PARTITIONING RUNOFF AND PERCOLATION OF URBAN SOILS IN RESPONSE TO PRECIPITATION AND SOIL CHARACTERISTICS

By

BRIAN JOSEPH PEARSON

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2011

To my mother, father, and wife, Ommy

ACKNOWLEDGMENTS

Completion of this study would not have been possible without the help and support of family, friends, and colleagues.

I would first like to thank my graduate advisor, Dr. Richard C. Beeson, Jr., for his time, commitment, and faith in my ability to successfully complete this work. His endless support and guidance are foundational to this work and my professional abilities. In addition to serving as my advisor, he also served as a close friend over the past several years. I would also like to thank my committee members, Drs. Carrie Reinhardt-Adams, Amy Shober, Michael Olexa, and Gary Knox for their support and expertise. Their guidance and insight was essential to this interdisciplinary research project.

I would like to thank my wife, Ommy Pearson, and my family for their support and encouragement throughout this process. I would also like to thank them for making me laugh and relax when I needed it most, and for their encouragement through the many trials of this degree program.

Lastly, I would like to thank my friends and colleagues at the Mid-Florida Research and Education Center. Specifically, I would like to thank Dr. Wayne Mackay, Dr. Dilma Silva, and Emily Massey for their help and support. I would also like to thank Dr. Michele Scheiber for her encouragement to initially pursue this research and giving me an opportunity to work at the research center.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BMP	Best Management Practice
D_b	Bulk density
DRP	Dissolved reactive phosphorus
EDV	Expected discharge volume
FAWN	Florida Automated Weather Network
GPS	Global Positioning System
HDPE	High-density polyethylene
IE	Infiltration-excess
K	Potassium
MREC	Mid-Florida Research and Education Center
MWAC	Mulch water absorptive capacity
NPRP	National Phosphorus Research Protocol
NRCS	National Resource Conservation Service
N	Nitrogen
ODV	Observed discharge volume
P	Phosphorus
PP	Particulate phosphorus
PAW	Plant available water
PI	Precipitation input
PSB	Plant shoot biomass
PVC	Polyvinyl chloride
SE	Saturation-excess
SWAC	Soil water absorptive capacity
TDT	Time domain transmissometry

USEPA	United Stated Environmental Protection Agency
VWC	Volumetric Water Content
WAT	Week after transplant
WEPP	Water Erosion Prediction Project

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

PARTITIONING RUNOFF AND PERCOLATION OF URBAN SOILS IN RESPONSE TO PRECIPITATION AND SOIL CHARACTERISTICS

By

Brian Joseph Pearson

December 2011

Chair: Richard C. Beeson, Jr.
Major: Horticultural Science—Environmental Horticulture

Soil nutrient applications are beneficial to plant growth and aesthetic quality, yet have the potential to degrade ground and surface water quality through stormwater nutrient leaching and runoff mechanisms. The fate of soil nutrients has been intensively researched in agricultural production, yet few studies have focused on urban residential landscapes. An examination of soil characteristics in newly constructed urban residential communities within Central Florida was conducted. Mean soil bulk density for over 50% of sampled communities was near 1.75 g cm^{-3}. A majority (90%) of sampled building sites contained coarse-textured sandy soils. Half of sampled sites had soil infiltration rates below the 100-year, 24-hour design storm intensity.

Three soils representing the textural range observed in these communities were used for in-depth runoff and leachate studies. Runoff boxes were constructed and filled with the three soil types. Influences of soil type, soil moisture level, and precipitation intensity on runoff and leachate volume were examined. Low soil moisture (≤ 40% plant available water) or precipitation intensity (2.5 cm hr^{-1} for 15 minutes) produced zero or near zero runoff and leachate volumes. Higher soil moisture (70 and 90% plant available water) and precipitation intensity (5.1 and 7.6 cm hr^{-1}) levels produced large

runoff and leachate volumes. Results suggest measureable stormwater runoff and leachate will occur in barren moist soils of urban residential communities under short interval, high intensity (≥ 5.1 cm hr^{-1}) precipitation events.

A 5.7 cm layer of pine bark mulch applied to the soil surface of runoff boxes decreased runoff volumes to zero and near zero values, while leachate volumes were not influenced at moderate precipitation intensity and soil moisture. Physical impedance and absorptive capacity of mulch therefore provides a potential reduction of stormwater nutrient runoff. Addition of six *Salvia farinacea* transplanted into each lysimeter had no influence on runoff or leachate volumes.

CHAPTER 1
INTRODUCTION

Soil nutrient applications are used to optimize growth and aesthetic quality of plants both in landscapes and production. Although beneficial for growth, fertilizers have been identified as a global concern due to their propensity to degrade water quality through stormwater runoff and leaching mechanisms (Franklin et al., 2006a; Morton et al., 1988; Petrovic, 1990; Schwartz and Shuman, 2005; Starr and DeRoo, 1981). The United States Environmental Protection Agency (USEPA) also concluded nutrient enrichment was a leading cause of national water quality degradation (USEPA, 2009). Nitrogen (N) and phosphorus (P), two elements commonly found in fertilizers, are responsible for ground and surface water quality degradation (Carpenter et al., 1998; Lal and Stewart, 1994; Petrovic, 1990). Although fertilizer applications are common in residential landscapes, environmental transport mechanisms of these sources responsible for water quality degradation are poorly understood (Franklin et al., 2006a; Keeney, 1986; McLeod and Hegg, 1984). Research examining factors responsible for translocation of nutrient additions is necessary for development of appropriate management plans (Franklin et al., 2006a; Schwartz and Shuman, 2005).

Fertilizer usage has historically focused on increasing agricultural crop yield (Chrispeels and Sadava, 1994). Given 60% of the world’s arable lands have mineral deficiencies or elemental toxicities, use of nutrient applications in agricultural crop production will likely continue, and increase with growing global crop demands (Fageria et al., 2008). Fertilizer usage is not limited to agricultural production. It is also frequently used in urban environments to promote landscape plant growth and establishment (Hensley, 2010; Knox et al., 1995; Varlamoff et al., 2001). Although nutrient additions are beneficial to landscape plant material, they can potentially degrade water quality if transported to ground or surface waters. Fertilizers transported through stormwater nutrient runoff and leaching mechanisms become non-point source pollutants, and can cause eutrophic effects and shifts in natural vegetation populations (Anderson et al., 2002; Craft, 1997; Davis et al., 2006; Fisher et al., 2006; Green and Galatowitsch, 2002; Miao et al., 2001). A large collection of research has examined the fate of nutrient additions in agricultural production (Barraclough et al., 1985; Chichester, 1977; Dabney et al., 2001; Gascho et al., 1998; McLeod and Hegg, 1984; Mosdell, 1985; Watson and Dowdell, 1986). Yet few studies have focused on nutrient losses from urban residential landscapes. A better understanding of this pollutant source is necessary for development of appropriate management plans and effective regulations (Barton and Colmer, 2006; Brown Gaddis et al., 2007; Shober et al., 2010).

Hydrology

Hydrologic mechanisms are responsible for transport of nutrients to surface and groundwater supply. Thus it is necessary to identify and understand these pathways as they are fundamental to stormwater nutrient runoff and leaching concerns.

Hydrologic Principles

Water movement through soil is generally classified as saturated flow, unsaturated flow, or vapor movement (Brady and Weil, 2002). Unsaturated and saturated flow are the most influential types of water movement when discussing stormwater nutrient runoff and leaching.

Saturated flow through soil is defined by Darcy’s law (Kirkham, 2005). This model defines the hydraulic gradient as the force determining direction and speed of water flow in saturated soil conditions. Traditional models identify macropores as influencing hydraulic gradients and controlling the majority of saturated water flow (Brady and Weil, 2002). Factors affecting size and configuration of soil macropores therefore impact saturated infiltration rates. Lai and Ren (2007) evaluated methods for quantifying saturated water flow. They determined a large (> 80 cm) diameter double-ring infiltrometer was necessary if used in soils with high spatial variability. Gregory et al. (2005) however, concluded that a 15 cm double-ring infiltrometer was adequate in quantifying saturated infiltration rates in Florida's coarse, sandy soils. Yet, the large spatial variability in macroporosity of urban soils makes accurate determination of saturated infiltration rate difficult to estimate, even when using a large diameter infiltrometer (Schulze-Makuch et al., 1999).

Traditional hydraulic models indicate that water flow does not occur in macropores of unsaturated soils. Rather, unsaturated water flow occurs in soil micropores and is controlled by soil matric potential gradients (Brady and Weil, 2002). Matric potential gradients are influenced by soil moisture content and soil texture. Large variability in soil texture, common to urban soil environments, may influence unsaturated water flow (Craul, 1992). Methods for quantifying unsaturated water flow have been investigated (Madsen and Chandler, 2007; Zhang, 1997). A disk infiltrometer provided direct measurement of hydraulic conductivity with exclusion of macropore flow. This resulted in less spatial variability when compared to double-ring infiltrometers and may be a better representative of infiltration rates in urban environments.

In contrast, non-traditional unsaturated water flow models propose macropore flow can occur when soils are not saturated (Towner, 1989). This type of flow is defined as "short-circuiting" or "non-matrix flow" (Bouma, 1981; Bouma et al., 1978). Short-circuiting flow places greater importance on soil pore continuity rather than soil pore size, such as decayed root tunnels. A model that includes “short-circuiting” presents challenges when estimating unsaturated water flow rates based upon macromorphological data obtained from existing soil survey reports (Bouma, 1981).

Two hydrologic models, saturation-excess and infiltration-excess, have been developed to describe soil stormwater flow. The saturation-excess model predicts stormwater discharge after soil has become saturated and unable to convey additional precipitation volume as subsurface flow (Dunne, 1983). Soil water absorptive capacity is highly influential to stormwater discharge in application of this model. The infiltration-excess hydrologic model predicts stormwater discharge when precipitation rate exceeds infiltration rate (Horton, 1933). Soil texture and structure are highly influential to stormwater discharge in application of the infiltration-excess model (Dunne, 1983).

Soil Compaction

Soil compaction in urban environments occurs through use of construction equipment, or through intentional strengthening of soil to provide the necessary engineering medium for load-bearing infrastructure (Brady and Weil, 2002; Grabosky and Bassuck, 1995; Jim, 1998). Soil compaction alters soil pore spaces and generally decreases soil infiltration rates (Raper, 2005). Numerous studies have examined this relationship in agriculture, but few studies conducted in urban environments exist.

A study in Florida examined the influence of residential construction on soil hydrology (Gregory et al., 2006). Construction activities reduced infiltration rates by 80 and 99% in front and back portions of a developed lot, respectively. Heavy equipment usage increased mean soil bulk density (from 1.34 to 1.49 g cm^{-3}), causing corresponding decreases in mean infiltration rates (from 73.3 to 17.8 cm hr^{-1}). A related study examined the influence of soil compaction and soil moisture on infiltration rates of various soil textural classes (Pitt et al., 2008). Compaction and soil moisture had significant effects on soil infiltration rates in clayey soils. In sandy soils, however, only compaction effects were significant. Thus soil moisture content may be of limited importance when discussing soil compaction in Florida's sandy soils.

In addition to influencing infiltration rates, soil compaction also affects soil surface water repellency. This relationship was examined among three soil types (non-repellent, strongly repellent, and severely water repellent) (Bryant et al., 2007). Soil compaction increased water infiltration of soils that were initially hydrophobic. Increased hydraulic conductivity was associated with a decrease in surface roughness. Thus under certain circumstances, compaction may improve site conditions by increasing soil infiltration rates.

Soil Surface Crusting

Soils left without vegetative cover may develop thin layers of surface soil crusts (Craul, 1992). These crusts are generally composed of disintegrated soil aggregates and very fine soil particles that fill soil pore spaces (Chen et al., 1980). Presence of a crust layer decreases infiltration rates, reduces hydraulic conductivity, and increases stormwater runoff and soil erosion (Blanco-Canqui and Lal, 2009; Le Bissonnais et al., 1998). Although a soil crust layer may be thin (0.1 mm diameter), permeability may be 2000-fold less than subsurface soils (Agassi et al., 1985; McIntyre, 1958). Open cracks that develop in soil crusts may promote bypass flow or "short-circuiting" flow allowing for localized areas of high permeability (Stolte et al., 1997; Van Stiphout et al., 1987). This condition may promote increased infiltration rate variability at larger spatial scales, a condition commonly observed in urban soils (Craul, 1992). Although soil crusts are common in urban environments, the extent to which crusts influence hydrology at a watershed-scale is unknown (Craul, 1992).

Urban Stormwater Flow

Anthropogenic activities in urban areas are responsible for unique soil and hydrologic characteristics. Urban soils tend to be compacted, include impervious surfaces, and have modified soil structures (Craul, 1992). Collectively, these characteristics reduce surface and subsurface water storage, increase stormwater surface flow, and lead to greater soil erosion (Konrad, 2005).

Urban areas containing high percentages of impervious surfaces load surrounding soils with high volumes of stormwater runoff during heavy precipitation events. Pappas et al. (2011) examined the influence of this “run-on” loading effect. They concluded that increases in impervious surfaces were directly related to increases in stormwater runoff volume and sediment loss. Similar research examined relationships between run-on water containing suspended sediment and its influence on soil erosion (Zheng et al., 2000). Both near-surface hydraulic gradients and run-on sediment load affected soil erosion. Few rainfall-runoff studies include this hydrologic component (Pappas et al., 2011). If run-on water volumes are not included in rainfall-runoff studies, experimental precipitation treatments may underestimate actual watershed flow volumes.

Urban watershed flow exhibits frequent, rapid changes in stormwater volume (Ehrenfeld et al., 2003). Peak urban stormwater flow can be 2- to 5-fold more intense, and can last 5- to 10-fold longer than stormwater flow in undisturbed areas (Booth and Jackson, 1997; Hollis, 1975). Epsey et al. (1969) described this characteristic as stormwater “flashiness.” Development of an index to further define and quantify this type of urban stormwater flow event had been investigated (Baker et al., 2004). These rapid, intense urban stormwater flow events intensify soil erosion and transportation of soil nutrients (Grimm et al., 2005; Hatt et al., 2004). A better understanding between the relationship of run-on stormwater flow, watershed flashiness, and stormwater nutrient loss is needed.

Nutrient Runoff and Leaching

Stormwater nutrient runoff and leaching studies are fundamental to understanding linkages between cultural practices, hydrology, and nutrient loss. Nutrient loss is affected by precipitation, soil moisture, fertilizer application characteristics, and presence of vegetative cover. Nutrient loss studies are affected by research scale, an important component that must be considered when interpreting research results. A review of these influential factors is necessary in understanding stormwater nutrient runoff and leachate concerns.

Precipitation and Irrigation

Precipitation events can have a substantial effect on stormwater nutrient runoff and leachate production in urban environments. Precipitation, from natural rainfall or applied irrigation, has two fates in landscapes. Precipitation will enter soil as groundwater or run off soil surfaces as surface water. Both fates are common in urban environments and directly influence mobility of applied nutrients.

Morton et al. (1988) examined N loss from Kentucky bluegrass (*Poa pratensis* L.) grown in sandy loam soils and managed under two irrigation treatments (tensiometer-controlled and time clock scheduled). Tensiometer-controlled treatments were designed to apply irrigation to avoid drought stress and prevent overwatering. Whereas scheduled irrigation treatments applied 1.25 cm of irrigation three times per week, regardless of natural rainfall, thus creating “overwatered” conditions. Nitrogen concentrations in leachate from scheduled irrigation treatments were 5- to 11-fold greater than tensiometer-controlled treatments. Similar research examined differences in nutrient loss from bermudagrass (*Cynodon dactylon* x *Cynodon transvaalensis*) managed under similar irrigation treatments (tensiometer-controlled and daily scheduled irrigation) (Snyder et al., 1984). Nitrogen losses from scheduled irrigation treatments were 2- to 29-fold greater than for tensiometer-controlled treatments. Additionally there was a significant season effect with peak N loss occurring in spring.

Stormwater nutrient runoff studies have also examined relationships between nutrient concentrations and precipitation rates. Nitrogen loss from Tifdwarf bermudagrass (*Cynodon dactylon* L.) was quantified under scheduled low, medium, and high application rates (Brown et al., 1977). Nitrogen loss concentrations and duration of peak N loss were significantly influenced by irrigation application rate. Nutrient loss concentrations increased with correspondingly greater irrigation applications. A similar study examined N and P loss in stormwater nutrient runoff from plots containing Tifway bermudagrass grown in a sandy loam soil (Shuman, 2002). Runoff volumes were related to rainfall rates and soil moisture, while N and P concentrations were related to time following nutrient application. Strong correlations between stormwater volume and soil moisture were observed throughout the experiment, with runoff volumes increasing with increasing soil moisture. Similar correlations between soil moisture and stormwater runoff volumes were also observed with bermudagrass grown in a silt loam soil (Cole et al., 1997). These results suggest that precipitation rates not only significantly influence leachate concentrations, but also duration of peak nutrient loss. In addition, these results support classic stormwater modeling theory, and reinforce relationships between stormwater runoff volume, precipitation volume, and soil moisture (Singh and Birsoy, 1977).

Time

Duration of time between nutrient application and precipitation events can influence stormwater nutrient runoff and leachate concentrations. Shuman (2002) observed increased N concentrations in stormwater runoff 72 and 168 hours after applying mono-ammonium phosphate to bermudagrass plots. Concentrations of N in stormwater increased with time following nutrient application, while P concentrations decreased. Shuman concluded that increased N concentrations resulted from conversion of ammonium to nitrate-N promoting greater N mobility. Brown et al. (1977) observed similar N loss in leachate resulting from conversion of ammonium to nitrate-N.

Short duration of time between nutrient application and precipitation may increase N and P loss. High N loss was observed when precipitation occurred 10 days after application of ammonium nitrate and sulfur-coated urea (Snyder et al., 1984). Although 85 to 95% of mean N leachate loss occurred as nitrate-N, ammonium loss was as high as 30%. Shuman (2002) observed greatest P loss when precipitation occurred shortly (4 hrs) after nutrient application. Chichester (1977) observed similar trends with agronomic crops where greatest N loss occurred when short durations existed between nutrient application and intense precipitation. Results suggest form and timing of nutrient additions are both important components of nutrient management.

Fertilizer Type

Relationships between fertilizer type and nutrient loss are well established (Brown, 1982; Gaudreau et al., 2002; Hummel, 1981; Hummel, 1984; Saha et al., 2005; Tarkalson and Mikkelsen, 2004). Three fertilizer types most commonly used in landscape and production systems include organic, inorganic soluble, and inorganic slow-release (Hensley, 2010). Soluble nutrient sources are mobile within soil thus possess high potential to degrade groundwater quality. However, this fertilizer form exhibits low leaching characteristics when conditions promoting rapid plant uptake and soil colloid adsorption are present (Gascho et al., 1998). Organic and inorganic slow release fertilizers have low leaching potential when applied at appropriate rates and are recommended in Florida landscape nutrient management plans (Florida Yards and Neighborhoods Program, 2006). Environmental nutrient concerns associated with organic fertilizers primarily focused on P loss (Havlin et al., 2005). Relationships between soil test P, fertilizer source, and environmental risk have been evaluated (Cox and Hendricks, 2000; Davis et al., 2005; DeLaune et al., 2004a; DeLaune et al., 2004b; Nair et al., 2004). Regardless of nutrient source, proper nutrient management plans minimize water quality degradation while benefitting plant growth and establishment (Campbell, 1994).

Vegetative Cover

Vegetative cover influences N and P loss through hydrological, chemical, and biological actions (Craul, 1992; Havlin et al., 2005; Lal and Stewart, 1994). However few studies examining this relationship exist.

Chichester (1977) compared nutrient loss from meadow grass (*Danthonia spicata* L., *Poa pratensis* L., *Medicago sativa* L.-*Dactylis glomerata* L.) and corn (*Zea mays* L.) managed under similar conditions. Stormwater N concentrations from the corn treatment were 5- to 10-fold greater than from meadow grass. Chichester concluded that reduced stormwater N concentrations from meadow grasses resulted from meadow grass's greater effectiveness at decreasing stormwater runoff and soil erosion. A similar study examined nutrient loss from two vegetative treatments (turfgrass and mixed-species landscapes) (Erickson et al., 2001). No differences were observed in stormwater nutrient runoff concentrations between treatments. However differences were observed in leachate concentrations. The mixed-species treatment lost > 30% of applied N while the turfgrass treatment lost < 2%. Greater vegetative density of the turfgrass treatment was responsible for reductions in leachate N loss. Their findings suggested that mixed-species landscapes may require nutrient application methods designed to target areas of nutrient uptake (Erickson et al., 2001). Additional research is needed to develop a better understanding of relationships between landscape plant materials, cultural practices, site conditions, and nutrient loss.

Research Scale

Stormwater nutrient runoff and leachate studies are often conducted at small, plot-level scales. Data collected from this research is “directionally” applied to larger scale watersheds (Smith and Pappas, 2010). Two research procedures (National Phosphorus Research Project protocol (NPRP) and Water Erosion Prediction Project (WEPP) protocol) have been developed to standardize experimental designs (SERA-17, 2008; Simanton and Renard, 1992). Both procedures outline design parameters necessary to examine P-loss at small spatial scales. Sharpley and Kleinman (2003) examined influence of plot scale on P loss using these protocols. Smaller plot size of the NPRP protocol resulted in greater overland flow volume and higher concentrations of dissolved reactive P (DRP) in stormwater runoff. Larger plot size of the WEPP protocol resulted in increased overland flow velocity, greater sediment discharge, and higher particulate phosphorus (PP) concentrations. Dissolved reactive P and soil test-P remained similar despite differences in plot size. Similar relationships between plot size and nutrient loss have been observed (Bloschl and Sivapalan, 1995; Le Bissonnais et al., 1998; Wauchope and Burgoa, 1995). Gascho et al. (1998) examined relationships between DRP, nitrate-N and plot size in stormwater nutrient runoff. Concentrations of both DRP and nitrate-N were similar regardless of plot size. High soil infiltration homogeneity and low precipitation rate (2.5 cm hr^{-1}) were responsible for recorded observations. Results support continued use of small, plot-level scale research to assess relationships between overland flow P and soil test-P.

National Phosphorus Research Project protocol outlines a process for construction and use of small scale runoff boxes (SERA-17, 2008). These devices increase sample size and treatment control while reducing experimental time and effort. Runoff boxes exhibit elevated runoff volumes and increased soil erosion when compared to larger, field scale plots (Guidry et al., 2006; Kleinman et al., 2004). Reductions in soil infiltration rates observed in runoff box studies result from modifications to soil structure that occur during experimental construction. Soil structural modifications include decreased macroporosity, destruction of natural soil structure, and elimination of complex horizons. Although runoff boxes exhibit hydrologic properties that differ from comparable field soils, they are recommended for use to examine variables that influence stormwater nutrient runoff or development of a nutrient extraction coefficient (Kleinman et al., 2004; Sharpley, 1995; Vadas et al., 2005).

Nutrient Use in the Environment

Nitrogen and P are required for proper plant growth and development (Chrispeels and Sadava, 1994). These elements are the most commonly deficient nutrients in non-legume plants. Thus they are commonly applied to landscapes to increase aesthetic quality or influence growth and establishment (Hensley, 2010).

Although N constitutes 78% of earth's atmosphere, it is largely unavailable to plant systems (Chrispeels and Sadava, 1994). Root systems of plant materials acquire N through symbiotic microorganism relationships, non-symbiotic soil microorganisms, atmospheric discharges forming N oxides, or through application of manufactured synthetic fertilizers. Manufactured fertilizer demand has increased worldwide from 22 to 85 million metric tons in the past 30 years (Havlin et al., 2005). In 2008, approximately 5.7 million metric tons of N were applied in the US (USDA, 2011). Currently, synthetic fixation of N exceeds global biological fixation rates (Mackenzie, 1998). Fate of applied N includes atmospheric loss from volatilization and denitrification, uptake by plant root systems, mineralization, and runoff or leaching into groundwater supply (Havlin et al., 2005).

Phosphorus (P) is less abundant in soils than either N or potassium (K) and ranges in concentrations from 0.005 to 0.15% in surface soils (Havlin et al., 2005). Availability of P to plant systems is primarily controlled by mineral solubility and not soil concentration. Fate of applied P includes immobilization, adsorption, precipitation into secondary minerals, uptake by plant root systems, and runoff or leaching into groundwater supply (Havlin et al., 2005). Application of P in the US during 2008 was approximately 1.93 million metric tons (USDA, 2011).

Application Practices

A detailed description of urban residential nutrient application practices are necessary when discussing stormwater nutrient runoff and leaching from urban residential areas. Application practices used in landscapes by homeowners or professional landscape management professionals are generally difficult to quantify and poorly documented in literature (Shober et al., 2010). Available studies are spatially limited given research constraints. However it is important to review available resources to gain perspective of usage patterns.

A study in Florida found that 80% of surveyed urban residential landscapes incorporated fertilizer applications as part of their landscape management plan (Knox et al., 1995). Homeowners and landscape professionals often applied more fertilizer than necessary or recommended by available best management practices (BMPs). A similar study conducted in Maryland found that 70% of surveyed urban residential landscapes incorporated fertilizer applications as part of their landscape management plan (Law et al., 2004). Application rates were dependent on user type. Average annual nutrient application rates of professionally managed landscapes ranged from 100.1 to 161 kg N ha^{-1} yr^{-1} (2.1 to 3.3 lbs N 1000 ft^{-2} yr^{-1}) (Law et al., 2004). Landscapes managed by homeowners had a similar average annual application rate of 106.9 kg N ha^{-1} yr^{-1} (2.2 lbs N 1000 ft^{-2} yr^{-1}), but greater variance with application rates ranging between 10.5 and 369.7 kg N ha^{-1} yr^{-1} (0.2 to 7.6 lbs N 1000 ft^{-2} yr^{-1}). This trend indicates that fertilizer consumers are either not well-informed or disregard available application rate recommendations. If typical usage patterns in Florida are similar to those described by Knox et al. (1995) and Law et al. (2004), inaccurate fertilizer application may be a significant contributor to non-point source pollution.

Accurate delivery of fertilizer is essential when managing nutrient additions. Revised nutrient application regulations may fail to demonstrate an impact if homeowners or landscape managers fail to accurately apply fertilizer. Arthurs and Stauderman (2010) examined factors influencing fertilizer application accuracy. An individual’s self-reported experience, gender, and age were not related to application accuracy. However, type of spreader used for nutrient application was influential. Additional studies examining fertilizer application practices in urban environments are needed.

Landscape Cultural Practices

Cultural practices have the ability to influence hydraulic properties of soils. Common cultural practices include tillage, mulching, and transplanting of vegetative cover.

Tillage is a common practice in agricultural production (Brady and Weil, 2002; Chrispeels and Sadava, 1994). Benefits of tillage include breakdown of soil clods, incorporation of soil organic matter, and an increase in soil porosity. Tillage is recommended in urban environments to reduce soil compaction and increase permeability (Black and Ruppert, 1998). Disruptions to macropore connectivity from tillage, however, can decrease infiltration rates in silt and sandy loam soils (Strudley et al., 2008). Wuest (2009) observed 26.8% lower infiltration rates following tillage of a silt loam soil.

Use of mulch in landscape design and management improves soil conditions and promotes growth and establishment of plant materials (Black and Ruppert, 1998; Hensley, 2010). Benefits include increased soil moisture, moderation of soil temperatures, and prevention of soil crusting. Wan and El-Swaify (1999) examined the relationship between inorganic mulch and stormwater runoff volume. Inorganic mulch applied in absence of plant materials increased stormwater runoff due to impervious characteristics of the mulch. When applied to areas containing plant materials, inorganic mulch decreased stormwater runoff volumes due to formations of micro-basins near plant stems. A similar study examined the influence of organic mulch (*Pennisetum* *purpureum*) on three soil series (Adekalu et al., 2007). Presence of mulch reduced stormwater runoff and soil erosion from sandy loam, sand clay loam, and loamy sand soils. Coarse soils with low organic matter, however, required larger application of mulch to achieve similar benefits as finer texture soils with greater concentrations of organic matter. Although reductions in stormwater runoff and soil erosion can be achieved with mulch applications, high application rates of organic mulch negatively influence plant establishment through interception of irrigation or precipitation (Gilman and Grabosky, 2004).

Growth of plant materials influences soil hydrology through stabilization of soil structure, reductions in soil erosion, and increases in soil infiltration rates. Root growth of black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L.) increased infiltration rates by a mean of 153% in severely compacted soils (Bartens et al., 2008). Increases in infiltration resulted from preferential water flow occurring along root channels of existing live roots.

Foliage of plant materials can intercept and direct precipitation or irrigation to plant stems. Preferential water flow directs water into surrounding soils along root channels (Johnson and Lehmann, 2006; Ladekarl, 1998). This action, termed “stemflow”, has also been observed with corn where infiltration rates increased > 60% (Dolan et al., 2001). Results suggest presence, size, and density of plant materials play a significant role in soil infiltration rates.

Urban Soil Characterization

Urban population growth requires construction of buildings, roads, and supporting infrastructure. These practices influence soil characteristics creating unique conditions. Urban soils are non-agricultural soils containing thick, anthropogenic surface layers created though mixing and filling actions (Bockheim, 1974). Soil characteristics in urban environments differ from rural areas by scale and intensity of human influence (Bullock and Gregory, 1991).

A wide array of construction and land use practices create high vertical and spatial variability in urban soils. These unique conditions are defined as “lithologic discontinuities” (Craul, 1985). Anthropogenically disrupted soil profiles vary in thickness; however, few studies have quantified this characteristic in urban environments. Craul and Klein (1980) examined presence of these profiles along roadways and recorded depths ranging between 6 and 35 cm. In addition to varying in depth, lithologic discontinuities were highly variable in texture, structure, organic matter content, pH, and bulk density. Accurate determination of vertical variability is difficult as soil profiles may not be parallel to soil surfaces and readily identifiable (De Kimpe and Morel, 2000). Patterns of construction and a variety of land use result in high spatial variability (Pavao-Zuckerman, 2008). Regional variances in construction practices coupled with differences in ecological patterns make comparisons of urban soil variability difficult (Pavao-Zuckerman and Coleman, 2005).

Urban construction practices often result in increased soil compaction and destruction of soil structure (Brady and Weil, 2002; Craul, 1985). These actions reduce soil macroporosity and negatively influence soil permeability, water-holding capacity, aeration, and root penetration. Disturbances to natural soil profiles result in a loss of macropore connectivity further reducing soil infiltration rates (Wuest, 2009). Although soils with low organic matter and fine soil texture are most likely to become negatively influenced by soil compaction, coarse texture soils are also at risk (Craul and Klein, 1980; Gregory et al., 2006). Studies examining relationships between soil compaction and infiltration are available; however, few have quantified changes in pore size distributions resulting from construction practices (Startsev and McNabb, 2001).

Urban development activities destroy soil aggregates and promote surface soil crusting and seal formation (Assouline, 2004; Craul, 1992). Soil crusts are common in urban soils and occur when soil is bare for long durations (Beasley, 1978; De Kimpe and Morel, 2000; Hillel, 1980; Kazman et al., 1983). Formation of crusts occurs from precipitation disintegrating and displacing soil aggregates into adjacent macropores. This action blocks preferential flow pathways and reduces soil infiltration rates (Agassi et al., 1985).

Chemical properties of urban soils differ from undisturbed soils (Craul, 1992). Construction activities oftentimes result in increased soil pH (Bockheim, 1974; Craul and Klein, 1980). Craul and Klein (1980) observed urban soil pH ranging between 6.6 and 9.0. Similar research in West Germany recorded mean soil pH of 8.0 in an urban area, while nearby, undisturbed forest soil had mean pH of 4.0 (Chinnow, 1975). High pH of urban soil resulted from high concentrations of calcium or sodium chloride found in de-icing solutions, calcium-enriched irrigation applied to the landscape, or release of calcium from construction materials.

Urban soils are often characterized with disrupted nutrient cycling and high levels of ecological heterogeneity (Craul, 1985; Ellis and Mellow, 1995). Disrupted nutrient cycling reduces accumulation of organic matter resulting in unique soil biogeochemistry (Kaye et al., 2006). Shifts in nutrient availability influence ecosystem functioning in newly constructed urban environments, and often require nutrient input for proper plant growth and establishment (Goldman et al., 1995; Hensley, 2010; Kaye et al., 2005). Although urban construction activities are described as negatively influencing biological soil activity, few studies have examined this relationship (Beyer et al., 1995).

Waste products generated from urban construction are often found in urban soil (Craul, 1992). Items include masonry, wood and paper, glass, plastic, metal, asphalt, and organic products. Waste materials reduce infiltration rates through water impedance and cause disruptions to nutrient cycling. High concentrations of waste products may also negatively influence biological soil activities.

CHAPTER 2
DETERMINING VARIABILITY IN CHARACHTERISTICS OF RESIDENTIAL LANDSCAPE SOILS THAT INFLUENCES INFILTRATION RATES

Central Florida receives high annual precipitation (137 cm yr^{-1}; NOAA, 2011) and has experienced rapid population growth within the past decade (U.S. Census Bureau, 2011). Mean population growth of three Central Florida's counties (Orange, Lake, and Seminole) was 28.2% between 2000 and 2010 (U.S. Census Bureau, 2011). Construction of new urban residences has continued in this region despite decreases in national housing trends. New housing construction in Florida accounted for 14.8% of the national average (U.S. Census Bureau, 2009).

Urban residential population growth requires construction of roads, homes, and supporting infrastructure. Construction activities impact urban soil characteristics often resulting in decreased soil infiltration rates (Craul, 1992). Soil infiltration rate is an important component of stormwater management as it defines percolation and allows estimation of stormwater runoff production from urban residential landscapes (Gregory et al., 2006; Petrovic, 1990). However, few studies have examined the relationship between urban residential soil characteristics and soil infiltration rates. Variability of construction practices and differences in regional ecological patterns make it difficult to generalize urban soil characteristics (Craul, 1985; Pavao-Zuckerman, 2008). Characteristics influential to infiltration rate include soil texture, soil bulk density, and soil moisture characteristics. A regional examination of relationships between soil characteristics and infiltration rates is needed to understand impacts of local construction activities.

The objectives of this study were to examine soil characteristics in newly constructed urban residential communities located within three Central Florida counties (Orange, Lake, and Seminole), and select representative soils for more intensive research. A goal of this investigation was to quantify soil characteristics and examine variability at plot-level and community-level scales, while examining relationships between soil characteristics and infiltration rates.

Material and Methods

Nine newly constructed urban residential communities were chosen to represent local, modern construction practices within Orange, Lake, and Seminole counties in Central Florida. These communities were selected based upon access and visual representation of local environmental variability. Five residential lots were randomly identified for sampling within each community. All selected lots had been prepared for housing construction through land clearing, backfilling, and leveling prior to sampling. No residential structures or vegetation were present at sampled lots; however, underground site utilities had been installed. If five lots were not available at sampling, all remaining sites within that community were selected. A total of 40 lots from 9 communities were sampled between January and May 2009.

Six soil samples were collected at random locations within each lot using a soil core sampler (Model 200; SoilMoisture Equipment Corporation, Santa Barbara, CA). Soil cores measured 5.7 cm in diameter and 3.0 cm in depth and were collected at a depth beginning 3.8 cm below soil surface. Collection location was recorded with a Global Positioning System (GPS) unit (Model Nuvi 200; Garmin International, Inc., Olathe, KS). Additional soil samples were collected using a soil auger (Model S-110;

Durham Geo-Enterprises, Inc., Stone Mountain, GA). Samples were collected at depths of 0-3, 28-33, 58-63, 89-94, and 119-124 cm below soil surface.

Three of the soil core samples were used for determination of soil bulk density. Cores were transferred to a laboratory oven (Model 18EM; Precision Scientific Group, Chicago, IL) and dried for analysis using the standard method of Blake and Hartge (1986). Soil core sample mass was measured using a top loading balance (Model PB5001: Mettler Toledo, Inc., Columbus, OH).

Two other soil core samples were used for determination of soil moisture retention characteristics. Cores were saturated under vacuum then placed in a ceramic plate extractor (Model 1500F1; SoilMoisture Equipment Corp.) and analyzed in accordance with ASTM method D6836 (ASTM, 2008). Moisture extraction was examined at 6.4, 9.8, 19.6, 39.2, 100, 500, and 1500 kPa to develop moisture retention characteristics. Sample mass at each pressure interval was recorded (Model PB5001; Mettler Toledo, Inc.). In addition to examining moisture retention characteristics, soil moisture data was used to quantify soil pore size distribution using the method of Klein and Libardi (2002).

One additional soil sample was collected within each lot at a depth of 0-3 cm using the soil auger. Samples were analyzed for particle size distribution for textural determination using the standard method of Gee and Bauder (1986).

Saturated soil infiltration rate was measured randomly within each lot using a falling head double-ring infiltrometer in accordance with the method described by Bouwer (1986). The double-ring infiltrometer was constructed of polyvinyl chloride (PVC) pipe measuring 30.5 cm in length. This device had an outer ring diameter of 10.2

cm, and an inner ring diameter of 5.1 cm. Both rings were installed to a depth of 10 cm below soil surface prior to measurement.

Statistical analysis of bulk density was conducted comparing mean values among lots and communities using the PROC GLM procedure in SAS (SAS Institute, 2008). Analysis of soil moisture characteristics compared mean soil moisture retention volumes between soil moisture potentials 6.4 and 100 kPa among lots and communities using the PROC GLM procedure and the Tukey-Kramer method. Given Florida's soil is dominated by sand particle size fractions (0.05 – 2 mm diameter), mean comparisons of percentage sand among communities was conducted using the PROC GLM procedure and Duncan's multiple range test. Mean comparisons of soil infiltration rates were analyzed among communities using the PROC GLM procedure and the Tukey-Kramer method. Regression analysis was conducted to examine relationships between soil infiltration rates, bulk density, soil moisture retention volume (between 6.4 and 100 kPa), and percentage of soil sand, silt, and clay using the PROC REG procedure in SAS (SAS Institute, 2008). All analytical tests were considered to be statistically significant if $P < 0.05$.

Results and Discussion

Soil Bulk Density

Mean soil bulk density (D_b) values ranged from 1.65 to 1.78 g cm^{-3} (Table 2-1). These values were similar to those observed by Gregory et al. (2006), where relationships between residential construction equipment use and soil compaction were examined. Observed D_b values were also similar to those found in newly constructed urban residential communities within Idaho and Washington (Scharenbroch et al., 2005). Over 50% of sampled communities had D_b values near 1.75 g cm^{-3}. When compaction exceeds this threshold value in sandy soils, plant root soil penetration can be negatively impacted (Voorhees, 1992). Ensuring soil compaction remains below this threshold may be necessary when attempting to successfully transplant and establish plant materials in newly constructed residential landscapes.

The variability of D_b among residential communities was low. Residential construction engineering practices require intentional, uniform strengthening of soil using a Proctor density test (Trowbridge and Bassuck, 2004). The test requires soil be compacted within 95% of peak Proctor density throughout the landscape prior to housing construction and is likely responsible for the similarity observed in soil D_b between communities. Although variability of D_b within each sampled lot was low, six lots had standard deviations > 0.10 g cm^{-3}. This trend was random and likely resultant of additional site traffic or equipment storage on these lots. Visual observation was made of construction equipment and vehicular storage on random lots at time of sampling. Efforts to avoid these lots were made; however, it was not possible to determine if sampled lots had additional traffic-induced compaction prior to sample collection.

Although no housing structures were built at time of sampling, significant increases in soil compaction resulting from additional construction activities are not likely, given high soil compaction values already imposed for Proctor density engineering standards. Assuming no additional soil disturbances occur, D_b would likely decrease with time resulting from improvements in physical, chemical, and biological soil characteristics (Scharenbroch et al., 2005).

Soil Moisture Retention Characteristics

Development of soil moisture retention characteristics allows for quantification of soil water volume at various soil matrix potentials. This information is pertinent for determining soil water holding capacity and water movement (Kirkham, 2005). Mean soil moisture retention volumes of communities ranged from 7.3 to 21.3 mL water 100 cm^{-3} soil between moisture potentials -6.4 and -100 kPa (Table 2-1). This matric potential range was selected as it represents the range of soil moisture available for plant uptake (Brady and Weil, 2002). Significant differences in soil moisture content were observed among communities. The coefficient of variation for mean soil moisture content within each lot ranged from 1.5 to 136.2 percent. High variability between replicate samples was likely a result of heterogeneity in soil pore size (Craul, 1985). Soil moisture retention characteristics of urban residential soils have not previously been reported.

Micropores (diameter 0.05 - 0.0002 mm) were the dominate pore size, representing 60% of mean soil pore space. Macropores (diameter > 0.05 mm) represented 21% of mean soil pore space while cryptopores (diameter < 0.0002 mm) accounted for 19% of mean soil pore space. The coefficient of variation for mean macroporosity within each lot ranged from 1.2 to 123.7 percent. High variability in macroporosity between replicate samples was likely a result of lithologic discontinuities resulting from construction activities. Dominance of soil micropores likely influenced soil characteristics restricting air and water movement (Brady and Weil, 2002). These conditions reduce infiltration rates and promote urban stormwater “flashiness” during intense precipitation events.

Soil Textural Classification

The proportion of sand ranged from 81.9 to 97.8%, with a mean of 93% for soils collected from the communities. Textural analysis determined 90% of soils (36 lots) were classified as sand, with only three lots containing loamy sand and one lot containing a sandy loam. No significant differences in the percentage of sand between communities were found. High sand content is typical in soils located within Central Florida (Harris et al., 2010). Similar percentages of soil sand content (89.3 to 96.2%) were observed in a related study in North Central Florida (Gregory et al., 2006).

United States Department of Agriculture - National Resource Conservation Service (NRCS) soil maps indicated that the sampled areas were mapped as Spodosols, Entisols, and Ultisols prior to urban residential development (NRCS, 2011). Results of textural classification analysis were similar to soil descriptions listed in NRCS soil maps for most (90%) sampled locations. In lots where soil textural classification differed from NRCS soil map description, clay content of soil was consistency greater. This may be due to improper identification of soil texture found within soil map resources or more likely from use of non-native soil in site leveling and grading activities (Zimmermann, 2008).

Saturated Soil Infiltration

Mean saturated soil infiltration rates in communities ranged from 11.2 to 63.6 cm hr^{-1}. Significant differences were observed (Table 2-1) among communities. High variability in saturated soil infiltration rate was also observed within communities. The maximum recorded infiltration rate was 111.1 cm hr^{-1}, while the minimum rate was 2.0 cm hr^{-1}. Similar infiltration rates and variability were observed in related studies (Gregory et al., 2006; Pitt et al., 2008).

Florida stormwater modeling and planning regulations require management to account for potential stormwater flow (FDOT, 2003). Saturated infiltration rates in 45% of sampled lots were below the 100-year, 24-hour design storm intensity of 26.7 cm hr^{-1} for Orlando, Florida (FDEP, 2006). Further, 30% of sampled lots had infiltration rates below the 5-year, 24-hour design storm intensity of 16.5 cm hr^{-1}. Thus a large percentage of sampled lots would likely produce stormwater runoff under intense precipitation events.

Regression analysis determined percentage soil sand was the only significantly correlated variable; however, percentage soil silt and clay were added to the model given their relationship to soil texture. Relationships between recorded and predicted infiltration rate were examined (Figure 2-1). One outlier was omitted given its predicted value was > 2 standard deviations from the recorded value. Soil bulk density was not a significant predictor of infiltration rate, although its relationship with infiltration is well established (Brady and Weil, 2002; Grabosky and Bassuck, 1995; Gregory et al., 2006; Jim, 1998; Pitt et al., 2008). Uniform construction practices and engineering standards likely caused uniformity among bulk density measurements (Trowbridge and Bassuck, 2004). The correlation coefficient of the regression model was low (r^2=0.43) and likely a result of high variability among recorded infiltration values.

Representative Soil Selection

Three soil types (Table 2-2) were chosen to represent the soil textural range observed in newly constructed urban residential communities within Central Florida. Sand and Loam soil textures (96.5% and 86.1% soil sand, respectively) were selected to represent the upper and lower range of observed percentage soil sand. A third soil type, designated Common (93.8% soil sand), represented mean percentage soil sand.

Summary

Soil compaction in newly constructed urban residential communities within Central Florida had low variability at both small (lot) and large (community) spatial scales. Lack of variability of soil bulk density likely resulted from consistent soil compaction conducted in compliance with construction engineering standards (Trowbridge and Bassuck, 2004). High levels of soil compaction were observed in a majority (> 50%) of communities. High D_b inhibits plant root growth and negatively influences plant establishment. Mechanical loosening of soils is recommended to improve site conditions and alleviate root penetration resistance within newly constructed urban residential communities. Low soil moisture retention values were a result of the high percentage of coarse, sandy textured soils; which also resulted in high variability of soil moisture due to pore size heterogeneity (Goncalves et al., 2010; Kirkham, 2005). Soils within newly constructed urban residential communities were dominated (60%) by soil micropores. These conditions restrict soil water and air movement, reduce soil water infiltration, and promote urban stormwater “flashiness” during intense precipitation.

Textural determinations mostly agreed with those of NRCS soil maps. The few textural differences likely resulted from construction practices which introduced non-native soils (Zimmermann, 2008). If urban soil characteristics differ from native soil, improper stormwater management plans may be developed. Nearly half of the sampled lots contained soil infiltration rates that were below the 100-year, 24-hour design storm intensity (FDEP, 2006). Under high rainfall intensities a majority of the lots could produce stormwater runoff. Relationships between saturated infiltration rates and recorded soil characteristics were relatively poor. High variability of soil characteristics are likely responsible for this relationship. Soil characteristic data, therefore, should not be used to estimate infiltration rates within newly constructed urban residential communities.

Construction of urban residential communities requires construction practices which have potential to alter soil characteristics from their natural, undisturbed conditions. Anthropogenic changes within these environments must be understood and incorporated into stormwater modeling to formulate successful management plans. Scientific literature examining soil modifications and impacts to urban residential hydrology is largely unavailable. Data collected in this study will assist in understanding soil characteristics and spatial variability in newly constructed urban communities within Central Florida.

Table 2-1. Soil characteristics of urban residential communities

Community	Bulk density ($g\ cm^{-3}$)	Soil moisture volume (mL water $100\ cm^{-3}$ soil)^{z}	Soil infiltration ($cm\ hr^{-1}$)
1	1.65 b^{y}	21.3 a	26.8 ab
2	1.73 ab^{y}	19.1 abc	58.3 ab
3	1.74 ab^{x}	9.8 cd	28.1 ab
4	1.78 a^{y}	7.6 d	16.6 b
5	1.67 b^{w}	8.4 d	11.2 b
6	1.71 ab^{y}	7.3 d	17.8 b
7	1.73 ab^{x}	8.9 d	43.7 ab
8	1.73 ab^{y}	12.9 bcd	47.4 ab
9	1.67 b^{y}	20.1 ab	63.6 a

^{z} Soil moisture volumes collected between soil matrix potential -6.4 and -100 kPa.
^{y} Means of 15, 10, and 5 replications for bulk density, soil moisture volume, and soil infiltration, respectively. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Tukey-Kramer).
^{x} Means of 9, 6, and 3 replications for bulk density, soil moisture volume, and soil infiltration, respectively. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Tukey-Kramer).
^{w} Means of 12, 8, and 4 replications for bulk density, soil moisture volume, and soil infiltration, respectively. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Tukey-Kramer).

Table 2-2. Soil texture of representative soil types

Soil type	Sand (%)	Silt (%)	Clay (%)
Sand	96.5 a^{z}	0.3 a	3.2 b
Common	93.8 a	2.8 a	3.4 b
Loam	86.1 b	1.3 a	12.6 a

^{z} Means of 6 replications. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Duncan).

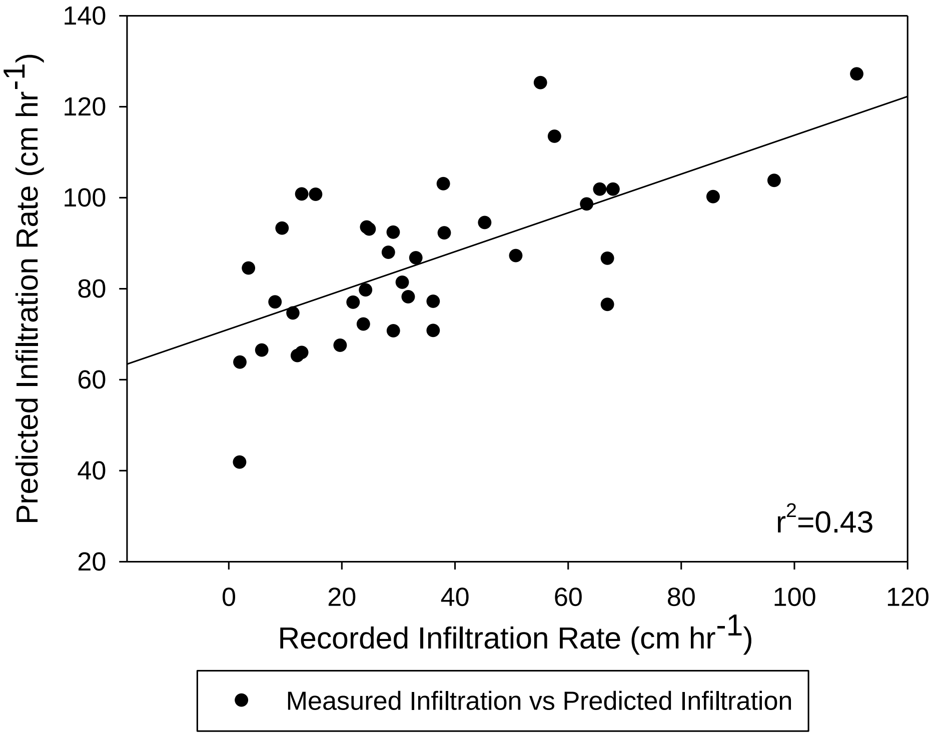

Figure 2-1. Regression of recorded infiltration rate and predicted infiltration rate of soil within urban residential communities. Predicted infiltration rate was calculated through the regression model ($Infiltration_{predicted}$= -1497.09 + 16.07 (% sand content) + 6.58 (% silt content) + 13.49 (% clay content).

CHAPTER 3
INFLUENCE OF SOIL TEXTURE, PRECIPITATION INTENSITY, AND SOIL MOISTURE ON STORMWATER RUNOFF AND LEACHATE

Nutrient applications of N and P possess the potential to degrade groundwater and surface water quality through stormwater nutrient runoff and leachate mechanisms (Franklin et al., 2006b; Petrovic, 1990; Schwartz and Shuman, 2005; Starr and DeRoo, 1981). Studies examining fate of nutrient application in agricultural production are available, yet few studies have focused on the fate of nutrient applied to residential landscapes. Studies examining nutrient losses in stormwater runoff and leachate from urban residential landscapes are needed in order to develop appropriate management plans and effective regulations (Barton and Colmer, 2006; Brown Gaddis et al., 2007; Shober et al., 2010).

Urban residential landscapes contain soil characteristics which differ from agricultural soils and also from natural, undisturbed soils as a result of construction activities (Craul, 1985). Urban soils often contain thick anthropogenic surface layers, and have disrupted nutrient cycling, high compaction, disrupted macropore connectivity, and surface soil crusts (Beasley, 1978; Bockheim, 1974; Craul, 1992; Craul and Klein, 1980; De Kimpe and Morel, 2000).

Twelve percent of national stormwater nutrient runoff originates from urban residential landscapes (USEPA, 1994). Discharge of nutrients in urban stormwater within Florida is likely greater than national estimates due to high population density, rapid urban growth, and unique environmental conditions (Shober et al., 2010). Regional examinations of nutrient levels in stormwater runoff are needed due to variability in construction practices and differences in ecological patterns (Pavao-Zuckerman and Coleman, 2005).

Small scale runoff boxes have been used to examine stormwater nutrient runoff (Guidry et al., 2006; Kleinman et al., 2004). Runoff boxes allow increased sample size and treatment control while reducing experimental time and effort. Although hydrologic properties of runoff boxes may differ from field soils, the use of these devices for examination of variables influencing runoff and leachate production are recommended (Kleinman et al., 2004; Sharpley, 1995; Vadas et al., 2005).

Two hydrologic models, saturation-excess (SE) and infiltration-excess (IE), describe soil stormwater flow (Dunne and Black, 1969; Horton, 1933). The SE soil model predicts runoff volume production after soil has become saturated and unable to convey additional precipitation volume as subsurface flow (Dunne, 1983). Antecedent soil moisture level directly influences soil water absorptive capacity (SWAC) and is highly influential to discharge volumes from SE soils (Buda et al., 2009). The IE soil model predicts runoff volume production when precipitation rate exceeds infiltration rate. Soil texture and structure are the most important factors influencing discharge volumes from IE soils (Dunne, 1983).

The objective of this study was to examine relationships between runoff and leachate volumes and representative soil characteristics of urban soils in Central Florida. A goal of this investigation was to quantify relationships between soil texture, soil moisture, precipitation intensity, and runoff and leachate volume.

Material and Methods

Lysimeter Design and Construction

Eighteen runoff boxes were constructed using 2.0 cm thick untreated lumber. The inside volume of each lysimeter box was 208 L (117.9 cm length, 92.5 cm width, and 19.1 cm height) (Figure 3-1A). The base of each lysimeter was constructed using untreated 1.3 cm thick plywood. Lysimeters were wrapped in 6 mil high-density polyethylene (HDPE) plastic sheeting (K50 White; Klerks Hyplast Inc., Chester, NC).

Leachate was collected using 3.2 cm diameter, 0.25 mm slotted Schedule 40 polyvinyl chloride (PVC) pipe along the base of one side within each lysimeter (Figure 3-1A). Drainage pipe was wrapped with filter fabric sock (Drain-Sleeve; Carriff Corporation, Inc., Midland, NC) to prevent clogging with sediment. A 3.2 cm diameter hole was cut into one side of each lysimeter to allow a drainage pipe to direct leachate outside of the lysimeter. Leachate drainage pipe extended 11 cm outside of each lysimeter and was fitted with a 90 degree Schedule 40 PVC fitting rotated to allow gravitational flow of leachate. A 9.5 mm diameter PVC reducing bushing and nozzle were installed onto the end of each leachate drainage pipe. Flexible PVC tubing (9.5 mm diameter and 12.7 cm length) was connected to each fitting and connected to a sealed 18.9 L HDPE container for leachate collection (Figure 3-1B). Leachate mass was measured using a top loading balance (Model D5-M0; Ohaus Scale Corporation, Florham Park, NJ) and used to determine volume. Temperature variability during data collection had a negligible effect on volume.

Runoff was collected using a rectangular (117.9 cm length, 3.2 cm width, and 8.3 cm height) extruded PVC micro channel drain (Micro Channel Drain Systems, NDS, Woodland Hills, CA). The micro channel drain was installed 4.8 mm below the top surface above the slotted drainage pipe (Figure 3-1A). A galvanized metal plate (121.9 cm length, 6 cm width, and 28 gauge thick) was installed 5 mm above each micro channel drain to prevent non-runoff water collection. A 9.5 mm diameter nozzle was installed on the bottom of each micro channel drain and connected to flexible PVC tubing (9.5 mm diameter and 12.7 cm length). A 9.5 mm hole was drilled into one side of the lysimeter to allow flexible tubing to be routed outside the lysimeter and into a second sealed 18.9 L HDPE container for leachate collection (Figure 3-1B). Runoff mass was recorded as described for leachate mass.

Lysimeters were arranged in three rows of six within an open sided greenhouse (30.5 m length and 18.3 m width). Each lysimeter was elevated approximately 64 cm above the soil surface using common 41 cm concrete blocks (Cemex, Orlando, FL) (Figure 3-1B). Composite shims (Nelson Wood Shims, Cohasset, MN) were placed under one side of each lysimeter to establish a 5% slope to direct runoff flow toward the micro channel drain. Percentage slope was measured using a magnetic angle locator (Model 700; Johnson Level & Tool Manufacturing Company, Inc., Mequon, WI). Lysimeters were filled with three soil types referred to as Sand, Common, and Loam (Table 3-1) to represent the range of soil types observed in newly constructed urban residential landscapes within Central Florida (Chapter 2). Natural Resource Conservation Service (NRCS) soil maps indicated Sand and Common soils were Tavares-Millhopper fine sand series while Loam soil was a Candler sand (NRCS, 2011). Six replicates per soil type were arranged into three completely randomized blocks. Soil was compacted using a hand tamper (Model HT10; Marshalltown Company, Marshalltown, IA). Irrigation was supplied to each lysimeter independently using a spray stake (Model Brown; Roberts Irrigation Company, Inc., Plover, WI) installed at the corner of each lysimeter pointing inward (Figure 3-1C).

Two soil samples were collected randomly within each lysimeter using a soil core sampler (Model 200; Soilmoisture Equipment Corporation, Santa Barbara, CA). Soil cores measured 5.7 cm in diameter and 3.0 cm in depth, and were collected at a depth beginning 3.8 cm below soil surface. One of the soil cores was transferred to a laboratory oven (Model 18EM; Precision Scientific Group, Chicago, IL) and dried for soil bulk density analysis using the standard method of Blake and Hartge (1986). Soil core sample mass was measured using a top loading balance (Model PB5001; Mettler Toledo, Inc., Columbus, OH). Soil bulk density samples were compared between lysimeters to ensure uniform soil compaction. The other soil core was placed in a ceramic plate extractor (Model 1500F1; SoilMoisture Equipment Corporation, Santa Barbara, CA) and analyzed in accordance with ASTM method D6836 (ASTM, 2008). Moisture extraction was examined at 6.4, 9.8, 19.6, 39.2, 100, 500, and 1500 kPa to develop moisture retention characteristics. Sample mass at each pressure interval was recorded (Model PB5001; Mettler Toledo, Inc., Columbus, OH). Plant available water (PAW) was calculated by examining soil water volume between -6.4 and -100 kPa. This matric potential range represents the range of soil moisture available for plant uptake (Brady and Weil, 2002; Kirkham, 2005; Morgan et al., 2001). In addition to examining moisture retention characteristics, soil moisture data was used to quantify soil pore size distribution using the method of Klein and Libardi (2002).

One additional soil sample was collected from each lysimeter at a depth of 0-3 cm using a soil auger (Model S-110; Durham Geo-Enterprises, Inc., Stone Mountain, GA). Samples were analyzed for particle size distribution for textural determination using the standard method of Gee and Bauder (1986).

Saturated soil infiltration rate was measured within each lysimeter using a falling head double-ring infiltrometer in accordance with the method described by Bouwer

(1986). The double-ring infiltrometer was constructed of PVC measuring 30.5 cm in length. This device had an outer ring diameter of 10.2 cm, and an inner ring diameter of 5.1 cm. Both rings were installed to a depth of 10 cm below soil surface prior to measurement.

Unsaturated soil infiltration rate was measured within each lysimeter using a mini disk infiltrometer (Decagon Devices, Inc., Pullman, WA) in accordance with the method described by Zhang (1997). All measurements were collected at -2 cm head to exclude macropore flow.

Synthetic Precipitation and Irrigation Design

Precipitation patterns within Florida have two distinct seasons: wet (June through September) and dry (October through May) (Black and Ruppert, 1998). Weather data, collected onsite at the Mid-Florida Research and Education Center (MREC, Apopka, FL) as part of the Florida Automated Weather Network (FAWN), was used to determine historical precipitation intensities. Mean precipitation intensity (recorded for a duration of 15 minutes) between January 2000 and December 2008 during the wet season was 7.8 cm hr^{-1} while dry season intensity was 3.2 cm hr^{-1}. Three irrigation heads (Inverted mini-wobblers; Senninger Irrigation, Clermont, FL) were installed 4.6 m apart and 1.55 m above lysimeters to simulate precipitation. Precipitation patterns were adjusted to ensure uniformity (88% Christiansen's Uniformity Coefficient) (Warrick, 1983). Synthetic precipitation was applied at three treatment levels (2.5, 5.1, and 7.6 cm hr^{-1}) for a duration of 15 minutes to represent the range of local historical precipitation. Two replicate precipitation events were run for each precipitation intensity level.

Lysimeter soil moisture was managed using a datalogger (CR1000; Campbell Scientific, Logan, UT) connected to two remote relay controls (SDM-CD16AC; Campbell

Scientific, Logan, UT). One time domain transmissometry (TDT) sensor (Model ACC-SEN-TDT; Acclima, Inc., Meridian, ID) was installed approximately 9 cm below soil surface within the center of each lysimeter. The datalogger was programmed to query each sensor every 30 minutes. If volumetric water content (VWC) was below the set point established for each lysimeter, irrigation would be activated (30 second duration for Sand and Common soil type and 60 second duration for Loam soil type). Greater irrigation application duration was needed for the Loam soil type to maintain VWC. Irrigation application time was based on trial and error. Volumetric water content was maintained at four treatment levels (40, 50, 70, and 90% PAW). Volumetric water content was examined within each lysimeter to ensure soil moisture was within 2% of the set point prior to each precipitation event.

Using the method described by Klein and Libardi (2002), soil moisture volumes between matric potentials -6.4 and -1500 kPa were used to estimate percentages of macropores (diameter > 0.05 mm), micropores (diameter 0.05 - 0.0002 mm) and crytopores (diameter < 0.0002 mm) for each soil sample. Soil water absorptive capacity was calculated as the soil moisture volume between matric potentials -6.4 and -100 kPa and included soil pores ranging in size from 0.01 to 0.007 mm (Bouwer, 1978).

A water balance approach was used to examine relationships between applied precipitation and discharge (runoff and leachate) volume. The water balance model (Expected discharge volume (EDV) = precipitation input (PI) – soil water absorptive capacity (SWAC)) was created which required calculation of soil water absorption, precipitation, and discharge volume. Expected discharge values represent summation of runoff and leachate volume. Precipitation input was calculated by multiplying precipitation intensity (5.1 and 7.6 cm hr^{-1}) and lysimeter surface area (10,905 cm^2). Given a 15 minute application period, PI was 13.9 and 20.6 L at 5.1 and 7.6 cm hr^{-1} intensities, respectively.

Soil water absorptive capacities were calculated based upon recorded soil water volume between soil matric potentials -6.4 and -100 kPa and included soil pore sizes which ranged from 0.01 to 0.0007 mm (Table 3-3) (Bouwer, 1978). Selection of this range was determined by systematic manual inclusion and exclusion of points along mean soil moisture dehydration curves developed for each soil type. Acceptance of a range was based upon its impact on the accuracy of the water balance model to estimate observed discharge volume (ODV). The optimum range was identical for all experimental soil types.

Statistical Analysis

Statistical analysis of relationships between soil texture, soil moisture, and precipitation intensity on runoff and leachate volumes were examined using the PROC MIXED procedure in SAS (SAS Institute, 2008). Statistical analysis of bulk density was conducted comparing mean values among soil treatments using the PROC GLM procedure in SAS (SAS Institute, 2008). Analysis of soil moisture characteristics compared mean soil moisture retention volumes between soil moisture potentials -6.4 and -100 kPa among soil treatments using the PROC GLM procedure. Comparisons of mean percentage soil sand, silt, and clay among soil treatments was conducted using the PROC GLM procedure and using Duncan’s multiple range test. Mean comparisons of saturated and unsaturated soil infiltration rates were analyzed among soil treatments using the PROC GLM procedure and using Duncan’s multiple range test. Runoff and leachate volume data were normalized (square root transformation) to improve statistical analysis but are presented as actual measured values (Dean and Voss, 1999). Unequal variances among treatment means existed. Residual plots were created to evaluate variability. Systematic removal of means with zero values established equal variances among remaining treatments. Thus the lowest precipitation intensity (2.5 cm hr^{-1}) and lowest soil moisture (40% PAW) treatments were omitted to minimize variability and improve statistical accuracy (Colee, 2011). All analytical tests were considered to be statistically significant if $P < 0.05$.

Results and Discussion

Soil Characteristics

Percentage soil sand ranged from 86.1 to 96.5% with a mean of 92.1% among soil types (Table 3-1). The proportion of soil clay was similar between Sand and Common soils but significantly greater in Loam with a mean of 12.6%. Percentage silt was similar among all soil textures. Textural analysis determined both Sand and Common soil types were classified as sands, while the Loam soil type was classified as loamy sand. High sand content is typical of soils located within Central Florida (Harris et al., 2010). Significant differences in mean sand and clay content were observed among soil types (Table 3-1).

Mean soil bulk density (D_b) for all soil types ranged from 1.58 to 1.69 g cm^{-3} (Table 3-2). These values were greater than expected for non-compacted - Silt loam and Sand soils (1.44 to 1.52 g cm^{-3}, respectively) (Hillel, 1980); but lower than observed in sampled urban residential communities (1.65 to 1.78 g cm^{-3}; Chapter 2). The lowest mean D_b was observed in the Loam soil and was likely a result of its high soil clay content relative to the Sand and Common soil types (Brady and Weil, 2002). Additional soil compaction within runoff boxes was limited by the inability to operate large compaction equipment within the runoff boxes (Gregory et al., 2006).

Saturated soil infiltration rate is a quantitative unit that defines the quantity of water per unit time that moves through soil during saturated soil conditions. Mean saturated soil infiltration rates ranged from 51.3 to 87.8 cm hr^{-1} (Table 3-2). Saturated soil infiltration rate for the Loam soil was significantly lower than for the Sand or Common soils. The minimum recorded infiltration rate was 34.6 cm hr^{-1} for the Loam soil while the maximum rate was 105.3 cm hr^{-1} for the Sand soil. Similar trends in saturated infiltration rate variability have been observed in related studies (Gregory et al., 2006; Pitt et al., 2008). Infiltration rate range was higher than those observed in newly constructed residential communities (Chapter 2). This likely also resulted from higher soil porosity associated with lower D_b within runoff boxes (Gregory et al., 2006).

Unsaturated soil infiltration rate is a quantitative unit that defines the quantity of water per unit time that moves through soil during unsaturated soil conditions. Mean unsaturated soil infiltration rates ranged from 2.7 to 51.4 cm hr^{-1} (Table 3-2). The unsaturated soil infiltration rate of the Loam soil was significantly lower than the Sand or Common soils. This trend was similar to saturated soil infiltration rate observations. The coefficient of variation ranged from 28.6 to 48.3 percent. High variability in unsaturated soil infiltration rates probably resulted from heterogeneity in sub-macropore soil volume (Craul and Klein, 1980; Gregory et al., 2006; Zhang, 1997).

Mean soil moisture retention volumes ranged from 13.4 to 23.5 mL water 100 cm^{-3} soil between soil moisture potentials -6.4 and -100 kPa (Table 3-2). This range was similar to moisture retention volumes observed in urban residential communities, where soil moisture retention volumes ranged from 7.3 to 21.3 mL water 100 cm^{-3} soil (Chapter 2). The Loam soil had significantly lower moisture retention than the Sand or Common soils. The relatively high clay content of the Loam soil resulted in greater soil moisture retention at higher (more negative) soil moisture potentials (data not shown) (Brady and Weil, 2002; Kirkham, 2005).

The distributions of pore sizes were similar across the three soil textures. Macropores (diameter > 0.05 mm) were the dominant pore size, representing 53% of mean soil pore space. Micropores (diameter = 0.05 - 0.0002 mm) represented 39% of mean soil pore space while cryptopores (diameter < 0.0002 mm) accounted for 8% of mean soil pore space. Soil micropores are responsible for SWAC during short duration, high intensity precipitation events given soil macropores are active in soil water drainage (leaching) and soil cryptopores are filled with water. Soil pore size distributions differed from observations in urban residential communities. This likely resulted from lower D_b within runoff boxes where macropore soil volumes had not been reduced from additional compaction (Gregory et al., 2006).

Runoff and Leachate

Non-linear relationships existed between treatment levels and runoff and leachate volumes (data not shown). Similar trends have been observed in related research (Kleinman et al., 2004). Runoff and leachate volume production were minimal and highly variable at the lowest precipitation intensity (2.5 cm hr^{-1}) and lowest soil moisture (40% PAW) levels. Rarely was runoff or leachate generated when either of these two parameters were a component of the combination of precipitation and soil moisture treatments. Statistical interactions between the remaining main effects (soil type × PAW, and soil type × precipitation intensity) were observed for runoff and leachate production relationships.

The Loam soil produced runoff at all moisture levels above 40% PAW and was the only soil texture for which this occurred (Figure 3-2A). The Loam soil also had the highest mean runoff volume at all soil moisture levels. The relationship between runoff volume and PAW from loam soils appeared curvilinear, but differences among means was not significant. Runoff from the Sand soil only occurred at the highest soil moisture (90% PAW). Unlike the Common soil, where runoff volume increased linearly with increasing %PAW above 50%, runoff from sand was zero at 70% PAW or less, but was comparable to that of the Loam soil at near saturated soil moisture levels. Similar linear relationships have been observed between soil moisture and runoff volume in sand soils (Shuman, 2002). Cole et al. (1997) observed a 16-fold increase in runoff volume from a silt loam soil when soil moisture was increased from 17% to 27.5% by weight. Relationships between soil moisture and runoff volume are highly influenced by soil texture.

The Loam soil produced the highest mean runoff volume at both precipitation intensity levels, increasing 4-fold between 5.1 and 7.6 cm hr^{-1} (0.9 and 3.6 L, respectively) (Figure 3-2B). Runoff from the Sand and Common soils was not significantly influenced by precipitation intensity, however there was a measurable increase between 5.1 and 7.6 cm hr^{-1} (0.07 and 0.28 L, respectively). Shuman (2002) observed similar trends where increased precipitation (25 to 50 mm) resulted in a 1.5-fold increase in runoff volume. Increased runoff volume as a response to higher precipitation intensities were observed where infiltration-excess conditions existed. The results presented here, however, are in contrast to those reported by Morton et al. (1988) and Erickson et al. (2001). In both studies, runoff was not observed despite high precipitation events (5 to 25 cm) and similar soil textures. Durations were not available, so intensity could not be calculated. Presence of vegetative cover in these earlier studies may also be responsible for observed differences (Cerdà, 1997; Rawls et al., 1989).

Leachate production was minimal for all soil types at 50% PAW, but measureable for each soil type at higher PAW levels (Figure 3-3A). The Common soil produced the most leachate at 70 and 90% PAW, with Sand soils producing greater mean leachate than Loam soils only at 90% PAW. Leachate volumes increased 3.5- and 4.5-fold between 70 and 90% PAW for Common and Sand soils, respectively (Figure 3-3A). Leachate volumes were measured at 50% PAW or higher for the Loam soils, but increases in %PAW had no significant influence on the volume of leachate produced.

Leachate volume increased approximately 2-fold for all soil types between precipitation intensities 5.1 and 7.6 cm hr^{-1} (Figure 3-3B). However, high variability precluded significant differences. Morton et al. (1988) observed a similar increase (1.9-fold) in leachate volume when precipitation and irrigation volumes were increased from a mean of 112.8 to 169.3 cm yr^{-1}. The Common soil produced significantly greater leachate volumes than Sand or Loam soils at both the 5.1 and 7.6 cm hr^{-1} precipitation levels (1.6 and 3.2 L, respectively). The Loam soil produced the lowest leachate volumes among soil types. Brown et al. (1977) made similar observations where leachate volume from sandy loam soils was lower than sandy soils regardless of precipitation intensity.

Calculated absorptive capacity for all soil types decreased with increased soil moisture (Table 3-3). This trend was expected as soil pores become increasingly occupied by soil water when the soil moisture level was increased. Sand had the largest SWAC amongst soil types and ranged from 24.5 to 4.9 L between 50 and 90% PAW. The Common soil had similar absorptive capacities to the Sand, ranging from 22.0 to 4.4 L between 50 and 90% PAW. The Loam soil had the lowest SWAC amongst soil types. Soil water absorptive capacity of the Loam soil was 1.5-fold less than Sand or Common soil at each soil moisture level and ranged from 13.9 to 2.8 L between 50 and 90% PAW. Although the Loam soil would be expected to have greater total soil porosity as a result of its high clay content relative to the Sand and Common soil types, it contained less micropore soil volume and thus had less SWAC than Sand or Common soil types (Table 3-1, Table 3-3).

Using the water balance model, EDVs were calculated for all soils at precipitation intensities 5.1 and 7.6 cm hr^{-1} (Table 3-4). Expected discharge volumes were reported as zero when SWAC > PI. Expected discharge volumes were greatest at high soil moisture levels. This trend was expected as SWAC decreased with increased soil moisture. At 50% PAW and precipitation intensity 7.6 cm hr^{-1}, the Loam soil had an EDV of 6.7 L. The Loam was the only soil type expected to produce measurable discharge at 50% PAW. Both the Common and Loam soil types had measurable EDVs at 70% PAW. The Sand soil type had the lowest EDVs amongst all treatment levels. At the lowest precipitation intensity level (5.1 cm hr^{-1}), the Sand soil was only expected to have measurable discharge volumes at the highest PAW level (90% PAW). Expected discharge volumes were similar among soil types at the highest precipitation intensity ($7.6\ cm\ hr^{-1}$) and soil moisture level (90% PAW) as a result of similar SWACs.

Observed discharge volume was calculated through the summation of recorded runoff and leachate volumes and compared to EDVs (Table 3-5, Figure 3-4). Relationships between EDV and ODV were high in both Sand and Common soils (r^2=0.922 and 0.999, respectively). Correlations between EDV and ODV in Loam were relatively low (r^2=0.565) due to high variance (coefficient of variance = 161.7 percent) from the combination of $5.1\ cm\ hr^{-1}$ precipitation and 90% PAW. The point could not be considered an outlier, which would have increased the correlation to 0.777. Textural heterogeneity (clods of soil clay) was observed only in Loam soil and was most likely responsible for variability in discharge volume prediction.

In most instances, EDVs were greater than ODVs among all soil types (Table 3-6, Figure 3-4). This likely resulted from greater SWAC than estimated. The observed relationships between EDV and ODV values supports the SE hydrologic model for representative test soils (Dunne, 1983; Dunne and Black, 1969). Increased antecedent soil moisture strongly influenced runoff and leachate volumes as a result of reduced SWAC. Similar relationships between increased soil moisture and related increases in runoff production have been observed (Buda et al., 2009; Castillo et al., 2003). Penna et al. (2011) observed significant increases in runoff volume whenever volumetric soil moisture exceeded 45%. Inclusion of antecedent soil moisture in rainfall-runoff models explained 92% of observed variability in a recent hydrological study conducted in Germany (Zehe et al., 2010).

Summary

Runoff and leachate production was significantly influenced by soil type, soil moisture, and precipitation intensity. Low soil moisture (40% PAW) or precipitation intensity (2.5 cm hr^{-1}) treatment levels produced minimal to no runoff and leachate over the 15 min precipitation interval. These observations resulted from sufficient SWAC at these lower levels. Insignificant runoff and leachate production at low treatment levels indicated that these urban residential soils are unlikely to produce stormwater runoff or leachate during short interval, low intensity ($\leq$ 2.5 cm hr^{-1}) precipitation events. Significant volumes of runoff and leachate were observed, however, at higher soil moisture (70% and 90% PAW) and precipitation intensities (5.1 cm hr^{-1} and 7.6 cm hr^{-1}). These results imply that newly constructed urban residential soils will produce stormwater runoff and leachate under short interval, intense precipitation events ($\geq$ 5.1 cm hr^{-1}) typically observed within Central Florida.

The Sand and Common soil types produced more leachate than runoff at all precipitation and PAW treatment levels. Given these soil types best represent the soil textural range observed in newly constructed urban residential communities within Central Florida in 2009, leachate may be a substantial concern to nutrient transport using similar practices (Morton et al., 1988; Rieke and Ellis, 1974). Nutrient management plans should emphasize minimization of fertilizer leaching potential through application of nutrients with low soil mobility.

Despite few differences among soil characteristics, soil type influenced both runoff and leachate volume. Our study indicates that textural changes resulting from construction practices will influence site hydrology. If changes to hydrologic soil properties are not identified, improper stormwater management plans may be developed.

Strong relationships between soil moisture and soil water discharge volumes were observed. Soil conditions with limited SWAC or limited ability to convey rainfall as subsurface flow will produce recordable runoff and leachate volumes. Reduction of soil porosity through site compaction is the most likely source of subsurface flow restriction within newly constructed urban residential soils. Modifications to soil that reduce SWAC or subsurface flow are therefore important to identify and prevent.

Urban soils often contain high vertical and spatial variability, disrupted macropore connectivity, and small soil aggregates which fill soil macropores and often result in soil surface crusts. However, only the Loam soil was observed to have high variability between EDV and ODV. This suggests that variability of sand soil characteristics that influence runoff prediction may be limited to textural heterogeneity.

Saturated and unsaturated soil infiltration rates among all soil types were greater than examined precipitation intensities. Yet significant volumes of runoff were recorded. This observation supports the saturation-excess (SE) hydrologic model application for these mainly sand soils. Although infiltration data may provide useful soil characteristic information, it may not be a reliable indicator of stormwater runoff potential if soils exhibit SE hydrologic behavior. Estimation of stormwater discharge should not be based solely upon infiltration and precipitation rate data. Use of scale research is likely necessary for accurate selection of hydrologic models and stormwater estimation.

Table 3-1. Textural characteristics of treatment soils

Soil type	Sand (%)	Silt (%)	Clay (%)
Sand	96.5 a[z]	0.3 a	3.2 b
Common	93.8 a	2.8 a	3.4 b
Loam	86.1 b	1.3 a	12.6 a

[z] Means of 6 replications. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Duncan).

Table 3-2. Physical characteristics of treatment soils

Soil type	Bulk density ($g\ cm^{-3}$)	Soil moisture volume (mL water 100 cm^{-3} soil)[z]	Saturated soil infiltration ($cm\ hr^{-1}$)	Unsaturated soil infiltration ($cm\ hr^{-1}$)
Sand	1.69 a[y]	23.5 a	87.8 a	47.7 a
Common	1.65 a	21.1 a	80.3 a	51.4 a
Loam	1.58 b	13.4 b	51.3 b	2.7 b

[z] Soil moisture volumes collected between soil matric potential -6.4 and -100 kPa.
[y] Mean of 6 replications. Means within columns not followed by the same letter are significant at $P \leq 0.05$ (Duncan).

Table 3-3. Calculated lysimeter soil water absorptive capacities (L)[z]

Soil Type	Soil moisture level (% PAW)		
	50%	70%	90%
Sand	24.5	14.7	4.9
Common	22.0	13.2	4.4
Loam	13.9	8.4	2.8

[z] Soil water absorptive capacities were calculated through multiplication of soil moisture volume (between matric potentials -6.4 and -100 kPa) and lysimeter soil volume.

Table 3-4. Expected discharge volumes (L)[z]

Precipitation Intensity	Soil Type	Soil moisture level (% PAW)		
		50%	70%	90%
5.1 cm hr^{-1}	Sand	0.0	0.0	9.0
	Common	0.0	0.7	9.5
	Loam	0.0	5.5	11.1
7.6 cm hr^{-1}	Sand	0.0	5.9	15.7
	Common	0.0	7.4	16.2
	Loam	6.7	12.2	17.8

[z] Expected discharge volumes (EDV) were calculated through application of the model: EDV = precipitation input (PI) – soil water absorptive capacity (SWAC). Precipitation input calculations were based upon precipitation application rate and runoff surface areas. Soil water absorptive capacity was calculated through multiplication of soil moisture volume (between matric potentials -6.4 and -100 kPa) and lysimeter soil volume. EDVs were reported as zero when SWAC > PI.

Table 3-5. Observed discharge volumes (L)[z]

Precipitation Intensity	Soil Type	Soil moisture level (% PAW)		
		50%	70%	90%
5.1 cm hr^{-1}	Sand	0.0[y]	1.2	6.4
	Common	0.0	2.4	7.7
	Loam	1.4	3.7	2.6
7.6 cm hr^{-1}	Sand	0.0	2.4	9.2
	Common	0.0	6.3	12.0
	Loam	3.9	7.4	6.1

[z] Observed discharge volumes (ODV) were calculated through summation of recorded runoff and leachate volumes.
[y] Means of 6 replications.

Table 3-6. Difference between expected and observed discharge volumes (L)[z]

Precipitation Intensity	Soil Type	Soil moisture level (% PAW)		
		50%	70%	90%
5.1 cm hr^{-1}	Sand	0.0	-1.2	2.6
	Common	0.0	-1.7	1.8
	Loam	-1.4	1.8	8.5
7.6 cm hr^{-1}	Sand	0.0	3.5	6.5
	Common	0.0	1.1	4.2
	Loam	2.8	4.8	11.7

[z] Difference between expected discharge volumes (EDV) and observed discharge volumes (ODV) were calculated through application of the model: Difference = EDV [precipitation input (PI) – soil water absorptive capacity (SWAC)] – ODV (runoff volume + leachate volume). Precipitation input calculations were based upon precipitation application rate and runoff surface areas. Soil water absorptive capacity was calculated through multiplication of soil moisture volume (between matric potentials -6.4 and -100 kPa) and lysimeter soil volume.

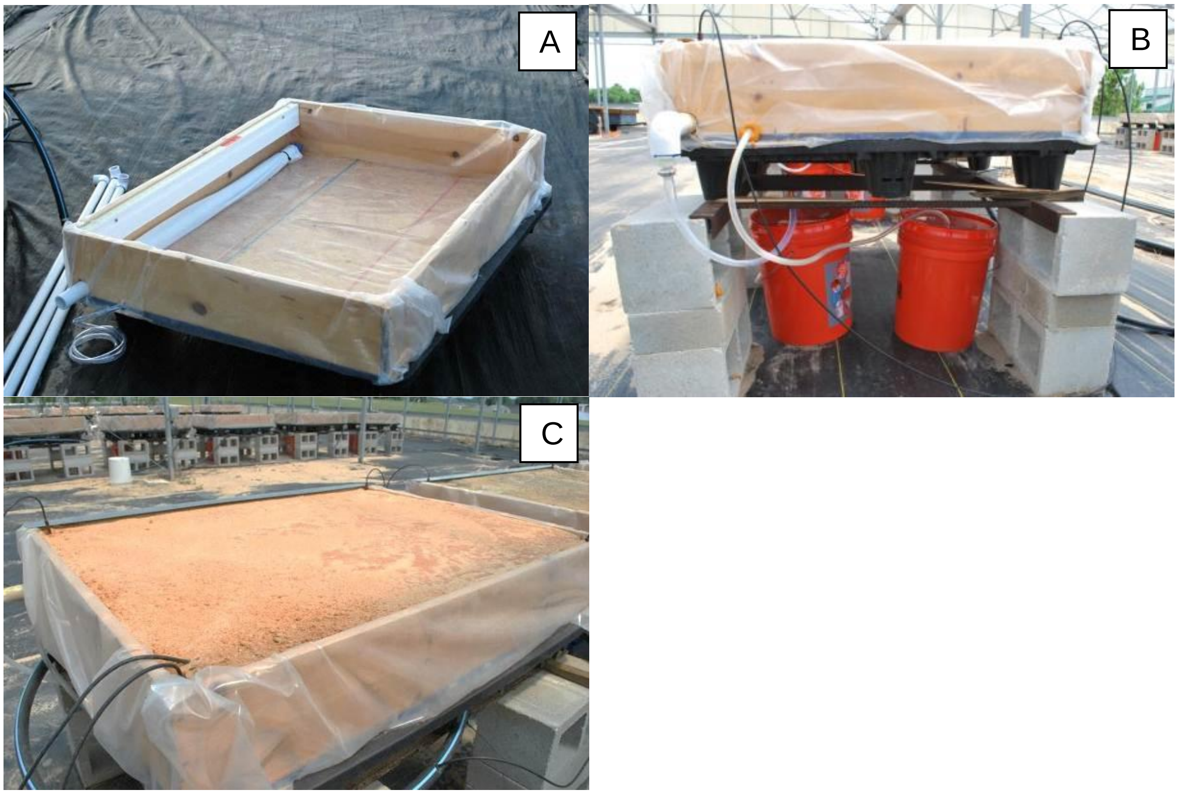

Figure 3-1. Lysimeter construction design. A) Runoff box without soil illustrating leachate and runoff collection systems. B) Side view illustrating drainage and lysimeter support system. C) Top view with backfilled soil and irrigation spray stakes installed in each corner.

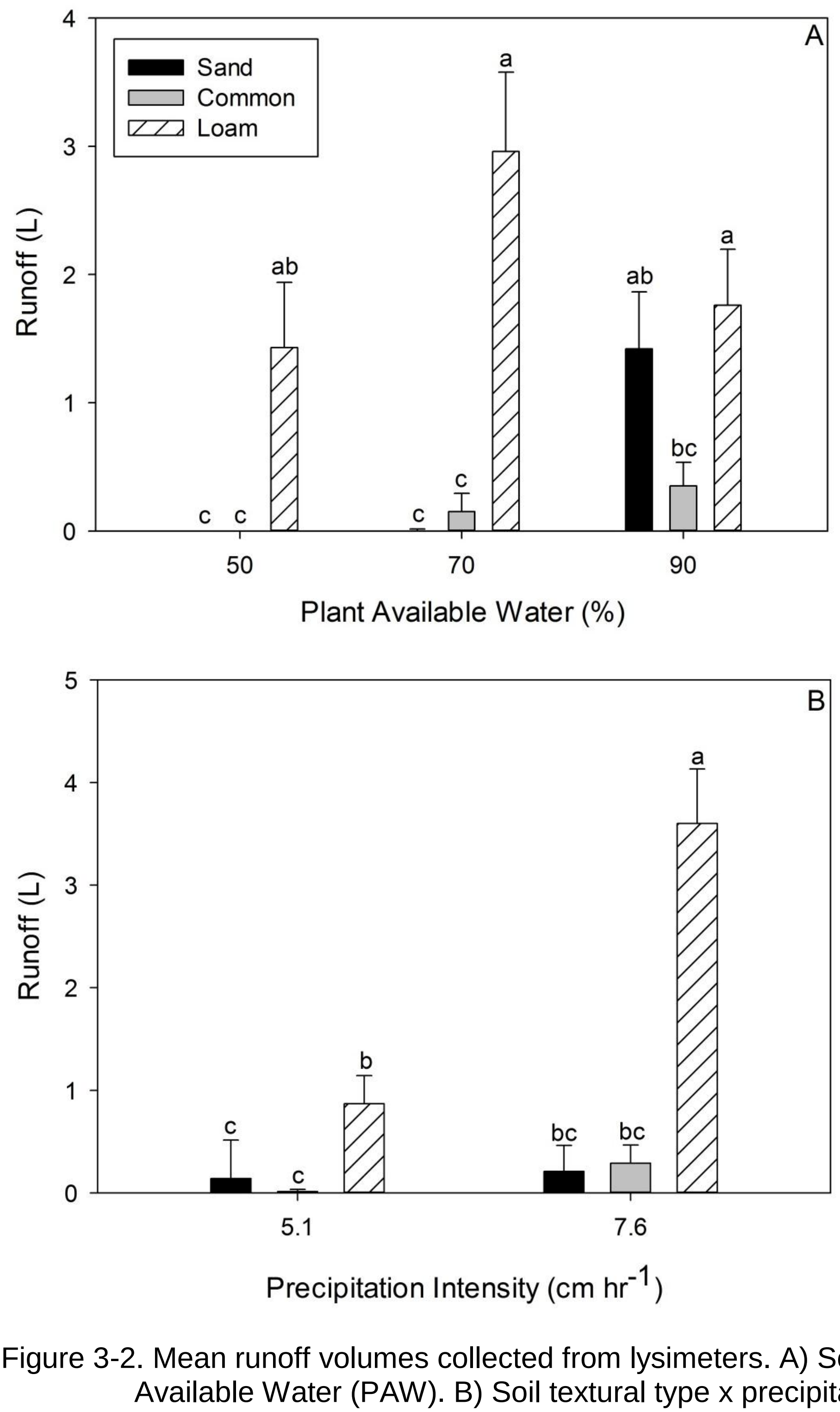

Figure 3-2. Mean runoff volumes collected from lysimeters. A) Soil textural type x Plant Available Water (PAW). B) Soil textural type x precipitation intensity. Means of 6 replications. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

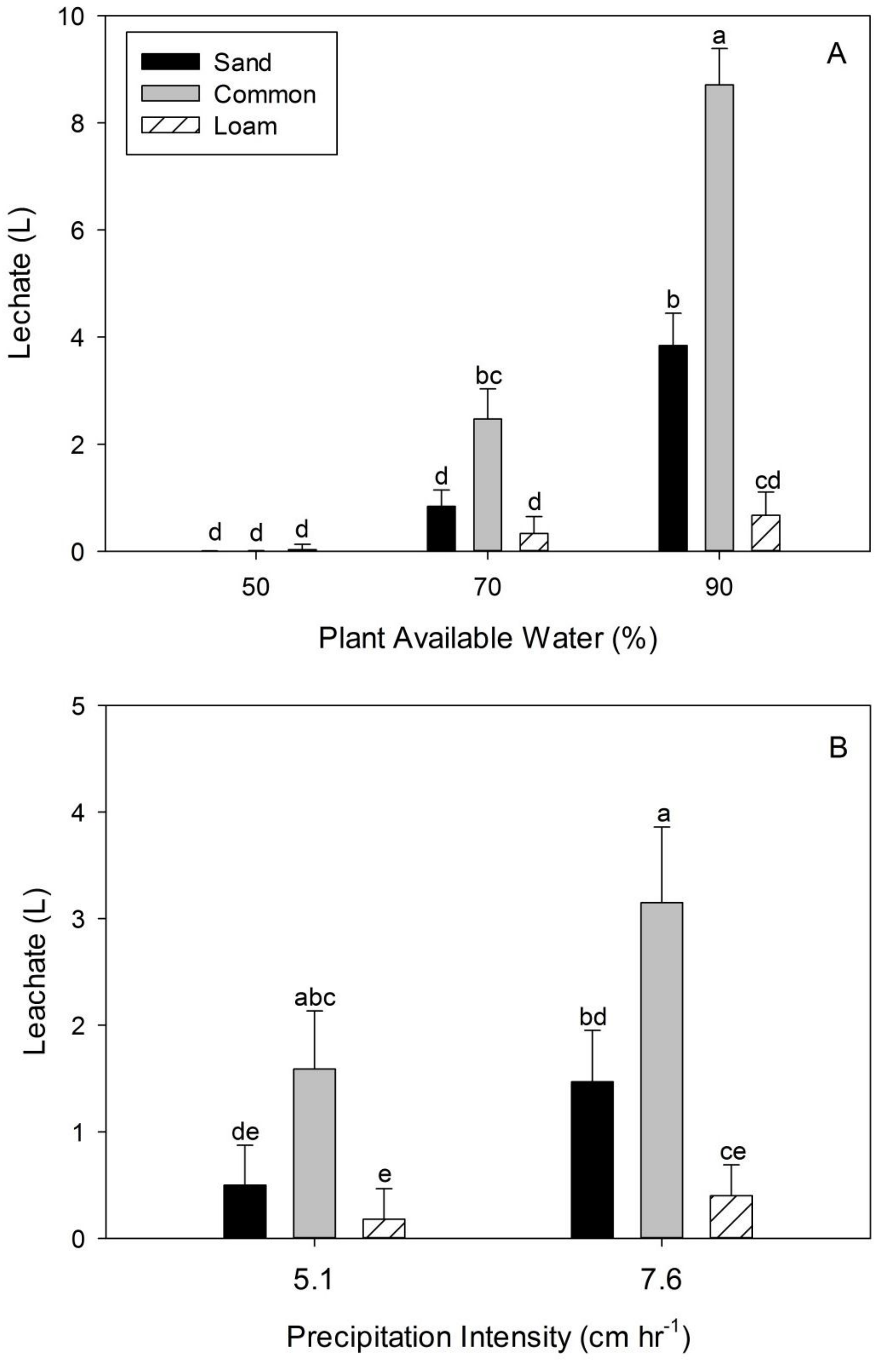

Figure 3-3. Mean leachate volumes collected from lysimeters. A) Soil textural type x Plant Available Water (PAW). B) Soil textural type x precipitation intensity. Means of 6 replications. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

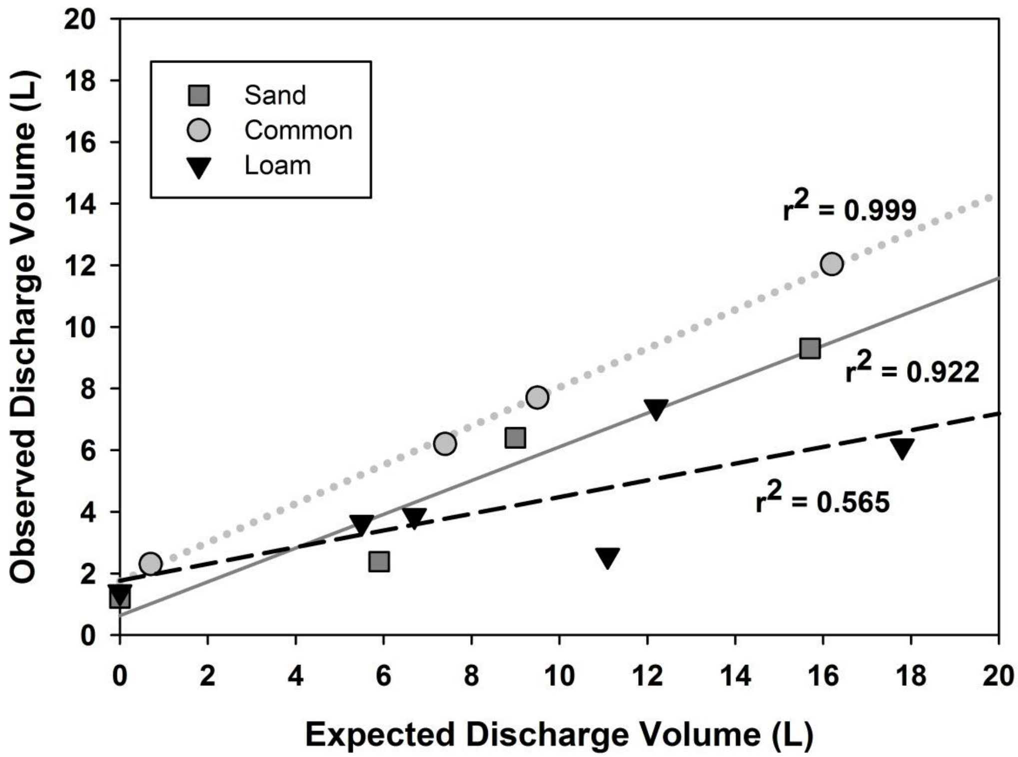

Figure 3-4. Regressions of expected and observed discharge volumes. Expected discharge volumes were calculated through the water balance model (Expected discharge volume (EDV) = precipitation input (PI) – soil water absorptive capacity (SWAC)). Soil water absorptive capacities were calculated based upon recorded soil water volume between soil matric potentials -6.4 and -100 kPa. EDVs were reported as zero when SWAC > PI.

CHAPTER 4
INFLUENCE OF MULCH AND PLANT MATERIALS ON STORMWATER RUNOFF AND LEACHATE

Nutrient enrichment of surface and groundwater supply from nonpoint sources are a national concern (USEPA, 1994; USEPA, 2009). Nutrients applied within urban environments possess the potential to contribute to this pollutant source through stormwater nutrient runoff and leaching mechanisms (Carpenter et al., 1998; Lal and Vandoren, 1990; Petrovic, 1990). Water quality degradation concerns resulting from urban residential fertilizer use has led to recent application bans within Florida (Carnathan, 2011; Hochmuth et al., 2011). Cultural practices, such as application of mulch or transplanting of landscape materials, have the ability to influence hydraulic properties of urban soils. Few studies have examined relationships between urban cultural practices and nutrient losses in stormwater runoff and leachate.

Nutrient applications are common in urban environments. A study conducted in Florida found that 80% of surveyed residences incorporated fertilizer applications as part of their landscape management plans (Knox et al., 1995). Nutrients were typically applied at higher rates than necessary or recommended by available best management practices (BMPs). A similar study conducted in Maryland found that 70% of residences regularly applied fertilizers. Application rates were found to vary depending upon the applicator and ranged from 10.5 to 369.7 kg N ha^{-1} yr^{-1} (0.2 to 7.6 lbs N 1000 ft^{-2} yr^{-1}) (Law et al., 2004). Arthurs and Stauderman (2010) also reported over-application of granular fertilizer ranging from 138 to 301% when push rotary spreaders were used.

Construction practices required for the creation of urban infrastructure alter soil characteristics. Urban soils are often characterized as containing thick, anthropogenic layers, disrupted soil profiles, high compaction, and disrupted nutrient cycling (Craul, 1985). Compaction of soil macropores resulting from the use of heavy construction equipment reduces soil water infiltration (Gregory et al., 2006). Decreased infiltration rates alter the hydrologic characteristics of urban soil and may promote greater stormwater runoff from urban environments (Kelling and Peterson, 1975). Application of traditional hydrological models may not accurately predict water flow within urban soils (Kirkham, 2005). Non-traditional hydraulic models that incorporate “bypass” or preferential flow may better represent soil water movement (Bouma, 1981; Bouma et al., 1978; Towner, 1989).

Use of mulch in landscape design and management is a common cultural practice that has potential to alter soil hydrology. Benefits of mulch include increased soil moisture and prevention of soil crusting (Black and Ruppert, 1998; Hensley, 2010). Wan and El-Swaify (1999) examined relationships between inorganic mulch applications and stormwater runoff. Inorganic mulch applied in the absence of plant materials was found to increase stormwater runoff volume as a result of the mulch’s impervious characteristics. However, stormwater runoff volumes were found to decrease when inorganic mulch was applied in the presence of plant materials due to the formation of micro-basins near plant stems. Adekalu et al. (2007) conducted a similar study to examine relationships between runoff volume and organic hay mulch (*Pennisetum purpureum*) application upon various soil textures. Mulch applications reduced stormwater runoff for all soil types. However, higher mulch application rates were needed on coarse textured soils to achieve similar stormwater reductions as finer textured soils.

Plant growth has the potential to influence soil hydrology through root proliferation. Penetration of plant roots into soil creates hydrologic channels (Craul, 1992). Actively growing plant roots contribute to infiltration through stemflow. Stemflow occurs when precipitation is intercepted by the plant canopy and water flows gravitationally down the stem and along root channels into surrounding soil. Stemflow was observed to increase infiltration rates by a mean of 153% in black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L) species (Bartens et al., 2008). When plant roots die, organic materials decompose and leave open continuous channels. If channels are open to the soil surface, preferential flow pathways allow water to infiltrate ahead of the wetting front (Aubertin, 1971; Craul, 1992).

The objectives of this study were to examine the relationship between mulch application, growth of plant materials, and runoff and leachate volumes generated from soils representative of those found in newly constructed urban residential communities within Central Florida. A goal of this investigation was to quantify the hydrologic impacts of mulch application and plant growth.

Material and Methods

Lysimeter Design and Construction

Eighteen runoff boxes (lysimeters), constructed for Chapter 3, were used to collect runoff and leachate mass. Lysimeters were arranged in three rows within an open-sided greenhouse (30.5 m length and 18.3 m width) and elevated approximately 64 cm above the soil surface using concrete blocks (Cemex, Orlando, FL). Runoff boxes were filled with three soil types referred to as Sand, Common, and Loam (Table 4-1) to represent the range of soil types observed in newly constructed urban residential communities within Central Florida (Chapter 2). Galvanized metal plates, which rose 8.0 cm above the wooden frame along the three upper sides, were installed on each lysimeter (Figure 4-1A). These were installed to maintain a uniform depth of mulch and prevent potential water loss over the outside edge when mulch was added. Irrigation was supplied to each lysimeter independently using a spray stake (Model BBK36B; Maxijet, Inc., Dundee, FL) installed at the corner of each lysimeter pointing inward.

Soil texture and bulk density were determined previously from two soil samples collected randomly within each lysimeter (Chapter 3). Plant available water (PAW) between -6.4 and -100 kPa was calculated, with data from the complete soil dehydration curve used to quantify soil pore size distribution (Chapter 3).

Saturated and unsaturated soil infiltration rate measurements were collected using a mini disk infiltrometer and double-ring infiltrometer as described in Chapter 3.

Synthetic Precipitation and Irrigation Design

Historical precipitation intensities were determined using weather data collected onsite at the Mid-Florida Research and Education Center (MREC) as part of the Florida Automated Weather Network (FAWN). Mean annual precipitation (15 minute duration) between January 2000 and December 2008 was 5.5 cm hr^{-1}. Synthetic precipitation was delivered using overhead irrigation constructed as described in Chapter 3. For the experiments described here, synthetic precipitation was applied at 5.1 cm hr^{-1} for a duration of 15 minutes weekly to represent historical annual precipitation intensity.

Lysimeter soil moisture was managed using a datalogger (CR1000; Campbell Scientific, Logan, UT) and one time domain transmissometry (TDT) sensor (Model ACC-SEN-TDT; Acclima, Inc., Meridian, ID) as described in Chapter 3. Volumetric water content (VWC) was maintained at 70% plant available water (PAW). Volumetric water content was examined within each lysimeter to ensure soil moisture was within 2% of the set point prior to each precipitation event.

Experiment 1

Pine bark mulch was purchased locally (Florida Potting Soils, Inc., Orlando, FL). Although individual pine bark nuggets had mean length and width of approximately 2.5 cm, a mechanical separator developed at MREC and described by Silva et al. (2011) was used to remove material with a maximum width less than 1.3 cm. Pine bark mulch was sieved to ensure consistent mulch size. Sieved pine bark was applied to the top surface of each lysimeter to a depth of approximately 5.7 cm (Figure 4-1A). Runoff and leachate volumes were recorded after each precipitation event and compared to discharge volumes produced from lysimeters in the absence of mulch (Chapter 3).

Water absorptive capacity of mulch was determined by collecting 900 cm^3 of mulch from lysimeters maintained at 70% PAW. Mulch mass was recorded using a top-loading balance (Mettler PE6000; Mettler Instrument Corp., Hightstown, NJ). Mulch was saturated for 24 hrs, drained of excess water without disturbing the three dimensional structure, then re-weighed. Mulch was then spread out and air-dried weight recorded. Differences in mulch weight between saturation and 70% PAW represented mulch water absorptive capacity (MWAC).

A water balance model approach, similar to the one described in Chapter 3, was used to examine relationships between applied precipitation and discharge (runoff and leachate) volume. The water balance model [Expected discharge volume (EDV) = precipitation input (PI) – (soil water absorptive capacity (SWAC) + mulch water absorptive capacity (MWAC))] required soil and mulch water absorption, precipitation, and discharge volume calculations. Expected discharge values represent summation of runoff and leachate volume. Precipitation input was calculated by multiplying precipitation intensity (5.1 cm hr^{-1}) and lysimeter surface area (10,905 cm^2). Given a 15 minute application period, PI was 13.9 L. Soil water absorptive capacities were calculated based upon recorded soil water volume between soil matric potentials -6.4 and -100 kPa and included soil pore sizes which ranged from 0.01 to 0.0007 mm (Bouwer, 1978). Observed discharge volumes (ODV) were calculated through the summation of recorded runoff and leachate volumes.

Experiment 2

One hundred fourteen container-produced (0.7 L) *Salvia farinacea* were obtained from a local commercial nursery (Batson's Greenhouse, Inc., Mt. Dora, FL). *Salvia farinacea* was selected based upon its tolerance of the expected temperature range (10 to 35 °C) within the open-sided greenhouse (Black and Gilman, 1997; Park Brown and Schoellhorn, 2006). Six plants were transplanted (Planting 1) into each lysimeter spaced apart approximately 14 cm on center (Figure 4-1B) on March 29, 2011. Shoots of the remaining 6 *Salvia farinacea* were severed at the soil line and dried at 65 °C until constant dry weight was obtained. Dry plant shoot biomass (PSB) was measured using a top-loading balance (Mettler PE6000; Mettler Instrument Corp., Hightstown, NJ). Average canopy height, widest canopy width, and width perpendicular to widest width were recorded for each plant immediately post-transplant and also measured every two weeks until harvest (eight weeks after transplant (WAT)). Plant growth measurements were used to calculate plant growth indices (growth index = height x width 1 x width 2). Controlled-release fertilizer (Nutricote 18-6-8; Florikan E.S.A. Corp., Sarasota, FL) was uniformly broadcast on top of mulch at a rate of 9.8 g N m^{-2} (4 lbs N 1000 ft^{-2}) at 3 WAT and immediately watered in by hand. Beginning 3 WAT, synthetic precipitation was begun with runoff and leachate volumes recorded.

Plant shoot growth was harvested 8 WAT. Shoots of all plants were severed at the soil line and dried at 65 °C until constant dry weight was obtained. Remaining material of transplanted root balls were removed with minimum disturbance of compacted soils and discarded. Increase in shoot biomass was determined by subtracting mean initial biomass from that recorded at plant harvest.

Another 114 container-produced (0.7 L) *Salvia farinacea* were obtained from the same local commercial nursery (Batson's Greenhouse, Inc., Mt. Dora, FL) and transplanted (Planting 2) as described above on June 1, 2011. As before, shoots of six plants were harvested for initial dry shoot biomass. Canopy measurements were recorded as in Planting 1 immediately post-transplant and every two weeks until harvest (8 WAT). Plant growth indices (growth index = height x width 1 x width 2) were calculated. As before, synthetic precipitation began 3 WAT and was applied weekly until harvest (8 WAT). Runoff and leachate volumes were recorded. At harvest shoots of all plants were severed at the soil line and dried at 65 °C until constant dry weight was obtained. Increase in shoot biomass was determined as in Planting 1.

Statistical Analysis

Experiments were designed and analyzed as a completely randomized block design with soil texture, mulch, and plant materials as treatments. Statistical analysis of relationships between mulch, plant materials, and runoff and leachate volumes were examined using the PROC MIXED procedure in SAS (SAS Institute, 2008). Statistical analysis of plant growth indices and plant shoot biomass (PSB) was conducted comparing differences in mean values between 0 and 8 WAT using the PROC MIXED procedure. Non-linear relationships existed between soil type and mean leachate volumes. Leachate volume data was normalized (square root transformation) to improve statistical analysis but are presented as actual measured values (Dean and Voss, 1999). All analytical tests were considered to be statistically significant if $P < 0.05$.

Results and Discussion

Soil Characteristics

As presented in Chapter 3, the percentage of soil sand ranged from 86.1 to 96.5% between soil types (Table 4-1). Percentage soil clay was similar for Sand and Common soils but significantly greater in Loam with a mean of 12.6%. Textural analysis determined both Sand and Common soil types were classified as sands while the Loam soil type was classified as loamy sand.

Mean saturated soil infiltration rates ranged from 51.3 to 87.8 cm hr^{-1} (Table 4-2). Saturated soil infiltration rate for the Loam soil was significantly lower than the Sand or Common soils. The minimum recorded infiltration rate was 34.6 cm hr^{-1} in the Loam soil while the maximum rate was 105.3 cm hr^{-1} in the Sand soil.

Mean unsaturated soil infiltration rates ranged from 2.7 to 51.4 cm hr^{-1} (Table 4-2). Unsaturated soil infiltration rate of the Loam soil was significantly lower than the Sand or Common soils. This trend was similar to saturated soil infiltration rate observations. The coefficient of variation ranged from 28.6 to 48.3 percent. High variability in unsaturated soil infiltration rates probably resulted from heterogeneity in sub-macropore soil volume (Craul and Klein, 1980; Gregory et al., 2006; Zhang, 1997).

Mean soil moisture retention volumes ranged from 13.4 to 23.5 mL water 100 cm^{-3} soil between soil moisture potentials -6.4 and -100 kPa (Table 4-2). The Loam soil had significantly lower moisture retention than the Sand or Common soils.

Distribution of soil pore sizes was similar between the three soil textures. Macropores (diameter > 0.05 mm) were the dominant pore size, representing 53% of mean soil pore space. Micropores (diameter = 0.05 - 0.0002 mm) represented 39% of mean soil pore space while cryptopores (diameter < 0.0002 mm) accounted for 8% of mean soil pore space. Soil micropores are responsible for soil water absorptive capacity (SWAC) during short duration, high intensity precipitation events given soil macropores are active in soil water drainage (leaching) and soil cryptopores are filled with water.

Experiment 1

Leachate volumes were not significantly influenced by mulch; however, textural differences were observed (Figure 4-2). The highest mean leachate volume (0.95 L) was produced from the Common soil type. Loam and Sand soils produced similar leachate volumes (0.33 and 0.14 L, respectively). The results presented here are in contrast to those reported by Adekalu et al. (2007). In their study, leachate volumes decreased in response to mulch application. Finer texture mulch (dried *Pennisetum purpureum*) likely created a more torturous pathway allowing greater opportunity for water to be absorbed by the mulch. Additionally this mulch may have had a greater water absorption capacity than the pine bark used in our study. Either scenario would have resulted in reduced water volumes reaching the soil surface and be responsible for observed differences.

Statistical interactions occurred in runoff volume production between soil type × mulch. Similar interactions between soil type and mulch were observed by Adekalu et al. (2007). Mean runoff volumes from the Sand and Common soil in the absence of mulch were minimal (0.01 and 0.05 L, respectively) (Figure 4-3). Application of mulch further reduced runoff production from the Sand and Common soils to zero. Highest runoff production (2.4 L) was observed from Loam soil in the absence of mulch. Mulch application also significantly reduced the mean runoff volume from Loam soil to zero. Reductions in runoff volumes as a result of mulch application have been observed in similar research (Adams, 1966; Adekalu et al., 2007; Barnett et al., 1967). Adekalu et al. (2007) observed runoff volume reductions of up to 63%. Runoff volumes in their study were not reduced to zero values as a result of mulch application, likely a result of greater precipitation application rates (15 cm hr^{-1}).

Experiment 2

Differences in plant growth indices during 0 to 8 WAT were not observed between consecutive plantings (Planting 1 and Planting 2); therefore, plant growth data at harvest was combined for statistical analysis. Largest growth indices were observed in the Sand and Common soils (0.08 and 0.06 m^3, respectively; Figure 4-4). Growth in Loam soil (0.03 m^3) was significantly less. This may have resulted from greater root penetration resistance as a result of higher soil clay content (Table 4-1), or as a result of greater moisture volume in Loam soil (Brady and Weil, 2002; Bucur and Horn, 2001).

No significant differences were observed in plant shoot biomass (PSB) between Planting 1 and Planting 2; therefore, PSB data was also combined for statistical analysis. Soil texture significantly influenced PSB (Figure 4-5). *Salvia farinacea* grown in Loam soil had significantly lower mean PSB (14.5 g) than those grown in Sand or Common soils (25.8 and 22.2 g, respectively). Plant shoot biomass trends were similar to plant growth indices. Lower PSB in Loam soil likely resulted from greater root penetration resistance as a result of higher soil clay content (Table 4-1) or as a result of greater moisture volume (Brady and Weil, 2002; Bucur and Horn, 2001).

Leachate volumes were not significantly influenced by time (WAT), planting (Planting 1 and Planting 2), or presence of mulch; therefore, data was combined for statistical analysis and presented in conjunction with results for Experiment 1 (Figure 4-2). Results are in contrast to those observed by Bartens et al. (2008) where establishment and growth of black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L) increased mean soil infiltration rate by 153%. Larger root size and depth from tree species (when compared to *Salvia farinacea*) were likely responsible for observed differences.

Runoff volumes were not significantly influenced by time (WAT) or planting (Planting 1 and Planting 2), but were impacted by presence of mulch. Mean runoff volume from the Common soil was minimal (0.03 L), while no runoff was observed from either Sand or Loam soil when mulch was present (data not shown). Zero and near zero runoff volume observations precluded differences in runoff volume resulting from presence of plant materials. Therefore, runoff volume data was combined for statistical analysis and presented in conjunction with results for Experiment 1 (Figure 4-3).

As described in Chapter 3, the Sand and Common soil had the largest SWAC (14.7 and 13.2 L, respectively) (Table 4-3). Soil water absorptive capacity of Loam was approximately 1.6-fold less than Sand or Common soil. Although the Loam soil would be expected to have greater total soil porosity as a result of its high clay content (relative to the Sand and Common soil types), Loam soil contained less micropore soil volume and thus less SWAC than Sand or Common soil types (Table 4-1, Table 4-3). Water absorptive capacity of mulch between saturated and air-dried was approximately 0.15 mL cm^{-3} mulch and was the maximum absorptive capacity of the mulch layer.

Given an estimated 62,160 cm^3 of mulch (117.9 cm length, 92.5 cm width, and 5.7 cm depth) was applied to each lysimeter, maximum MWAC was approximately 9.2 L $lysimeter^{-1}$. Water absorptive capacity of mulch between saturated and 70% PAW was 0.084 mL cm^{-3} or 5.2 L $lysimeter^{-1}$. Available moisture content of mulch varied between lysimeters and was dependent upon duration of time between lysimeter soil moisture irrigation and precipitation events.

Water absorptive capacities (sum of SWAC and MWAC) for Sand and Common soil types were greater than precipitation input; therefore, EDVs were zero (Table 4-4). Loam soil had the greatest EDV (0.3 L). Common and Loam soils had ODVs of 0.95 and 0.5 L, respectively. Sand soil had the lowest ODV of 0.1 L. Observed discharge volumes were greater than EDVs for all soil types. Expected discharge volume from the Common soil was zero, however, 0.95 L of discharge was observed. Strong relationships between EDVs and ODVs were observed for both the Sand and Loam soil type. Given that runoff volumes were near zero or zero value, leachate volumes were mostly responsible for measurable ODVs.

Runoff volumes were reduced to zero or near zero value as a result of mulch application. High maximum absorptive capacity of mulch (9.2 L water $lysimeter^{1}$) and physical overland flow impedance likely intercepted and absorbed potential runoff water. Measureable runoff volumes would be expected to occur if mulch and soil were saturated as a result of greater precipitation volumes. Leachate volumes were not influenced by presence of mulch or plants and were observed despite high water absorptive capacities. This suggests that leachate volume production occurred as a result of preferential (bypass) soil water flow where soil water bypassed the bulk soil (Bouma, 1981; Towner, 1989).

Summary

Runoff volumes from all soil types were significantly reduced by mulch application. The greatest reduction in runoff volume (2.4 L) was observed when mulch was added to the Loam soil. Physical impedance and absorptive capacity of pine bark mulch, therefore, provides a significant potential environmental benefit through reduction of stormwater nutrient runoff (Adekalu et al., 2007; Wan and El-Swaify, 1999). Application of mulch upon newly constructed urban residential soils is recommended to reduce stormwater runoff potential.

Leachate volumes were not significantly influenced by the presence of mulch. The greatest mean leachate volume (0.95 L) was observed from the Common soil. Consistent leachate volumes in the Loam soil resulted from preferential soil water flow (Bouma, 1981; Bouma et al., 1978; Towner, 1989). Application of finer texture mulch would make soil water infiltration pathways more torturous and would have likely resulted in decreased leachate volumes. Additional research examining the hydrologic influence of various mulch types is necessary. Unsynchronized maintenance of soil moisture led to high variability in available MWAC. This was due to a continuously dynamic gradient between an air-dried surface and 70% PAW moisture at the soil-mulch interface.

Growth of *Salvia farinacea* was influenced by soil texture. Highest growth indices and plant shoot biomass were observed in the Sand and Common soils. Penetration of plant roots into soils did not significantly influence runoff or leachate volumes. We hypothesize that plant root size and depth was not great enough to create increased hydrologic channeling or stemflow conditions.

Mulch influenced the hydrologic properties of soils representative of those found in newly constructed urban residential communities within Central Florida. Reductions in runoff volume occurred through overland stormwater flow impedance and increased water absorptive capacity. Our results support the use of mulch in urban soils to reduce potential of stormwater nutrient runoff.

Table 4-1. Textural characteristics of treatment soils

Soil type	Sand (%)	Silt (%)	Clay (%)
Sand	96.5 a[z]	0.3 a	3.2 b
Common	93.8 a	2.8 a	3.4 b
Loam	86.1 b	1.3 a	12.6 a

[z] Means of 6 replications. Means within columns not followed by the same letter are significant at $P \le 0.05$ (Duncan).

Table 4-2. Physical characteristics of treatment soils

Soil type	Bulk density ($g\ cm^{-3}$)	Soil moisture volume (mL water 100 cm^{-3} soil)[z]	Saturated soil infiltration ($cm\ hr^{-1}$)	Unsaturated soil infiltration ($cm\ hr^{-1}$)
Sand	1.69 a[y]	23.5 a	87.8 a	47.7 a
Common	1.65 a[y]	21.1 a	80.3 a	51.4 a
Loam	1.58 b[y]	13.4 b	51.3 b	2.7 b

[z] Soil moisture volumes collected between soil matric potential -6.4 and -100 kPa.
[y] Mean of 6 replications. Means within columns not followed by the same letter are significant at $P \le 0.05$ (Duncan).

Table 4-3. Calculated lysimeter water absorptive capacities (L)[z]

Soil Type	No Mulch	Mulch
Sand	14.7	19.9
Common	13.2	18.4
Loam	8.4	13.6

[z] Soil water absorptive capacities were calculated through multiplication of soil moisture volume (between matric potentials -6.4 and -100 kPa) and lysimeter soil volume. Mulch absorptive capacities were determined as water content held by pine bark mulch.

Table 4-4. Expected and observed discharge volumes (L)[z]

Soil Type	Expected discharge volume	Observed discharge volume
Sand	0.0	0.1
Common	0.0	0.95
Loam	0.3	0.5

[z] Soil water absorptive capacities were calculated through multiplication of soil moisture volume (between matric potentials -6.4 and -100 kPa) and lysimeter soil volume in addition to pine bark mulch absorptive capacities. Observed discharge volumes represent summation of recorded runoff and leachate volumes.

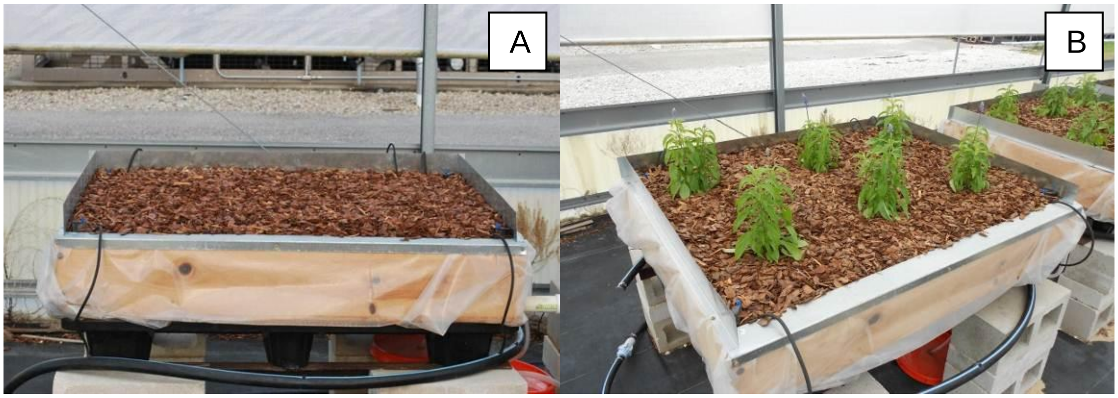

Figure 4-1. Lysimeter design modifications, mulch, and transplanted materials. A) Runoff box with galvanized metal plates installed to direct water infiltration. B) Runoff box with six *Salvia farinacea* transplanted and spaced apart approximately 14 cm on center.

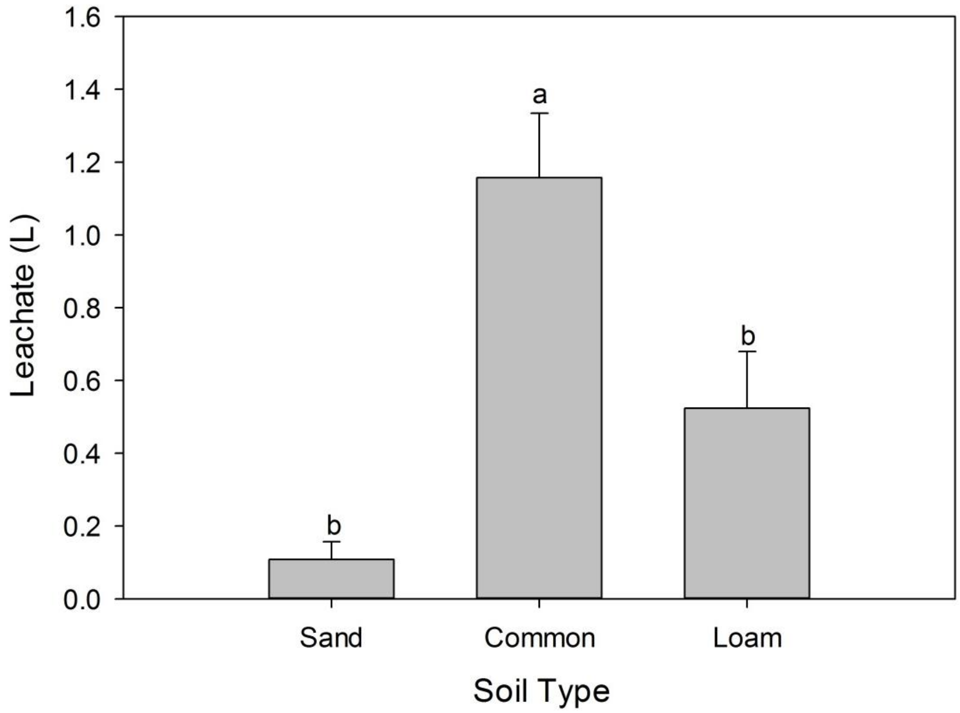

Figure 4-2. Mean leachate volumes collected from lysimeters which received 5.1 cm hr^{-1} precipitation (duration 15 minutes). Means of 12 replications, 6 replications without mulch, 6 replications with mulch. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

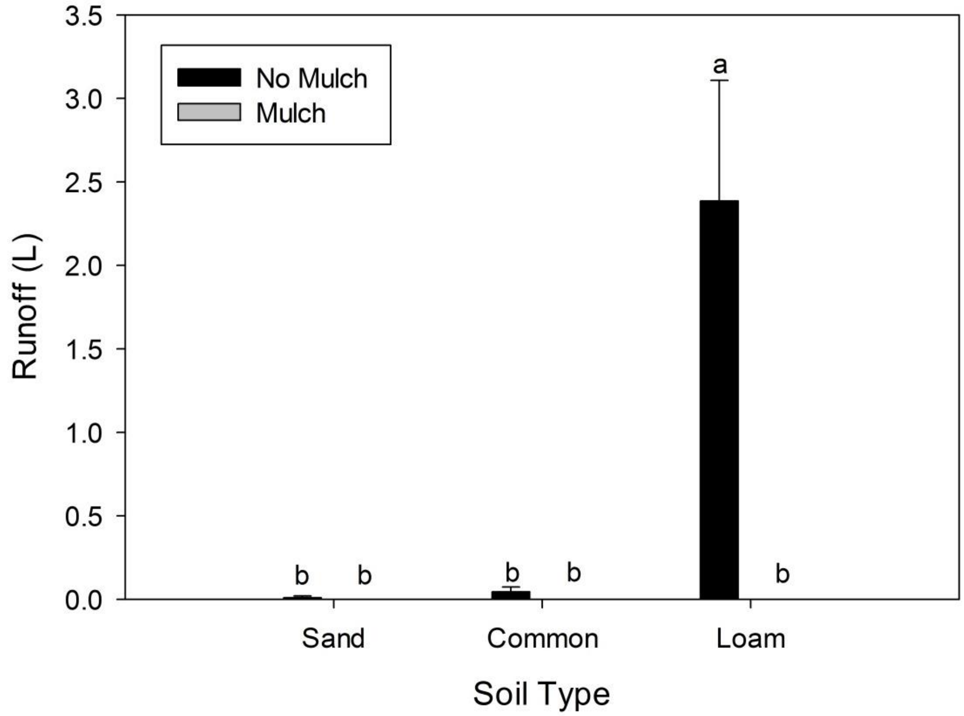

Figure 4-3. Mean runoff volumes collected from lysimeters which received 5.1 cm hr^{-1} precipitation (duration 15 minutes). Means of 6 replications. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

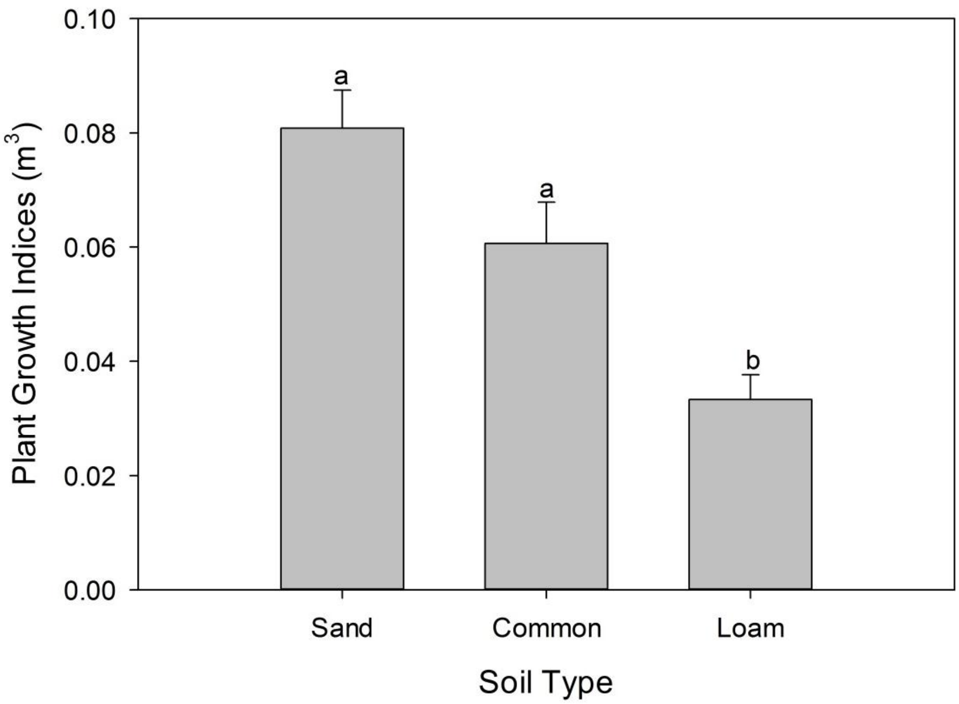

Figure 4-4. Mean plant growth indices (plant growth index = canopy height x widest canopy width x width perpendicular to widest width). Values represent the mean growth of 36 Salvia farinacea over an 8 week period with soil moisture maintained at 70% plant available water. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

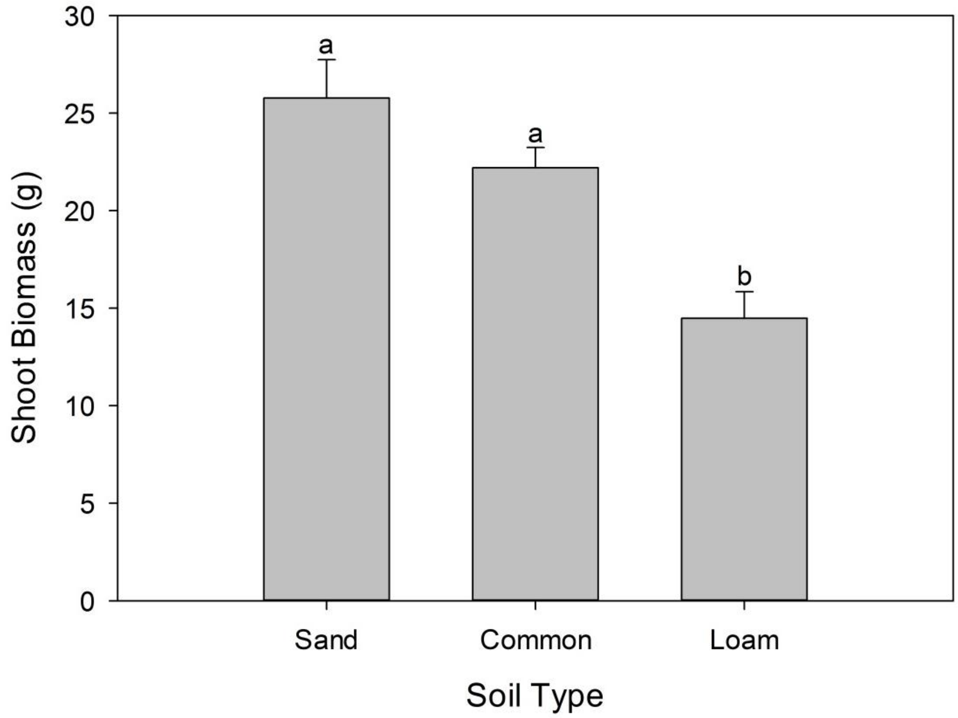

Figure 4-5. Mean increase in plant shoot biomass (PSB) (dry mass of plant shoots). Values represent the mean increase in PSB of 36 *Salvia farinacea* over an 8 week period with soil moisture maintained at 70% plant available water. Error bars represent standard error of the mean and columns with the same letters are not significantly different at $P \leq 0.05$ (Tukey-Kramer).

CHAPTER 5
CONCLUSIONS

Nutrients in stormwater runoff and leachate are an important component of water quality management. Knowledge of the mechanisms creating runoff and leachate, related to soil characteristics, is essential to assessing the potential for nutrient losses. This is especially important in newly constructed urban residential communities where prepared sites rarely resemble the pre-existing native conditions.

Newly constructed urban residential lots within planned communities in Orange, Lake, and Seminole counties in Florida were sampled to quantify soil characteristics and examine variability at plot-level and community-level scales. Relationships between soil characteristics and infiltration rates were examined, and served as the basis for selection of representative soils for more intensive research.

Native soil was disturbed at all sites due to installation of utilities (water, sewer, etc.) and grading and compaction for road and building foundations. Backfill soil was a major component at all sites and could be identified in some sites up to 1 m deep. Soil compaction was found to be uniform at both small plot-level and community-level scales as a result of industry-regulated consistent site compaction practices. Mean soil bulk density for over 50% of communities was near 1.75 g cm^{-3}. High D_b values indicate potential inhibition of plant root growth. Mechanical loosening of soils should be encouraged to improve soil conditions. Soil textural analysis determined that a majority (90%) of sampled lots contained coarse-textured sandy soils, with 10% of sampled lots containing soil textures that differed from those described in National Resource Conservation Service (NRCS) soil maps. Nearly half of sampled lots contained soils with infiltration rates below the 100-year, 24-hour design storm intensity. However, infiltration rates were highly variable at plot-level and community-level scales. Under high rainfall intensities a majority of barren lots would potentially produce stormwater runoff. Relationships between saturated infiltration rates and measured soil characteristics were relatively poor. High variability of soil characteristics was responsible for this relationship.

Identification of soil characteristics in newly constructed urban residential communities allowed for selection of representative soil types. Three soil types (Sand, Common, and Loam) were chosen to represent soil textural ranges observed locally in residential landscapes. The Sand and Loam soil types contained 96.5 and 86.1% sand, respectively. The Common soil type contained 93.8% sand and represented the most common soil textural type observed. Shallow runoff boxes (lysimeters) were constructed and filled with representative soils and compacted to > 90% of that measured in the urban community sites. Influences of soil type, soil moisture level, and precipitation intensity on runoff and leachate volume through 19 cm of soil depth were examined. Low soil moisture (≤ 40% plant available water) or precipitation intensity (2.5 cm hr^{-1}) levels produced minimal, and no runoff and leachate over a 15 min precipitation interval. Large levels of runoff and leachate were observed to occur at higher soil moisture (70% and 90% plant available water) and precipitation intensities (5.1 and 7.6 cm hr^{-1}). This implies that stormwater runoff and leachate (at depths < 19 cm) would occur in these newly constructed urban residential communities under short interval, high intensity (≥ 5.1 cm hr^{-1}) precipitation events similar to those observed during summer months within Central Florida.

Soil texture influenced runoff and leachate volume production. Higher soil clay content of the Loam soil produced significantly ($P \leq 0.05$) greater runoff and leachate volumes. Textural changes resulting from construction practices, therefore, have potential to influence site hydrology. Quantification of soil textural modifications that influence urban residential soil hydrology is necessary for development of appropriate stormwater management plans and effective regulations.

The saturation-excess hydrologic model predicts production of stormwater runoff once soils have become saturated. Basing soil water absorption capacity on plant available water between -6.5 and -100 kPa soil matric potential resulted in exceptional model fit for the Sand and Common soils. The fit was significant, but less than perfect, for the Loam soil due to greater textural heterogeneity. Increased antecedent soil moisture strongly influenced runoff and leachate volumes as a result of reduced water absorption capacity. Although infiltration rate data provides useful soil characteristic information, it was not a reliable indicator of stormwater runoff in these soils. Estimation of stormwater discharge should not be based solely upon infiltration and precipitation rate data. The saturation-excess hydrologic model should be applied in estimation of stormwater runoff and leachate from newly constructed residential communities with similar soil characteristics evaluated here.

Application of mulch in landscape design and management is a common cultural practice most often conducted for aesthetic and weed control value. It also has added benefits of: increasing soil moisture, preventing soil crusting, and increasing soil organic matter. Mulch applications can also alter soil hydrology. A 5.7 cm layer of pine bark mulch applied to the soil surface of runoff boxes decreased runoff volumes to zero and near zero values for all soil types at moderate precipitation rates (5.1 cm hr^{-1}) and moderately high plant available soil water (70%). Leachate production was not influenced by the presence of mulch. Physical impedance and absorptive capacity of pine bark mulch provides a significant potential environmental benefit through reduction of stormwater nutrient runoff. Use of mulch in urban residential landscapes is recommended to aid in reduction of stormwater runoff potential. Further investigation is warranted to elucidate the dynamics of mulch water holding capacity.

Plant growth has the potential to influence soil hydrology through root proliferation creating hydrologic soil channels during growth and from decay after root death. However the planting and sequential growth of a summer annual flowering plant for two months did not influence runoff or leachate volumes. Nor was there an influence after replanting and an additional eight weeks of growth. Root size and depth of *Salvia farinacea* was insufficient to create increased hydrologic channeling or stemflow conditions. Additional research incorporating various plant materials and growth durations is needed to better determine hydrologic impacts.

LIST OF REFERENCES

Adams, J.E., 1966. Influence of Mulches on Runoff, Erosion, and Soil Moisture Depletion1. Soil Sci. Soc. Am. J. 30:110-114.

Adekalu, K.O., Olorunfemi, I.A., and Osunbitan, J.A., 2007. Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. Bioresource Technology 98:912-917.

Agassi, M., Morin, J., and Shainberg, I., 1985. Effect of Raindrop Impact Energy and Water Salinity on Infiltration Rates of Sodic Soils1. Soil Sci. Soc. Am. J. 49:186-190.

Anderson, D.M., Glibert, P.M., and Burkholder, J.M., 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. Estuaries 25:704-726.

Arthurs, S. and Stauderman, K. 2010. Evaluating how accurately lawn fertilizers are applied using homeowner equipment.

Assouline, S., 2004. Rainfall-Induced Soil Surface Sealing. Vadose Zone J. 3:570-591.

ASTM, 2008. Standard D6836, Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge. ASTM International, West Conshohocken, PA.

Aubertin, G.M., 1971. Nature and extent of macropores in forest soils and their influence on subsurface water movement. Research Paper US Forest Service NE-192:33 pp.

Baker, D.B., Richards, R.P., Loftus, T.T., and Kramer, J.W., 2004. A new flashiness index: Characteristics and applications to midwestern rivers and streams. JAWRA Journal of the American Water Resources Association 40:503-522.

Barnett, A.P., Diseker, E.G., and Richardson, E.C., 1967. Evaluation of Mulching Methods for Erosion Control on Newly Prepared and Seeded Highway Backslopes1. Agron. J. 59:83-85.

Barraclough, D., Geens, E.L., Davies, G.P., and Maggs, J.M., 1985. Fate of fertilizer nitrogen. III. The use of single and double labelled N15 ammonium nitrate to study nitrogen uptake by ryegrass. Journal of Soil Science 36:593-603.

Bartens, J., Day, S.D., Harris, J.R., Dove, J.E., and Wynn, T.M., 2008. Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management? J. Environ. Qual. 37:2048-2057.

Barton, L. and Colmer, T.D., 2006. Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. Agric. Water Manage. 80:160-175.

Beasley, R.P., 1978. Sediment and Erosion Control. Iowa State University Press, Ames.

Beyer, L., Blume, H.P., Elsner, D.C., and Willnow, A., 1995. Soil organic-matter composition and microbial activity in urban soils. Sci. Total Environ. 168:267-278.

Black, R. and Gilman, E.F., 1997. Your Florida guide to bedding plants. University Press of Florida, Gainesville.

Black, R.J. and Ruppert, K.C., 1998. Your Florida landscape: a complete guide to planting and maintenance: tres, palms, shrubs, ground covers and vines. UF/IFAS Cooperative Extension Service, Gainesville, FL.

Blake, G.R. and Hartge, K.H., 1986. Bulk density, *In* G.S. Campbell, et al., eds. Methods of soil analysis. Part 1, Physical and mineralogical methods. Soil Science Society of America, Madison, Wis.

Blanco-Canqui, H. and Lal, R., 2009. Crop Residue Removal Impacts on Soil Productivity and Environmental Quality. Crit. Rev. Plant Sci. 28:139-163.

Bloschl, G. and Sivapalan, M., 1995. Scale Issues In Hydrological Modeling - A Review. Hydrol. Process. 9:251-290.

Bockheim, J.G., 1974. Nature and properties of highly disturbed urban soils, Division S-5, Soil Science Society of America, Philadelphia, PA.

Booth, D.B. and Jackson, C.R., 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. JAWRA Journal of the American Water Resources Association 33:1077-1090.

Bouma, J., 1981. Soil morphology and preferential flow along macropores. Agric. Water Manage. 3:235-250.

Bouma, J., Dekker, L.W., and Wösten, J.H.M., 1978. A case study on infiltration into dry clay soil II. physical measurements. Geoderma 20:41-51.

Bouwer, H., 1978. Ground-water hydrology. McGraw-Hill Book Co., New York.

Bouwer, H., 1986. Intake rate: Cylinder infiltrometer, *In* G.S. Campbell, et al., eds. Methods of soil analysis. Part 1, Physical and mineralogical methods. Soil Science Society of America, Madison, WI.

Brady, N. and Weil, R., 2002. Elements of the Nature and Properties of Soils. Pearson Education, Inc., Upper Saddle River, New Jersey.

Brown Gaddis, E.J., Vladich, H., and Voinov, A., 2007. Participatory modeling and the dilemma of diffuse nitrogen management in a residential watershed. Environmental Modelling & Software 22:619-629.

Brown, K.W., Duble, R.L., and Thomas, J.C., 1977. Influence of management and season of fate on N applied to golf greens. Journal of Agronomy 69:667-671.

Brown, K.W., Thomas, J.C., and R.L. Duble, 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff losses from greens. Agronomy Journal 74:947-950.

Bryant, R., Doerr, S.H., Hunt, G., and Conan, S., 2007. Effects of compaction on soil surface water repellency. Soil Use Manage. 23:238-244.

Bucur, D. and Horn, R., 2001. Influence of bulk density and moisture on penetration resistance on different soil texture types. Cercetari Agronomice in Moldova 34:101-106.

Buda, A.R., Kleinman, P.J.A., Srinivasan, M.S., Bryant, R.B., and Feyereisen, G.W., 2009. Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania. Hydrol. Process. 23:1295-1312.

Bullock, P. and Gregory, P.J., 1991. Soils in the urban environment. Blackwell Scientific Publications, Oxford.

Campbell, L., 1994. Beneficial impact of precision nutrient management on the environment and future-needs. Communications in Soil Science and Plant Analysis 25:889-908.

Carnathan, P., 2011. Say so long now to nitrogen's quick fix, St. Petersburg Times, St. Petersburg.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., and Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559-568.

Castillo, V.M., Gómez-Plaza, A., and Martínez-Mena, M., 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. Journal of Hydrology 284:114-130.

Cerdà, A., 1997. Seasonal changes of the infiltration rates in a Mediterranean scrubland on limestone. Journal of Hydrology 198:209-225.

Chen, J., Tarchitzky, J., Morin, J., and Banin, A., 1980. Scanning electron microscope observations on soil crusts and their formation. Soil Sci. 130:49-55.

Chichester, F.W., 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. Journal of Environmental Quality 6:211-217.

Chinnow, D., 1975. Bodenveranderungen durch Carbonate und Streusalze im Westberliner Stadtgebiet. Mitt. Dtsch. Bodenkundl. Ges. 22:355-358.

Chrispeels, M.J. and Sadava, D.E., 1994. Plants, Genes, and Agriculture. Jones and Bartlett Publishers, Boston, MA.

Cole, J., Baird, J., Basta, N., Huhnke, R., Storm, D., Johnson, G., Payton, M., Smolen, M., Martin, D., and Cole, J., 1997. Influence of buffers on pesticide and nutrient runoff from bermudagrass turf. Journal of Environmental Quality 26:1589-1598.

Colee, J., 2011. Person Communication, Gainesville, FL.

Cox, F.R. and Hendricks, S.E., 2000. Soil Test Phosphorus and Clay Content Effects on Runoff Water Quality. J. Environ. Qual. 29:1582-1586.

Craft, C., 1997. Dynamics of nitrogen and phosphorus retention during wetland ecosystem succession. Wetlands Ecology Management 4:177-187.

Craul, P.J., 1985. A description of urban soils and their desired characteristics. Journal of Arboriculture 11:330-339.

Craul, P.J., 1992. Urban Soil in Landscape Design. John Wiley & Sons, Inc., New York, NY.

Craul, P.J. and Klein, C.F. 1980. Characterization of streetside soil in Syracuse, New York, New Brunswick, NJ 3).

Dabney, S.M., Delgado, J.A., and Reeves, D.W., 2001. Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis 32:1221-1250.

Davis, A.P., Shokouhian, M., Sharma, H., and Minami, C., 2006. Water quality improvement through bioretention media: Nitrogen and phosphorus removal. Water Environ. Res. 78:284-293.

Davis, R.L., Zhang, H., Schroder, J.L., Wang, J.J., Payton, M.E., and Zazulak, A., 2005. Soil Characteristics and Phosphorus Level Effect on Phosphorus Loss in Runoff. J. Environ. Qual. 34:1640-1650.

De Kimpe, C.R. and Morel, J.L., 2000. Urban soil management: A growing concern. Soil Sci. 165:31-40.

Dean, A. and Voss, D., 1999. Design and analysis of experiments. Springer, New York, NY.

DeLaune, P.B., Moore, P.A., Carman, D.K., Sharpley, A.N., Haggard, B.E., and Daniel, T.C., 2004a. Development of a phosphorus index for pastures fertilized with poultry litter - Factors affecting phosphorus runoff. Journal of Environmental Quality 33:2183-2191.

DeLaune, P.B., Moore, P.A., Carman, D.K., Sharpley, A.N., Haggard, B.E., and Daniel, T.C., 2004b. Evaluation of the phosphorus source component in the phosphorus index for pastures. Journal of Environmental Quality 33:2192-2200.

Dolan, M.S., Dowdy, R.H., and Lamb, J.A., 2001. Redirection of precipitation by a corn canopy and related soilwater status. Communications in Soil Science and Plant Analysis 32:739-750.

Dunne, T., 1983. Relation of field studies and modeling in the prediction of storm runoff. Journal of Hydrology 65:25-48.

Dunne, T. and Black, R.D., 1969. An experimental investigation of runoff production in permeable soils. Transactions-American Geophysical Union 50:145.

Ehrenfeld, J.G., Cutway, H.B., Hamilton, R.I., and Stander, E., 2003. Hydrologic description of forested wetlands in northeastern New Jersey, USA - An urban/suburban region. Wetlands 23:685-700.

Ellis, S. and Mellow, T., 1995. Soil and environment. Routledge, New York.

Erickson, J.E., Cisar, J.L., Volin, J.C., and Snyder, G.H., 2001. Comparing nitrogen runoff and leaching between newly established St. Augustinegrass turf and an alternative residential landscape. Crop Science 41:1889-1895.

Espey, W.H., Winslow, X.X., and Morgan, C.W., 1969. Effects of Watershed Changes on Streamflow. University of Texas Press, Austin, TX.

Fageria, N.K., Baligar, V.C., and Li, Y.C., 2008. The Role of Nutrient Efficient Plants in Improving Crop Yields in the Twenty First Century. Journal of Plant Nutrition 31:1121-1157.

FDEP, 2006. The Florida Stormwater Erosion and Sedimentation Control Inspector's Manual. In: Florida Department of Environmental Protection (ed.), Tallahassee, FL.

FDOT, 2003. Drainage Manual. In: Florida Department of Transportation (ed.). Office of Design, Tallahassee, FL.

Fisher, T.R., Benitez, J.A., Lee, K.Y., and Sutton, A.J., 2006. History of land cover change and biogeochemical impacts in the Choptank River basin in the mid-Atlantic region of the US. Int. J. Remote Sens. 27:3683-3703.

Florida Yards and Neighborhoods Program, 2006. A Guide to Florida-Friendly Landscaping: Florida Yards & Neighborhoops Program. University of Florida, Institute of Food and Agricultural Sciences, Gainesville, FL.

Franklin, D.H., Cabrera, M.L., and Calvert, D.V., 2006a. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Science Society of America Journal 70:84-89.

Franklin, D.H., Cabrera, M.L., and Calvert, V.H., 2006b. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Science Society of America Journal 70:84-89.

Gascho, G.J., Wauchope, R.D., Davis, J.G., Truman, C.C., Dowler, C.C., Hook, J.E., Sumner, H.R., and Johnson, A.W., 1998. Nitrate-nitrogen, soluble, and bioavailable phosphorus runoff from simulated rainfall after fertilizer application. Soil Science Society of America Journal 62:1711-1718.

Gaudreau, J.E., Vietor, D.M., White, R.H., Provin, T.L., and Munster, C.L., 2002. Response of turf and quality of water runoff to manure and fertilizer. Journal of Environmental Quality 31:1316-1322.

Gee, G.W. and Bauder, J.W., 1986. Particle Size Analysis, *In* G.S. Campbell, et al., eds. Methods of soil analysis. Part 1, Physical and mineralogical methods. Soil Science Society of America, Madison, WI.

Gilman, E.F. and Grabosky, J., 2004. Mulch and planting depth affect live oak (Quercus virginiana Mill.) establishment. Journal of Arboriculture 30:311-317.

Goldman, M.B., Groffman, P.M., Pouyat, R.V., McDonnell, M.J., and Pickett, S.T.A., 1995. CH4 uptake and N availability in forest soils along an urban to rural gradient. Soil Biology and Biochemistry 27:281-286.

Goncalves, R.A.B., Gloaguen, T.V., Folegatti, M.V., Libardi, P.L., Lucas, Y., and Montes, C.R., 2010. Pore size distribution in soils irrigation with sodic water and wastewater. Rev. Bras. Cienc. Solo 34:701-707.

Grabosky, J. and Bassuck, N.L., 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. Journal of Arboriculture 21:187-201.

Green, E.K. and Galatowitsch, S., M. , 2002. Effects of *Phalaris arundinacea* and nitrate-N addition on the establishment of wetland plant communities. Journal of Applied Ecology 39:134-144.

Gregory, J.H., Dukes, M.D., Jones, P.H., and Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. J. Soil Water Conserv. 61:117(118).

Gregory, J.H., Dukes, M.D., Miller, G.L., and Jones, P.H., 2005. Analysis of double-ring infiltration techniques and development of a simple automatic water delivery system. Applied Turfgrass Science:1-6.

Grimm, N.B., Sheibley, R.W., Crenshaw, C.L., Dahm, C.N., Roach, W.J., and Zeglin, L.H., 2005. N retention and transformation in urban streams. Journal of the North American Benthological Society 24:626-642.

Guidry, A.R., Schindler, F.V., German, D.R., Gelderman, R.H., and Gerwing, J.R., 2006. Using simulated rainfall to evaluate field and indoor surface runoff phosphorus relationships. Journal of Environmental Quality 35:2236-2243.

Harris, W.G., Chrysostome, M., Obreza, T.A., and Nair, V.D., 2010. Soil Properties Pertinent to Horticulture in Florida. HortTechnology 20:10-18.

Hatt, B.E., Fletcher, T.D., Walsh, C.J., and Taylor, S.L., 2004. The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams. Environmental Management 34:112-124.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., and Nelson, W.L., 2005. Soil Fertility and Fertilizers: An introduction to Nutrient Management. Prentice Hall, Upper Saddle River, N.J.

Hensley, D.L., 2010. Professional Landscape Management. Stipes Publishing, L.L.C., Champaign, IL.

Hillel, D., 1980. Fundamentals of Soil Physics. John Wiley, New York.

Hochmuth, G., Nell, T., Sartain, J., Unruh, J.B., Martinez, C., Trenholm, L.E., and Cisar, J.L., 2011. Urban water quality and fertilizer ordinances: Avoiding unintended consequences: A review of the scientific literature. In: IFAS (ed.). UF, Gainesville, FL.

Hollis, G.E., 1975. The effects of urbanization on floods of different recurrence intervals. Water Resour. Res. 11:431-435.

Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Transactions-American Geophysical Union 14:446-460.

Hummel, N.W., Jr., Waddington, D.V., 1981. Evaluation of slow-release nitrogen sources on Baron Kentucky bluegrass. Soil Science Society of America Journal 45:966-970.

Hummel, N.W., Jr., Waddington, D.V., 1984. Sulfur-coated urea for turfgrass fertilization. Soil Science Society of America Journal 48:191-195.

Jim, C.Y., 1998. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. Urban Ecosystems 2:171-181.

Johnson, M.S. and Lehmann, J., 2006. Double-funneling of trees: Stemflow and root-induced preferential flow. Ecoscience 13:324-333.

Kaye, J.P., Groffman, P.M., Grimm, N.B., Baker, L.A., and Pouyat, R.V., 2006. A distinct urban biogeochemistry? Trends in Ecology & Evolution 21:192-199.

Kaye, J.P., McCulley, R.L., and Burke, I.C., 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology 11:575-587.

Kazman, Z., Shainberg, I., and Gal, M., 1983. Effect of Low-Levels of Exchangeable Sodium and Applied Phosphogypsum on the Infiltration-Rate of Various Soils. Soil Sci. 135:184-192.

Keeney, D., 1986. Sources of nitrate to ground water. Critical Review Environmental Control 16:257-304.

Kelling, K.A. and Peterson, A.E., 1975. Urban Lawn Infiltration Rates and Fertilizer Runoff Losses under Simulated Rainfall1. Soil Sci. Soc. Am. J. 39:348-352.

Kirkham, M.B., 2005. Principles of Soil and Plant Water Relations. Elsevier Academic Press, Burlington, MA.

Klein, V.A. and Libardi, P.L., 2002. Densidade e distribuição do diâmetro dos poros de um Latossolo Vermelho, sob diferentes sistemas de uso e manejo. Rev. Bras. Cienc. Solo 26:857-867.

Kleinman, P.J.A., Sharpley, A.N., Veith, T.L., Maguire, R.O., and Vadas, P.A., 2004. Evaluation of phosphorus transport in surface runoff from packed soil boxes. Journal of Environmental Quality 33:1413-1423.

Knox, G.W., Israel, G.D., Davis, G.L., Black, R.J., Schaefer, J.M., and Park Brown, S., 1995. Environmental Landscape Management: Use of Practices by Florida Consumers. In: IFAS (ed.). UF, Gainesville, FL.

Konrad, C.P. 2005. Effects of urban development on floods. Tacoma, WA.

Ladekarl, U.L., 1998. Estimation of the components of soil water balance in a Danish oak stand from measurements of soil moisture using TDR. Forest Ecology and Management 104:227-238.

Lai, J. and Ren, L., 2007. Assessing the size dependency of measured hydraulic conductivity using double-ring infiltrometers and numerical simulation. Soil Science Society of America Journal 71:1667-1675.

Lal, R. and Stewart, B.A., 1994. Soil processes and water quality. Advances in soil science. Lewis Publishing, Boca Raton, FL.

Lal, R. and Vandoren, D.M., 1990. Influence of 25 Years of Continuous Corn Production by 3 Tillage Methods on Water Infiltration for 2 Soils in Ohio. Soil Tillage Res. 16:71-84.

Law, N., Band, L., and Grove, M., 2004. Nitrogen input from residential lawn care practices in suburban watersheds in Baltimore county, MD. Journal of Environmental Planning and Management 47:737 - 755.

Le Bissonnais, Y., Benkhadra, H., Chaplot, V., Fox, D., King, D., and Daroussin, J., 1998. Crusting, runoff and sheet erosion on silty loamy soils at various scales and upscaling from m(2) to small catchments. Soil Tillage Res. 46:69-80.

Mackenzie, F., 1998. Our Changing Planet: An Introduction to Earth System Science and Global Environmental Change. Prentice Hall, Inc., Upper Saddle River, NJ.

Madsen, M.D. and Chandler, D.G., 2007. Automation and Use of Mini Disk Infiltrometers. Soil Sci Soc Am J 71:1469-1472.

McIntyre, 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 85:185-189.

McLeod, R.V. and Hegg, R.O., 1984. Pasture runoff water quality from application of inorganic and organic nitrogen sources. Journal of Environmental Quality 13:122-126.

Miao, S.L., McCormick, P.V., Newman, S., and Rajagopalan, S., 2001. Interactive effects of seed availability, water depth, and phosphorus enrichment on cattail colonization in an Everglades wetland. Wetlands Ecology and Management 9:39-47.

Morgan, K.T., Parsons, L.R., and Adair Wheaton, T., 2001. Comparison of laboratory- and field-derived soil water retention curves for a fine sand soil using tensiometric, resistance and capacitance methods. Plant and Soil 234:153-157.

Morton, T.G., Gold, A.J., and Sullivan, W.M., 1988. Influence of Overwatering and Fertilization on Nitrogen Losses from Home Lawns. Journal of Environmental Quality 17:124-130.

Mosdell, D.K., and R.E. Schmidt. 1985. Temperature and irrigation influences on nitrate losses of *Poa pratensis* L. turf., Avignon, France 1-5 July.

Nair, V.D., Portier, K.M., Graetz, D.A., and Walker, M.L., 2004. An environmental threshold for degree of phosphorus saturation in sandy soils. Journal of Environmental Quality 33:107-113.

NOAA, 2011. Climates of the States, Climatography of the United States No. 60. In: National Oceanic and Atmosphere Administration (ed.), Asheville, NC.

NRCS, 2011. Web Soil Survey. USDA.

Pappas, E.A., Huang, C.-h., and Bonta, J.V., 2011. Do Upslope Impervious Surfaces Impact the Run-on/Runoff Relationship? J. Hydrol. Eng. 16:345-350.

Park Brown, S. and Schoellhorn, R., 2006. Your Florida guide to perennials. University Press of Florida, Gainesville.

Pavao-Zuckerman, M.A., 2008. The Nature of Urban Soils and Their Role in Ecological Restoration in Cities. Restoration Ecology 16:642-649.

Pavao-Zuckerman, M.A. and Coleman, D.C., 2005. Decomposition of chestnut oak (Quercus prinus) leaves and nitrogen mineralization in an urban environment. Biology and Fertility of Soils 41:343-349.

Penna, D., Tromp-van Meerveld, H.J., Gobbi, A., Borga, M., and Dalla Fontana, G., 2011. The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Hydrol. Earth Syst. Sci. 15:689-702.

Petrovic, A.M., 1990. The fate of nitrogenous fertilizers applied to turfgrass. Journal of Environmental Quality 19:1-14.

Pitt, R., Shen-En, C., Clark, S.E., Swenson, J., and Choo Keong, O., 2008. Compaction's Impacts on Urban Storm-Water Infiltration. Journal of Irrigation & Drainage Engineering 134:652-658.

Raper, R.L., 2005. Agricultural traffic impacts on soil. Journal of Terramechanics 42:259-280.

Rawls, W.J., Brakensiek, D.L., and Savabi, M.R., 1989. Infiltration Parameters for Rangeland Soils. Journal of Range Management 42:139-142.

Rieke, P.E. and Ellis, B.G., 1974. Effects of nitrogen ferilization on nitrate movement under turfgrass, p. 120-130, Proc. 2nd Int. Turfgrass Res. Conf. ASA, Blacksburg, VA.

Saha, S.K., Trenholm, L.E., and Unruh, J.B., 2005. Effect of fertilizer source on water use of st. augustinegrass and ornamental plants. Hortscience 40:2164-2166.

SAS Institute, 2008. SAS/STAT 9.2, Cary, NC.

Scharenbroch, B.C., Lloyd, J.E., and Johnson-Maynard, J.L., 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49:283-296.

Schulze-Makuch, D., Carlson, D.A., Cherkauer, D.S., and Malik, P., 1999. Scale Dependency of Hydraulic Conductivity in Heterogeneous Media. Ground Water 37:904.

Schwartz, L. and Shuman, L., 2005. Predicting runoff and associated nitrogen lossses from turfgrass using the root zone water quality model (RZWQM). Journal of Environmental Quality 34:350-358.

SERA-17, 2008. National Phosphorus Research Project. North Carolina State University, Raleigh.

Sharpley, A. and Kleinman, P., 2003. Effect of rainfall simulator and plot scale on overland flow and phosphorus transport. Journal of Environmental Quality 32:2172-2179.

Sharpley, A.N., 1995. Dependence of runoff phosphorus on extractable soil-phosphorus. Journal of Environmental Quality 24:920-926.

Shober, A.L., Denny, G.C., and Broschat, T.K., 2010. Management of Fertilizers and Water for Ornamental Plants in Urban Landscapes: Current Practices and Impacts on Water Resources in Florida. HortTechnology 20:94-106.

Shuman, L.M., 2002. Phosphorus and nitrate nitrogen in runoff following fertilizer application to turfgrass. Journal of Environmental Quality 31:1710-1715.

Silva, D., Cox, D., and Beeson, R.C., 2011. Development and evaluation of a large rotary root seperator. Hortscience 46:676-678.

Simanton, J.R. and Renard, K.G., 1992. Overland flow: Hydraulics and erosion mechanics. John Wiley & Sons, New York, NY.

Singh, V.P. and Birsoy, Y.K., 1977. Some statistical relationships between rainfall and runoff. Journal of Hydrology 34:251-268.

Smith, D.R. and Pappas, E., 2010. Do plot studies generate "directionally" correct assessments of field-level phosphorus losses? J. Soil Water Conserv. 65:289-297.

Snyder, G.H., Augustin, B.J., and Davison, J.M., 1984. Moisture sensor-controlled irrigation for reducing N leaching in Bermuda-grass turf. Journal of Agronomy 76:964-969.

Starr, J.L. and DeRoo, H.C., 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Science 21:531-536.

Startsev, A.D. and McNabb, D.H., 2001. Skidder Traffic Effects on Water Retention, Pore-Size Distribution, and van Genuchten Parameters of Boreal Forest Soils. Soil Sci. Soc. Am. J. 65:224-231.

Stolte, J., Ritsema, C.J., and de Roo, A.P.J., 1997. Effects of crust and cracks on simulated catchment discharge and soil loss. Journal of Hydrology 195:279-290.

Strudley, M.W., Green, T.R., and Ascough, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil and Tillage Research 99:4-48.

Tarkalson, D.D. and Mikkelsen, R.L., 2004. Runoff Phosphorus Losses as Related to Phosphorus Source, Application Method, and Application Rate on a Piedmont Soil. J Environ Qual 33:1424-1430.

Towner, G.D., 1989. The Application of Classical Physics Transport-Theory to Water-Movement in Soil - Development and Deficiencies. Journal of Soil Science 40:251-260.

Trowbridge, P.J. and Bassuck, N.L., 2004. Trees in the Urban Landscape: Site Assessment, Design, and Installation. John Wiley and Sons.

U.S. Census Bureau, 2009. New Residential Construction. In: Bureau, U. S. C. (ed.), Washington D.C.

U.S. Census Bureau, 2011. Current Population Survey: 2010. U.S. Census Bureau, Washington D.C.

USDA, 2011. Fertilizer Consumption and Use. In: USDA (ed.). USDA.

USEPA. 1994. National water quality: 1994 report to Congress (appendices). United States Environmental Protection Agency, Washington, D.C.

USEPA, 2009. National Water Quality Inventory: Report to Congress. In: USEPA (ed.), Washington, DC.

Vadas, P.A., Kleinman, P.J.A., Sharpley, A.N., and Turner, B.L., 2005. Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. Journal of Environmental Quality 34:572-580.

Van Stiphout, T.P.J., Van Lanen, H.A.J., Boersma, O.H., and Bouma, J., 1987. The effect of bypass flow and internal catchment of rain on the water regime in a clay loam grassland soil. Journal of Hydrology 95:1-11.

Varlamoff, S., Florkowski, W.J., Jordan, J.L., Latimer, J., and Braman, K., 2001. Georgia homeowner survey of landscape management practices. HortTechnology 11:326-331.

Voorhees, W.B., 1992. Wheel-induced soil physical limitations to root growth Advances in Soil Science 19:73-95.

Wan, Y. and El-Swaify, S.A., 1999. Runoff and soil erosion as affected by plastic mulch in a Hawaiian pineapple field. Soil and Tillage Research 52:29-35.

Warrick, A.W., 1983. Interrelationships of irrigation uniformity terms. Journal of Irrigation and Drainage Engineering-Asce 109:317-332.

Watson, C.J. and Dowdell, R.J., 1986. The comparative effects of ammonium nitrate, urea, or a combination of nitrate/urea granualar fertilizer on the efficiency of nitrogen recovery by perennial ryegrass. Fertilizer Resource 11:69-78.

Wauchope, R.D. and Burgoa, B., 1995. Pesticide runoff studies: Towards a new protocol. Lewis Publishing, Boca Raton, FL.

Wuest, S.B., 2009. Comparison of Preferential Flow Paths to Bulk Soil in a Weakly Aggregated Silt Loam Soil. Vadose Zone J 8:623-627.

Zehe, E., Graeff, T., Morgner, M., Bauer, A., and Bronstert, A., 2010. Plot and field scale soil moisture dynamics and subsurface wetness control on runoff generation in a headwater in the Ore Mountains. Hydrol. Earth Syst. Sci. 14:873-889.

Zhang, R.D., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Science Society of America Journal 61:1024-1030.

Zheng, F., Huang, C., and Norton, L.D., 2000. Vertical Hydraulic Gradient and Run-On Water and Sediment Effects on Erosion Processes and Sediment Regimes. Soil Sci. Soc. Am. J. 64:4-11.

Zimmermann, A., 2008. Constructing Landscape: Materials, Techniques, Structural Components. Birkhäuser Architecture, Berlin, Germany.

BIOGRAPHICAL SKETCH

Brian Joseph Pearson was born in Morristown, New Jersey and relocated to Florida with his family in 1991. An interest in environmental science led Brian to the University of Florida where he received a Bachelor of Arts degree in 2003. Brian's continued interest in environmental science motivated him to continue his education. Brian received a Master of Science degree in Interdisciplinary Ecology from the University of Florida in 2004. Upon graduating, he worked as an environmental consultant. This experience motived Brian to return to the University of Florida in 2005 and work as both a biological scientist and as a faculty instructor while in pursuit of a doctoral degree. Brian was awarded a Doctor of Philosophy degree in 2011.