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Nutrient Dynamics in Stormwater Runoff from Green Roofs with Varying Substrate

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NUTRIENT DYNAMICS IN STORMWATER RUNOFF FROM GREEN ROOFS WITH VARYING SUBSTRATE

NUTRIENT DYNAMICS IN STORMWATER RUNOFF FROM GREEN ROOFS WITH VARYING SUBSTRATE

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in
Crop, Soil, and Environmental Science

By

John M. Fohner
University of Arkansas
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Environmental, Soil, and Water Science, 2009

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ABSTRACT

One major concern with urban development is the increasing amount of stormwater runoff from large expanses of impervious surfaces. These impervious surfaces reduce the ability of stormwater to infiltrate into the soil and eventually groundwater, which leads to greater amounts of surface runoff. Green technology serves as a viable solution to many of the environmental problems presented by modern development. Fifteen mock, extensive green roofs were built in the fall of 2008 at the Watershed Research and Education Center in Fayetteville, Arkansas. The goals of this project were to (1) measure the amount of stormwater runoff from varying treatments and control roofs, (2) measure the stormwater runoff quality from varying treatments, and (3) study the release of nutrients over time from the green roofs with added compost. Our results show that after an initial flush of nutrients from green roofs with added compost, many nutrient concentrations, such as total organic carbon (TOC), total nitrogen (TN), nitrate-N (NO_3-N), and other physiochemical properties have been reduced. However, even after two years, P concentrations in runoff water still exceed 1 mg/L from green roofs using compost in the growing matrix. Analysis of the remaining nutrients in the compost shows that TP loads from green roofs with added compost could be elevated for a number of years. The results from this study provide a benchmark for developing green roofs in Northwest Arkansas or other similar climactic regions.

This thesis is approved for recommendation
to the Graduate Council.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Over the past century, urban development has changed the natural landscape in a number of ways. One major concern is the increasing amount of stormwater runoff from large expanses of impervious surfaces present in urban areas. These impervious surfaces reduce the ability of rainfall to infiltrate into the soil and eventually recharge groundwater, leading to greater amounts of surface runoff. The United States Environmental Protection Agency (USEPA) has estimated that nearly five times more runoff is generated from an urban city block than a wooded area of the same size (USEPA 2003). Impervious surfaces also increase peak flow and reduce the time it takes stormwater to reach peak flow (i.e., time to concentration). These effects combine to cause a number of environmental problems, including: higher rates of stream degradation, loss of ecosystem functions, higher peak flow events, more frequent flooding, and the addition of pollutants such as oils, petroleum products, chemicals, nutrients, and sediment into streams (Berndtsson et al. 2006, 2009; Mallin 2009; USEPA 2003).

One way to counter act these effects is through low impact development that minimizes the hydrologic impact of urban areas. Green roof technology has been around for centuries but still serves as a viable solution to many of the environmental problems caused by modern development. A green roof consists of plants, a growing matrix, and a drainage system. Green roofs exist in two main types: intensive and extensive. Intensive green roofs have a growing matrix deeper than 15 cm. The added weight of this matrix must be accounted for in the design of the green roof. Extensive green roofs have a growing matrix with depths between 5 to 15 cm. Extensive green roofs support smaller plants with shallow fibrous root systems such as grasses and small succulents. These extensive green roofs can be retrofitted to previously constructed buildings, because the shallow soil depth and smaller plants are relatively lightweight (Carter and Butler 2008). Green roofs are growing in popularity in the United States but have been prevalent in many European countries for several decades now. In fact, it is estimated that 14% of all flat roofs in Germany are green roofs (Kohler and Keeley 2005).

The most important benefit generated from green roofs is increased water retention (VanWoert et al. 2005, Hathaway et al. 2008, Bliss et al. 2009). Green roofs can also possibly improve stormwater runoff quality (Berndtsson et al. 2006, 2009; Hathaway et al. 2008) and delay the initial time of runoff by distributing the stormwater over a longer period of time by releasing the water at a slower rate (Mentens et al. 2006; Hathaway et al. 2008). Research has also shown that green roofs not only reduce stormwater runoff, but offer a number of other benefits. These benefits include increasing and protecting biodiversity in urban areas (Oberndorfer et al. 2007; Cuffney et al. 2009). Research has also shown that green roofs can improve the energy efficiency of buildings (Hilten 2005), increase the lifespan of the roof membrane (Dunnett and Kingsbury 2004), sequester carbon (Getter et al. 2009), and help to mitigate the urban heat island effect (Alexandri and Jones 2008). However, green roof efficiency to provide these benefits varies, based upon green roof design and climate conditions. This project will specifically focus on green roofs for climactic conditions representative of the Ozark Highlands in Northwest Arkansas.

PROBLEM STATEMENT

Over the past 10 years a number of studies have been done on the water retention capabilities of green roofs and nutrient runoff from green roofs. However, only a couple of studies have been conducted in the Ozark Highlands (Toland et al. 2012). The establishment and function of green roofs is dependent on the climate conditions in the region. Therefore, it is important to understand that water retention and nutrient runoff vary from climate to climate or region to region. While some studies have observed the effects of adding compost to the media versus the green roofs with no compost added, very few studies include media size as a factor (fine vs. coarse). Furthermore, most green roofs studies have focused on a one-year period. This study includes first year data from Toland 2010, as well as new second year data measuring the changes in water retention and nutrient runoff annually.

STUDY SITE DESCRIPTION

Fifteen mock green roofs were built in the fall of 2008 at the Watershed Research and Education Center located on the UA Division of Agriculture-Arkansas Agricultural Research and Extension Center in Fayetteville, Arkansas. The green roofs were built at a 2% slope, to mimic standard commercial roof construction. This study site contained five treatments with 3 replicates: coarse media with compost, coarse media without compost, fine media with compost, fine media without compost, and a control. Commercially available mushroom compost was added to the specified treatments at 15% by volume.

A water proofing membrane was the bottom layer of all fifteen roofs such that stormwater was collected using a gutter and funnel and stored on site. The 12 mock green roofs were each fitted with a drainage layer between the traditional roofing surface and the growing media to minimize the amount of soil transported into the collecting barrels. Plants were established on each of the mock green roofs at the start of the study. Plant growth was monitored throughout the study without the addition of any fertilizers after establishment.

OBJECTIVES

The goals of this project were to (1) evaluate nutrient leaching from growing media with and without added compost on green roofs, and (2) evaluate water retention as a function of growing media, total precipitation and precipitation intensity. This study should provide valuable data on the benefits of green roofs in the Northwest Arkansas area or in similar climactic regions.

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CHAPTER 2: LITERATURE REVIEW

Impervious surfaces can represent up to 60% of the landscape in urban areas. Furthermore, urban land area is projected to reach 8.1% of total land area in the United States by 2050 (Nowak and Walton 2005). Impervious surfaces do not allow rainwater to infiltrate the soil surface to recharge groundwater or cycled through plant transpiration. As a result, a large amount of stormwater runs off directly into urban streams. Degradation of these streams occurs because impervious surfaces increase peak discharge and reduce the time to concentration over the runoff hydrograph. There are a number of different best management practices (BMPs) to help mitigate this high urban runoff, including: rain gardens, wet and dry retention ponds, bioswales, sand filters, and constructed wetlands. However, many of these mitigation strategies can be expensive and may require a large surface area making wide spread use of these BMPs unfeasible for densely populated urban areas.

STORMWATER RUNOFF

One possible solution to the increased runoff in densely populated areas is green roofs. Green roofs can utilize otherwise limited-use space on rooftops to help mitigate these hydrologic effects of urban development. Studies have shown that green roofs can reduce runoff by up to 100% for individual rainfall events depending on the characteristics of the rainfall event (antecedent moisture conditions, intensity, duration, etc.), slope of the roof, and the type of green roof (DeNardo et al. 2005). VanWoert et al. (2005) reported that stormwater runoff was reduced by 96% when cumulative rainfall was less than 25 mm. Carter and Rasmussen took this even further by reporting that when total rainfall is < 25 mm, there is a 90 % reduction in stormwater, rainfall between 25mm and 76mm results in a 54% reduction, and rainfall greater than 76mm results in > 48% reduction (Carter and Rasmussen 2006). Hathaway et al. (2008) reported an average retention of 64% of all rainfall on green roofs, as well as a 75% reduction in peak discharge from roof tops.

Green roofs not only reduce the volume of stormwater runoff (Bliss et al. 2009; Berndtsson et al. 2006, 2009; Hathaway et al. 2008), but also delay the initial time to runoff and slow the time it takes stormwater to reach waterways. The reduced runoff volume and time to runoff ultimately decrease peak discharge reaching urban streams. Reduced peak discharge can decrease stream bank degradation such as erosion and down cutting by reducing the number of channel forming events that occur in urban streams. This is important because large amounts of money are spent on stream restoration projects in urban areas. In 2005, it was estimated that an average of $66.7 million a year has been spent on stream restoration projects in the United States since 1990 (Bernhardt et al. 2005).

There are a number of factors that can affect green roof performance such as plant species, media composition, media depth, roof slope, and climate (Dunnett and Kingsbury 2004; VanWoert et al. 2005). Plant species is an important factor in green roof performance, because plants selected specifically for the climate of the area will be easier to establish because they are adapted to the local climate. Substrate composition and depth is also an important factor that can play a role in how much storm water is retained by the green roof, as well as the survival of the plants on the green roof. Green roofs can be built on as slope as great as 45^o, however as the slope of a green roof increases, the capacity of the roof to store stormwater decreases. All of these factors need to be considered when designing green roofs. Climate may be the single most important factor that influences green roof performance. Temperature extremes and precipitation affects plant growth. Rainfall intensity is also a factor that can be highly influential, with water retention decreasing with increasing intensity. This is due to the storage capacity of the green roofs being reached more quickly with more intense precipitation events.

WATER QUALITY

While green roofs have shown great promise in reducing the volume of stormwater runoff, there are still several questions surrounding stormwater runoff water quality. Green roofs can present a potential source of nutrients to runoff and in order for green roofs to become a viable stormwater mitigation option, the potential nutrient concentrations and loading from green roofs needs to be quantified. This can be difficult however as there are a number of factors that could potentially influence nutrient loading from roofs. Climate, roof slope, substrate composition, rainfall characteristics, and antecedent moisture conditions could all potentially affect nutrient loading from green roofs. The variability in green roof design is in part due to the lack of quantifiable research on those various green roof designs, resulting in very few industry standards for green roofs construction.

There have been several studies focused on this issue of the quality of stormwater runoff from green roofs (Camm 2011, Berndtsson et al. 2006, 2009; Getter and Rowe 2006; Dunnett and Kingsbury 2004; Hathaway et al. 2008, Bliss et al 2009). Runoff water from green roofs has been shown to have elevated levels of a number of different nutrients, including: phosphorus (P), dissolved organic carbon (DOC), potassium (K), calcium (Ca), zinc (Zn), and in some cases nitrogen (N) (Camm 2011, Bliss et al. 2009, Berndtsson et al. 2006, 2009; Hathaway 2008). This is due in part to the addition of organic matter to the substrate to promote plant growth. Elevated nutrients in stormwater runoff could lead to a number of problems, such as eutrophication in urban streams, ponds, and lakes. Berndtsson et al. (2006, 2009) suggested that green roofs could be a potential sink for nitrate-N (NO_3-N) and ammonium-N (NH_4-N). Researchers at North Carolina State University documented increases in total N (TN) in green roof runoff to be 1.3 mg/L greater than that of the control roofs (no substrate), as well as a 0.8 mg/L increase in total P (TP) concentrations (Hathaway et al. 2008). However, TN loads decreased in the runoff from the control roof due to the reduction in the volume of runoff. Gregoire and Clausen (2011) showed that TN concentrations in runoff from modular green roofs decreased from 0.896 mg/L in the control roofs to 0.490 mg/L in the green roofs. Similarly, TP concentrations were also shown to decrease from 0.197 mg/L in the control roofs to 0.043 mg/L in the modular green roofs. One further study focusing on runoff concentrations, reported runoff P concentrations from green roofs to be 2 – 3 mg/L without measurable TN from the green roofs or control roofs (Bliss et al. 2009). Clearly, there are varying results when it comes to measuring green roof water quality and variations in green roof design makes it difficult to discern the effect green roofs have on runoff water quality.

There are, however, trends that have been observed in recent green roof studies. One such trend that has been observed in a number of studies is the “first flush” effect (Toland 2010, Berndtsson et al. 2006, Van Seters et al. 2009). Initial samples taken in these green roof studies show very high concentrations of many nutrients, including P, N, and C. Some studies have even reported initial nutrient concentrations in runoff of 104 mg/L TN, 4 mg/L TP, and 119 mg/L of TOC (Toland 2010). However, these concentrations quickly recede to levels more typical of stormwater runoff, hence the first flush of nutrients. This first flush of nutrients is concerning because N and P are limiting nutrients in many aquatic systems. Toland et al. (2012) showed that nutrient levels could remain elevated for several months after green roofs were built.

There are various ways to remove P from runoff and several recent studies have aimed at utilizing these technologies to help mitigate elevated nutrients in green roof runoff. Many of these technologies use the processes of phosphorus adsorption, ion exchange, and precipitation reactions (Zhang et al. 2008). A 2011 study in Canada showed that by utilizing these natural processes, engineered media consisting of mineral aggregates, blond peat, perlite, sand and vegetable based compost could reduce P concentrations in green roof runoff from 1.30 mg/L to 0.97 mg/L in 2009 and 1.18 mg/L to 0.16 mg/L in 2010 (Camm 2011).

Conventional rooftops themselves can represent a potential threat to runoff water quality. Typical roof construction commonly calls for some petroleum based product to be used in commercial roof construction. These roofs degrade over time contributing heavy metals and petrochemicals to runoff and ultimately urban streams. Green roofs can prevent the premature weathering of roofing membranes and extend the life span of the roof (Dunnett and Kingsbury 2004). This would reduce the need to replace the roof every 20 years or so, as well as reducing a potential pollutant source when the roof material degrades from ultraviolet light exposure and time.

Atmospheric deposition can also represent an important source of pollutants to rooftops. A study by Wu et al. (1998) in the Piedmont region of North Carolina reported that atmospheric deposition could account for as much as 10% to 30% of TP and NO_3-N, and 30% to 50% of orthophosphates (PO_4-P). Atmospheric deposition and rainfall nutrient concentrations vary constantly across the US, and the effect of this source on stormwater runoff is locally dependent. Concentrations not only vary spatially, but also yearly. The National Atmospheric Deposition Program (NADP) reports that atmospheric deposition of inorganic N in Northwest Arkansas and the Piedmont region of North Carolina are similar, with deposition of P being insignificant. At the NADP site approximately 0.5 km from our study site in Fayetteville, Arkansas, N deposition measured approximately 5 kg/ha/yr with an average concentration of 1.0 mg/L while P measured less than 0.1 kg/ha/yr or less than 0.01 mg/L. This nutrient source should be considered when evaluating nutrient loss from green roofs during rainfall events.

The potential loading of N and P are the greatest concern with green roofs, because they have historically been the most common nutrients associated with causing impairment in streams (Bannerman et al. 1993; Line et al. 2002). Nitrogen and P leach from the growing media of green roofs most commonly in the forms of NO_3 and PO_4. Runoff from green roofs can contain concentrations of NO_3 and PO_4 that is much greater than that contributed from rainfall. In an effort to prevent this nutrient loss, many green roof designs contain a nutrient retention barrier (Hathaway et al. 2008, Berndtsson et al. 2009, VanWoert et al. 2005, Carter and Butler 2008). This research has shown that these retention barriers generally cannot reduce nutrient concentrations to that of rainfall or green roofs that do not contain added compost.

When evaluating nutrient concentrations and loads from green roof runoff, these values need to be put into context with runoff from the landscape (both urban and agriculture). Massey et al. (2010a,b,c) showed that in Northwest Arkansas TN loads in stormwater runoff from urban areas range from 16 – 19 kg/ha/yr and loads of TP range from 1.0 – 1.6 kg/ha/yr. Furthermore, loads from unfertilized pasture ranged from 9 – 18 kg/ha/yr and 1.2 – 2.2 kg/ha/yr for TN and TP, respectively, and 1.1 – 1.5 kg/ha/yr and 0.07 – 0.12 kg/ha/yr for forest for TN and TP, respectively. This data is specific to Northwest Arkansas, and the unit area loads could be directly compared to that from green roofs.

ECOLOGICAL BENEFITS

Replacing traditional roofs with green roofs can also provide a number of ecological benefits to urban areas. Drought tolerant plant species that are specifically adapted to the regional microclimate work best to provide habitat and improve the water retention capabilities of the roof during the growing season. Plant species is also an important factor in providing habitat and can also increase the retention of nutrients in the growing media (Ewel et al. 1991). Green roofs also provide habitat for many insects, spiders, beetles, and even birds and some researchers are looking into using green roofs to help re-establish native plant species to an area (Dewey et al. 2005).

The ecological benefits of green roofs can also spread downstream to the urban channels receiving the stormwater runoff. Cuffney et al. (2010) showed that benthic macroinvertebrate assemblages were directly related to urban intensity, because land use influences the biological, chemical, and physical properties of streams. This study also showed that streams were degraded relative to undeveloped conditions even at very low levels of urbanization. Land use changes affect watershed hydrology, but green roofs could be used to help restore some of the predevelopment conditions in urban areas in an attempt to protect streams and aquatic communities.

The urban heat island effect is a phenomenon that has been documented for decades, where increases in day and night ambient air temperatures in urban areas are observed relative to surrounding rural areas due to large expanses of impervious surfaces in urban areas reflecting the sun’s radiation (Arnfield 2003; Akbari 2005). Plants on green roofs can help mitigate the urban heat island effect through the cooling effects of plant transpiration. Excess heat has been reported to cause psychological disorders, organ damage, and death in humans (USEPA 2003). The implementation of green roofs on a large-scale basis could help reduce the effects of the urban heat island.

Green roofs also have the ability to assist in the mitigation of carbon footprints, because increasing the energy efficiency of a building reduces the amount of energy consumed. Energy Plus is a building simulation model supported by the United States Department of Energy, which was used to predict the reductions in energy consumption when green roofs are in place. The model was used to predict the typical energy savings of a building with 2000 m^2 of green roof in Houston, TX and Chicago, IL. The model estimated total energy reductions of approximately 2%, and a 9-11% reduction in natural gas consumption (Sailor 2008). The energy reductions were much greater in the winter than the summer, ranging from savings of 2800 MJ to 200 MJ and 800 and 250 MJ per month for Chicago and Houston, respectively (Sailor 2008). In a study conducted by Getter et al. (2009), extensive green roofs were shown to sequester 375 g C/m^2 in above and below ground biomass over a 2-year period. As previously stated, the urban heat island effect can increase the ambient air temperatures in an urban area and therefore increase the amount of energy that is consumed in an effort to cool these temperatures during warmer months. Akbari (2005) estimated that by reducing the urban heat island effect, green roofs implemented on a wide scale basis could reduce energy consumption in urban areas by 25%. This wide scale implementation of green roofs could play a major factor in reducing energy needs.

ECONOMIC INCENTIVES

Increased energy efficiency in buildings from the use of green roofs can translate to economic savings. Green roofs act as insulation for a building, intercepting the hot summer sun before it reaches the building and trapping heat inside the building during winter months.

Typically a majority of the energy savings with green roofs will come during the summer months by reducing heat transfer into buildings. This is because of the thermal properties of the air filled pores within the growing media. Typically during the summer months rainfall is less and soil pores are less saturated, versus saturated soil pores in winter months when rainfall is generally greater. This could also be due to the cooling effect of plant transpiration on green roofs. Wong et al. (2005) showed air temperatures to be up to 14 °C lower on roofs with vegetation, reducing energy consumption and saving up to 15% on costs per year. For example, Laberge (2003) estimated that energy savings for the Chicago city hall could be $4,000 annually and $100 million annually for the city of Chicago if all roofs were converted to green roofs.

Federal, state, and local governments are beginning to promote the construction of green roofs through policy and incentive programs under the stormwater management provisions set forth by the Clean Water Act. Approval for NPDES (National Pollutant Discharge Elimination System) permits is contingent on the implementation of BMPs for stormwater management, which includes green roofs. Tax credits and other economic incentives are also being offered to cities that are integrating green roofs into the design of government buildings. Universities such as the University of Arkansas and federal departments such as the United States Department of Defense are requiring all newly constructed buildings to meet Leadership in Energy and Environmental Design (LEED) Silver Certification. Green roofs can account for up to 15 LEED points (Carter and Fowler 2008). It is apparent that green roofs will become more prevalent in urban environments, and research needs to understand and quantify the effects of BMPs on hydrology and pollutant transport.

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CHAPTER 3: NUTRIENT DYNAMICS IN STORMWATER RUNOFF FROM GREEN ROOFS WITH VARYING SUBSTRATE

INTRODUCTION

Green roof technology has been around for centuries, but can still be used to solve the ecological challenges we face today. There are a number of ecological benefits associated with green roofs, including: stormwater runoff reduction, potentially improved runoff water quality, enhanced biodiversity in urban areas, reduced erosion and stream degradation in urban streams, and many more. The ecological benefit with the greatest impact from green roofs is the reduction of the volume of stormwater runoff, however studies have shown increases and decreases in chemical concentrations and loads from green roofs during rainfall (Hathaway et al. 2008, Berndtsson et al. 2006 & 2009, Bliss et al. 2009).

There are two types of green roofs, extensive and intensive. Extensive green roofs have a shallower media depth, support smaller plant species, and can be retrofitted to existing structures. Intensive green roofs have a greater media depth, support larger plants, and typically need to be considered in the design of the building or structure. Extensive green roofs have been the greater focus of research because of the ease of retrofit and the relatively low maintenance required to maintain the roofs. Green roofs can be effective at reducing stormwater runoff from slopes ranging from 2 – 45%, with the greatest runoff reduction resulting from green roofs built at the commercial standard of 2% (VanWoert et al. 2005). Studies have shown that green roofs can reduce stormwater runoff up to 100% depending on the intensity and length of the rainfall event, depth of media, slope of the roof, along with several other factors (Berndtsson 2010).

There have been a number of recent studies on the effects of nutrient runoff from green roofs. Some studies report green roofs to be a source of a number of nutrients to stormwater, most importantly nitrogen (N) and phosphorus (P), while others report green roofs to be a sink for N (Berndtsson 2010, Toland 2010, Berndtsson et al. 2009, Hathaway et al. 2008). This in part is due to the numerous variations in green roof media composition, design, data collection techniques, and climactic factors. Study length could also have an effect on the nutrient runoff from green roofs as several studies have shown evidence of a “first flush” in green roofs where initial runoff concentrations are very high but quickly return to near base levels after only a few weeks or months (Toland et al. 2012, Van Seters, 2009, Berndtsson et al. 2006).

The goals of this project were to compare stormwater reduction and nutrient transport in stormwater runoff between four green roof treatments and the control over a 2.5-year period. There have been a number of studies conducted on green roofs in the last 10 years; however, a green roof’s function is highly dependent on regional climate and rainfall characteristics. This study should provide data for the Ozarks Highlands in Arkansas, Oklahoma, and Missouri and other similar climates. This project focused on nutrient dynamics over a 2-year period in order to quantify the chemical quality of stormwater runoff from green roofs and observe changes in nutrient loading and concentrations annually.

METHODS

Fifteen 1.22 m x 1.22 m mock extensive green roofs were constructed at the UA Division of Agriculture Watershed Research and Education Center in Fayetteville, Arkansas in the fall of 2008. The roofs were built with a 2% slope and a 2.54 cm gap down slope to allow water to drain to a gutter placed on the roofs, and down to a 75.7 L collection barrel. The arrangement for the green roofs was a randomized block design with 3 replicates. Twelve of the green roofs were fitted with a with a green roof drainage layer provided by JDR Enterprises, Inc. (Alpharetta, GA) directly above the waterproofing membrane. This drainage layer consists of a root barrier, plastic corrugated drainage material, and filter fabric. Covering the drainage layer was a lightweight aggregate growing matrix provided by Chandler Materials (Tulsa, OK). Six of the roofs had 7.62 cm deep media, three fine textured (75% of particles < 2.4 mm) and three coarse textured (75% of particles > 4.8 mm). Six roofs had a 7.62 cm growing matrix composed of 85% (by volume) media, three fine textured and three coarse textured, along with 15% (by volume) mushroom compost (Toland 2010). Material analysis of the media and compost was performed at the Agricultural Diagnostic Laboratory on the University of Arkansas campus in Fayetteville, Arkansas (Toland 2010). Plants were donated by Emory Knoll Farm (Street, MD) and were selected for drought tolerance, because these roofs were not irrigated.

Stormwater runoff measurements were taken after every rainfall event. In the first year of the study, the volume of runoff was estimated by weighing the collection barrels. Due to the ease of measuring, during the second year of the study, volume was calculated by measuring the height of the water in the barrels and using the known barrel dimensions to determine a runoff volume. When runoff exceeded 1 L, water samples were collected for water quality analysis. This was done by mixing the runoff for 15 seconds and field washing the collection bottles 3 times before collecting the sample. These samples were brought back to the lab, refrigerated in the dark at 4^{o} C, and then composited each week based on event runoff volumes for water quality analysis.

Turbidity, pH, and electrical conductivity of the composite water samples were measured at the laboratory. Turbidity was measured using a VWR Model 800 Turbidity Meter, VWR International (Radnor, PA). The pH of the samples was measured using an Oakton waterproof double junction pH Meter, Oakton Instruments (Vernon Hills, IL). Electrical conductivity was measured using a Thermo Orion Model 105 conductance meter, Thermo Fisher Scientific Incorporated (Waltham, MA). Concentrations of total nitrogen (TN), total phosphorus (TP), and organic carbon (TOC), as well as soluble reactive (SRP), ammonium (NH_4-N), nitrate (NO_3-N) plus nitrite NO_2-N, and chloride (Cl^-) were analyzed at the Arkansas Water Resources Center Water Quality Lab. This lab is certified for the above constituents by the Arkansas Department of Environmental Quality, and methods, equipment and detection limits are available at http://uark.edu/depts/awrc/waterqualitylab.htm.

The runoff water volume (Q) collected and the nutrient concentrations (C) were used to determine load (L) for select periods of time by the equation:

$$L = \sum_{i=1}^{n} Q_i * C_i$$

where (i) represents the weekly composite and (n) represents integer sample size. The flow-weighted concentration (FWC) or event mean concentration for select time periods was calculated using the equation:

$$FWC = \frac{L}{\Sigma Q_i}$$

where (L) represented constituent load. Nutrient concentrations, loads, and trends were compared over the 2.5-year study period (September 2008 – March 2011), and stormwater runoff was compared between water years 2009 and 2010. JMP 9.0, Statistix 9, and Microsoft Excel were used for statistical analysis conducted for each runoff parameter measured using the logarithmic transformed data. All data was analyzed using a one-way analysis of variance

(ANOVA) and means were separated using significant difference (LSD) based on an alpha (α) of 0.05.

RESULTS AND DISCUSSION

Stormwater Runoff

One of the primary objectives of this study was to evaluate water retention as a function of green roof treatment and total precipitation. Total rainfall near the study site was 1134 mm in 2009 and 1186 mm in 2010, similar to that which is typically observed for Northwest Arkansas (2005 – 2011 water year range: 886.3 – 1324.1 mm, NADP, 2011). The control roofs stored 22 and 33 mm of rainfall for 2009 and 2010, respectively, resulting in 98% of the total precipitation leaving as stormwater (Table 1). The control roofs had a small amount of storage, likely due to the uneven surfaces of the membrane materials on the roofs resulting in surface detention and possible evaporation from the roof surface depending on air temperature and time between rainfall events. Water quantity measurements were made soon after rainfall occurred, to limit possible evaporation from the collecting barrels.

On an annual basis, green roofs retained significantly more stormwater than the control roofs (Table 1). Among the green roof treatments, the fine with compost (FN) treatment retained the most rainfall with an average of 55% retention in 2009 and 52% in 2010. The fine with no compost (FC) treatment was the second most effective treatment with 50% retention in 2009 and 47% in 2010. This was followed by coarse with compost (CC) with 37% in 2009 and 37% in 2010 and coarse without compost (CN) with 34% retention in 2009 and 31% in 2010. There was no statistical difference in stormwater reduction from 2009 to 2010 between the individual treatments showing that as time passes, the hydrologic function of the green roofs is maintained.

These annual runoff and retention characteristics are similar to those found in other green roof studies of similar design. Berndtsson (2010) compared a number of retention and runoff studies and found the range of average stormwater retention to be 45 – 78% between six studies. Furthermore, retention for individual rainfall events from the six studies ranged from 5 – 100% based on the rainfall and roof characteristics. Monterusso et al. (2004) also reported rainfall retention to range from 39 – 58% of total rainfall during the study period. Annual rainfall retention from the green roofs in this study ranged from 30 – 46%.

Interestingly, the addition of compost had no effect on the total volume of runoff retained during the first year (2009). There was, however, increased stormwater retention in the fine media treatments (FN and FC) as compared to the coarse media treatments (CC and CN) during 2009. This can be expected as smaller particle size increases surface area and micropore space to retain water molecules more tightly and increase storage. The addition of compost may have the ability to decrease the rate at which stormwater runs off, but it does not likely affect total runoff in subsequent years based on the lack of differences observed in 2010 between FN and FC. Compost likely plays an important role in stormwater runoff mitigation because the rate of runoff is one of the most important factors when determining the impact of a given rainfall event on a watershed or area of study, and other studies have suggested similar benefits from a hydrologic perspective (Hilten et al. 2008, VanWoert et al. 2005).

Total rainfall was greater in 2010 than 2009 leading to an increase in runoff in 2010 as expected. After initial rainfall storage, runoff seems to increase linearly as total rainfall increased. This linear increase was documented in each green roof treatment (Figure 2). This is to be expected as once the roof media reaches storage capacity, runoff would be proportional to rainfall. Average storage for the green roof treatments during the 2-year study ranged from 3 mm across the coarse media to 5 mm across the fine media, based on the x-intercept of the linear regressions (Figure 1). The maximum storage estimated from the data varied 5 – 11 mm for green roofs with coarse media and 9 – 12 mm for fine media. It is well documented that green roofs can retain near 100% of rainfall during smaller rainfall events. For example, DeNardo et al. (2005) reported that when rainfall was less than 25 mm, there was a 96% reduction in stormwater runoff. In a similar study, VanWoert et al. (2005) reported a 99% reduction when rainfall was <2 mm and an 83% reduction when rainfall was between 2 – 6 mm. This is congruent with the data presented in this study with 100% retention when rainfall was <3 mm for the coarse media and <5 mm for the fine media.

It is evident that total rainfall and rainfall intensity play an important role in the percent of stormwater retained in green roofs. Plant cover and evapotranspiration could also play a small role in the percent of stormwater retained. This would result in greater retention in the summer months when plant growth is increased and higher temperatures increase evapotranspiration. However, VanWoert et al. (2005) reported that plant growth did not play a significant role in stormwater retention and that the characteristics of the media, such as particle size and percent compost, play the more important role in stormwater retention. Based on this study, it was evident that the green roof media plays the largest role in determining retention characteristics and runoff volumes. These green roofs provide an excellent urban BMP to capture all the rainfall during small events, resulting in no runoff.

Water Quality

Carbon

Mean TOC concentrations measured over the study period were variable across treatments at the beginning of this study, where the greatest TOC concentrations (up to 100 mg/L) were observed in the runoff from green roofs with compost in the growing media (CC and FC). The least TOC concentrations were observed in runoff from the control roofs the first month, but mean TOC from the control roof runoff approached that of the green roofs without added compost (CN and FN) within the first year. By the second year of the study (2010), mean TOC concentrations were still variable across treatments but relatively similar (same order of magnitude) across treatments (Figure 2). However, differences in TOC transport in runoff from the roofs were apparent in the second year when hydrology was considered.

The loads of TOC showed contrasting trends between years across the treatments. During 2009, the TOC loads were greatest from the green roofs that included compost in the growing media (CC and FC). The loads exceeded 28 kg/ha/yr when compost was added to the growing media. The TOC loads were almost three times less from the control roofs (9.9 kg/ha/yr) during 2009 (Table 2). The least TOC loads were observed from the green roofs without compost added to the growing media. These results showed that green roofs can reduce TOC loads relative to these control roofs during the first year, except when compost is included in the growing media at the rate used in this study.

The trends in annual TOC loads across green roof treatments changed during the second year (2010) relative to the control roof. The green roofs with compost in the growing media (CC and FC) had greater TOC loads compared to the green roof without added compost (CN and FN), showing the continued loss of TOC from the compost in runoff. However, the greatest TOC loads (24.0 kg/ha/yr) were observed from the control roofs during the second year, despite having mean TOC concentrations within the same order of magnitude of the other treatments.

These results suggest that over the long-term, the conventional roofs could be a greater potential source of TOC relative to green roofs. This could be due to two reasons: degradation of the roofing membranes over time, and green roofs serving as a sink for C that is being deposited on the roofs through atmospheric deposition. The conventional roofs are exposed to sunlight and the UV rays degrade the roofing material over time (Line et al. 2002). Green roofs can increase the life span of roofs by serving as a protective barrier between the rooftop and UV rays (Dunnett and Kingsbury 2004). Green roofs also might have the ability to store TOC relative to the control roofs from atmospheric deposition.

Phosphorus

Mean TP concentrations in runoff water varied across the green roof treatments and control roofs during the study period (Figure 3). The differences were distinct in the first runoff events, where mean TP concentrations varied from 1.45 – 4.75 mg/L in the runoff from green roofs with compost (FC and CC, respectively), 0.05 – 0.30 mg/L in runoff from green roof without compost added (FN and CN, respectively), and 0.03 mg/L in the runoff from the control roofs. The differences in runoff TP concentrations remained distinct until March 2009, when TP was relatively similar between the two compost treatments (FC and CC) and even between the green roofs without compost (FN and CN). After March 2009, mean TP concentrations were greatest in runoff from green roofs with added compost added (1.58 – 1.93 mg/L), and generally less than 0.30 mg/L for the other treatments (FN, CN, and control). Toland et al. (2012) observed mean TP concentrations (1.57 – 1.82 mg/L) in runoff from green roofs with added compost was also elevated ~2 years after establishment. The runoff concentrations observed in our study were within the range of other studies, where green roofs contained compost (0.6 – 1.4 mg/L, Hathaway et al. 2008; 0.8 – 2.1, Bliss et al. 2009; 0.46 – 4.39, Monterusso et al. 2004). The majority of the TP concentrations in runoff water was in the dissolved form, representing up to

90% of TP across the roof treatments; and consistent with other studies (Toland et al. 2012, Berndtsson et al. 2009).

The loads of TP showed similar trends to that of concentrations in the runoff from green roofs with added compost as compared to the no compost and controls (Table 2). In 2009, TP loads were greatest from the green roofs with added compost (CC), with 21.5 kg/ha/yr, which was 23 times greater than loads from the membrane control (0.9 kg/ha/yr). The FC treatment followed with an annual load of 14.4 kg/ha/yr, 16 times greater than the control. On an annual basis, there was no significant difference between the control and the no compost treatments (FN and CN) with loads ranging from 0.9 – 2.1 kg/ha/yr. Toland (2010) documented seasonal loads, showing that TP loads were more than 10 times times greater from the green roofs with added compost compared to controls during the first three months after establishment. The loads from green roofs might be seasonal due to changes in rainfall runoff, but is apparent that leaching from compost would be greatest when the green roofs are established.

During the second year (2010) of our study, annual TP loads continued to be significantly greater from the green roofs with added compost (FC and CC) compared to other treatments (FN, CN, and control) (Table 2). However, annual TP loads from the CC treatment decreased from 21.5 kg/ha/yr in 2009 to 15.1 kg/ha/yr in 2010, showing no significant difference from that of the FC treatment measuring 14.6 kg/ha/yr. The green roofs with compost added to the growing media still produced TP in excess of 14 times greater than the range of the green roofs without the added compost and membrane control roofs (0.8 – 1.0 kg/ha/yr). Annual TP loads were not significantly different across the treatments FN, CN, and control during 2010, which was similar to 2009 results.

While few studies have looked at green roofs on a multiple year basis, a number have reported increased P concentrations and loads similar to those shown in our study (Hathaway et al. 2008, Bliss et al. 2009, Berndtsson et al. 2006 & 2009, Toland 2010). Hathaway et al. (2008) focused on a 15-month study period, while Toland (2010) and Berndtsson et al. (2006 & 2009) focused on a 12-month period, and Bliss et al. (2009) chose 15 storm events over several months. This focus on P loss from green roofs over multiple years is important because as shown above, green roofs with added compost at 15% by volume represent a potential P source for not only one year, but also potentially several years into the future. The relationship between P concentration and time was used to estimate the return to background levels at ~0.2 mg/L ($P=1.8617e^{0.0005t}$, $R^2=0.231$, $P=0.0001$) for the green roofs with added compost. It was estimated that P concentrations would not reach background concentrations until October 2020, which is more than a decade after establishment. Although green roofs provide a reduction in stormwater runoff, it is clear that the addition of compost needs to be further studied to maximize plant growth and establishment while minimizing the potential for P loss.

The altering of the landscape by urban development is causing a shift from pervious to impervious surfaces, with previous land use varying from forest to pastures among other classifications. It is important to put the concentrations and loads from green roofs with compost (in particular) into the context of these other land uses, especially pastures. For example, several studies have shown that pastures represent a P source to runoff because of P stored in the soil (Sharpley et al. 2008), land-applied animal manure and fertilizers (Lentz and Westermann 2010, Slaton et al. 2004, Withers et al. 2001, Sauer et al. 1999), and even deposition from grazing cattle. The P concentrations from green roofs with 15% compost were similar to that in runoff from a pasture with poultry litter application (1.20 mg/L; Sauer et al. 1999) or liquid cattle manure and inorganic P fertilizer (3.8 and 6.5 mg/L; Withers et al. 2001). Phosphorus loads from the green roofs with 15% compost were shown to be greater than those typically observed from pasture and agricultural soils. For example, Sharpley et al. (2008) reported average P loads of 0.64 kg/ha/yr (range: 0.12 – 1.57) from an agricultural watershed containing managed crop land, forest, and pasture. Furthermore, P losses of 3.1 kg/ha from agricultural soils in Northwest Arkansas were reported by Slaton et al. (2004), which was similar to P losses from a furrow irrigated field in Indiana (3.4 kg/ha; Lentz and Westerman, 2010); even these P losses are less than that typically observed from the green roofs with 15% compost. Green roofs provide many benefits, but we need to keep in perspective the effects of compost addition to P losses during rainfall events.

Nitrogen

Nitrogen concentrations in runoff from green roofs varied over the study period. Similar to TOC, TN showed a “first flush” of nutrients from the added compost treatments (FC and CC). During the initial rainfall events, runoff concentrations from the compost added treatments (FC and CC) measured nearly 105 mg/L for TN with NO_3-N representing up to 95% of TN. After the “first flush” nitrogen concentrations then decreased and began to approach the concentrations observed in runoff from FN, CN, and control roofs (Figure 4).

After the first 6 months concentrations of TN and NO_3-N continued to vary, ranging from 0.05 – 10 mg/L for TN and 0.01 – 8 mg/L for NO_3-N. These concentrations are similar to those found in other studies. Hathaway et al. (2008) reported TN concentrations in runoff from green roofs with 15% compost to range from 0.7 – 6.8 mg/L, while Berndtsson et al. (2009) reported TN concentrations in green roof runoff in the range of 2.3 mg/L and NO_3-N concentrations of 1.03 mg/L, which was similar to our study. Looking at other land uses, Sauer et al (1999) measured TN in runoff from pasture plots in Northwest Arkansas and found that TN concentrations in runoff from poultry litter amended pasture were 64.9 mg/L, which was similar to the initial rainfall events in our study. However, in the same study, NO_3-N concentrations in poultry litter runoff measured 2.94 mg/L. However, unlike our study, NO_3-N only represented a small portion of TN. Lentz and Westerman (2010) reported runoff concentrations of NO_3-N of 0.21 – 0.27 mg/L for irrigated cropland, while Qing et al. (2011) reported NO_3-N concentrations of 4.8 – 5.5 mg/L in runoff from a mixed use watershed in the Appalachian Valley. The concentrations of TN in the green roof treatments (1.10 – 2.23 mg/L) in 2010 were also within the range of concentrations found in local and regional streams in Northwest Arkansas (0.60 – 3.67 mg/L) (Massey et al. 2010).

In 2009, average TN loads from the compost added green roofs (FC and CC) ranged from 154 – 190 kg/ha/yr, respectively (Table 2). Loads from control roofs and green roofs without added compost averaged significantly less ($P < 0.05$) than the compost added treatments, ranging from 11.9 – 16.2 kg/ha/yr. A similar relationship was found with loads of NO_3-N from the green roofs where the compost added green roofs contained significantly greater N loads compared to the no compost treatments in 2009 (Table 2). However, there was very little NH_4-N loss relative to TN and NO_3-N. The control and CC treatment showed the greatest loss, with the other 3 treatments not being significantly different. This is interesting because it shows that NH_4-N loss is not correlated to compost and may be explained by another factor. In 2009, NO_3-N accounted for approximately 72% of the TN in runoff from the compost added green roofs and approximately 45% of the TN from the no compost roofs while NH_4-N represented between 1.5 and 14 % of TN in runoff. In the same time period, NO_3-N from the control accounted for 27% of the TN in runoff while NH_4-N from the control represented 43% of the TN in runoff.

In 2010, average TN loads decreased significantly from 2009. The green roofs with added compost (FC and CC) ranged from 14.6 – 15.1 kg/ha/yr, approximately 9% of their 2009 loads. This was also the trend among the no compost green roofs (CN and FN) and the control roofs with 2010 TN loads of approximately 5 – 8% of their 2009 loads (Table 2). There was also a significant decrease in loads of NO_3-N from 2009 to 2010 in the compost added green roofs, with 2010 loads ranging from 2.1 – 7.1 kg/ha/yr for the FC and CC treatments, respectively. This was approximately 2 – 5% of their 2009 loads. There was not a significant decrease among the no compost and control treatment from 2009 to 2010. The decrease in NO_3-N loads could be a result of a number of different factors. After an initial flush of NO_3-N, the green roofs could be storing NO_3-N compared to the green roofs. From 2009 to 2010 atmospheric deposition of NO_3-N ranged from 6.9 – 8.5 kg/ha/yr while NO_3-N loads from the green roofs were generally less (2.1 – 7.1 kg/ha/yr). This could be a result of microbial activity in the green roof substrate storing NO_3-N or plant uptake.

The only treatment to show a significant decrease from 2009 to 2010 in terms of NH_4-N was the CC treatment, decreasing from 6.7 kg/ha/yr in 2009 to 2.6 kg/ha/yr in 2010. Interestingly, the runoff from the control roof contained the greatest NH_4-N load with 6.5 kg/ha/yr and all other treatments containing significantly less NH_4-N in the runoff. Atmospheric deposition of NH_4-N in 2010 near our study site was approximately 3.0 kg/ha/yr. Loads of NH_4-N from the green roofs were generally less than atmospheric deposition in 2010 while loads from the control roofs were nearly double. This would suggest that the green roofs could be storing NH_4-N in 2010.

There have been mixed results when it comes to N loading from green roofs (Gregoire and Clausen 2011, Berndtsson 2010, Toland 2010, Berndtsson et al. 2006 & 2009, Hathaway et al. 2008). While green roof studies can vary based on a number of factors, the N loads from our study were similar to other green roof studies. Berndtsson et al. (2006) estimated an annual TN load of approximately 3.8 kg/ha/yr from established vegetative roofs, which were similar to the green roofs without compost in 2010. Similarly, Gregoire and Clausen (2011) reported export of TN from green roofs to be 4.27 kg/ha/yr and TN from the control roof of 10.82 kg/ha/yr. Hathaway et al. (2008) showed there to be no difference in TN loading from green roofs compared to the control. Our study shows that in the short term, green roofs are a source of TN and NO_3-N. In year 2, TN loads from the compost added treatments (FC and CC) continued to be significantly greater than the green roof treatments without compost.

However, in comparison to other land uses, TN loads in 2010 from the compost added treatments were similar to N loads reported by Slaton et al. (2004) (11.40 kg/ha) in the Northwest Arkansas area. Total N loads exceeded that of pasture land during the first year of the study, however, during the second year loads were similar to pasture land use (0.2 – 1.5 kg/ha/yr), except for the compost treatments (Harmel et al. 2009). TN loads from green roofs was also less than that seen in Sauer et al. (1999) from fertilized plots (40.8 kg/ha/yr for dairy feces and 260 kg/ha/yr for poultry litter). Precipitation could also be a source of TN and NO_3-N loads in runoff representing 13.8 kg/ha/yr for TN and 6.9 kg/ha/yr for NO_3-N (Table 2) in northwest Arkansas based on the National Atmospheric Deposition Program (NADP). Gregorie and Clausen (2011) reported TN loads from precipitation to be 6.29 kg/ha/yr and NO_3-N loads to be 2.72 kg/ha/yr in Connecticut in 2009.

Loads of TN in the compost added green roofs (FC and CC) were similar to that of fertilized pastureland and greater than pasture and mixed land uses in 2009. In 2010, loads were similar to other land uses for most green roof treatments, excluding the CC treatment.

Precipitation could also play an important role in contributing to not only TN loads, but NO_3-N loads as well. Following the trends in TN loading from the green roofs, TN and NO_3-N loads from all green roof treatments would be expected to be similar to the control roofs and mixed land use in the near future.

Nutrients Remaining In Media

Nutrients in the green roof media were measured at the beginning and end of the study period (December 2008 and March 2011) to assess losses during the study and nutrient amounts remaining in the media at the end of the study (Tables 3, 4, and 5). At the end of the study (March 2011), WEP was greatest (0.24 mg/kg) in the fine media with compost (FC) whereas the other treatments (CC, CN, and FN) were not significantly different (0.06 – 0.09 mg/kg). The trend in water extractable K and NH_4-N was similar to that of WEP. Interestingly, NO_3-N content in the media was not significantly different across treatments ranging from 0.63 – 1.23 mg/kg. Initial water extractable NO_3-N in the media with compost treatments was measured at 65 mg/kg (Toland 2010). This suggests that, approximately 1.4% of the original NO_3-N in the compost is remaining in the CC treatment and 1.9% in the FC treatment. However, N concentrations in local rainfall were measured at approximately 1.0 mg/L (NADP, 2011) which could account for the continued increase in N concentrations from the green roofs.

The Mehlich-3 extractable K, Al, and Fe content in the fine media with or without compost (FC and FN) was significantly greater compared to the coarse media (CC and CN) (Table 5) suggesting that media size, not compost influences these elements. There were significant differences in M3P content in the media relative to compost. M3P content in the fine media with compost (FC) was greatest measuring 91.0 mg/kg, followed by the coarse media with compost (CC, 25.0 mg/kg), fine media alone (FN, 6.4 mg/kg), and then coarse media alone (CN) measuring less than 1.0 mg/kg. This shows that compost and media particle size both influenced M3P contents, where the fine media had a greater affinity to store M3P.

Phosphorus saturation ratios (PSRs) for the compost treatments ranged from 0.26 to 0.36 for the CC and FC treatments, respectively. The green roofs without added compost only contained PSRs of 0.01 and 0.02 for the CN and FN treatments, respectively. A higher PSR means that the media has a greater potential to release P, which is consistent with the addition of compost. There is a strong correlation between increasing PSR and increased dissolved P in runoff from soils (Maguire and Sims 2002, Paulter and Sims 2000, Pote et al. 1996) which would lead us to believe that the green roof treatments containing compost would have greater concentrations of P in runoff, which is consistent with our results (Figure 3).

At the beginning of the study, P content in the green roof substrate was measured to be 532 mg/kg. By the end of the study, the FC treatment had the greatest amount of TP remaining in the media (226 mg/kg) which was 42% of the original P content. This was followed by the CC treatment (147 mg/kg) or 27% of the initial amount. The FN and CN treatments had 76 and 47 mg/kg TP remaining at the end of the study with the initial substrate only measuring 3.4 and 2.1 mg/kg, respectively (Toland 2010). However, the initial media sample did not take into account the amount of P contributed from the planting of green roofs plants, which contained plugs of soil high in organic matter and likely nutrients. Total P for all green roof treatments was much greater than M3P, suggesting that P is stored in forms not extracted by water or M3 solutions. While these extractions suggest that greater than 50% of the P from the initial media has been lost from the FC treatment and almost 75% from the CC treatment, this does not take into consideration the P uptake from the green roof plants.

The fine and coarse media with compost (FC and CC) had the greatest TN content remaining with 773 mg/kg for the CC treatment and 662 mg/kg for the FC treatment. The media without compost had more than ten times less TN stored, and it was surprising that the least TN content was observed in the FN treatment (14 mg/kg). This shows that the compost does serve as a potential long-term source of N to plants, which is the reason for applying it to green roof media.

The organic C content of the media (fine and coarse) with compost was greatest across the FC and CC treatments (Table 6). However, trends in concentration show that TOC runoff from the green roofs was relatively similar to that of the control and in some cases less than. In 2010, the TOC loads from the control roofs were greater than that from the green roof treatments and are evidence that the membrane only roofs can be a source for TOC. Not only do green roofs show a potential to reduce the premature weathering of roofing membranes that may contribute to TOC in runoff (Dunnett and Kingsbury 2004), but green roofs also have the ability to reduce runoff TOC through carbon sequestration (Getter and Rowe 2009).

CONCLUSIONS

Green roofs are generally accepted as a method to reduce stormwater runoff as shown by a number of studies (Toland 2010, Bliss et al. 2009, Hathaway et al. 2008, Carter and Rasmussen 2006, Moran et al. 2005, VanWoert et al. 2005, Denardo et al. 2005, Monterusso et al. 2004). This reduction plays an important role in the hydrologic cycle and can have several beneficial effects on urban streams and ecological functions. There are, however, a number of concerns with increased P and N loading from green roofs. During the study period, stormwater runoff reduction ranged from 37% to 55% across all treatments. This reduction was based on a number of design and climate factors and is consistent with other similar green roof studies (Toland 2010, Hathaway et al. 2008, Bengtsson et al. 2005, VanWoert et al. 2005). The green roofs with fine media showed greater runoff reduction over the green roofs with coarse media and the addition of compost did not show a significant increase in stormwater reduction (Figure 1).

The addition of compost increased the loads of SRP, TP, TN, NO_3-N, and TOC from green roofs in 2009 (Table 2). However, in 2010, only loads of TP and SRP in the compost treatments remained greater than the loads from control roofs and green roofs without added compost. Total P remained significantly greater in the composted treatments well into year 2 and nutrient content in the green roofs at the end of the study indicated that P concentrations could remain elevated in the runoff from the green roofs well into the future. Further studies should focus on varying the % by volume of compost addition in order to reduce nutrient loss from the green roofs as well as selecting a media size to maximize stormwater retention.

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Table 1. Total rainfall along with stormwater runoff from each green roof treatment for water year 2009 and 2010. Letters denote significant differences across treatments within a given year and numbers denote significant differences between years. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

	WY 2009 (mm)	% Rainfall	WY 2010 (mm)	% Rainfall
Rainfall	1134		1186	
Control	1112^{A}	$98\%^{1}$	1153^{A}	$97\%^{1}$
CC	709^{B}	$63\%^{1}$	748^{B}	$63\%^{1}$
CN	749^{B}	$66\%^{1}$	816^{B}	$69\%^{1}$
FC	570^{C}	$50\%^{1}$	626^{C}	$53\%^{1}$
FN	514^{C}	$45\%^{1}$	575^{C}	$48\%^{1}$

Table 2. Mean total nutrient loading for total phosphorus (TP), total nitrogen (TN), and total organic carbon (TOC) in runoff water from green roof treatments in water years 2009 and 2010. Letters denote significant differences among treatments within a given year, and numbers denote significant differences between years within a treatment ($\alpha=0.05$). [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

Treatment	SRP (kg/ha/yr)	TP (kg/ha/yr)	NO$_3$-N (kg/ha/yr)	NH$_4$-N (kg/ha/yr)	TN (kg/ha/yr)	TOC (kg/ha/yr)
2009						
Atmospheric Deposition	-	-	8.5	3.7	17.0	-
Control	$0.3^{C,1}$	$0.9^{C,1}$	$3.6^{B,1}$	$6.9^{A,1}$	$16.2^{C,1}$	$9.9^{B,1}$
CC	$19.1^{A,1}$	$21.5^{A,1}$	$138^{A,1}$	$6.7^{A,1}$	$190.4^{A,1}$	$30.8^{A,1}$
CN	$1.5^{C,1}$	$2.1^{C,1}$	$7.4^{B,1}$	$2.2^{B,1}$	$15.9^{C,1}$	$5.1^{C,1}$
FC	$12.8^{B,1}$	$14.4^{B,1}$	$111^{A,1}$	$2.4^{B,1}$	$154.6^{B,1}$	$28.1^{A,1}$
FN	$0.7^{C,1}$	$1.2^{C,1}$	$5.3^{B,1}$	$0.8^{B,1}$	$11.9^{C,1}$	$4.8^{C,1}$
2010						
Atmospheric Deposition	-	-	6.9	3.0	13.8	-
Control	$0.4^{C,1}$	$0.8^{B,1}$	$3.3^{B,1}$	$6.5^{A,1}$	$18.5^{B,1}$	$24.0^{A,2}$
CC	$11.4^{A,2}$	$15.1^{A,2}$	$7.1^{A,2}$	$2.6^{B,2}$	$26.2^{A,2}$	$16.4^{B,2}$
CN	$0.8^{C,1}$	$1.0^{B,2}$	$6.9^{A,1}$	$2.5^{B,1}$	$17.9^{B,1}$	$7.8^{C,2}$
FC	$11.0^{A,1}$	$14.6^{A,1}$	$2.1^{B,2}$	$1.6^{B,1}$	$16.5^{BC,2}$	$15.7^{B,2}$
FN	$0.6^{C,1}$	$0.9^{B,1}$	$4.0^{B,1}$	$1.0^{B,1}$	$12.1^{C,1}$	$7.26^{B,2}$

Table 3. Water extractable nutrients in green roof media at the end of the study period, March 2011. Letters within a column indicate differences based on means separation using the least significant difference ($\alpha = 0.05$). [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

Treatment	P (mg/kg)	K (mg/kg)	NO_3 (mg/kg)	NH_4-N (mg/kg)
CC	0.09^B	$<0.01^B$	0.91^A	$<0.7^B$
CN	0.06^B	$<0.01^B$	0.63^A	$<0.7^B$
FC	0.24^A	0.70^A	0.92^A	1.44^A
FN	0.07^B	$<0.01^B$	1.23^A	$<0.7^B$

Table 4. Mehlich-3 extractable nutrients in green roof media at the end of the study period, March 2011. Letters within a column indicate differences based on means separation using the least significant difference ($\alpha = 0.05$). [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

Treatment	P (mg/kg)	K (mg/kg)	Al (mg/kg)	Fe (mg/kg)	PSR[*]
CC	25^{B}	13^{B}	48^{B}	17^{B}	0.26^{B}
CN	$<1.0^{D}$	11^{B}	55^{B}	19^{B}	0.01^{C}
FC	91^{A}	40^{A}	148^{A}	53^{A}	0.36^{A}
FN	6.4^{C}	29^{A}	186^{A}	68^{A}	0.02^{C}

[*] PSR, P saturation ratio represents the moles of M3P relative to M3Al and M3Fe

Table 5. Total nutrients in green roof media at the end of the study period, March 2011. Letters within a column indicate differences based on means separation using the least significant difference ($\alpha = 0.05$). [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

Treatment	TP (mg/kg)	TN (mg/kg)	TOC (mg/kg)	N:P Ratio
CC	147^{B}	773^{A}	7540^{A}	$19:1^{A}$
CN	47^{D}	46^{B}	578^{C}	$6:1^{B}$
FC	226^{A}	662^{A}	6537^{A}	$8:1^{B}$
FN	76^{C}	14^{C}	1682^{B}	$1:2^{C}$

Figure 1. Relation between runoff and rainfall for the green roofs. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

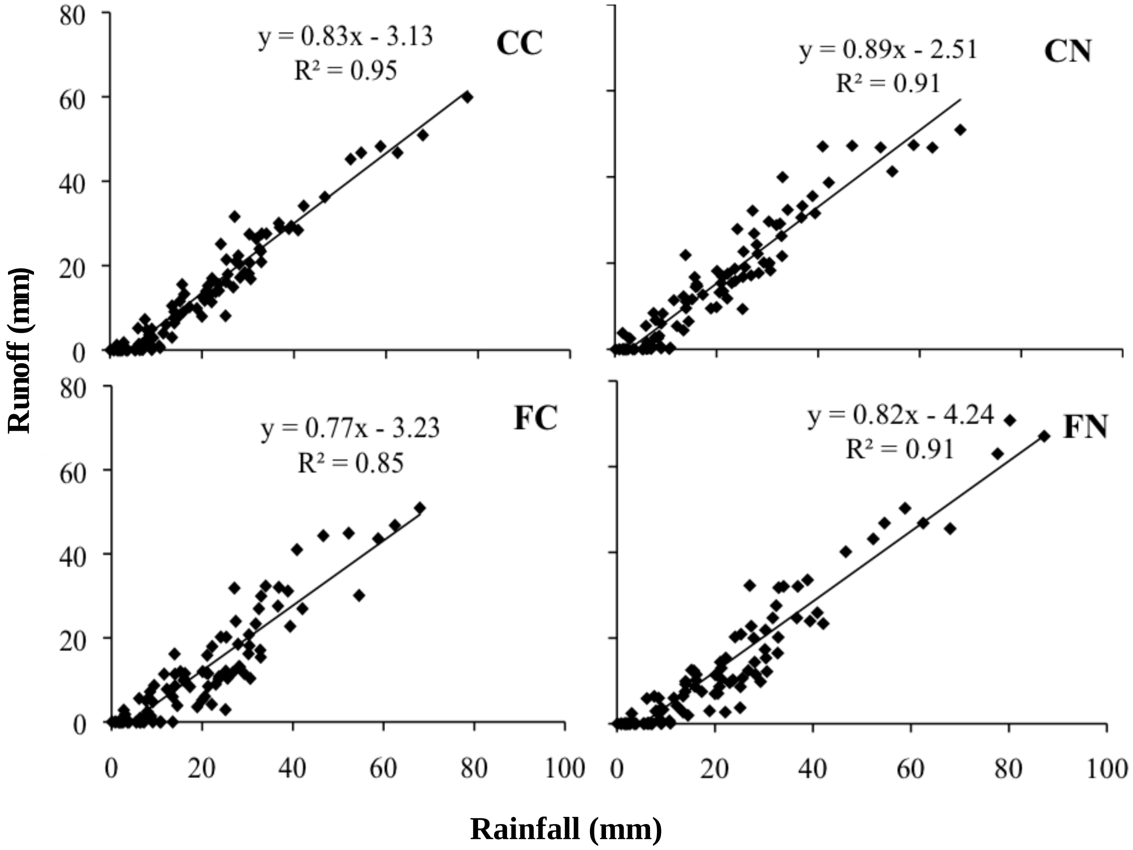


Figure 2. Mean total organic carbon (TOC) concentrations in mg/L from the control roofs and various green roof treatments at the Watershed Research and Education Center in Fayetteville, Arkansas from September 2008 to March 2011. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

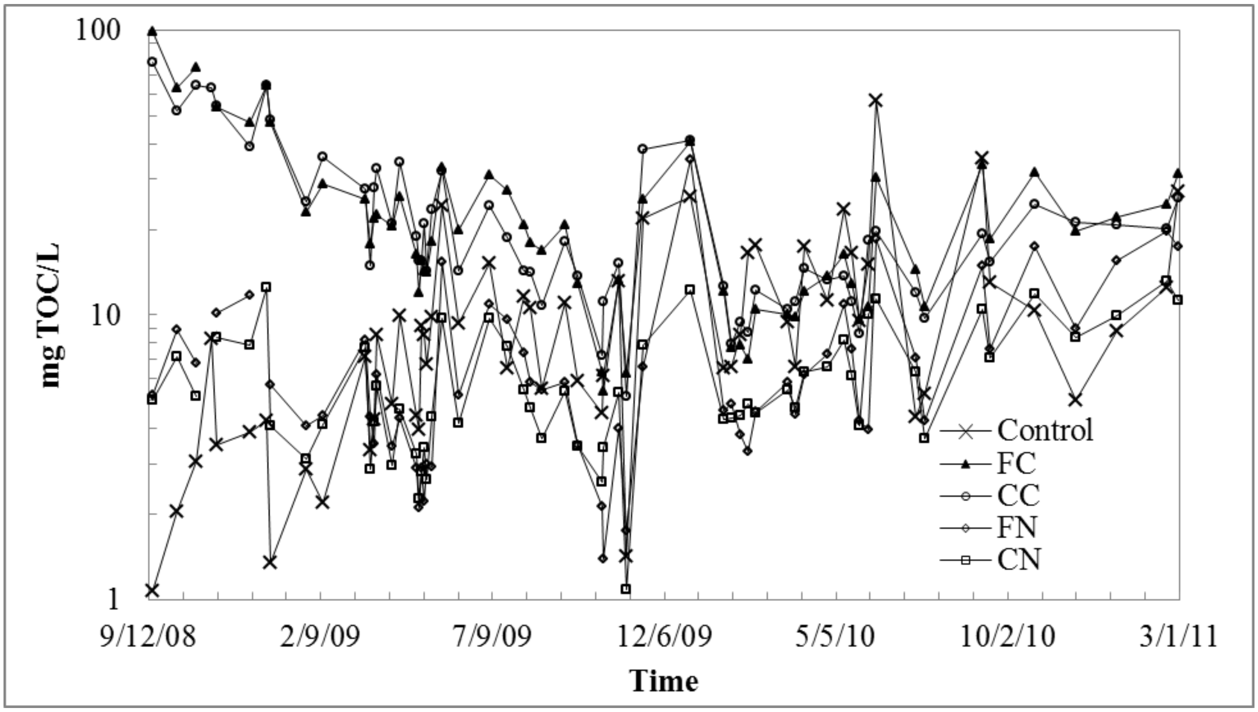


Figure 3. Mean total phosphorus (TP) concentrations in mg/L from the control roofs and various green roof treatments at the Watershed Research and Education Center in Fayetteville, Arkansas from September 2008 to March 2011. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

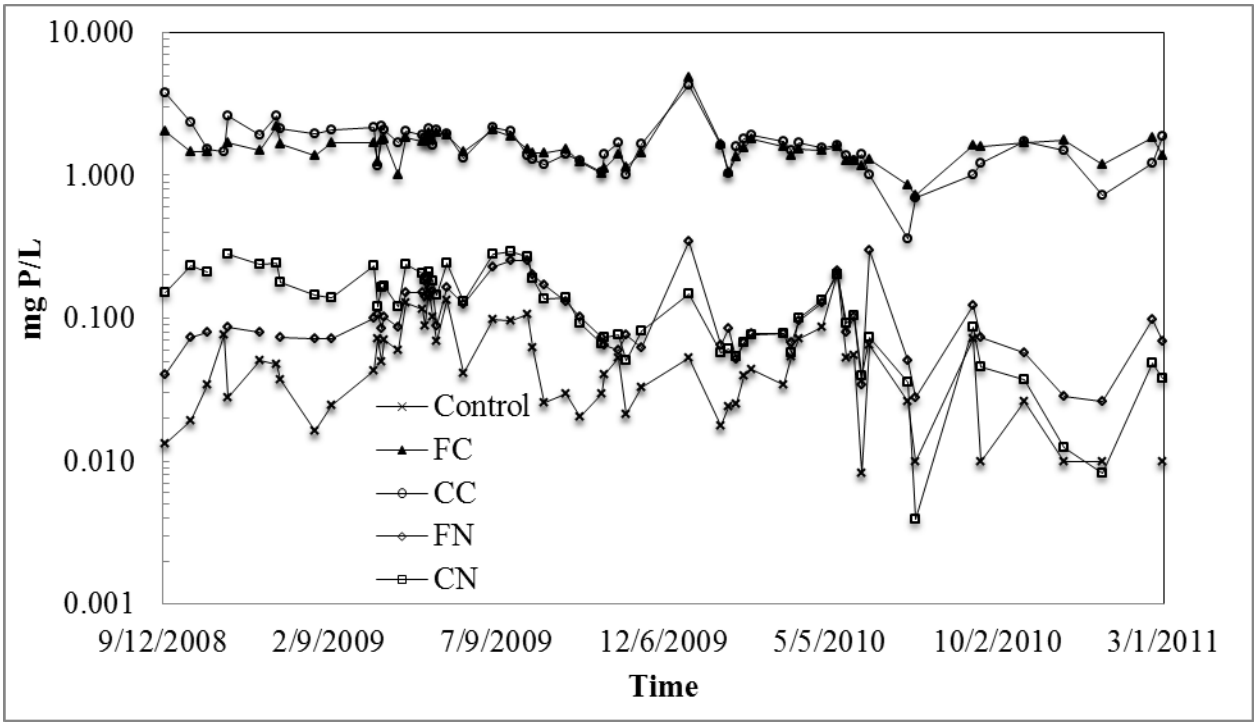


Figure 4. Mean total nitrogen (TN) concentrations in mg/L from the control roofs and various green roof treatments at the Watershed Research and Education Center in Fayetteville, Arkansas from September 2008 to March 2011. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

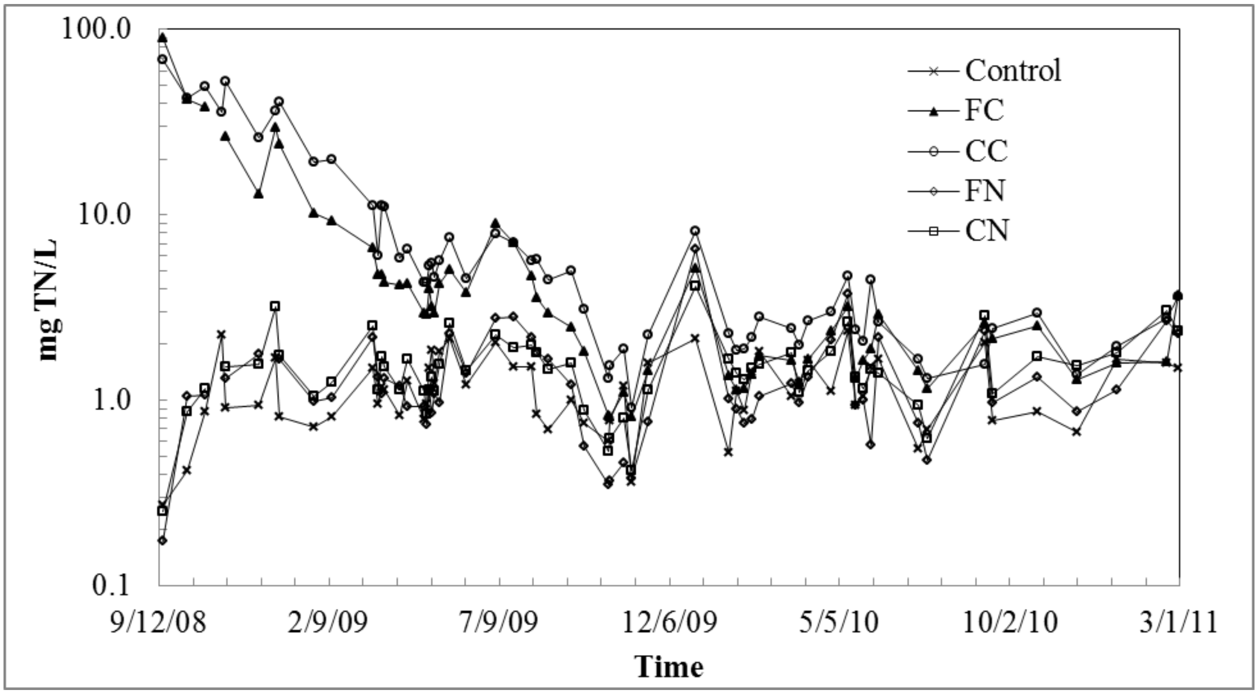


Figure 5. Mean nitrate-nitrogen (NO_3-N) concentrations in mg/L from the control roofs and various green roof treatments at the Watershed Research and Education Center in Fayetteville, Arkansas from September 2008 to October 2010. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]

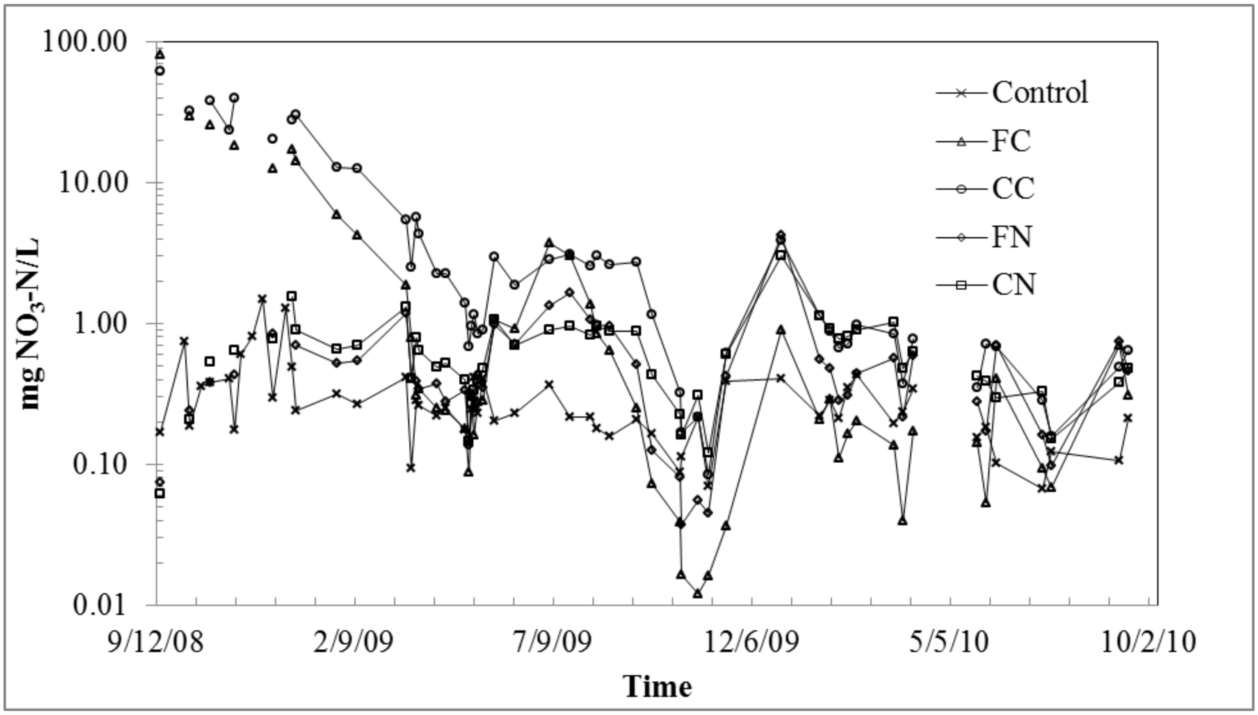
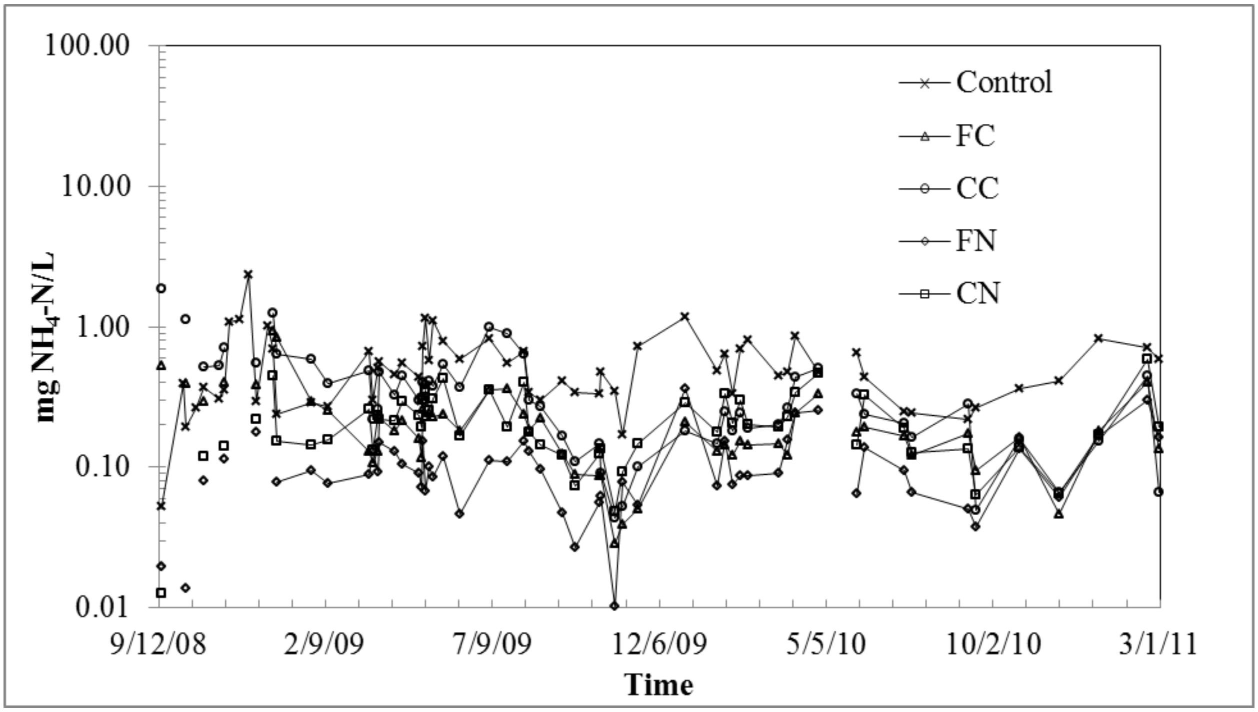


Figure 6. Mean ammonium (NH_4-N) concentrations in mg/L from the control roofs and various green roof treatments at the Watershed Research and Education Center in Fayetteville, Arkansas from September 2008 to March 2011. [Abbreviations: coarse media with compost (CC), coarse media without compost (CN), fine media with compost (FC) and fine media without compost (FN).]



APPENDIX:

Date	Precip. (mm)
09/15/08	80.20
10/04/08	3.50
10/07/08	32.90
10/16/08	9.10
10/23/08	25.20
11/06/08	10.70
11/10/08	20.90
11/15/08	2.30
11/24/08	2.60
12/02/08	2.00
12/04/08	0.10
12/09/08	14.50
12/19/08	1.80
12/24/08	9.00
12/27/08	30.40
01/09/09	2.00
01/27/09	54.60
02/09/09	7.20
02/11/09	36.70
02/17/09	2.20
02/26/09	6.20
03/01/09	3.90
03/08/09	0.80
03/13/09	5.60
03/21/09	30.20
03/24/09	28.30
03/27/09	7.90
03/28/09	22.20
03/30/09	8.70
04/02/09	6.50
04/04/09	2.20
04/12/09	58.80
04/19/09	21.30
04/27/09	1.70
04/30/09	10.90
05/04/09	62.50
05/06/09	27.10
05/08/09	16.20
05/10/09	15.20
05/13/09	15.70
05/15/09	14.00
05/17/09	7.20
05/26/09	25.13
06/04/09	5.40
6/10/09	18.90
6/11/09	3.70
6/13/09	27.90
6/14/09	25.31
6/15/09	6.10
6/16/09	1.60
6/26/09	0.10
7/3/09	25.60
7/6/09	26.80
7/14/09	0.90
7/22/09	29.30
7/28/09	1.60
7/31/09	30.60
8/2/09	7.60
8/6/09	24.10
8/11/09	32.80
8/19/09	7.10
8/21/09	30.30
8/28/09	6.40
9/3/09	20.60
9/7/09	21.30
9/10/09	31.80
9/14/09	1.50
9/17/09	20.00
9/18/09	6.30
9/22/09	40.90
9/24/09	2.70
10/2/09	7.00
10/7/09	13.50
10/8/09	9.10
10/9/09	68.00
10/12/09	9.40
10/14/09	11.60
10/23/09	17.30
10/27/09	21.10
10/30/09	46.70
11/17/09	23.70
12/25/09	16.10
1/22/10	27.40
1/23/10	14.00
2/3/10	12.20
2/5/10	13.90
2/8/10	8.50
2/22/10	15.90
3/23/10	38.90
3/25/10	32.50
4/3/10	23.00
4/25/10	39.40
5/11/10	28.10
5/13/10	8.00
5/14/10	52.30
5/16/10	34.00
5/19/10	1.50
5/20/10	36.90
5/26/10	33.00
5/27/10	3.00
6/7/10	22.10
7/10/10	77.70
7/13/10	114.70
7/17/10	104.20
9/2/10	42.10
9/9/10	87.20
9/14/10	23.60
10/19/10	13.50
10/24/10	20.10

*Rainfall data provided by K.Brye (University of Arkansas)

Average Stormwater Runoff (mm)

2009

Date	Control	CC	CN	FC	FN
10/4/08	1.66	0.00	0.00	0.00	0.00
10/7/08	33.27	20.81	21.67	15.09	9.33
10/16/08	10.34	0.20	0.27	0.03	0.04
10/23/08	24.07	16.52	16.83	12.23	8.22
11/6/08	6.46	0.96	0.13	0.04	0.02
11/10/08	22.85	14.76	15.41	12.04	6.47
11/15/08	2.48	0.00	0.00	0.00	0.00
11/24/08	3.14	0.00	0.02	0.00	0.01
12/2/08	1.95	0.00	0.00	0.00	0.00
12/4/08	0.03	0.00	0.00	0.00	0.00
12/9/08	15.37	7.45	6.53	4.19	0.81
12/19/08	2.83	0.00	0.02	0.00	0.00
12/24/08	7.57	0.90	0.71	0.62	0.04
12/27/08	25.46	19.50	20.10	17.85	14.71
1/9/09	0.78	0.00	0.00	0.00	0.00
1/27/09	49.14	36.04	38.22	30.58	25.66
2/9/09	6.03	0.29	0.22	0.00	0.06
2/11/09	35.91	30.44	30.62	27.82	22.82
2/17/09	2.24	0.00	0.03	0.00	0.02
2/26/09	6.05	0.25	0.15	0.01	0.04
3/1/09	3.00	0.00	0.00	0.00	0.00
3/8/09	0.53	0.00	0.00	0.00	0.00
3/13/09	2.94	0.00	0.07	0.00	0.00
3/21/09	33.73	19.23	19.67	17.21	12.28
3/24/09	25.14	17.69	17.74	12.68	10.00
3/27/09	7.16	2.35	2.79	2.71	2.68
3/28/09	21.80	17.93	18.19	17.61	17.15
3/30/09	8.25	2.58	3.20	1.66	0.92
4/2/09	5.55	0.13	0.21	0.00	0.00
4/4/09	1.98	0.00	0.00	0.00	0.00
4/12/09	48.65	46.83	47.43	43.61	40.57
4/19/09	20.75	12.65	13.54	8.99	7.32
4/27/09	1.20	0.00	0.00	0.00	0.00
4/30/09	11.56	0.40	0.43	0.08	0.06
5/4/09	56.25	41.25	43.75	35.00	29.38
5/6/09	33.59	31.93	32.20	32.08	31.85
5/8/09	18.42	13.48	14.68	11.90	10.90
5/10/09	13.59	11.66	11.66	11.92	12.36
5/13/09	20.24	15.38	16.81	11.83	11.21
5/15/09	12.48	9.19	9.58	8.89	8.77
5/17/09	5.37	0.91	1.48	0.06	0.39
5/26/09	22.82	8.94	9.99	3.48	2.09
6/4/09	3.79	0.00	0.03	0.00	0.01
6/10/09	17.77	10.54	9.53	3.97	1.69
6/11/09	3.90	0.01	0.10	0.04	0.01
6/13/09	27.30	22.30	24.31	18.85	19.46
6/14/09	26.01	21.55	22.72	20.40	20.80
6/15/09	6.03	5.27	5.49	5.54	5.86
6/16/09	1.50	0.00	0.00	0.00	0.00
6/26/09	0.33	0.00	0.00	0.00	0.00
7/3/09	28.91	18.65	19.12	10.38	8.53
7/6/09	22.29	14.64	17.19	12.21	11.81
7/14/09	1.39	0.00	0.00	0.00	0.00
7/22/09	30.45	19.39	20.17	12.21	10.14
7/28/09	2.04	0.00	0.00	0.00	0.00
7/31/09	27.27	17.69	18.33	10.94	10.00
8/2/09	11.96	7.19	8.47	5.40	6.04
8/6/09	33.68	26.01	27.95	20.88	19.11
8/11/09	34.24	23.88	26.33	17.39	16.33
8/19/09	6.62	0.16	0.15	0.00	0.01
8/21/09	35.22	27.28	29.70	21.05	19.82
8/28/09	7.05	0.26	0.20	0.00	0.03
9/3/09	20.43	12.43	13.23	6.53	4.91
9/7/09	23.55	15.34	16.96	10.58	12.69
9/10/09	34.68	26.79	28.87	23.74	24.07
9/14/09	1.78	0.04	0.03	0.00	0.00
9/17/09	16.18	8.20	11.04	6.45	9.55
9/18/09	4.07	1.27	1.60	0.61	0.17
9/22/09	44.89	29.45	30.38	22.68	26.38
9/24/09	5.69	0.47	2.60	0.00	0.00

Average Stormwater Runoff (mm)

2010

Date	Control	CC	CN	FC	FN
10/2/09	8.39	0.20	0.90	0.60	0.00
10/7/09	13.30	11.46	10.30	5.99	6.68
10/8/09	9.59	5.66	5.99	4.79	4.11
10/9/09	62.56	43.19	45.91	35.46	32.60
10/12/09	6.59	2.71	8.29	8.60	3.74
10/14/09	12.58	3.66	11.38	11.26	6.28
10/23/09	21.87	10.10	12.68	8.22	7.85
10/27/09	20.05	15.29	16.88	15.67	14.63
10/30/09	49.37	31.12	35.09	27.35	23.93
11/17/09	27.46	14.59	15.55	10.48	10.97
12/25/09	14.78	10.36	9.67	7.52	6.54
1/22/10	25.15	15.89	17.02	12.88	11.56
1/23/10	12.85	8.29	8.70	6.48	5.68
2/3/10	11.20	7.22	7.58	5.66	5.15
2/5/10	23.31	15.48	21.87	16.67	7.41
2/8/10	10.58	4.19	2.60	6.59	2.93
2/22/10	16.78	9.89	14.48	10.58	8.85
3/23/10	51.62	35.86	35.55	31.15	33.03
3/25/10	30.15	26.36	27.67	25.95	28.36
4/3/10	26.36	13.18	14.83	9.38	9.37
4/25/10	43.09	31.86	29.55	23.08	23.52
5/11/10	32.75	20.97	21.22	13.67	13.75
5/13/10	7.61	4.79	6.19	2.65	2.79
5/14/10	49.94	32.98	35.50	27.51	23.92
5/16/10	32.47	21.01	23.08	17.73	16.01
5/19/10	9.69	1.20	0.00	0.00	0.00
5/20/10	33.87	22.18	22.92	17.39	15.57
5/26/10	34.24	22.41	22.61	17.38	15.74
5/27/10	2.61	1.80	1.77	0.60	2.46
6/7/10	23.97	11.82	11.78	5.96	8.76
7/10/10	71.12	48.59	52.07	40.52	35.05
7/13/10	105.52	71.73	77.45	59.81	57.94
7/17/10	95.86	65.17	70.36	54.34	49.16
9/2/10	52.72	36.45	38.68	28.15	27.39
9/9/10	76.84	54.87	58.88	45.04	41.48
9/14/10	25.96	15.95	21.11	10.91	11.50