer connection findings in the catchment • If seeking more in depth knowledge on impacts to aquatic species, include bioassay analysis of local aquatic life. • Conduct a historical investigation to discover site's legacy (past agricultural sites may leave residual nutrient pollution)

Table 23 outlines the details that should allow for a sound analysis of the results of a sampling campaign, whether researchers are addressing concentration, loading or yields. The characteristics listed all have the potential to influence nutrient export and are therefore important to document when trying to interpret nutrient in stormwater runoff data. For example, intense storms may have the potential to dislodge more particulate pollution, soil type may control how much phosphorus is able to exit the lawn and impervious surface directly impacts an area’s ability to infiltrate and manage stormwater runoff.

3.3.4 Interdisciplinary Collaboration

By 2001, companies selling lawn maintenance products, such as fertilizer, began to market their products by insinuating that lawn maintenance drives a sense of community, family and connectedness, with both community and the biological world (Robbins & Sharp, 2009). Competing with these messages to implement community behavior changes for the sake of nutrient management will take a concerted effort. Engineers and scientists can use the help of social scientists in areas like this to implement strategies to obtain the best possible outcome.

These marketing attempts used by fertilizer companies should not discourage policy makers and community members hoping to foster behavioral changes for the benefit of the environment. Rather, we should take advantage of the vast information and lessons learned from public relations and marketing researchers who have researched potential successful avenues for facilitating a consumer behavior. Furthermore, we can also access research that exposes attempts to foster consumer behavior that do not work and avoid wasting time and resources on attempting such approaches in our own community. This highlights the need for corroboration and research on some of the social sciences and public relations work that has already been carried out.

3.4 Closing Remarks

For this thesis I have successfully gathered and discussed research on nutrients in stormwater runoff from residential areas. This review and discussion addressed social dimensions of lawn management, lawn nutrient modeling and nutrient sampling and analysis techniques. Based on collection and interpretation of relevant research, specific topics for future research were identified and recommendations for approaches to future residential diffuse nutrient pollution research were outlined. Future work that sufficiently records influential factors of nutrient movement and transformation in the system being studied will help the scientific community gain a better understanding of nutrient cycles in urban and residential areas, while providing important groundwork for sound policy and nutrient management practices.

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APPENDICES

Appendix A Additional Information and Tables from the Center for Watershed Protection

Table A.1 Lawn Care Practices: A Comparison of Nine Homeowner Surveys. Adapted from Information Provided by The Center for Watershed Protection (1999)

Study	Respondents	% of Lawns Fertilized	% of Soil Tests	Other Notes
Maryland	403	87%	NA	
Virginia	100	79%	> 20%	
Minnesota	981	75%	12%	Avg. times fertilized per year: 2.1 40% left clippings
Maryland	100	88%	15%	58% left clippings
Minnesota	136	85%	18%	78% left clippings
Wisconsin	204	54%	NA	Avg. times fertilized per year: 2.4
Baltimore	164	73%	NA	Avg. times fertilized per year: 2.1
Florida	659	82%	Na	Avg. times fertilized per year: 3.2 59% left clippings
Chesapeake Bay	656	50%	16%	Avg. times fertilized per year: 1.73

Table A.2 Comparison of Demographics for CWP and Chesapeake Bay Program Surveys (from Center for Watershed Protection, 1999)

Center for Watershed Protection Survey Demographics

Age Categories	
18-24	5%
25-34	16%
35-44	25%
45-54	23%
55-64	12%
65+	19%

Income Categories	
Under $15,000	8%
$15,000 - $25,000	9%
$25,001 - $35,000	17%
$35,001 - $50,000	18%
$50,001 - $75,000	24%
$75,001 - $100,000	13%
$100,000 +	12%

Chesapeake Bay Program Survey Demographics

Age Categories	
18-24	11%
25-34	21%
35-44	23%
45-54	19%
55-64	12%
65+	14%

Income Categories	
$12,000 or Less	4.4%
$12,000 - $20,000	9.7%
$20,000 - $30,000	16.5%
$30,000 - $50,000	29.4%
$50,000 - $75,000	18.9%
$75,000 - $100,000	13.4%

Table A.3 Comparison of Demographics for CWP and Chesapeake Bay Program Surveys (from Center for Watershed Protection, 1999)

Center for Watershed Protection Survey Demographics

Education Categories	
Less Than High School	9.2%
High School Graduate	29.8%
Vocational/Technical	3.9%
Some College	20.5%
College Graduate	22.9%
Advanced Degree	13.7%

Race Categories	
White	90%
Black/African-American	7%
Hispanic	1%
Other	2%
Asian	1%
Native American	1%

Gender	
Male	50%
Female	50%

Chesapeake Bay Program Survey Demographics

Education Categories	
Less Than High School	23.2%
High School Graduate	30.4%
Some College	24.2%
College Graduate	13.8%
Post Graduate	8.3%

Race Categories	
White	77.2%
Black/African-American	18%
Hispanic	1.2%
Other	2%
Asian	1.5%

Gender	
Male	48%
Female	52%

Appendix B Seasonal N and P Box-and-Whisker Plots

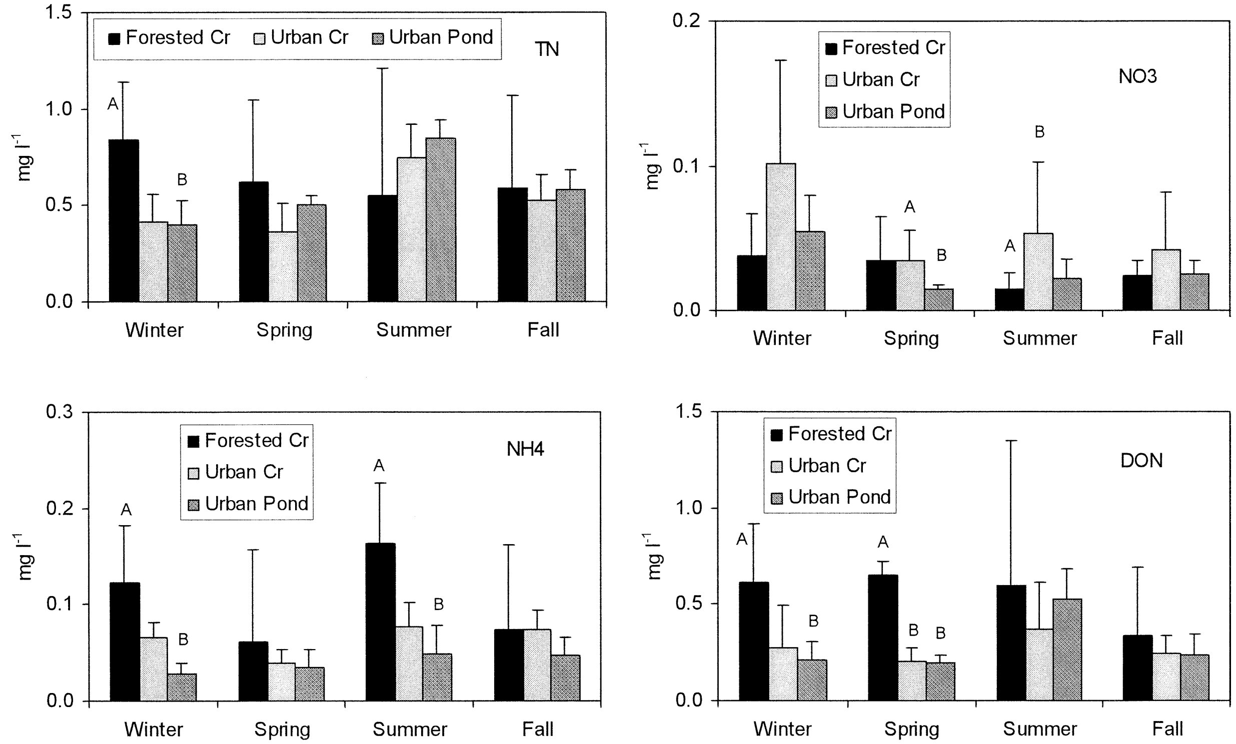

Figure B.1 Seasonal Nitrogen Fraction Distribution Based on Creek Type. Letters Above Indicate Significant Differences at $p < 0.05$ (from Tufford et al., 2003)

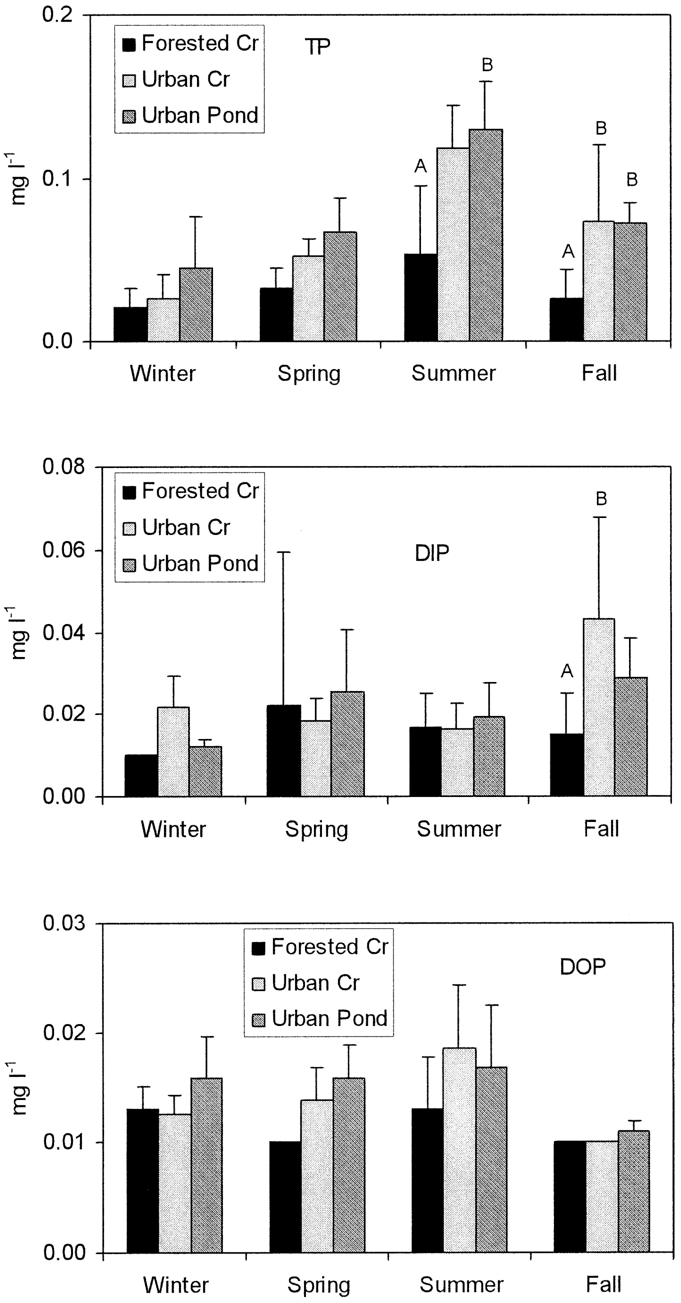

Figure B.2 Seasonal Phosphorus Fraction Distribution Based on Creek Type. Letters Above Indicate Significant Differences at $p < 0.05$ (from Tufford et al., 2003)

Appendix C Comparison of Nutrient Pollution Studies

	A	B	C	D	E
1		**Characterization of Storm Water–Suspended Sediments and Phosphorus in an Urban Catchment in Florida Arias et al. 2013**	**Effects of Lawn Maintenance on Nutrient Losses via Overland Flow During Natural Rainfall Events Authors Spence et al. 2012**	**The residential landscape: fluxes of elements and the role of household decisions Fissore et al. 2011**	**Phosphorus Runoff from Turfgrass as Affected by Phosphorus Fertilization and Clipping Management Bierman et al., 2010**
2	**Objective**	Test the function level of a hydrodynamic street interceptor as stormwater treatment	Help define nutrient losses associated with overland flow from residential lawns	Assess biogeochemical cycling of nutrient as flux from residential landscapes using modeling	Quantify P runoff after turf fertilization, evaluate P effects of clipping removal & effects on turf quality
3	**Location**	Gainesville, FL	Cary, NC	Ramsey & Anoka Counties Minneapolis-St. Paul, MN	St. Paul, MN
4	**Climatic Region**	*Not reported*	Humid Sub-tropical	*Not reported*	*Not reported*
5	**Geological, Metorological Characteristics**	Not discussed	Piedmont region of NC 30 yr mean annual rainfall = 1179mm	*NA*	- Soil: fine-silty over sandy or sandy skeletal, mixed, superactive - Plot previously pasture - Plot controlled with 10 cm high plastic stuck 6-7cm deep - Plots sodded with Kentucky blue grass, midnight II, Award & Rugby II
6	**Number of Sites**	1 Residential	3 Residential Lawns (not watershed or basin)	flux estimate for 360 households	24 plots
7	**Other distinguishing characteristics**	Retirement community	R1 = high maintenance fescue lawn (HMFL) R2 = low maintenance fescue lawn (LMFL) R3 = forested residential landscape (FRL) These lawns were located on the same street <100m from one another	- randomized sampling of owner-occupied, single-family houses in proportion to housing density - Questionnaire addressed landscape mgmt practices (fertilizer application, irrigation, etc.), pet waste mgmt. - Field measurements were conducted to estimate vegetative net primary production (NPP)	Site prepared by stripping previous vegetation and grading for uniform 5% slope to promote runoff and reflect local topography. Initial site soil sampls were taken and tested before application of fertilizer.
8	**Temporal area conditions or considerations**	*NA*	*NA*	- Limitation: with such a model, parsing out exit pathways (runoff volatalization, nitrification, denitrification, etc.) was not possible	Total precipitation was 11% above 30yr average. Precipitation during frozen soil conditions was 10% of total precip.
9	***Watershed Characteristics***				
10	**Total Area(s) (of watershed/drainage basin)**	55 ha Main catchment: 40 ha	R1 = 33.5 m^2 R2 = 27.9 m^2	*NA*	Each plot area: 2.4 x 7.3 m, because of the funnel for collecting runoff, area was 17.1 m^2
11	**Percent Impervious Area (s)**	15%	*NA*	*NA*	*NA*
12	**Lawn management practices**	*NA*	"R1 = high maintenance fescue lawn (HMFL), maintained by owner R2 = low maintenance fescue lawn (LMFL), maintained by lawn service R3 = forested residential landscape (FRL), no maintenance	Accounted for statistically in the model through use of 360 randomly selected returned homeowner questionnaires	Controlled for each plot: 1. No fertilizer 2. 0xP + N + K (no P applied) 3. 1xP + N + K (low P rate) 4. 3xP + N + K (high P rate) applied May, Sept, Oct
13	***Sampling Methodologies***				
14	**Time of year sampled**	Jan-Sept 2007	*NA*	*NA*	Sept 2004 - Oct 2007
15	**Type of site used for sample collection**	Street interceptor and the hydrodynamic (HDS) outlet	*NA*	*NA*	controlled plots
16	**Number of Events**	10 (1 was an "irrigation" event)	Varied at each location	*NA*	*NA*
17	**Method for deciding when to pull stormwater samples *(First flush, composite, etc.)***	- Previous dry time (>24 hr) - Rainfall depth of event (> 1mm)	A rainfall event was defined as rainfall depth of 2.54 mm or more.Of the 87 rainfall events occurred during a 20-month monitoring period, during the monitoring period, overland flow was generated during 15 events from the HMFL, 18 events from the LMFL, and 8 events from the FRL. An overland flow event was defined as a min. collection V of 2.7 cm^3 ⁄ m^2 (100 ml)	*NA*	Samples were pulled through the duration of the expereiment either as snow melt or regular runoff.
18	**Sampling Method**	Hand collected using acid-washed, plastic bottles. Generally, samples were collected every 1–2 min when large variation in concentrations and flows were observed. Sampling frequency decreased to 5–10 min once concentrations and flows began to decline.	Overland flow was monitored continuously for 20 months using an overland flow sampling system located in delineated area in each lawn so that 100% of runoff followed natural flow paths to the outlet ports and collected in sterile Nalgene(R) B3 media bags (Thermo Fisher Scientific, Rochester, NY). Metal landscape edging (placed 50.8 mm into ground) was used to confine runoff to the delineated areas.	Assumptions and calc methods: - Fertilizer Application rate constant for fertilizing households & a different rate assumed for households employing lawn mgmt companies (based on surveys) - nitrogen deposition constant used - NPP and species specific nutrient uptake equations were used - litter remaining on site in equilibrium with decomposition	After each runoff event, runoff water was mixed, runoff V from each plot measured & a sample was collected in a 125-mL high density polyethylene container. During large runoff events, V measurements were made more than once in a 24-h period to avoid exceeding storage capacity of collectors. Samples for these events were collected from the initial filling of the 114- L overflow container.

	A	B	C	D	E
19	**Laboratory Methods**	Processed and analyzed UF according to the USEPA method 365.1 for water and soil		*NA*	*Described for P sampling below*
20	**Weather details recorded or calculated**	Rainfall depth (range: 1.77 - 27.9 mm) Storm duration (range: 21 - 178 min) Rainfall intensity (range 1.4 - 20 mm/h) Antecedent dry days (2.7 - 24) Temperature Solar Radiation Atmospheric pressure Wind speed & direction	*NA*	*NA*	*NA*
21	**Stormwater details recorded or calculated**	Rainfall runoff lag t (range 3 - 38 min) Runoff V (range 97 - 2102 m^3) Runoff flow speed (20 - 637 L/s) *hyetorgraphs and hydrographs were generated*	*NA*	*NA*	*NA*
22	**Additional site details recorded**	Water levels and temperatures of ponds in the catchment	*NA*	*NA*	*NA*
23	***Nitrogen Information***				
24	**Nitrogen Species Evaluated**	*NA*	Ammonium (NH4-N) nitrite + nitrate-N (NO3-N) TDN TKN	Nitrogen	*NA*
25	**Sampling and testing methods (individual, composite, etc)**	*NA*	NH4-N: Quick Chem 8000 Automated Ion Analyzer NO3-N: colorimetric methods TDN: automated TOC with total nitrogen analyzer HMFL mean TN: 5.64 mg/L LMFL mean TN: 5.67 mg/L FML mean TN: 1.86 mg/L	***all in kg element household^{-1} year^{-1}*** Inputs: Atm deposition 1.5 Fertilizer application 11.5 Dog excreta 1.4 Outputs: Leaf export 1 Lawn clipping 0.5 Accumulation: Soil 3.9 Tree wood 1.7	*NA*
26	**Technique used to determine specific source of nitrogenous pollution**	*NA*	*NA*	Based on the model itself	*NA*
27	***Phosphorus Information***				
28	**Phosphorus Species Evaluated**	TP fractionated to: TDP, PP in SS and PP	TP PO4-P	Phosphorus	RP (reactive phosphorus), TP
29	**Sampling and testing methods (individual, composite, etc)**	Composite at inlet: median TP = 0.346 mg/L at HDS outlet: median TP = 0.308 mg/L	Individual - later calculated as means HMFL mean TP = 0.87 mg/L LMFL mean TP = 0.92 mg/L FRL mean TP = 0.32 mg/L	***all in kg element household^{-1} year^{-1}*** Inputs: Atm deposition 2.6E-2 P Fertilizer application banned 0 Dog excreta 0.2 Outputs: Leaf export 7E-2 grass clipping 8E-2 Accumulation: Soil 0.6 Tree wood 0.2	RP - colorimetrically by molybdenum-blue method TP - colorimetric initially and later measured after nitric-sulfuric acid digestion
30	**Technique used to determine specific source of phosphorus pollution**	*NA*	*NA*	Based on the model itself	*NA - controlled plots*
31	***Findings and notes***				
32		- Phosphorus levels were not as high as expected meaning that some other ecological factor is heavily influencing pond eutrophication - Proper maintenance and upkeep of hydrodynamic interceptors is crucial to achieve and maintain their intended performance	- Total runoff V collected from the LMFL was higher than from the HMFL and FRL, but on average <1% of the total rainfall was collected from the three landscapes. - Nutrient unit area losses from the HMFL, LMFL, and FRL were 1,000 times less than fertilizer and throughfall inputs- most likely due to well-structured soils (low bulk densities) with high infiltration rates. - "Demonstrated that frequency of runoff, total runoff V, and nutrient losses during natural rainfall events are lower from highly maintained (i.e., irrigation, fertilizer application, and reseeding) densely uniform manicured lawns than low maintenance lawns and forested residential landscapes."	- P inputs were dominated by pet waste (84%) of to landscape due to Minnesota restrictions on P fertilizer, followed by deposition. This is slightly worrisome as most other research denotes P deposition as little or no concern. - Landscape nitrogen accumulation accounted for 38% of total N inputs - Based on this model, deposition of both N & P is contingen upon lot size (therefore linearly increases with lot size) - Number of trees per household, irrigation practices, leaf/clipping removal and fertilization rates varied considerably among households Among the 360 randomly selected households who responed... 28% - never fertilize (29% of whom rarely or never fertilize) Of the 72% who fertilize... 14% rarely or never irrigate	-When soil was frozen, a higher % of precipitation was lost as runoff: 1% precip on Non frozen soil converted to runoff qhil 5 to 27% of precipitation lost as runoff on frozen soil - Analysis of P conc. In runoff, runoff depths & P loss in runoff for all yrs showed significant effects from fertilizer application & season **For all 3 years** - plots receiving no fertilizer had significantly lower quality turf. The fertilized plots (regardless of amount) all basically had the same quality of grass. Clipping application improved turf grass quality two years and had no effet the third. - All 3 years of study showed significant linear increases of flow-weighted P cocentrations. Phosphorus losses in runoff from turfgrass were most affected by fertilizer application, frozen vs. nonfrozen soil conditions, runoff depth, and turf quality/growth. There was an overall correlation of increased P when fertilizer applications were high and precipitation (leading to

	F	G	H	I	J
1	**New Insights into the Quality of Urban Storm Water in South Eastern Australia** **Francey et al. 2010**	**Stormwater runoff and export changes with development in a traditional and low impact subdivision** **Dietz and Clausen, 2008**	**The effects of land use on stream nitrate dynamics** **Poor and McDonnell, 2007**	**Effects of suburban development on runoff generation in the Croton River basin, New York, USA** **Burns et al., 2005**	**Fertilizer Source Effect on Ground and Surface Water Quality in Drainage from Turfgrass** **Easton and Petrovic (2004)**
2	Report large-scale stormwater monitoring of pollutants during dry and wet weather flow	Compare pollution in stormwater from a traditional subdivision compared to a LID development	Examine nitrates in streams from 3 catchments with similar atm deposition, size & geology, but diff land use	To study effects of impervious area, septic leach-field effluent, and a riparian wetland on runoff generation	Measure nutrient loss from leaching and runoff from multple fertilized plots
3	SE suburbs of Melbourne, Australia	Waterford, CT	near Corvallis, OR	Croton River Basin, NY	Ithaca, NY
4	Temperate	*Not reported*	Mild with dry summer, wet winter	*Not reported*	temperate
5	*NA*	- Soil type: Canton and Charlton with typical infiltration rate for this type of soil is 33 cm hr^-1	- Low N deposition (1.52 kg/ga/yr) Forest Catchment Soils: approx.y 1 m of weathered basalt bedrock, well-drained silty clay loams Ag Soils: poorly drained silty clay loams and clays, bedrock at 2m Residential soils: poorly drained silty clay loams and clays, bedrock at 2m	The basin consists of 12 reservoirs that supply 492 million L of H2O / day to New York City (~10% of the City's supply). It is largely underlain by Precambrian sedimentary and igneous rock; elevations range from 200-500 m above sea level. Soils are developed on glacial till, are medium to moderately textured & generally well drained	- soil type: sandy loam sand content ranged from 43-70%, silt from 19-39% and clay from 8-22%
6	6 + 1 large roof	2: traditional, LID	3: Forrested, Agricultural & Residential	2 Residential, 1 control	3 replicates of each treatment, 5 fertilizer treatments = 33 plots
7	- The 6 catchments are separately sewered and have different land uses	- Traditional: 17 lots, curb & gutter stormwater collection, 8.5m asphalt road, typical landscape/turf, roof runoff directed to lawn or driveway - LID: 12 lots, 6.1m wide ecostone paver road and grass swales (vs stormwater collection), bio0retention cul-de-sac, bioretention also incorporated into each lot, 7 homes had ecostone or crushed stone drivways	Forrested catchment: 2nd growth Douglas Fir, Tree cover 98.1% Agricultural: sheep & cattle grazing, clover, wheat & fescue growth, Tree cover 52.8% Residential: includes Oregon State U campus, Tree cover 83.1%, Impervious 15% --> Each catchment had a clean/distinct expression of land use	HIGH: High density residential (2.8 houses/ha) MED: Medium density residential (1.6 houses/ha) UND: Undeveloped -All houses in the stdy area use septic systems with drainfields - Most of the homes get waters from either individual or community wells.	- A stainless steel border placed to a depth of 8cm was used to delineate the plots and prevent up-slope runoff contamination - there was variation in infiltration based on slope & soil particle distribution
8	Mean annual precipitation = 600-800mm; rainfall was slightly below avg. over sampling period	Climate influenced by continental polar and maritime tropical air masses Mean annual precipitation = 1237mm	Avg temp: 11.5C, Avg annual precipitation: 111 cm/yr	- Mean annual precipitation = 1299mm - Winter of 2001-2 during study was very dry compared to the 30 yr avg., meaning little snowmelt made it to the streams.	rainfall; humidity; calculated evapotranspiration; average temperature; wind speed; solar radiation; snowfall
9					
10	Recorded separately for each catchment	Traditional = 2 ha LID = 1.7 ha	Each subbasin ~ 50 ha (of the 33 km^2 Oak Creek Watershed)		each plot = 1m x 2m
11	Recorded separately for each catchment	Traditional = 32% LID =	15% for residential	HIGH: 11.1%, MED: 6.2%, UND: 0%	*NA*
12	Details not explored in this study	Not discussed	Lawn management not discussed, but primary vegetation noted as: Douglas Fir, alder, ash, sword ferns, and blackberry mixed with lawns and ornamental shrubs	Not discussed	Controlled fertilized plots - One received 50 kg/ha fertilizer at each application, the 2nd received 100 kg/ha, and the 3rd was a control plot receiving 0.
13					
14	Nov 2003 - Dec 2005	1999-2002	12/9/2003, 2/23/2004, 4/13/2004	Mar. 2000–Aug. 2002	July 2000-May 2001
15	stormwater pipes	stormwater pipe	catchment outlet	streams	Controlled plots
16	Varied by catchment. Mininimum of 17 events & min. of 10 for dry weather	measurements and samples taken weekly from each catchment	3	27 storms (Aug. 2001 & Aug. 2002)	33 precipitation events
17	A flow-weighed sampling approach was used. Event defined as >0.6mm, time between evnts was a minimum of 4 hours	*NA*	"ISCO Model 1672 autosamplers were used at sampling locations for hourly sampling on the rising limb of the hydrograph and a bi-hourly sampling on the falling limb" Grab samples were also pulled from each site during the 2003/4 field season	Storm was defined as precipitation greater than 2.5 mm followed by no rainfall for at least 3 h, & an increase in stream discharge at HIGH of at least 30% above the pre-event value within 3 h.	Not described
18	Sigma 900 autosmaplers were employed with preset flow rate trigger values, different for each catchment. At least 5 samples were taken in an interval no more than 2 h. Dry weather samples were taken after at least 3 days without rain. If a composite had to be made (meaning only EMC could be determined) the sample was tested for additional nitrogen species (NH3 and NOx)	- Flow-weighted samples were collected automatically by an ISCO sampler - "Mass export (kg ha^-1 yr^-1) calculated by multiplying weekly cumulative flow by weekly sample concentration values, dividing by the watershed area, and summing for the year. Total nitrogen (TN) values were calculated by summing TKN and NO3-N mass export values."	Collected & preserved samples by Standard Methods for the Examination of Water and Wastewater (Clesceri et al., 1998)	All 3 streams were sampled weekly or biweekly during baseflow conditions (at least 3 rain-free days prior to sampling) for chemistry and isotope analyses.	- "cationic and anionic exchange resins were installed monthly directly below the root zone (depths varied with depth of rooting) to capture nutrients and estimate leaching past the root zone." - Clipping samples were regularly collected and tested for P content

	F	G	H	I	J
19	Australian National Association of Testing Authorities laboratory analyzed all smaples for TSS via measurement of sediment mass,and total phosphorus (TP) and total nitrogen (TN) via colorimetric flow injection analysis	Test methods not discussed in detail	Test methods not discussed in detail	Test methods not discussed in detail	(Below)
20	Total event rainfall, avg/ rainfall intensity per event, and max. rainfall intensity (at 6min interval)	Not discussed	Precipitation duration & depth, antecedent dry days,	Precipitation, evapotranspiration	precipitation depth
21	Event Mean Concentration (EMC) Site Mean Concentration (SMC) Pollutograph	*NA*	Stream stage height, rating curves, peak discharge, hydrographs, time to peak, hydrograph response t, recession coefficients, hydraulic conductivity, storage coefficient & vol.	Stream Discharge, Groundwater levels, recession constants,recession curves, hydrographs, aquifer baseflow residence time	*NA*
22	*NA*	*NA*	Soil samples taken and GW samples taken from existing wells	*NA*	At turf establishment, stormwaterr samples were visiually noted to contain high amounts of sediment
23					
24	TN	nitrate+nitrite (NO3-N), ammonia nitrogen (NH3-N), TKN	Nitrate	Nitrate	Nitrate and Ammonium both as N
25	Australian National Association of Testing Authorities laboratory analyzed all smaples (TN) via colorimetric flow injection analysis Values recorded separately for each site and presented in text as EMC< SMC or mean	Lachat colorimetric flow injection system	Nitrate Export in kg/ha/storm Forested: Storm1: 0.012, Storm2: 0.005, Storm3: 0.010 Agricultural: Storm1: 0.121, Storm2: 0.040, Storm3: 0.21 Residential: Storm1: 0.131, Storm 2: 0.108, Storm3: 0.131	Stream water and groundwater samples were collected biweekly for NO3- analysis for 1 year. Reported only box and whisker plot: HIGH: min 3 mg/L, max 9 mg/L MED: min 4 mg/L, max 1 mg/L	"Analysis of runoff and leachate (ion resin extracts) solution was performed with an inductively coupled argon plasma optical emission spectrometer"
26	*NA*	*NA*	*NA*	*NA*	Based on what type of fertilizer the plot received
27					
28	TP	TP	*NA*	*NA*	Phosphate (PO4^3-)
29	Australian National Association of Testing Authorities laboratory analyzed all samples total phosphorus (TP)using colorimetric flow injection analysis Values recorded separately for each site and presented in text as EMC< SMC or mean	Lachat colorimetric flow injection system	*NA*	-Standard Method 4500-P-E	"Analysis of runoff and leachate (ion resin extracts) solution was performed with an inductively coupled argon plasma optical emission spectrometer"
30	*NA*	*NA*	*NA*	*NA*	Based on what type of fertilizer the plot received
31					
32	-TN concentrations were higher during baseflow - EMCs of all pollutants monitored did not correlate well with simple hydrological parameters, however, event pollution loads correlated with rainfall intensity to a power, summed over the event duration - Impact of land use on pollutant concentrations was not destinguishable. - The first-flush effect was was note significant at all sites except the roof.	- In the traditional neighborhood, TN and TP exports increased by two orders of magnitude compared to its exports during predevelopment. The LID neighborhood exports did not change pre/post development. - Stormwater volumes in the traditional subdivision increased 49,000% with an increase from 1 to 32% impervious surface.	-"Runoff ratios increased with increasing development, with the highest ratios in the residential catchment" - Marked differences in export rates among the 3 catchments: Forested catchment - minimal export for three monitored storms (fall, winter, spring) Residential catchment - high export for all three storms. Agricultural catchment displayed elevated export in the fall (similar to the residential catchment), exports decreased progressively throughout the rainy period - "varying nitrate inputs have a large affect on nitrate dynamics" - Baseflow consistently highest in the residential catchment, lowest in forest	- Results agreed with that of previous work, showing that the relationship between peak preceipitation rate and peak runoff strengthens as the percentage of impervious area increases. - Baseflow concentrations of nitrate were elevated in HIGH and MED compared the UND. This was most likely due to septic tanks, but also possibly influenced by fertilizer practices.	-Unfertilized plot had higher runoff & pollution concentrations in runoff for N species compared to the fertilized plots - As turf grass became more established, NH4+-N concentrations decreased in runoff. - Urea application at 100 kg/ha was the only plot that yielded higher amounts of nitrate in runoff compared to unfertilized control. - N loss tended to follow solubility trends= synthetic fertilizers w/more soluble N produced higher N losses. - Plots receiving swine waste produced the highest conc of P runoff. - P was most likely to be lost in the form of clippings while N was most likely to be lost in leachate. - Leaching was a function of fertilizer source, timing, infiltration rate, shoot density & antecedent soil moisture - Despite reductions in nitrogen loss over time from established turf plots, the concentrations found in the experiment were high enough to be problematic for aquatic organisms.

	K	L	M	N	O
1	**Water Quality Characteristics of Storm Water from Major Land Uses in South Florida** **Graves et al., 2004**	**Nitrogen Fluxes and Retention in Urban Watershed Ecosystems** **Groffman et al. 2004**	**Impacts of Urbanization on Nutrient Concentrations in Small Southeastern Coastal Streams** **Tufford et al., 2003**	**Variations of the Nutrients Loads to the Mainland U.K. Estuaries: Correlation with Catchment Areas, Urbanization and Coastal Eutrophication** **Nedwell et al., 2002**	**Nitrogen Balance for the Central Arizona–Phoenix (CAP) Ecosystem** **Baker et al. 2001**
2	Characterize stormwater quality from dominant land uses in a coastal watershed	Evaluate long-term data on N losses & input –output N budgets for various land uses in multiple watersheds	Evaluate the effects of urbanization, seasonality, and hydrography on nutrient concentrations in small coastal streams during **baseflow** conditions	Calculate and analyze nutrient loads from different regions	Create a detailed N mass balance for an arid, urban ecosystem
3	south central coast, FL	Baltimore County, MD	Hobcaw Barony and Murrells Inlet, NC	United Kingdom, multiple locations	Central Arizona - Phoenix
4	humid sub-tropical	Atlantic Coastal Plain	Moist Subtropical	multiple	Arid
5	- relatively flat, elevation: 0 - 25m - Annual rainfall: 1300mm (20-40% becomes stormwater, depending on land use)	- Gently sloping to hilly - Underlain by igneous and metamorphic rocks - Dominated by Legore, Joppa and Sassafrass soils - Annual precipitation ~ 380mm, with greatest intensities in summer and early fall. Runoff & evopotranspiration exceed precipitation in April-Sept	'Both are bar built salinity estuaries with 1 outlet to Atlantic, Slopes: 0-6%, Elevation: sea level-10m - Mean temp: 18.3 C (65 F) - Annual precipitation: 133cm (52in), most occuring June-Sept -	*NA*	- In arid environments like AZ, dry deposition becomes more important and there are often large pools of stable N fixed to clays and therefore only partially available to vegetation
6	63 sampling sites representing 7 different land uses	one completely forested, one ag, & six urban/suburban watersheds,	10 streams emptying into 2 high salinity estuaries	93 major estuaries (on Britain mainland)	1 major metro area
7	- Involved 2 close proximity estuarine systems, Indian River Lagoon (IRL) and the St. Lucie Estuary (SLE), its largest tributary. The SLE was a freshwater estuary until construction of the St. Lucie Inlet - Land use in the watershed primarily citrus ag, cattle pasture, urban and isolated wetland ~ 25, 23, 16, and 13 %t of the total land area, respectively. & 74% of urban land = residential	- Watershed is 20% forrested (w/ primary tree species described in detail in document) - Atmospheric deposition was estimate based on US EPA's CASTNET	- Extremely important: No point sources of nutrient pollution in the study areas - Noted NPS sources: commercial fertilizer, septic systems, auto exhaust, impervious surface runoff - Murrells inlet highly altered & impacted by boat traffic, dredging & shore alteration; Hobcaw Barony close to its natural state, but residential turf grass & landscaping prevalent	This study looked at annual loads in streams, not concentrations from individual events.	Land use: 13% urband, 10% crop, & 150,000 cows live within the system Number of cats & dogs in the system were considered WW sources were considered Pervious (50% fertilized), impervious of residential areas were considered.
8	"Drainage is afforded by an interconnected web of ditches and tertiary, secondary, and large primary canals."	- Pop. At time of study: 356,000	- Precipitation during study year was higher than avg	*NA*	Inputs were divided into deliberate (fertilizer, food, dairy industry) and inadvertent (combustion derived NOx)
9					
10	2,200 km^2	recorded seperately for each individual drainage area	Separate drainage area noted for each stream, all less than 1.5 km^2 except one	Different for each estuary	NA
11	*NA*	recorded seperately for each individual drainage area	Figures not noted	*NA*	NA
12	*NA*	Details not explored in this study	Details not explored in this study	*NA*	Not explored in depth beyond the assumption that 50% of homeowners fertilize
13					
14	Jan 1998 - July 2000	1999-2001	1999	Data from 1995 & 1996	*NA*
15	Not discussed in detail	Typicaly at or within a few meters of the gauging stations (stream/river)	streams	stream/river emptying into estuary	*NA*
16	115 (for urban)	weekly for 3 years	*NA*	Varied by region/estuary	*NA*
17	- Qualified rain event = preceded by at least 72 hrs of no rain & precipitation in inches was between 25th - 75th percentile of historic rainfall - Samples were collected within 24 hours following a "qualified rain event" - Samples collected only when there was visual flow in direction indicative of runoff	Note by event - samples pulled weekly. No particular weather patterns were avoided in attempt to have a random sampling scheme.	Samples were gathered within one hour of low tide to capture the maximum effect of watershed drainage into the streams	*NA*	*NA*
18	Collection sites were selected so upstream land use reflected one land use type only Grab samples were collected in accordance with the storm water sampling guidelines proposed by Timpe et al. (1996)	Water samples were collected & stored in 150-mL Nalgene low-density polyethylene bottles	Grab samples were drawn monthly from ten different streams at base flow period	- Annual average water flow and annual average concentration of nutrients obtained from the Harmonised Monitoring Scheme data set held at the U.K. Environment Agency's Environmental Data Centre - Frequency and number of samples drawn varied from region ot region	*NA*

	K	L	M	N	O
19	All containers for nutrients were washed with 1:3 diluted hydrochloric acid & thoroughly rinsed w/deionized water. All sample bottles were prelabeled & sets of bottles for each site were sealed in individual labeled plastic bags under controlled laboratory conditions.	Blanks & spikes were processed with samples in the University of Maryland at Baltimore County laboratory weekly before being shipped to the Institute of Ecosystem Studies for chemical analysis.	- filtered and unfiltered samples were analyzed after alkaline persulfate digestion - Standard methods from APHA	*NA*	*NA*
20	Not discussed	Estimates of daily loads of N and NO3- exported from watersheds were based on runoff (mm d-1) vs. concentration relationships derived from weekly chemistry data	*NA*	*NA*	
21	Not discussed	Avg: peak daily average storm flows of 43, 88, and 137 m^3 s^{-1} at recurrence intervals of 2, 5, and 10 years, respectively	*NA*	*NA*	*NA*
22	Samples taken by hand or by bottle on stick method		*NA*		
23					
24	TN, total organic N, ammonia (NH3-N), nitrate plus nitrite (NO2+3-N)	NO3-, TN	TN, TDN, NO2+NO3, NH4, DIN, DON	nitrate+nitrite, NH$_4$+	
25	-" All analyses were performed using standard, approved analytical techniques (FDEP, 1992; APHA, 1998)." - Each run included spike analysis & duplicates at a frequency of 10% Residential results were not delineated from the urban results. The following are mean values found in the urban catchments for 115 qualified events: TN: 1.07 mg/L, Org N: 0.92 mg/L, Inorganic N: 0.13 mg/L, NH3-N: 0.06 mg/L, NOx-N: 0.07 mg/L	NO3-: Ion chromatograph TN: pursulfate digestion hollowed by analysis of NO3-	- Nitrate: manual hydrazine reduction - Standard methods 4500-NO3 & 4500-NO3-F	*NA*	
26	*NA*	*NA*	*NA*	*NA*	
27					
28	TP	*NA*	TP, TDP, DIP, DOP	PO$_4$3-	
29	-analyses performed using standard, approved analytical techniques - Each run included spike analysis & duplicates at a frequency of 10% - Residential results were not delineated from the urban. The following is a mean value found in the urban catchments for 115 qualified events: TP: 0.22 mg/L	*NA*	-ascorbic acid reduction method, 4500-P-E	*NA*	
30	*NA*	*NA*	*NA*	*NA*	
31					
32	-Runoff from most land use types had low DO conc. Sediment & nutrient concentrations were closely related to land use, particularly to amount of fertilizer applied in each land use. - On avg., organic N comprises 70-95% of the total N. Except for row crop runoff, NO3+NO2 were low in conc. constituting ~1/2 or less of the total inorganic N concn - Inorganic N constitutes ~5% of TN in stormwater from wetland, while runoff from pasture & urban contains about twice that amount - "An increasing scale exists among land uses based on their propensity to release nitrogen in its most soluble, readily assimilated form. This in turn has implications for receiving waters when those are estuaries, as the latter are typically N-limited systems". - TP and TN were low in urban and wetland runoff compared to citrus ag, pasture, row crops, dairy and residual LU sites	-Nitrogen retention (including in soils, vegetation, gaseous loss, harvest and export, grass clippings and leaves) were estimated at 95% for the forested watershed, 77% in the ag watershed and 75% for suburban watersheds -Hydrologic analysis of these areas showed that runoff patterns were heavily influenced by % impervious surface cover -The authors suggested that low annual variability & importance of low flow yields meant the urban and suburban watersheds are not entirely dominated by storm-water flows conveyed by infrastructure, meaning that natural hydrologic pathways and processes remain important regulators of water and N yield in these ecosystems.	- Large differences in concentration results seasonally. TN, DON, NH4 and TP were greatest during the summer; - could be a result of evapotranspiration causing these particular species to be more concentrated, accelerated decay of detritus, or increased tourist activity (auto exhaust, etc.). - TP = highly stratified by season, researchers expected it to be higher in summer due to increased rainfall and resulting increased particulate mobility. - There were significant differences by station type. NH4 concentrations at the urban ponds were less than those for both forested and urban creeks. - DON is seasonally higher from forrested areas during winter and spring - DOP, in general, is negligible in baseflow - After partitioning data into growing & non-growing season, some variability was explained for certain models	- Large variation in nutrient loads between estuaries caused linear plots to be unusable - This study used a parameter for nutrient measurement not found in other studies called TOxN, which was defined as: nitrate+nitrite - Several estuaries had TOxN loads significantly higher than other estuaries. These estuaries were called draining catchments with high nitrate soils. - Scottish and west Wales estuaries had very low loading - Ammonium loads showed less regional correlation trends than TOxN - They used an evaluation factor on a per km^2 basis in order to take away some of the nutrient load disparity between quite large and quite small catchments.This analysis showed that TOxN was relatively constant among watersheds. PO4 and NH4 loads showed greater geographic variation	- Input of fixed N input was 98 Gg/y. Of this, 51 Gg N/y was mediated or deliberately added by people. Combustion added 36 Gg.y. Total fixed N output was 78 Gg N/y, most of which was gaseous N products of combustion and denitrification. Basically, humans mediate 80% of the N inputs in this system (mostly as food, fertilizer & NOx from exhaust) -This ecosystem has seen relatively consistent increases in groundwater nitrate levels since 1970 (increased by more than 5 mg NO3-N/L in 39% of the monitored wells; less than 5% of wells experienced a decline in nitrate by more than 5 mg/L). This trend tended to follow increase in use of commerical fertilizers. In this instance there was an approximate 10 y lag from fertilization to leaching into groundwater aquifers.

	P	Q	R	S	T
1	**Comparison of Pollutant Removal Efficiency for Two Residential Storm Water Basins Bartone et al., 1999**	**Relationships Between Landscape Characteristics and Nonpoint Source Pollution Inputs to Coastal Estuaries Basnyat et al., 1999**	**Assessment of Nonpoint Source Pollution in Stormwater Runoff in Louisville, (Jefferson County) Kentucky, USA Marsh, 1993**	**Deep Nitrate Movement in the Unsaturated Zone of a Simulated Urban Lawn Exner et al. 1991**	**Urban stormwater quality II. Comparison of three New Zealand catchments. Williamson, 1986**
2	Compare two different storm management setups () for their treatment capabilities	Establish relationships among changes in NO3 & sediment loads in water from ag & urban areas due to contact w/riparian forest	*NA*	Simulate to record deep nitrate movement under fixed irrigation and variable fertilization applications	Compare concentration distribution/variation of nutrients in stormwater from 3 catchments
3	Randolph Township, NJ	Fish River, AL	Louisville, KY	Simulation	2 in Takapuna, Auckland, & 1 in Hillcrest, Hamilton - New Zealand
4	*Not reported*	*Not reported*	*Not reported*	*NA*	*Not reported*
5	*NA*	Land was classified into 1 of 7 categories: urban & residential, active agricultural, inactive agricultural, forest, wetlands/grasslands, orchards/tree crops, barren	*NA*	Upper 0.4 m of soil = Bayard fine sandy loam. San content increased with depth to 0.8m. Fine sand from 0.8-1.8m, & intermediate vadose zone composed of silt with medium sand to 3.6m. Water table - 17m below surface	Different among catchments: slope, soil type Same: climate & vegetation
6	2 Residential	1st season: 24; 2nd season: 15	2 Residential	5 controlled plots receiving various rates of fertilizer application (including one control)	3
7	R1: has detention basin with a low-flow concrete channel R2: has a detention basin with vegetated channel R1 & R2: were medium-density residential areas with single-family detached houses that had minimum lot sizes of 0.23 ha (0.57 acres)	*NA*	R1: typical medium density single family dwellings with good soil infiltration R2: low-density, residential area with large houses built on small lots	6x6 meter plots were marked off with 1.5m buffer zone between each.	Auckland - Chartwell: 1.49 km^2, commercial (6%) and residential (79%), pasture/scrub/parks/schools (15%) land uses Auckland - Motorway: 11 km^2, residential (67%), industrial(12%), pasture etc(14.5%) & developing (6%) land uses Hillcrest: 1.14 km^2, residential (76%) & pasture etc(24%) land uses
8	At time of writing, the master plan for the township required construction of detention basins on lots for new residential subdivisions.	*NA*	During time of study, landscape and lawn care companies, applying fertilizer were common throughout the year, and new house construction& additions to existing houses was also ongoing.	*NA*	*NA*
9					
10	R1: 9.02 ha (22.3 acres) R2: 12.0 ha (29.6 acres)	13,772 ha	*NA*	*NA*	Chartwell 1.49 km^2, Motorway, 11 km^2 & Hillcrest 1.14 km^2
11	*NA*	*NA*	*NA*	*NA*	Motorway 30%, Hillcrest 25-33%
12	*NA*	*NA*	*NA*	For the 5 plots, each were treated with the following ammounts of ammonium nitrate: 1. 1.0. 1.5. 2.0. 2.4 N/100m^2	*NA*
13					
14	1996 *assumed*	1995/96 winter and spring	1-year period (1991-1992)	1988	7 March 1982 - 27 June 1983
15	Inlet and outlets of 2 different basins	Selected for hydrologic convergence - lowest point on basin boundary	Storm drain outfall	*NA*	streams
16	4	9 times between Jan95-May95 14 times between Dec 95-May96		*NA*	Motorway: 11, Chartwell: 4, Hillcrest: 15
17	Sampling for each event began when the basins had enough storm water flow for sample collection and prior to the first flush of storm water.	Collected biweekly during winter and spring	- Antecdent dry period of 96 h or more - Storms 0.1 in. or greater. - Conducted during a variety of events to represent different intensitieies, durations, antecedent conditions & seasons	*NA*	Automatic water samplers were used. Samplers activated at preset stage heights
18	A "grab" sample of storm water was collected and decanted into a series of sample bottles and then placed into a cooler for transport and storage.	Grab samples pulled from streams bi-weekly during winter and spring	A 20 min first flush sample (constant time-constant volume recommended by EPA) - 5s collection every 120 s during first 20min of runoff 3 hour composite sample - runoff water was collected with an ISCO automatic sampler, for the duration of the storm event, or the first 3 h, whichever was shorter.	Plots were each fertilized with a different pre-specified amount of fertilizer and then each plot received the same watering scheme (once every 3 days) for 34 days. At the end of 34 days, 6m continuous core samples were taken from each plot for analysis.	Samples were taken with autmatic samplers for both baseflow and stormflow

	P	Q	R	S	T
19	Ammonia - Nitrogen: electrode TKN: electrode Nitrate-nitrogen: Colorimetric Nitrite-nitrogen: Spectrophotometric Orthophosphate: Ascorbic acid manual single reagent TP: Ascorbic acid manual single reagent	(below)	Employed methods recommended by USGS Techniques of Water Resources Investigations		Described in another publication - Williamson 1985
20	Rainfall depth (range: 2.16 - 3.56) Storm duration (range: 210 - 484 min)	*NA*	Rainfall depth Max. 1-h intensity Antecedent dry period No. of rain events between collection Total monthly rain depth	*NA*	*NA*
21	Water depth at center of influent and effluent pipes (for volumetric flow calculation)	*NA*	*NA*	*NA*	*NA*
22	*NA*	Only 13 sites were sampled in 2nd yr due to low flow	*NA*	*NA*	*NA*
23					
24	Ammonia TKN Nitrate Nitrite	nitrate		NO3	NH4-N, NO3-N, ON
25	Samples hand collected at inlet and outlet of the two storm collection systems (in both respective residential areas) Results reported as mass loading R1 Ammonia mean = 0.13 mg R1 TKN mean = 0.72 mg R1 Nitrate mean = 0.29 mg R1 Nitrite mean = 0.01 mg R2 Ammonia mean = 0.08 mg R2 TKN mean = 0.85 mg R2 Nitrate mean = 0.49 mg R2 Nitrite mean = 0.01 mg Reporting only inlet means	interconductive argon plasma (ICAP) method & ion chromatography	First flush and composite were taken, only means were reported for the 2 sites. R1: mean nitrite = 0.14 R1: mean nitrate = 0.3 R2: mean nitrite = 0.11 R2: mean nitrate = 0.3	*NA*	**Median Baseflow Conc. in mg/m^3** Motorway: NH4 = 55, No3 = 436, ON = 558, TN = 945 Chartwell: NH4 = 31, No3 = 273, ON = 429, TN = 707 Hilcrest: NH4 = 123, No3 = 2784, ON = 452, TN = 3740 **Stormwater in mg/m^3** Motorway: NH4 = 54, No3 = 393, ON = 1425, TN = 1703 Chartwell: NH4 = 38, No3 = 797, ON = 1874, TN = 2762 Hilcrest: NH4 = 132, No3 = 895, ON = 1490, TN = 3640
26	*NA*	Land use delineation via geosptial data only	*NA*	*NA*	*NA*
27					
28	TP Orthophosphate	*NA*	TP	*NA*	TP, DRP,
29	Samples hand collected at inlet and outlet of the two storm collection systems (in both respective residential areas). Results reported as mass loading R1 TP mean = 0.1 mg R1 othophosphate mean = 0.04 mg R2 TP mean = 0.14 mg R2 othophosphate mean = 0.07 mg Reporting only inlet means	*NA*	First flush and composite were taken, only means were reported for the 2 sites. R1: mean TP = 0.1 R2: mean TP = 0.21	*NA*	**Median Baseflow Conc. in mg/m^3** Motorway: TP = 65, DRP = 13 Chartwell: TP = 27, DRP = 4 Hilcrest: TP = 37, DRP = 5 **Stormwater in mg/m^3** Motorway: TP = 394, DRP = 36 Chartwell: TP = 644, DRP = 35 Hilcrest: TP = 266, DRP = 15
30	*NA*	*NA*	*NA*	*NA*	*NA*
31					
32	The influent concentrations in this study are low in comparison with urban storm water runoff values from previous research.	- as forest in a contributing zone increases (or agricultural land decreases), stream nitrate levels will decrease. Residential/urban/built-up: identified as strongest contributor of nitrate in model - Water chemistry varied both by basin and season - Forest areas appeared to act as a sink or transformation zone. Basically the more forest in the zone, the more nitrate appeared to decrease. - Grasslands/wetlands were also shown to be nitrate transformation zones - Authors noted the importance of scale when using geospatial data (such as for land cliassification) - the finer the better - This work suggested that WQ would be higher when undeveloped land was located adjacent to streams, however the authors noted that previous researchers found conflicting data.	"A storm that takes longer to deposit an equivalent amount of rain allows time for infiltration, storage, evaporation, and possible concentration of pollutants on both pervious and impervious surfaces. The more intense storms are not only capable of dislodging more toxins from surfaces, but also create greater runoff volume, with a larger immediate input of pollutants into the receiving waters... There is so much variation in weather, from storm to storm, season to season, and even year to year, and there are so many different ways that land uses contribute to the system that to draw a single conclusion about their effects is impossible." - First flush and composite samples shouwed significantly different concentrations of organic nitrogen	- As much as 95% of the applied fertilizercould leach below the turfgrass root system - In all 4 plots that received fertilizer, nitrate leached below the root systems of the turf. - High uniform nitrate concentrations in the control plot suggested that the water alone may supply enough nitrate supply for the turf grass - Homeowners & municipalities should creidt NO3 in irrigation water as an available N source	- The 2 Takapuna sites had higher suspended solids & P than Hillcrest. NH4 levels were higher in Hillcrest. - Storm flows diluted nitrate concentrations in Hillcrest, but raised them in the 2 Takapuna sites. Theory for differences: higher specific flows and subsoil erosion in Takapuna (Auckland) & septic tank influences - In Hillcrest, SS fell before the storm flow peak and decreased rapidly thereafter. In the 2 Auckland catchments, SS followed flow throughout the event. - NH4 and DRP varied in all catchments, but formed small portions of TN and TP (respectively) over all. - Hillcrest had higher nitrate and NH4 concentrations - septic tanks are widely used there and a probablistic culprit - Authors concluded that high correlation in Chartwell were representative of a more uniform land use. Weaker correlations were expected for Motorway due to development & soil erosion

Appendix D Compiled Fertilizer Application Rates

Table D.1 Summary of Fertilizer Application Rates (from Law et al., 2004)

Reference	Application rate	Comments	Study location
Kelling & Peterson (1975)	49 kg N/ha	Homeowner applied	9 urban lawns (locations not given)
	298 kg N/ha	Fall application	
	225 kg N/ha	Considered high/ excessive	
Flipse *et al.* (1984)	107 kg N/ha/yr		Long Island, NY
Starr & DeRoo (1980)	180–195 kg N/ha/yr	2 applications per year	Windsor, Connecticut, field plots
Liu *et al.* (1997)	149 kg N/ha/yr	Moderate application rate divided equally amongst 3 applications per year	Kingston, Rhode Island, field plots
Garn (2002)	146–171 kg N/ha/yr	Assumed residents followed manufacturers recommended rates, 4 applications per year	Lakeshore lawns in Walworth County, Wisconsin
King *et al.* (2001)	49–540.9 kg N/ha	Range of average *reported* application rates for roughs, fairways, tees and greens	Golf course in Austin, TX
Morton *et al.* (1988)	97 kg N/ha/yr	Low	Kingston, Rhode Island, field plots
	244 kg N/ha/yr	High	
Miltner *et al.* (1996)	196 kg N/ha/yr	5 applications of 39.2 kg N/ha	Michigan State University, field plots
Erickson *et al.* (2001)	50 kg N/ha	Moderate application rate	University of Florida, field plots
NCSU Water Quality Group (2000)	29–151kg N/ha (average)	Based on household survey data	4 North Carolina communities
	0–2148 kg N/ha		
Petrovic (1990)	24–224 kg N/ha	Based on compilation of application rates in a literature review	
	49 kg N/ha/yr	Prior to 1940	
	267 kg N/ha/yr	1970s	
CWP (2000)	97.5–195 kg N/ha/yr	Current extension and garden literature recommended rates	

Appendix E The Importance of Protecting Coastal Estuaries

Coastal counties in the US sustain the highest population growth rates and densities (Figure F.1). Stormwater quantity and quality impacts have the potential to be more pronounced in coastal regions (Graves et al., 2004). Urban expansion along uncontrolled shoreline development can cause substantial water quality degradation (Basnyat et al., 1999). The National Research Council reported in 2000 that 60% of coastal rivers and estuaries are moderately to severely degraded as a result of anthropogenic activity, including activities from urban and agricultural land alteration and activities (as cited in Graves et al., 2004). Anthropogenic eutrophication and hypoxic zones are closely linked to population density in coastal watersheds (Pereira, 2000; Vitousek et al., 1997). N_r controls a majority of primary production in estuarine, near-shore coastal zone, and open-ocean waters, which potentially exacerbates eutrophication (EPA Science Advisory Board, 2011). Increased deposition of N_r into terrestrial and aquatic ecosystems also alters sequestration of carbon (EPA Science Advisory Board, 2011). Coastal land is seen by consumers as highly valuable and is, therefore, highly sought after. As development in coastal areas continues, it is important to evaluate these regions purposefully.

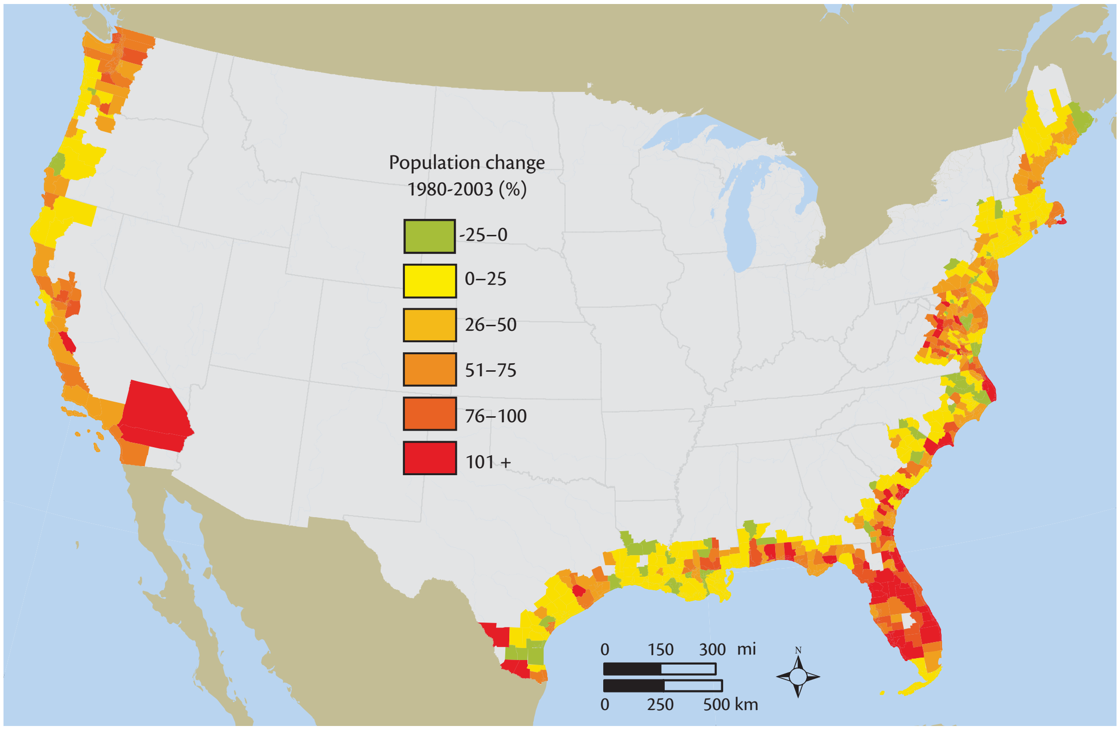

Figure E.1 Percent Population Change in Coastal Counties from 1980-2003 (Bricker et al., 2007)

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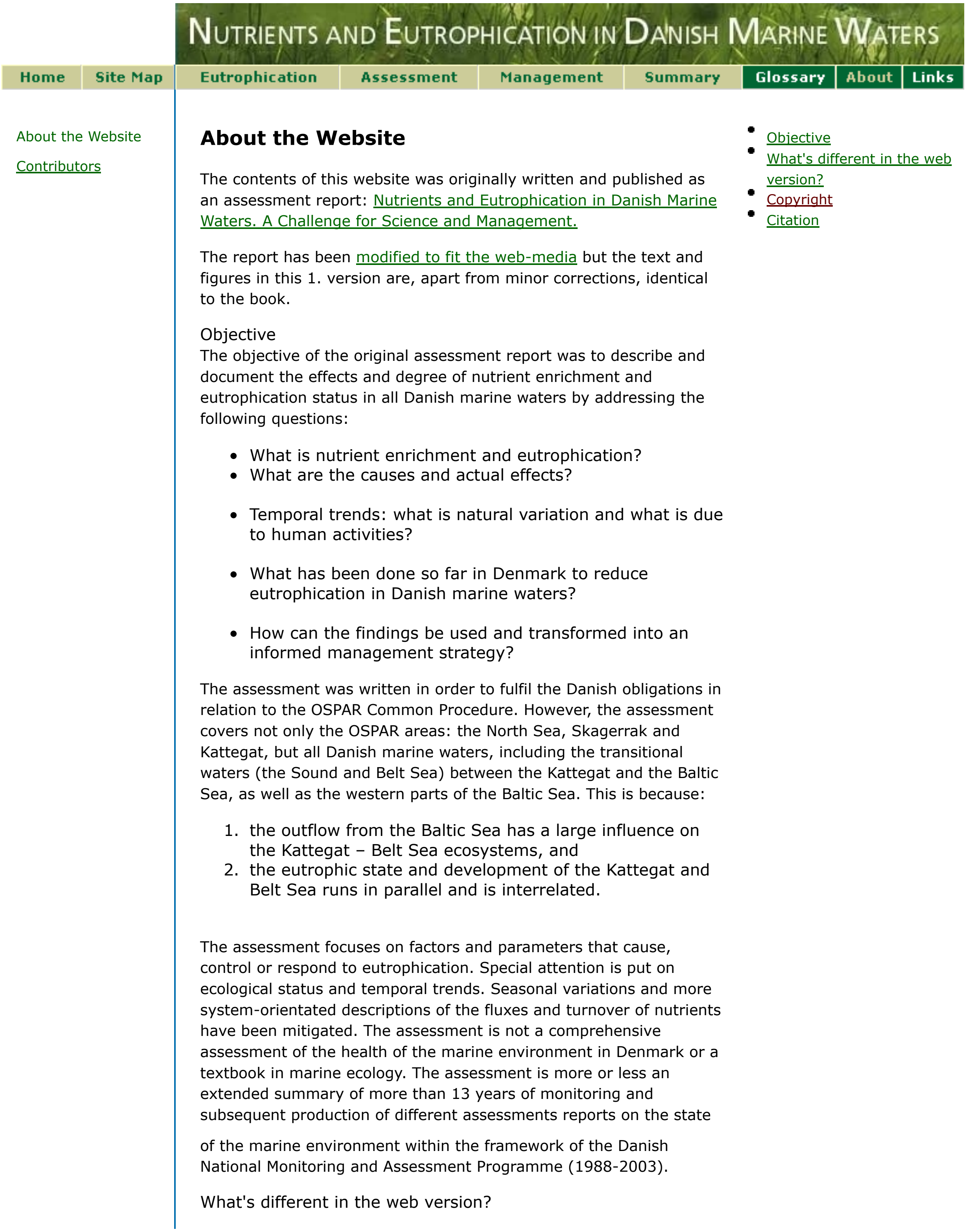

About the Website

The contents of this website was originally written and published as an assessment report: Nutrients and Eutrophication in Danish Marine Waters. A Challenge for Science and Management.

The report has been modified to fit the web-media but the text and figures in this 1. version are, apart from minor corrections, identical to the book.

Objective

The objective of the original assessment report was to describe and document the effects and degree of nutrient enrichment and eutrophication status in all Danish marine waters by addressing the following questions:

- What is nutrient enrichment and eutrophication?
- What are the causes and actual effects?
- Temporal trends: what is natural variation and what is due to human activities?
- What has been done so far in Denmark to reduce eutrophication in Danish marine waters?
- How can the findings be used and transformed into an informed management strategy?

The assessment was written in order to fulfil the Danish obligations in relation to the OSPAR Common Procedure. However, the assessment covers not only the OSPAR areas: the North Sea, Skagerrak and Kattegat, but all Danish marine waters, including the transitional waters (the Sound and Belt Sea) between the Kattegat and the Baltic Sea, as well as the western parts of the Baltic Sea. This is because:

1. the outflow from the Baltic Sea has a large influence on the Kattegat – Belt Sea ecosystems, and
2. the eutrophic state and development of the Kattegat and Belt Sea runs in parallel and is interrelated.

The assessment focuses on factors and parameters that cause, control or respond to eutrophication. Special attention is put on ecological status and temporal trends. Seasonal variations and more system-orientated descriptions of the fluxes and turnover of nutrients have been mitigated. The assessment is not a comprehensive assessment of the health of the marine environment in Denmark or a textbook in marine ecology. The assessment is more or less an extended summary of more than 13 years of monitoring and subsequent production of different assessments reports on the state of the marine environment within the framework of the Danish National Monitoring and Assessment Programme (1988-2003).

What's different in the web version?

Figures
Most of the figures are presented as clickable thumbnail-versions which links to a larger figure. The figure-pages can also be accessed by links i the figure text and many of the figure-pages can be accessed directly by hyperlinks in the text.

Data
Many of the background data for the figures has been made available and can be downloaded from the figure-pages.

Glossary
Selected words from the glossary are hyperlinked form the text.

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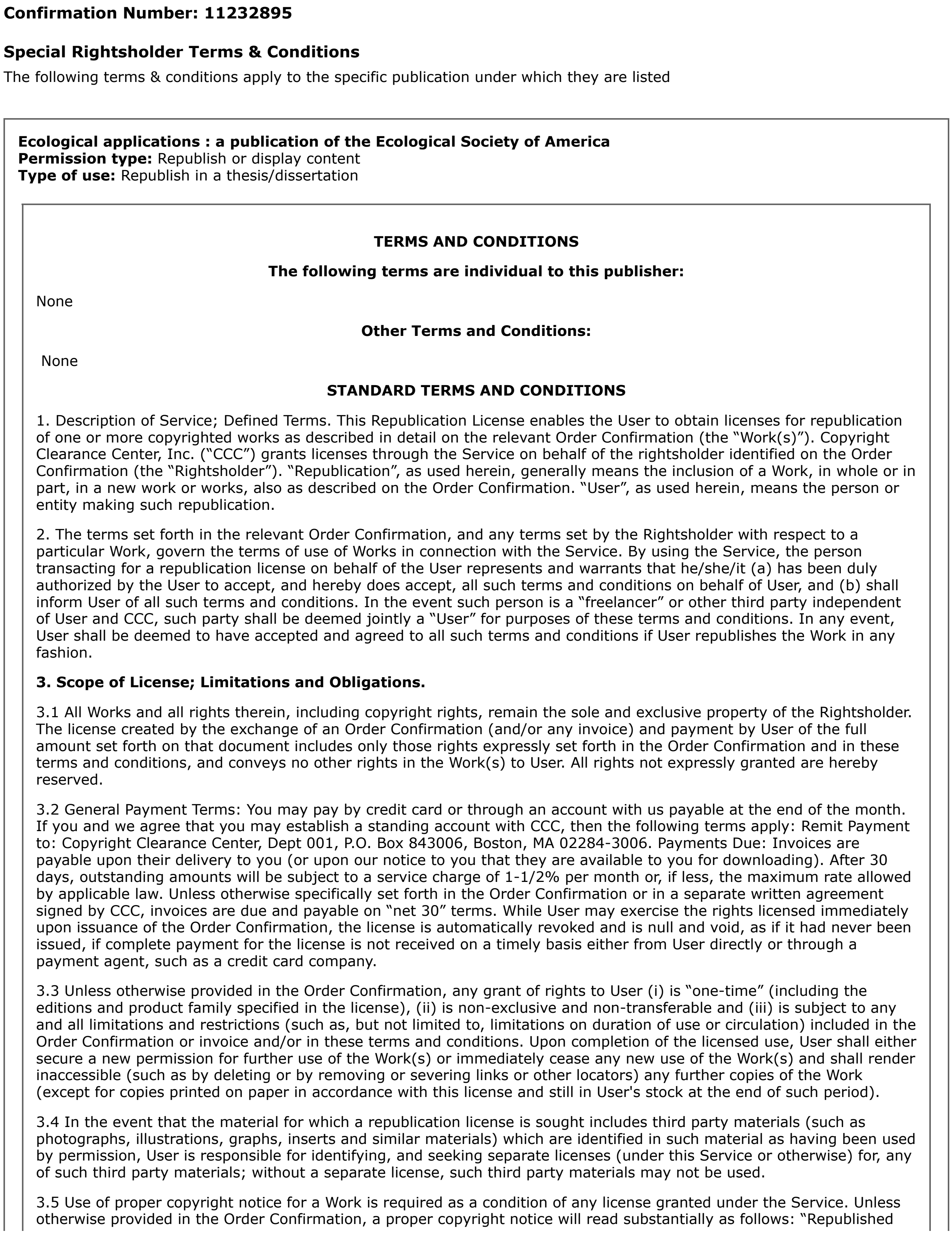

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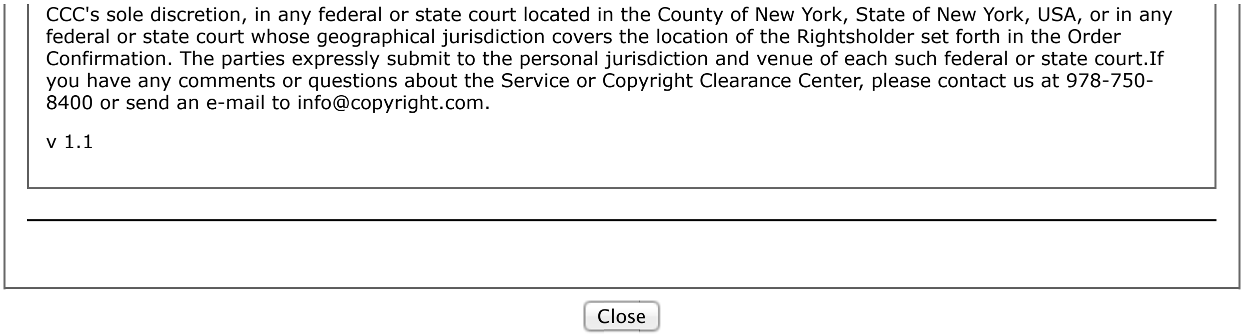
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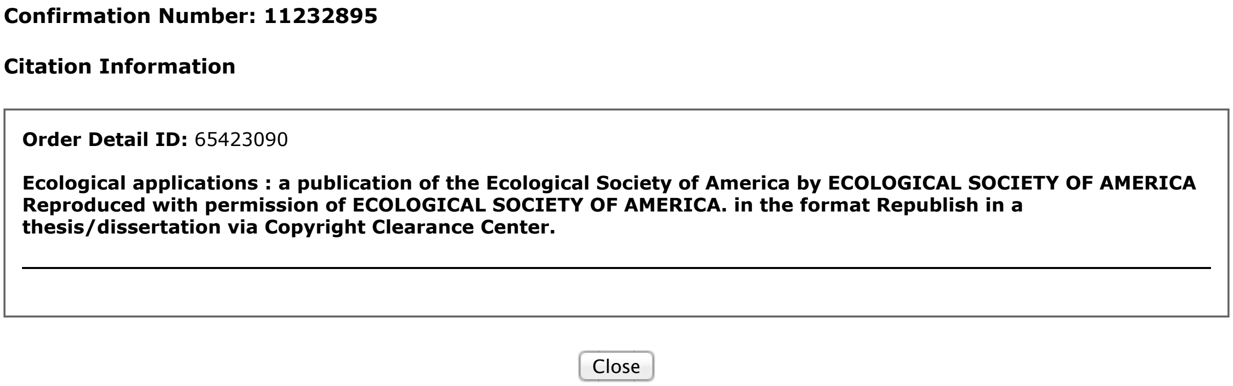
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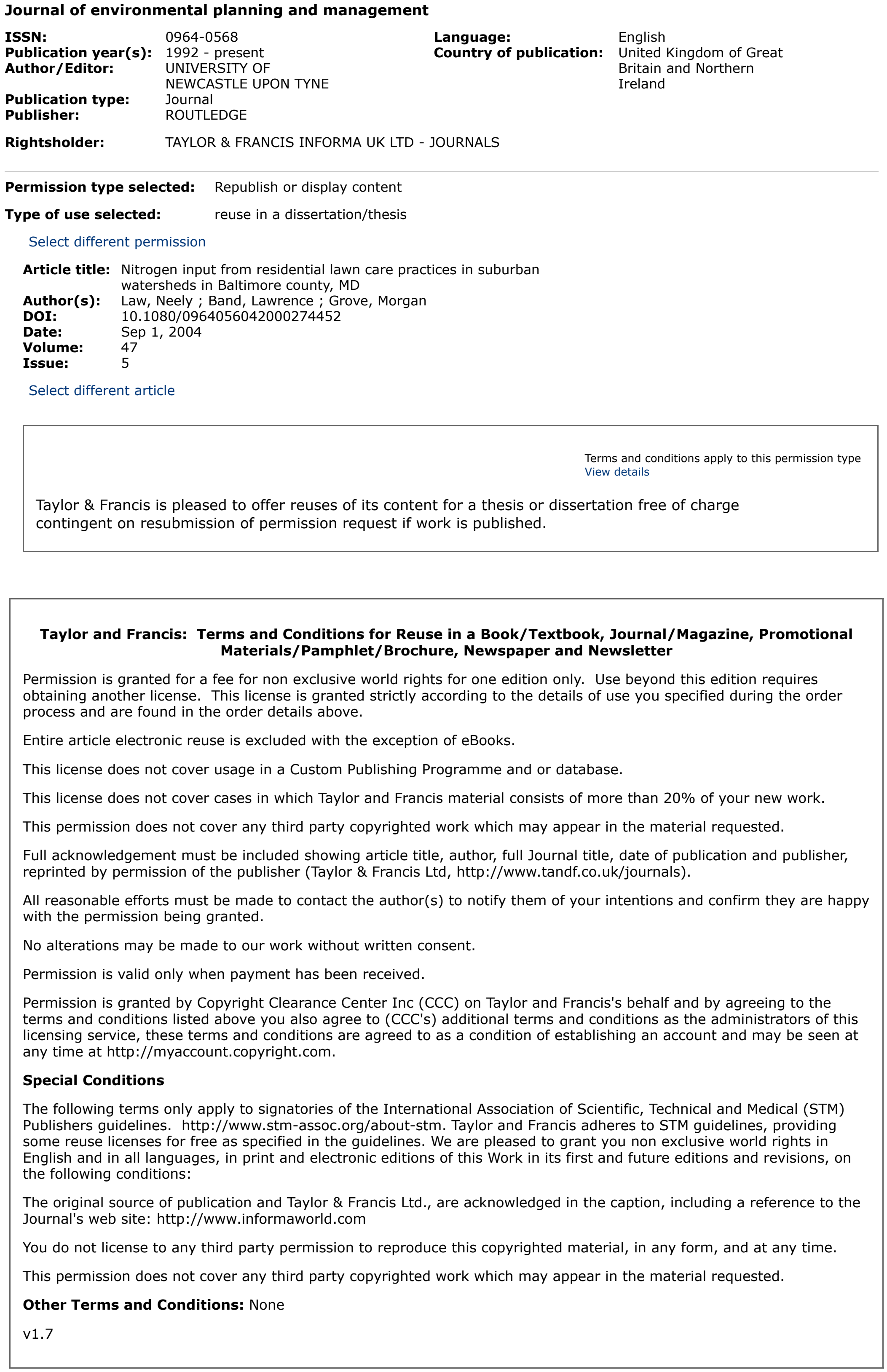

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Melissa Rachelle Butcher graduated from the University of Texas at Arlington with a Bachelor of Arts in French in 2006. She previously worked for the Federal Emergency Management Agency out of the Region VI office in Denton, Texas. She graduated from the University of South Florida (USF) with a Bachelor of Science in Civil Engineering in 2013. She worked on graduate coursework while pursuing her B.S. in Civil Engineering at USF as part of the Accelerated Program in engineering.

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