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Performance quantification of extensive green roof substrate blend: Expanded shale and biochar

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Performance Quantification of Extensive Green Roof Substrate Blend:

Expanded Shale and Biochar

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Abstract

Urban stormwater management practices often involve the redirection of runoff to local waterbodies. As such, the quality of runoff directly affects the condition of these receiving waters. Green roofs offer many benefits to the urban environment including attractive aesthetics, thermal insulation for buildings and stormwater runoff reduction. Unfortunately, in order to promote the spread of vegetation, fertilization is often practiced that can lead to elevated nutrient concentrations in runoff and, ultimately, nearby streams, rivers and bays. Different amounts of biochar, pyrolyzed biomass, were added to model green roof trays to test for the ability of this charcoal-like substance to prevent nitrate and phosphate leaching. Analysis of leachate from natural and simulated rain events showed statistically significant differences of average nitrate concentrations for two out of four rain events, though none for phosphate. Samples from the natural rain event exhibited a clear inverse relationship between nitrate concentration and biochar quantity. The second simulated rain event, however, produced nitrate concentrations that rose and subsequently fell as biochar quantity increased. Further research is needed on the method by which biochar attracts anions though different experimental designs and equipment may more conclusively reveal that biochar can play a role in green roofs as a soil amendment. More noteworthy, though, may be the consistently high nutrient concentrations in leachate originating from the fertilized model trays. The fertilizer application rate of 5 g N/m2 may not be suitable for the substrate and vegetation used in this study but nonetheless it is strongly recommended that controlled-release fertilizer types are used.

Introduction

According to the World Health Organization, over half of the global population lived in urban areas in 2010 and the proportion is expected to rise to 70% by 2050 (WHO, 2014). This trend of urbanization is associated with shifts from "agriculture-based activities and towards mass industry, technology and service" (WHO-UN, 2010). The expansion of such economic sectors has resulted in considerable land use changes, all of which impact the soils they occupy. Soils provide numerous environmental services that are largely inhibited as urban development intensifies. Typical biomass production, biodiversity, "storage, filter, buffer, and transformation functions" are severely limited or cease to occur when urban soils are designated as the "physical basis for technical, industrial, and socioeconomic structure in cities" (Nehls and Wessolek, 2011). Many problems arise as urbanization spreads and covers more soils previously used for agriculture or left untouched (Norra and Stubben, 2003). In order to recognize and address the impacts of urban development, urban soils should be considered "part of ecosystems, and thus…considered in the context of urban ecosystem research" (Norra and Stuben, 2003). If they cannot be left untouched, ameliorating negative impacts of development should be a priority. One way in which this is being done is through the construction of green roofs.

Soil provides numerous environmental, economic and social benefits. Generally, the qualities viewed as directly beneficial to human health and, occasionally, welfare are considered during the process of implementing land use changes. In fact, *land use* implies that humans determine the utility of the soil. Utility is often determined in terms of economic benefits provided, thus changes that result in the expansion of industry, technology or services are the most desired. This is the phenomenon that drives urbanization and alters soils in a way we believe to be valuable. Fortunately, many other benefits of urban soils have been recognized though they seemingly clash with short term, economic ambitions. Beneficial functions include providing plants for food, recreational sites, flood prevention, contaminant treatment, carbon sequestration, temperature buffering and even historical, cultural archiving (Norra and Stuben, 2003). As urbanization spreads, these benefits likely disappear or become too difficult to restore. Though urbanization causes different types of changes under different circumstances, the most ubiquitous outcome is the anthropogenic 'sealing' of soils in these areas. Broadly, such sealing impacts energy capture and flow, water movement, gas diffusion and local microbiology (Scalenghe and Marsan, 2009). These impacts can occur immediately or advance over a long period of time. Negative impacts can include "decreased radiation absorption", less water infiltration and more runoff, the creation of a "barrier for [a] perched water table", reduced gas exchanges, reduced biodiversity, and a general increase in water and wind erosion (Scalenghe and Marsan, 2009). Though these effects are known and hydrologic impacts well studied, there is a need for more evidence to quantify the influence of sealing on broader issues such as biodiversity (Scalenghe and Marsan, 2009).

Though scientific methods of quantifying soil quality exist, the results of such quantification are often not adequately incorporated into land use change decisions. To a large extent, the negative consequences of sealing soils are externalized to areas outside of the built environment. With this in mind, soil quality quantification is not enough if the results are not actively taken into account via soil quality evaluation. Some methods of evaluation suggested in the literature involve taking a ‘goods and services’ approach where soils are “assessed on the basis of what we require a particular soil to do” with attributes of environmental protection (Vščcaj *et al.*, 2008). This approach takes into account tangible products provided to society as well as less quantifiable ecosystem services. When defining soil quality, the major factors to consider include its ability to “attenuate environmental contaminants, pathogens, and offsite damage”, the “relationship between soil and plant, human and animal health”, and its ability to “enhance plant and biological productivity” (Vščcaj *et al.*, 2008). These functions can be linked to quality of life metrics including soil contribution to “health, physical environment, scenic quality and housing, and natural resources” (Vščcaj *et al.*, 2008). Increasing public awareness of such links will work to couple the quantification of soil quality with methods of evaluation utilizing more ecologically inclusive criteria. Strengthening this association is “economically sound and will help to modify the future planning to protect soils of highest ecological functionality from destruction by construction activities” (Lehmann and Stahr, 2007). If such activities must take place, efforts to reduce the negative impacts should be of high priority. For example, if a development acts as an impervious surface, adding vegetative and soil layers to form a green roof is one way to retain some of the otherwise lost environmental services. The environmental value of urban soils must be incorporated into development decisions as humans increasingly depend on these rapidly growing areas to support healthy lifestyles. By recognizing that diminishing the health of soils via urbanization ultimately degrades our quality of life, land use changes can be executed in a more sustainable manner.

Though urbanization often causes much onsite environmental degradation, many problems are effectively externalized. One of the most important examples of this is the negative effects constant development has on nearby waterbodies. By creating impervious surfaces, stormwater runoff is typically directed into local streams or rivers. Pollutants present on these surfaces are washed away and deposited into freshwater and marine ecosystems. Nutrients are vital to aquatic life but too much of a good thing can become detrimental. As excess nutrients from urban and rural regions are transported to their respective watersheds' drainage points, a phenomenon known as eutrophication can occur. Plant growth, including that of algae, stimulated by this fresh influx of nutrients accelerates and subsequently decomposes. This process of decomposition consumes great amounts of oxygen and algae blooms block sunlight from reaching the floor of the sea, river or lake in question. As a result, aquatic organisms perish in areas referred to as 'dead zones'. An example of the considerable damage caused by eutrophication is the hypoxic expanse seen primarily during the summer months in the Chesapeake Bay located on the eastern shore of the United States (Kemp *et al.*, 2005). Dead zones, present throughout the world, also cause great economic and social damage as societies rely on these previously-healthy environments for numerous ecosystem services.

As the most significant consumers of electricity, cities must center their building and renovation efforts on energy efficiency. Pursuing LEED certification for buildings is one approach to “save energy, use fewer resources, reduce pollution, and contribute to healthier environments for their occupants and the community” (Katz, 2014). By using technologies such as motion-activated lights, ENERGY STAR products, and sustainable building materials the development and operation of buildings can be more efficient and conserve resources. By maximizing the use of the heat and sunlight, buildings can embrace the permaculture principle of catching and storing valuable energy. Reducing electricity use more often than not reduces demand for coal-fired power plants, the chief sources of carbon dioxide in the nation and emitters of numerous toxins. Efficient use of water is also essential as this resource supply becomes scarce and unpredictable with a swiftly changing global climate and diminishing aquifer levels due to over extraction. If cities are to assist in conserving water they must look at the extent to which impervious surfaces cover the land they sit upon. These growing population centers are where green roofs, if installed and managed appropriately, have the opportunity to become extraordinarily valuable assets.

Green Roofs

Green roofs have grown in popularity for their aesthetics, thermal insulation properties and, perhaps most importantly, role in stormwater management. The origin of roof gardens traces back thousands of years to Mesopotamian civilizations. This practice may have been demonstrated most notably by descriptive accounts of the Hanging Gardens of Babylon (Dunnett and Kingsbury, 2008). Europe has recognized and accepted the role of green roofs for centuries. Norway and Ireland utilized sod and thatch roofs as insulators from cold winter weather. In the mid-19th century, the use of concrete in creating flat-roofed buildings allowed for greater load capacities resulting in the expansion of rooftop gardens in Europe and the U.S. until flat roofs became a dominant urban development feature in the 20th century (Dunnett and Kingsbury, 2008). Today, many cities in Germany, Sweden and other European nations require green roofs to be incorporated into new building designs, even with little to no financial incentive (Cantor, 2008).

Green or vegetated roofs are primarily divided into two types: intensive and extensive. Intensive installations tend to have depths greater than six inches to support large vegetation whereas extensive setups are shallower, supporting sedums and short grass cover. These classifications, as well as simple-intensive and semi-extensive, do not have globally accepted depth measurements though studies rarely classify intensive setups as having depths any less than about 100 mm (3.9 inches) (Kosareo and Ries, 2007; Mentens *et al.*, 2006). Deeper substrates can support larger vegetation, such as shrubs and tall grasses, as well as retain more water. However, the added weight requires a foundation structurally capable of holding a heavier-than-usual load. For this reason, extensive green roofs are the most common option for typical single-family homes and other buildings only able to retrofit rather than completely remodel. Fewer materials as well as limited construction and operating costs often make extensive green roofs a more attractive option for the general public and small businesses.

Green roofs are retrofitted with various layers that perform significant functions. A vegetative layer provides soil stabilization and evapotranspiration while a substrate layer provides essential nutrients and water for floral growth. Stormwater is also retained until reaching saturation, an important environmental benefit. The number and type of layers beyond these depends on the purpose and style of the roof. Often there are filter, drainage and shielding layers that prevent loose particles and stormwater from damaging the basic roof structure (Mentens *et al.*, 2003).

Green roofs can provide numerous benefits apart from their attractive aesthetics. Working as building insulators, they can significantly reduce heating and/or cooling loads. Models developed to represent the thermal behaviors of green roofs showed that large foliage, in concert with other factors such as leaf thickness, reduced canopy air temperature and heat flux thus reducing average indoor air temperatures (Elena Del Barrio, 1998; Kumar & Kaushik, 2005). Protection from solar radiation, which increases the lifetime of the roof itself, comes from vegetative shading as well as plant absorption for biological functions such as photosynthesis. A study by Chih-Fang Fang (2008) also concluded that the area of leaf coverage as well leaf thickness related positively to thermal reduction without considering the effects of a soil layer. Findings from simulations conducted using a hotel green roof predicted vast energy consumption savings (up to 48%) under varying conventional insulation and night ventilation scenarios (Niachou *et al.*, 2001). Important performance limitations, however, were pointed out by Sailor (2008), such as the unwanted cooling effects of shading during winter months as well as the significance of local climate on building energy consumption.

The characteristics of modern urban cities result in a phenomenon known as urban heat islands (UHI). Human activities like transportation and particular city materials that absorb considerable short-wave solar radiation, like concrete and asphalt, result in higher temperatures, particularly at night, when it is reradiated into the atmosphere (Solecki *et al.*, 2005). This rise in temperature can exacerbate heat stress, air pollution, other public health issues and energy demand. In fact, "urban temperatures can be up to 5-12°C warmer than the surrounding countryside" in certain weather conditions (Lee *et al.*, 2013a). Mitigation strategies proposed include applying a reflective coating (e.g. white paint) to these absorbing materials and installing urban vegetation, such as that found with some green roofs (Solecki *et al.*, 2005). Green roofs are capable of cooling their surrounding environments as vapor from evapotranspiration cools ambient air. Lee *et al.* (2013a) state that "a maximum surface temperature reduction of 10°C and ambient temperature reduction of over 4°C are possible" by incorporating green roofs into the urban environment under certain parameters. More significant reductions may be possible when compared to black tar roofs.

Mitigating stormwater runoff is one of the primary objectives of green roof technology. Not only does vegetation uptake a portion of rain water, and later release it via evapotranspiration, the substrate layer may retain water until reaching field capacity – the ability of soil to hold water against gravitational forces. The degree to which this occurs and aids stormwater management depends on a number of factors. Much quantitative work has been conducted on the ability of green roofs to attenuate runoff and its peak (Carter and Jackson, 2007; Kikuchi and Koshimizu, 2013; Kohler *et al.*, 2002; Lamera *et al.*, 2014; Lee *et al.*, 2013b). Simulations run by Lee *et al.* (2013b) showed that the water retention capability of extensive green roofs is strongly correlated with total rainfall amount and intensity. Generally, as intensity increases, stormwater mitigation performance decreases (Carter and Rasmussen, 2006). Substrate depth, preexisting substrate moisture and seasonal climate conditions are also noteworthy factors as shallower depths and winter conditions yield significantly reduced water holding capacity (Buccola and Spolek, 2010; Mentens *et al.*, 2006). Mentens *et al.* (2006) observed that rainfall retention can range from 45% to 75% for extensive and intensive green roofs, respectively. The results of Harper *et al.* (2014) attest to that range as their nine-month pilot study using an experimental green roof block planted with 18 different succulent species showed a runoff reduction of roughly 60%. Some studies show that the slope of a green roof may have an effect on retention volume (Getter *et al.*, 2007; VanWoert *et al.*, 2005; Villarreal and Bengtsson, 2005) though some have found no correlation (as cited in Berndtsson, 2010).

Green roofs are also being increasingly utilized for pollution abatement. Plant stomata remove gaseous pollutants from the atmosphere, leaves capture particulate matter and the evaporative and transpiration cooling effects reduce the incidence of photochemical reactions that create pollutants such as ground level ozone (Rowe, 2011). Rowe (2011) reviewed a vast amount of literature on the pollution reduction functions of green roofs and found much evidence to support the claim that they are sinks of atmospheric pollutants, sequester carbon dioxide, reduce noise and filter runoff. Despite these benefits, green roofs are also seen as a source of some pollutants, particularly nutrients, due to the materials used for installation. Some pollutants may be utilized by vegetation, however, continuous inundation results in only temporary storage as saturation is reached (Speak *et al.*, 2014). While concentrations of certain pollutants may appear higher in green roof discharge, significant stormwater retention reduces their overall amounts compared to conventional roofs (Rowe, 2011). This aspect of green roof performance is widely perceived to require further quantitative research. Although low maintenance species are favored during plant selection for extensive setups, the drawback of green roof installation and focus of this study is that organic material and fertilizers are often employed during manufacturing and for propagation (Emilsson *et al.*, 2007). These practices result specifically in high nitrogen and phosphorus levels in green roof runoff (Emilsson *et al.*, 2007; Moran *et al.*, 2003). The age of green roofs is believed to be positively related to contaminant retention (Berndtsson *et al.*, 2006; Köhler *et al.*, 2002), thus the issue of leaching may diminish over time but addressing this inadequacy as the industry expands will be necessary in order to protect the health of runoff-receiving waterbodies. This is particularly true for extensive systems with shallow, less retentive soils.

Biochar

Modern biochar is the term for biomass products produced via the process of pyrolysis. During pyrolysis, biomass, typically agricultural waste such as wood or manure, is burned with little or no oxygen and converted into a solid composed of approximately 70 to 90% carbon (Winsley, 2007; W. Teel, personal communication, October 11, 2014). Carbon content may fall outside of this range based on the type of biomass used. What differentiates biochar from conventional charcoal is its intended use as a soil amendment or general ecosystem service provider (Joseph and Taylor, 2014).

Near the turn of the 19th century, "European explorers in the Amazonia found patches of dark, high fertility soils amidst the highly weathered and acidic oxisols in the region" (Winsley, 2007). These dark, charcoal-enriched soils, termed *terra preta de indio*, "dark earths" or simply anthrosols, were created by natives who discovered the positive effects of adding charcoal-like material to soil, specifically its ability to "capture nutrients and hold them even when dowsed by the frequent rains" (Teel, 2011). Though there has been debate about the introduction of biochar into Amazonian society, many have confirmed the suspicion that this soil amendment was at least partly applied to soils deliberately (as cited in Glaser and Birk, 2012). The existence of substantial native populations hundreds of years before the arrival of European explorers in modern South America has been proposed, suggesting intricate societal development that certainly involved alterations to the natural environment. Such soil modifications were likely necessary in a region known for its infertility due to rapid decomposition of organic matter (Glaser *et al.*, 2001; Woods and Glaser, 2004). Additionally, rapid nutrient leaching makes conventional fertilizer application impractical even today (Glaser *et al.*, 2001). Unfortunately, disease brought over by the early explorers wiped out the natives along with their knowledge of this unique, soil-enhancing practice (Morgan, 2013).

One of biochar's unique qualities is its stability in soils. As evidenced by the European explorers' find, biochar is an exceptionally stable form of carbon. Radiocarbon dating of *terra preta* soils has established the age of this charred material to be over 3000 years old (Glaser, 2001). Its chemical and microbiological stability is attributed to its polyaromatic structure (Knicker, 2011). The ability to act as a sink for atmospheric carbon dioxide over the long-term has made biochar a product of great interest to researchers studying it in the context of global climate change. Lehmann *et al.* (2006) claim that, for particular types of feedstock, biochar retains about 50% of the original biomass carbon after conversion, compared to 3% for the burning involved in the common slash and burn method used to temporarily infuse nutrients into soils. Slash and burn also releases considerable amounts of greenhouse gases including carbon dioxide and nitrous oxides. Nonetheless, it is important to consider the full life-cycle of biochar, including land use changes, when determining its net carbon sequestration potential as its production also generate greenhouse gases. Estimates range from the process resulting in net greenhouse gas emissions to significant net carbon sequestration, depending on numerous factors such as the type of feedstock grown (Roberts *et al.*, 2010; Woolf *et al.*, 2010). This implies that careful planning of biochar production may work to significantly slow rapid climate change. Reducing the impact of climate change not only involves carbon sequestration but also lowering greenhouse gas emissions. Low-temperature biochar production results in off-gases that may be utilized as a source of bio-energy (Lehmann, 2007). Combustion of these gases for heat or electricity along with byproducts such as biofuel oils are innovative concepts that could enhance the efficiency and utility of the biochar production process but require further research.

The temperature at which biochar is created heavily influences its physical and chemical properties. For a single feedstock, significant differences among biochar products may be witnessed if pyrolyzed between the ranges of 300-400°C, 400-500°C or above 500°C (±50°C). Some affected properties include water-holding capacity, surface area, pore volume, pH, and heavy metal adsorption (Joseph and Taylor, 2014). These properties are also decided by category of feedstock. For example, wood is said to produce a "harder biochar, that [has] a higher porosity, surface area and water-holding capacity than biochars" in other categories such as high ash manure products (Joseph and Taylor, 2014).

Modern researchers have claimed that biochar not only physically endured the test of time in the Amazon, but kept tropical soils fertile for hundreds or thousands of years (Glaser, 2007; Maddox, 2013). These dark soil patches, whose locations often correlate with pre-Columbian village sites, contained large amounts of carbon and nutrients in the A horizon or topsoil layer (Woods and Glaser, 2004). Analytical studies found these black earth soils to "have higher soil nutrient stocks, more favorable indices of soil fertility (cation exchange, pH, levels of toxic Al) and extremely high amounts of soil phosphorus" compared to typical Amazonian oxisols (as cited in German, 2003). Researchers found similar soils at sites of Australian Aboriginals, termed *Terra Preta Australis*, with high carbon content due to charring and other chemical and physical improvements beneficial to agriculture. Though dated, Tryon (1948) discovered the "availability" of calcium to be roughly three times greater with the addition of hardwood charcoal than the base cation exchange capacity, though this included ash that could leach before actually being utilized. This indicates that biochar may work as a secondary soil conditioner as well as a direct fertilizer (Glaser, 2002). The liming effect biochar provides may also be able to counteract acid rain that proves problematic in many urban areas. Chemical analysis of a synthesized biochar created by Chia *et al.* (2014) supports the conclusions that such products have "high concentrations of exchangeable cations, available phosphorus and high acid neutralizing capacity". It is important to note, however, that such improvements may not be fully observed immediately after biochar is applied to soils as the effects of aging are not thoroughly understood (Downie *et al.*, 2011).

A principal advantage of biochar is its ability to increase soil fertility and agricultural productivity. Due to its high observed cation exchange capacity, compared to that of other organic matter, it attracts and holds positively-charged particles such as calcium, magnesium, and potassium. Similarly, considerable phosphate (an anion) adsorption has been witnessed, though the process by which this happens has not been fully explained (Lehmann, 2007). This quality increases the opportunity of vegetation to take advantage of nutrients and, in turn, reduces nutrient leaching. One study showed that greater amounts of biochar application significantly increased nitrogen use efficiency and increased radish yields (Chan *et al.*, 2007). Similarly, it has been shown that biochar created via fast pyrolysis may be able to "raise high yield rates of corn another 20%" (Renner, 2007). Productivity boosts have also been witnessed in "crops such as soybeans, sorghum, potatoes, maize, wheat, peas, oats, rice and cowpeas" (Winsley, 2007).

The health and abundance of microbial communities in soils strongly affects "structure and stability, nutrient cycling, aeration, water use efficiency, disease resistance and C [carbon] storage capacity" (Brussaard *et al.*, 1997). A survey investigating the microbiology of *terra preta* soils in the Western Amazon discovered significantly greater bacterial species richness (25%) compared to surrounding forest soils (Kim *et al.*, 2007). Mycorrhizae colonization has not been proven to respond in any one particular way when biochar is added to soils (Biederman and Harpole, 2012; Makoto *et al.*, 2009; Warnock *et al.*, 2007). When they become more abundant, however, these fungi provide plants with secondary root systems capable of drastically increasing nutrient uptake efficiency. On the other hand, colonization may decrease when there is less need for fungi services as the biochar provides greater nutrient and water availability (Lehmann *et al.*, 2011). The effects of biochar on microbial communities are lesser known than its well-studied physical and chemical properties but are nonetheless important and add a layer of complexity when detailing its degree of influence in soils.

Methodology

To simulate green roof structures, 20 Eco-Roof, LLC Eco-Standard trays were filled with conventional substrate constituents and divided into five groups based on amounts of supplemented biochar. Each 30.5 x 61.0 x 8.4 cm tray included 46 holes across the base for adequate drainage and was filled with 9.53 mm diameter expanded shale to a height of 6.4 cm. The commercial expanded shale provided by Luck Stone Specialty Products in Ruckersville, VA was quoted as having a density of 0.8 g/cm^3 and chosen for its lightweight and porous nature. The trays were divided into five groups of four trays each, as seen in Table 1. The control group was left as is while groups A, B, C and D were augmented with 2%, 5%, 8% and 10% biochar by volume, respectively. The biochar was largely created using yellow pine as the feedstock and has an individual particle density between 0.27 and 0.33 g/cm^3 (Becker, 2011). Another 1.3 cm thick application of compost provided by facilities management from James Madison University (JMU) was added on the surface of all trays though its specific composition was unknown. Three sedum plugs, each roughly 7.6 cm tall and 2.5 cm wide, were transplanted into each tray to better simulate the plant propagation stage of a green roof as well as to provide physical soil stabilization, nutrient consumption and water uptake. One plug of each of the following species of sedum was planted in each tray: S. *cauticola* 'Lidakense', S. *rupestre* 'Angelina', and S. *hybridum* 'Immergrunchen' (Appendix A). Sedums are common extensive green roof vegetation that can typically survive in the Unites States Department of Agriculture's (USDA) hardiness zones three through ten. These

20 tray setups were placed on top of clear, plastic tote containers measuring 35.6 x 20.3 x 12.4 cm with 3 holes drilled into each lid, as seen in Figure 1. This allowed for a sample of infiltrated water to be collected after each rainfall event. The full experimental setup is shown in Appendix B.

Control Group (w/o biochar)			
Control 1	Control 2	Control 3	Control 4

Group A (2% biochar by volume)			
A1	A2	A3	A4

Group B (5% biochar by volume)			
B1	B2	B3	B4

Group C (8% biochar by volume)			
C1	C2	C3	C4

Group D (10% biochar by volume)			
D1	D2	D3	D4

Table 1: Grouping diagram of model trays.

Figure 1: Diagram of model tray atop tote container with leachate (left) and aerial view of tote container lid (right).

Roughly three weeks after the trays were moved to their permanent location at the Small Wind Training and Testing Facility on JMU's campus, Sam's Choice Deep Feeding All Purpose Plant Food fertilizer was applied in the amount of 5 g N/m^2

evenly to all trays. This amount is considered comparable to a medium dosage in German green roof guidelines though the fertilizer used was conventional rather than the recommended control release type (Emilsson *et al.*, 2007). The product contained both ammonium (NH_4^+) and nitrate (NO_3^-) forms of nitrogen. Over the three weeks, numerous unrecorded rain events occurred that likely flushed most of the powdered-form biochar applied to the model trays, as well as some of the applied fertilizer, and helped establish the sedum root systems.

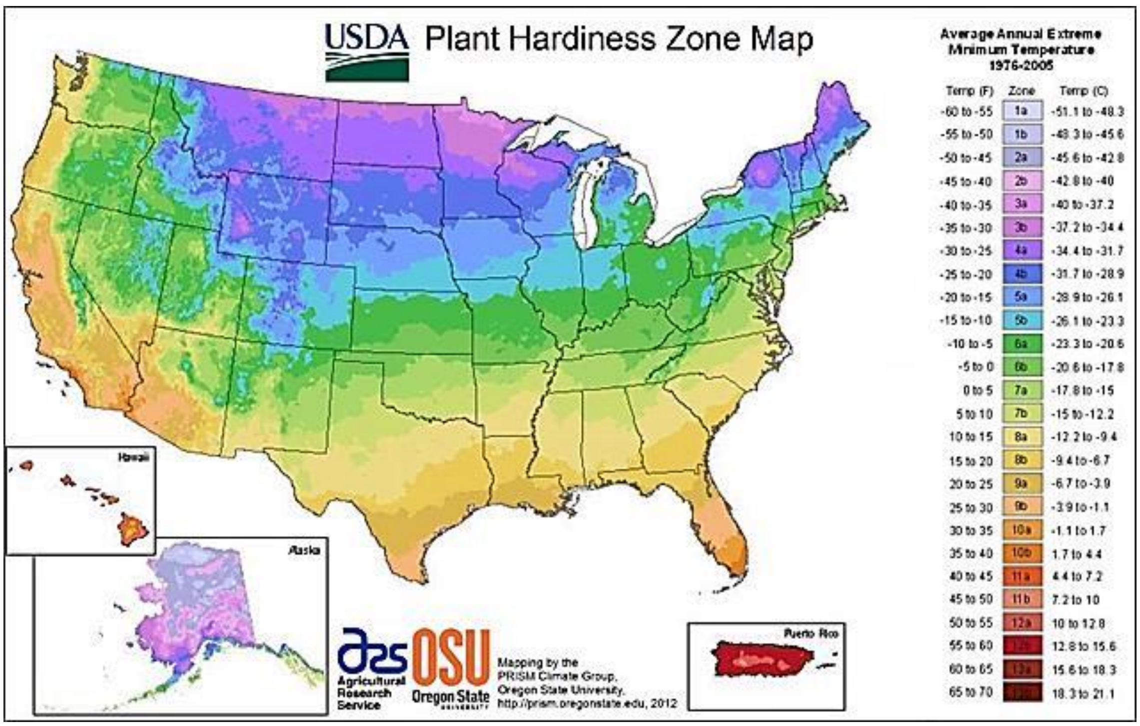

Figure 2. USDA standard from which to determine if plants will thrive in particular regions of the United States (USDA, 2012).

Due to the lack of sufficient natural rainfall events to produce leachate, simulated events were also conducted, totaling one natural and three simulated rainfall events. For the simulated events, a watering can was filled with an amount of tap water equivalent to 1.9 cm of rain for each tray. It took roughly 28 seconds to water each tray resulting in an estimated simulated rainfall intensity of 0.675mm/sec. A watering can was used as a rain simulator instrument was not available. The amount of water chosen was based on observations of the degree of absorption and leaching resulting from previous natural rainfall events. Tap water was deemed adequate as the nutrient levels are negligible in the area (HVAPU, 2013) and the focus of analysis on differences seen between groups of trays. Fertilizer was also applied shortly before the third simulated rain event.

Within 24 hours of the natural rainfall event, samples of infiltrated water were transferred into plastic collection bottles and brought to the Environment Lab located in the Integrated Science and Technology building at JMU for refrigeration. A Dionex DX100 ion chromatograph (IC) was used to analyze each prepared sample for nitrate and phosphate concentrations in accordance with Method 4110 – Determination of Anions by Ion Chromatography (APHA, 1998). The CDS software package from Chromeleon was used to produce numerical and graphical measurement outputs for further analysis. These materials and instruments were chosen to best simulate green roof practices while considering their availability and difficulty of use during the short time frame this study was conducted.

Results and Analysis

After an initial natural rain sample set was analyzed by the IC, it was observed that phosphate and some nitrate readings fell below the IC's sensitivity. Thus their respective peaks could not be delineated by the Chromeleon software and the event data was left out of statistical analysis. On the other hand, fertilizer application increased these levels greatly among the first water samples obtained. Elevated concentrations can be seen in Appendix C for the natural rain event and third simulated event as they occurred shortly after fertilizer applications. Due to the IC's limited period of analysis for each sample, the amount of nitrate recorded for most samples analyzed from events following fertilization (as well as a few phosphate samples) is less than the actual total amounts in these samples. In other words, the actual quantities of nitrate and phosphate in these particular samples were greater than the IC had time to analyze. These "greater than" nitrate or phosphate values took the visual form of plateaued peaks in the software's graphical display. Such readings are denoted in Appendix C.

To determine if differences in nitrate and phosphate levels between groups were significant for a given rainfall event, the One Way ANOVA statistical test was used within Microsoft Excel. This test was an appropriate method as there were more than three groups and each group was independent of the others. The null hypothesis was that the nutrient levels were comparable across all groups. The alternative hypothesis was that the nutrient levels differed significantly between groups. The data obtained from each event and ANOVA test results are shown in Appendix C.

	Statistical Significance Between Groups (p-value)			
	Natural Event	**Simulated Event 1**	**Simulated Event 2**	**Simulated Event 3**
Nitrate	0.029	0.948	0.028	0.120
Phosphate	0.058	0.980	0.786	0.303

Table 2: Only nitrate concentrations for the natural rain event and second simulated rain event proved significantly different across groups (p-value < 0.05).

	Average Nitrate Concentrations (ppm)			
	Natural Event	**Simulated Event 1**	**Simulated Event 2**	**Simulated Event 3**
Controls	326.58	70.31	105.12	297.45
Group A	262.06	68.45	145.36	338.53
Group B	220.61	77.49	169.40	355.70
Group C	193.07	72.27	132.31	350.98
Group D	172.56	76.03	100.52	360.44
Standard Deviation	61.20	3.80	28.64	25.48

Table 3: Average nitrate concentrations varied in magnitude and pattern across rainfall events.

The statistical significance between groups for each event and both nutrients was determined, resulting in a total of eight p-values, as seen in Table 2. Of these eight, differences in nitrate levels between groups were significant (p-value < 0.05) among samples from the natural rain event (p-value = 0.029) and second simulated event (p-value = 0.028). As only differences in average nitrate concentrations were significant for these two events, only relevant nitrate data is shown in Table 3. For the natural rain event, average nitrate levels for each group had a strongly inverse relationship to the quantity of biochar added. As shown in the summary table in Appendix C, the average nitrate concentration reduction across groups was roughly 38.51 ppm. The greatest reduction, 64.53 ppm, was seen between the control group and Group A (containing 2% biochar by volume). The average nitrate concentration was 41.44 ppm less for Group B compared to Group A, 27.54 ppm less for Group C compared to Group B, and 20.51 ppm less for Group D compared to Group C. Average concentrations ranged from 172.56 ppm in Group D to 326.58 ppm in the control group. For this rain event, there were three “greater than” values from the control group, four from Group A, two from Group B, one from Group C and none from Group D. This general decline in the number of samples with nitrate concentrations too large to be fully accounted for also relates inversely to biochar quantities added. Thus, despite inaccurate readings provided by the ion chromatograph the difference in nitrate levels between groups may remain statistically significant if analyzed properly. The difference in phosphate levels between groups was not deemed significant (0.058) though it was close to the 0.05 threshold.

For the second simulated rain event, average nitrate concentrations had an inverse and then converse relationship to the quantity of biochar added. Concentrations rose from 105.12 ppm in the control group to 145.36 ppm in Group A, then to 169.40 ppm in Group B containing 5% biochar by volume. Average concentrations then fell in a similar manner from 169.40 ppm to 132.31 ppm in Group C, then to 100.52 ppm in Group D containing 10% biochar by volume. There were no “greater than” values from this simulated event indicating that for all intents and purposes the p-value obtained for nitrate concentration differences between groups should be viewed as accurate. Again, the differences in phosphate levels between groups were not considered significant.

A pertinent question arising from the collected data is why nitrate concentrations are the only measurements with statistically significant patterns witnessed across groups, even if only for two rainfall events. Most fertilizers are nitrogen-based thus this phenomenon is highly relevant to green roof practices. The addition of biochar with biosolid application has been shown to lower nitrate leaching but the exact method by which it does this has not been identified. In one particular study, it was proposed that biochar may have absorbed nutrients present in applied biosolids (Knowles *et al.*, 2011). More specifically, Sika and Hardie (2013) concluded that pine wood biochar, similar to that used in this study but derived from sawdust, significantly reduced ammonium nitrate leaching in South African sandy soils. Reductions were also observed in a similar study and primarily credited to biochar's ability to physically absorb nutrients and water in its microporous structure (as cited in Sika and Hardie, 2013). Nonetheless, the process by which the nitrogen cycle is altered becomes even more elusive when considering that biochar's high total negative charge should repel anions such as nitrate. This characteristic requires much research in order to determine if a substantial tradeoff is being made. For example, raising the pH of soils via biochar application may simply decrease nitrification, thus resulting in the buildup of less-leachable ammonium (Kemmitt *et al.*, 2005).

Another interesting observation is the different patterns the statistically significant natural and simulated rainfall events produced, as seen in Figure 3. Samples from the natural rain event displayed a clear reduction in nitrate concentrations, though generally very high due to fertilization, as biochar volume increased. On the other

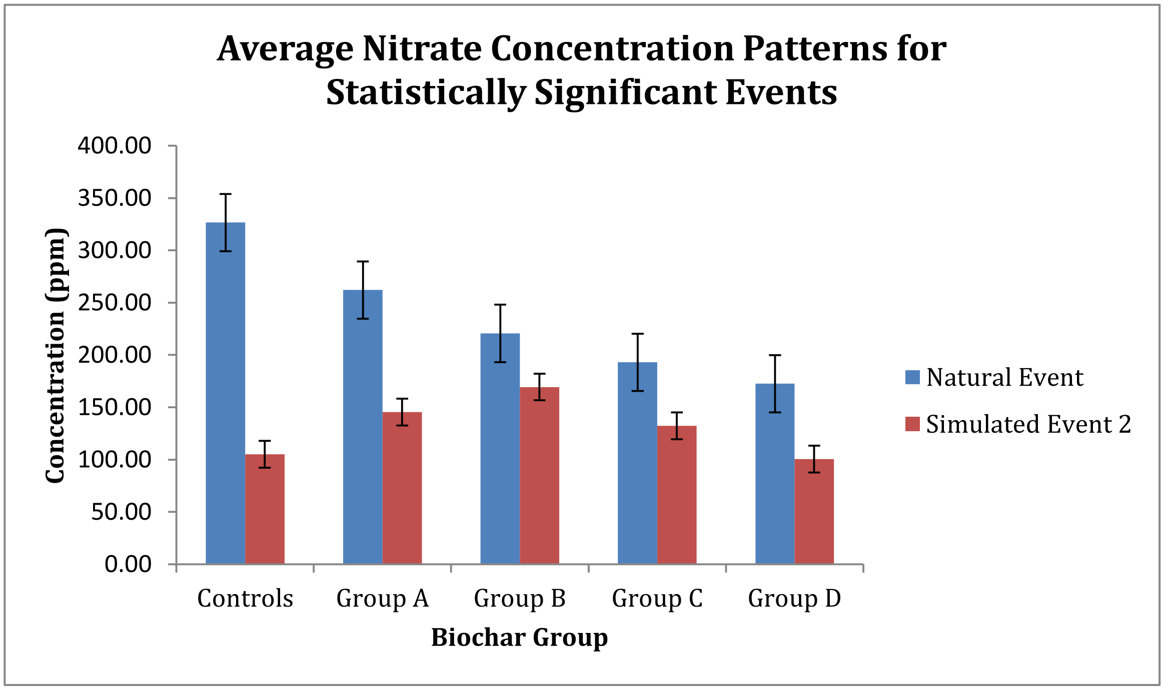

Figure 3: Average nitrate concentrations were inversely related to biochar quantity for the natural rain event but followed a bell-shaped pattern for the second simulated event. Error bars represent standard error.

hand, the second simulated rainfall event produced more bell curve-like results with the lowest average nitrate concentrations found in the control group and Group D samples. The simulated event may have represented the results of a first-flush effect in that there was no precipitation between fertilization and the start of the actual event. Furthermore, the fertilizer may have filled the pore space available in the biochar during the natural rain event and remained full of nitrate so that the fertilizer applied for the second simulated event had no option but to wash away with the leachate. Despite the significant difference between rainfall intensity and previous amounts of precipitation for each event, no surface runoff resulted from any of the simulated rain treatments. This trend attests to the porosity of the expanded shale constituent even with intense simulated rainfall. When rainfall intensity is moderate, biochar may have more time to absorb water and, consequently, nutrients such as nitrate before becoming fully saturated. When storm events produce short, intense rains, as is predicted by climate change models, there may be a minimum biochar quantity that can effectively reduce nitrate retention. For simulated event two, average nitrate concentrations did not drop below that of the control group in any group other than Group D with 10% biochar by volume. With this much biochar however, it is important to take into consideration other effects on soil quality such as acidification. Supporting the idea that a threshold quantity of biochar may be required for intense storm events, Group C did produce nitrate concentrations lower than that of Group A.

This study had several limitations that should be addressed in future studies in order to obtain more data of statistical significance and confirm the aforementioned conclusions. In order to compose a more complete picture of the effect of biochar on green roof systems, all leachate should be collected. Doing this would allow for water retention and evapotranspiration measurements to be conducted. To precisely measure rainfall in the event that natural precipitation is not enough, a rain simulator instrument would be required. Though the ion chromatograph used in this study was capable of handling tens of samples at a time with minimal preparation, better-suited equipment would have fewer issues, if any, in terms of measuring particularly high or low nutrient concentrations. This study clearly shows that it is easily possible to add nutrients in excess and significantly affect experimental data. Lastly, a better understanding of the composition of compost, if used, would facilitate analysis and potentially direct research in discovering a proper balance between compost and biochar use as way to reduce synthetic fertilizer application across the green roof industry.

Conclusions

With the largely proven benefits of green roofs gaining attention in many regions across the globe, future progress for the industry will depend on minimizing the shortcomings of installation and management practices. Of these, the still-required use of nitrogen-based fertilizers to promote early growth of vegetation, no matter how resilient, contributes to the issue of excess nutrient loads reaching important waterbodies via urban runoff. Stormwater management systems throughout the U.S. direct overflow into streams and rivers that effectively relocate pollutants elsewhere. Externalizing the environmental issues modern cities cause to downstream environments, many of which urban centers directly or indirectly depend on, represents an unsustainable, stopgap course of action that creates a linear flow of nutrients away from population centers. Green roofs offer an opportunity in the challenge to transform the conditions under which the majority of the world's population lives into more ecologically and people-friendly ones. Extensive green roofs in particular deliver an ideal combination of environmental services and physical build qualities that allow them to be established on many existing structures. Despite their flexibility, the weaknesses of extensive green roof practices must be addressed.

It is clear from the limited data gathered that increasing biochar quantities reduced average nitrate concentrations but not average phosphate concentrations. This interesting phenomenon of anion retention is certainly a property that calls for much further research. Biochar's chemical and physical structure may give it this unique characteristic that other soil amendments with high cation exchange capacities are unable to duplicate. Additionally, biochar's low density makes it an enticing green roof amendment in combination with other lightweight constituents such as expanded shale. Its carbon sequestration potential will also likely make it more desirable to the green roof industry.

Much more research should be conducted on the role of biochar in green roof structures but early findings support the recommendation for its consideration as a soil amendment with numerous useful qualities that can be utilized in a wide range of circumstances. The urbanization of the planet and rapid climate change presents challenges that will require complex and adaptable solutions. However, the services provided by green roofs and supplementary biochar amendments can be taken advantage of promptly, an attractive characteristic many other proposals do not offer. Whether or not biochar becomes a common constituent in the green roof industry, it is essential that current fertilization practices are reevaluated in the context of the effects modern approaches to stormwater management have on the surrounding environment.

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Appendix A

Sedum plugs listed top to bottom: S. *rupestre* 'Angelina', S. *cauticola* 'Lidakense' and S. *hybridum* 'Immergrunchen'

Appendix B

Plastic tote containers for collection of infiltrated rainwater (left) and final setup (right).

Appendix C

Nitrate and phosphate concentrations for each event with following summary and ANOVA test results. Concentrations marked with an asterisk are less than the actual total due to restricted IC analysis run times.

Natural Event (8/23/14): Nitrate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
324.123*	254.737*	218.798*	129.665	110.985
406.531*	280.051*	262.755*	171.772	202.658
393.611*	245.478*	181.605	309.997*	157.239
182.074	267.963*	219.294	160.844	219.348

Natural Event (8/23/14): Phosphate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
233.744	186.286	211.933	190.576	186.287
588.458*	87.972	224.055	108.021	220.206
650.527*	216.567	239.689	282.582	307.559
221.822	223.156	281.624	199.146	308.032

SUMMARY (Nitrate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	1306.3393	326.58484	10591.123
Group A	4	1048.2295	262.05737	229.02357
Group B	4	882.45199	220.613	1100.8727
Group C	4	772.27894	193.06973	6394.7504
Group D	4	690.23068	172.55767	2373.7114

ANOVA (Nitrate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	59936.233	4	14984.058	3.6211778	**0.0294692**	3.0555683
Within Groups	62068.444	15	4137.8962			
Total	122004.68	19				

SUMMARY (Phosphate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	1694.5513	423.63781	51811.236
Group A	4	713.98101	178.49525	3899.7288
Group B	4	957.29998	239.325	924.27428
Group C	4	780.32452	195.08113	5090.8995
Group D	4	1022.0842	255.52106	3835.3084

ANOVA (Phosphate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	152278.9	4	38069.726	2.9033623	**0.0579615**	3.0555683
Within Groups	196684.34	15	13112.289			
Total	348963.24	19				

Simulated Event 1 (9/28/14): Nitrate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
90.047	55.382	86.203	60.235	62.108
65.666	55.090	101.569	68.643	77.425
58.420	74.799	57.807	107.538	95.198
67.105	88.526	64.400	52.652	69.401

Simulated Event 1 (9/28/14): Phosphate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
21.148	15.437	27.064	14.296	11.985
21.382	15.337	19.342	12.018	17.864
16.006	21.203	13.648	26.645	22.273
14.775	21.372	10.743	12.056	17.755

SUMMARY (Nitrate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	281.23891	70.309728	187.58869
Group A	4	273.79717	68.449294	264.2082
Group B	4	309.9789	77.494725	404.82758
Group C	4	289.06905	72.267263	595.56574
Group D	4	304.13254	76.033136	202.37227

ANOVA (Nitrate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	231.38443	4	57.846107	0.1748079	**0.9479091**	3.0555683
Within Groups	4963.6874	15	330.91249			
Total	5195.0718	19				

SUMMARY (Phosphate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	73.310854	18.327714	11.76542
Group A	4	73.349148	18.337287	11.613317
Group B	4	70.795883	17.698971	51.733571
Group C	4	65.015704	16.253926	49.125561
Group D	4	69.877685	17.469421	17.795533

ANOVA (Phosphate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.641583	4	2.9103956	0.1024546	**0.9799157**	3.0555683
Within Groups	426.1002	15	28.40668			
Total	437.74179	19				

Simulated Event 2 (9/30/14): Nitrate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
126.923	144.923	216.861	130.548	72.989
106.527	125.631	169.352	144.173	101.041
81.638	136.139	121.128	174.455	133.022
105.380	174.765	170.258	80.074	95.017

Simulated Event 2 (9/30/14): Phosphate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
19.732	19.809	23.674	19.775	12.302
17.681	11.347	19.044		16.222
19.660	10.883	8.383	20.815	
7.866	18.266	26.642	13.925	17.773

Samples from trays C2 and D3 did not contain enough phosphate for the ion chromatograph to detect.

SUMMARY (Nitrate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	420.46694	105.11674	342.94479
Group A	4	581.45846	145.36462	446.36574
Group B	4	677.59994	169.39999	1527.8087
Group C	4	529.24995	132.31249	1549.5475
Group D	4	402.06954	100.51739	614.96024

ANOVA (Nitrate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13122.837	4	3280.7092	3.6601766	**0.0284471**	3.0555683
Within Groups	13444.881	15	896.32538			
Total	26567.717	19				

SUMMARY (Phosphate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	64.937939	16.234485	32.030419
Group A	4	60.305502	15.076375	21.355915
Group B	4	77.743371	19.435843	64.071529
Group C	3	54.514334	18.171445	13.796529
Group D	3	46.296574	15.432191	7.9494334

ANOVA (Phosphate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	52.100174	4	13.025044	0.4277351	**0.7861175**	3.1791171
Within Groups	395.86552	13	30.451194			
Total	447.96569	17				

Simulated Event 3 (10/2/14): Nitrate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
297.348*	272.338*	327.324*	361.086*	376.594*
298.060*	353.492*	329.290*	383.124*	336.605*
261.436*	358.694*	379.923*	327.082*	358.467*
332.942*	369.578*	410.493*	332.636*	370.103*

Simulated Event 3 (10/2/14): Phosphate (ppm)				
Controls	**Group A**	**Group B**	**Group C**	**Group D**
798.624*	624.021*	786.637*	920.344*	1030.565*
792.568*	893.651*	806.988*	965.868*	867.040*
642.426*	921.846*	991.744*	838.297*	874.899*
868.358*	855.908*	1109.059*	872.498*	970.042*

Sample B3 was not fully extracted from its vial by the ion chromatograph thus the summaries and ANOVA results below do not take it into account.

SUMMARY (Nitrate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	1189.79	297.45	852.36
Group A	4	1354.10	338.53	1991.95
Group B	3	1067.11	355.70	2252.47
Group C	4	1403.93	350.98	680.99
Group D	4	1441.77	360.44	308.77

ANOVA (Nitrate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10144.946	4	2536.2366	2.2182156	**0.1195814**	3.1122498
Within Groups	16007.151	14	1143.3679			
Total	26152.098	18				

SUMMARY (Phosphate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Controls	4	3101.9763	775.49408	9052.4147
Group A	4	3295.426	823.8565	18478.275
Group B	3	2702.684	900.89466	32602.71
Group C	4	3597.0074	899.25185	3104.631
Group D	4	3742.5465	935.63662	6196.5809

ANOVA (Phosphate)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	67331.422	4	16832.855	1.3412548	**0.3034023**	3.1122498
Within Groups	175701.12	14	12550.08			
Total	243032.55	18				