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Soil-water-energy nexus of green roofs

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SOIL-WATER-ENERGY NEXUS OF GREEN ROOFS

by

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ABSTRACT

As the urban landscape continues to sprawl into previously undeveloped land to accommodate population growth, the need to design cities that effectively manage urban stormwater is imperative for a sustainable future. Green roofs use rain-harvesting techniques to reduce urban stormwater discharge while simultaneously providing traditional roof services as well as several ecosystem services. However, green roof media design varies greatly among commercial applications, and little guidance is available to engineers when selecting the media for prospective green roofs. Efforts to maximize stormwater retention and enhance urban heat island mitigation capabilities of green roofs while concurrently reducing nutrient loading were examined in this research by investigating the soil-water-energy nexus of green roof media design. Two commercially available green roof media, Arkalyte and GAF, were investigated with hydrogel amended and non-amended conditions to compare the thermal and hydraulic properties of green roof media in field and lab applications to determine performance under different climatic conditions. Concentrations of total nitrogen, total organic carbon, and total phosphorous in green roof leachate decreased due to the addition of hydrogel amendments to green roof media in the in-vitro investigation. The hydrogel amendment increased field capacity green roof media by 4% to 26% in the field application of this research; however, hydrogel did not substantially impact the rate at which water was evapotranspired, indicating greater evapotranspiration can be achieved while concurrently decreasing stormwater runoff, through media amendment approaches.

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NOMENCLATURE

Symbol	Description
λ	Latent Heat of Vaporization

1. INTRODUCTION

1.1. URBANIZATION

Today just over half the world's population live in urbanized areas, and by 2050 the urbanized population will increase to 66% according to the United Nations (United Nations, 2019). As populations grow, urbanized areas must grow as well to accommodate the large populations resulting in urban sprawl and expansion into rural areas making what was once pervious space, impervious. The total amount of impervious surfaces within a city varies substantially spatially. New York has a total impervious area of 61.1% while Nashville only has 17.7% (Nowak & Greenfield, 2012). Impervious surfaces include sidewalks, roadways, parking lots, and roof tops, all of which are the components of a thriving city; however, these impermeable surfaces cause several negative environmental and human health impacts.

1.2. URBAN HYDROLOGY AND CLIMATE

Impervious surfaces have a direct, quantifiable effect on urban hydrology. Having a large number of impervious areas increases flood risk and frequency (Jones et al., 2005). Areas that have high densities of impervious surfaces experience reductions in interception, infiltration, and evapotranspiration because those surfaces disconnect the natural water cycle within cites (Stovin, Vesuviano, & Kasmin, 2012). Infiltration is reduced by impervious surfaces because the rainfall cannot penetrate the ground surface. The runoff coefficient is also impacted with increased transport velocity of runoff to local water bodies. This urban stormwater management disruption is further exacerbated by increased precipitation events in many urban settings and climate uncertainty. Collectively, these changes to the urban watersheds lead to an increased volume and rate of stormwater entering collection networks, often including combined sewer systems (CSS) in older, large metropolitan areas, which convey municipal wastewater and stormwater through the same sewer network. During flood conditions, wastewater and stormwater that is typically treated by municipal wastewater treatment plants is by-passed into a combined sewer overflow (CSO) system. CSOs directly discharge a mixture of stormwater and municipal sewage into surface waters without treatment for pathogens, nutrients, or other toxic substances, thereby causing degradation of urban hydrology as well as potentially damaging infrastructure (Berretta, Poë, & Stovin, 2014).

Impervious surfaces in urban areas also adversely affect urban climates by disrupting the natural water cycle and decreasing the areas albedo. The impervious surfaces cause a phenomenon known as the urban heat island (UHI) effect, whereby annual mean temperatures are 1-3°C warmer in urban environments than their surrounding rural counterparts (EPA, 2020). The temperature difference between rural and urban areas has been shown to be as high as 12°C during evening and overnight hours (EPA, 2020). With the advent of urban sprawl, urban areas are reducing the area of cooler rural areas, which could potentially increase ambient temperatures globally.

1.3. GREEN INFRASTUCTURE

The impervious area in urban watersheds can be significantly reduced by implementing green infrastructure best management practices (BMPs) such as green roofs, permeable pavement, rain gardens, etc. Green infrastructure reconnects the hydrologic cycle in urban areas which permits natural infiltration and evapotranspiration of stormwater to occur unlike impervious grey infrastructure. Using green infrastructure, specifically extensive green roofs to concurrently alleviate pluvial flooding and combat urban heat islands is quickly becoming a more accepted and applied approach in large urban areas. Many investigations have been conducted on green roofs effects on urban hydrology and urban heat island mitigation; however, knowledge is limited on how to predict the hydrological and heat mitigation performance of green roofs before it is constructed in the field. At present, no green roof design guidance exists that assesses the impacts of green roof media design and selection on the hydrological and urban heat island mitigation performance; therefore, advancing the green roof media design has not been effective or, in most cases, evaluated at all. Linkage to water quality impacts have also not been fully presented and certainly not integrated into one comprehensive design guidance tool.

Another difficulty associated with extensive use of the green roof lies in that a majority of benefits associated with green roofs are societal benefits and very qualitative. Most of the current models focus on the water benefit with no little consideration of energy benefit and are empirical in nature. There is a lack of definitive models that can comprehensively quantify the coupled water and energy benefits of green roofs for the urban community. As a result, the added green roof construction cost is typically bore solely by the building owner as few economic vehicles are in place, such as subsidies, tax incentives, or service fee reductions implemented to facilitate installation of green roofs to combat costs afforded only by the building owner.

1.4. INVESTIGATION OBJECTIVES

The core purpose of this investigation is to understand the interaction between green roof media properties, water budgets, and climate conditions of green roofs and integrate these properties when designing a field-scale green roof for optimum performance. To accomplish the abovementioned goal, the following objectives were established:

1) Develop a methodology to collect, sample, and test nutrient concentrations from green roof media;
2) Quantify and describe the effect of amendment on water holding capacity, nutrient retention, and potential ET rate impacts; and
3) Determine media evapotranspiration coefficients (crop coefficients) for different green roof media and green roof media mixtures.

The standardized testing methodology used in the investigations provide design guidance for green roof optimization of potential urban heat island mitigation and stormwater retention while minimizing the potential negative impacts caused by nutrient runoff. The results of this investigation will contribute to a design guidance tool for green roofs, and particularly for optimizing the performance and benefits of various green roof media mixtures.

2. LITERATURE REVIEW

2.1. URBAN SPRAWL

In today's modern society and economy, urban environments are favored over rural counterparts. Urban and suburban environments in the United States and around the world have seen a significant population growth over the past decades, while the rural population growth rates have decreased (Parker et al., 2018). Globally, it is projected that by 2050 there will be three urban dwellers to every two rural dwellers (Satterthwaite, McGranahan, & Tacoli, 2010). In the United States alone, the United Nations project that urban areas are home to 90% of the total U.S. population (Li, Bou-Zeid, & Oppenheimer, 2014). The rural exodus can be attributed to factors such as industrialization of the global economy, modernization of society and technology, and the belief of better employment opportunities in urban and suburban areas (Pawan, 2016).

To accommodate the increasing population, rural and suburban areas must also grow spatially. Urbanization is the phenomenon known to describe this spatial growth of land used for residential, industrial, commercial, and transportation purposes into the surrounding rural environment. Since 1880, the United States Census Bureau has included a record of rural and urban populations. In 2010 the Census Bureau defined urban areas as "Urbanized Areas (UAs) of 50,000 or more people;" and "Urban Clusters (UCs) of at least 2,500 and less than 50,000 people", whereas, rural areas were defined as "…all population, housing, and territory not included within an urban area" (Ratcliffe, Burd, Holder, & Fields, 2016). The 2010 Census Bureau estimated that the U.S. urban land cover was approximately 68 million acres or about 3% of the total U.S. land cover

(Bigelow & Borchers, 2017). The United States Department of Agriculture notes that urban land use has steadily increased over time, and once land has been urbanized, it rarely reverts back to an undeveloped use (Bigelow & Borchers, 2017).

2.1.1. Urbanizations Effect on Urban Hydrology. Prior to 1972, urban stormwater was largely unregulated, and industrial as well as municipal wastes in urban areas entered water bodies untreated (Franzetti, 2005). The water on urban surfaces transports pollutants, pathogens, and nutrients into nearby water bodies, which can cause significant impairments and degradation. Urban stormwater is estimated to be the primary source of impairment for 13 percent of assessed rivers, 18 percent of lakes, and 32 percent of estuaries in the U.S. (Council, 2009). In 1972 the Clean Water Act (CWA) and the National Pollutant Discharge Elimination System (NPDES) was created and, in part, addressed the growing issue of urban stormwater management and degradation of urban water bodies. The NPDES regulation created water-quality standards for industrial and municipal wastes that discharge into water bodies which led to the establishment of combined sewer systems and combined sewer overflow (CSO) systems in large metropolitan areas. These CSO systems convey both municipal sewage as well as industrial process wastewater in the same pipe network. Rainwater is also conveyed in this system during wet weather conditions. Theoretically this sewage-rainwater mix was to be treated at a treatment facility before being discharged into receiving water bodies; however, during large rainstorm events the sewage bypasses the treatment facility and is directly discharged into the receiving water bodies. In 1990, the U.S. EPA created Stormwater Amendments to the Water Quality Act of 1987, which required updates to the CSO systems and no longer allowed CSO systems to discharge raw, untreated sewage into water bodies. Cities now must separate municipal wastewater and stormwater into sanitary sewer systems (SSSs) and municipal separate storm sewer systems (MS4s), construct massive reservoirs to contain the CSO wastewater until wastewater treatment capacity is available, or minimize the volume of stormwater entering the combined system through the use of best management practices (BMP) (Alberti, 2008).

2.1.2. Urban Heat Islands (UHIs). The Urban Heat Island is a well-documented phenomenon that describes increased ambient temperatures in urbanized areas as compared to geographically similar rural areas. The cause of UHIs are multifactorial but commonly attributed to land use alterations like the use of low albedo construction materials in urban areas with a concurrent reduction of vegetated areas. Hubbart et al. 2014 (Hubbart et al., 2014), investigated the impact of urban land use intensity on local climate parameters such as average air temperature, relative humidity, average wind speed, and solar radiation. Results indicated higher average temperatures in urban areas than rural counterparts as well as alterations in urban energy budgets due to land use intensity (Akbari et al., 2005).

Albedo, or the ability for a material to reflect solar radiation, is measured on a scale of 0 to 1, where 0 indicates total absorption of solar radiation and 1 indicates complete reflection of solar radiation. Materials used in urban development, such as asphalt, concrete, and rubber roofing membranes, often have low albedo and absorb significant amounts of solar radiation. When the solar radiation that is absorbed by these materials is released, the excess thermal energy is observed by increased ambient temperatures in the urban areas. Asphalt typically has an albedo value of 0.05-0.15, and Portland gray concrete has an albedo value of 0.20-0.0.40 (Cantor, 2008). Akbari et al

(Akbari, Menon, & Rosenfeld, 2007) projected that increasing roof and pavement albedo by about 0.25 and 0.10, respectively, can result in a net albedo increase for urban areas of about 0.1. Several investigations have linked the increase of albedo using “cool material” in urban areas to reduced daytime and nighttime temperatures in the urban environment (Susca, Gaffin, & Dell’Osso, 2011).

2.2. GREEN INFRASTRUCTURE

Best Management Practices (BMP) techniques are used to reduce stormwater pollution as well as volume of runoff entering CSOs in urban areas. BMP’s often include green infrastructure (GI) techniques, which have gained popularity over the years due to their efficacy of mitigating urban stormwater pollution and excess runoff. Unlike gray infrastructure, green infrastructure uses natural techniques designed specifically to mimic natural processes while performing the same functions as gray infrastructure. The purpose of green infrastructure is to reconnect the water cycle in cities by increasing the amount of pervious spaces or harvesting the rainfall to be stored until it can be used later. GI typically fall into two types of technology, vegetated GI and non-vegetated GI.

2.2.1. Non-vegetated Green Infrastructure. Non-vegetated green infrastructure techniques include cisterns, rain barrels, sand filters, and permeable and porous pavement. These techniques use infiltration, storage, and sedimentation to recharge groundwater, retain stormwater for alternative uses, and remove pollutants in the urban environment. Non-vegetated green infrastructure techniques primarily focus on reconnecting the soil-water aspects of the water cycle.

Cisterns and rain barrels are very similar by design; both techniques' primary mode of stormwater mitigation is to simply capture rainwater and store it in a container, known as rain harvesting. This reduces the amount of stormwater runoff by capturing the stormwater before it enters the sewer systems. Cisterns are typically larger than rain barrels and are used for commercial applications; whereas, rain barrels are smaller and connected to residential homes. Retained water is commonly used for irrigation in dry periods or for non-potable uses.

Permeable pavement and pervious pavers are similar in function but are designed in very different ways. The goal of both techniques is to allow the rainwater to infiltrate into the soil underlying the pavers, however, how water is transported through the pavers to the underlying soil differs. Pervious pavement and asphalt are made with little to no sand and A/C ratios of 4.0 to 4.5, creating large enough voids in the concrete matrix that allows rain-water to flow through (NRCS, 2005b). In contrast, permeable pavers are made from solid materials, and water is transported to the soil through voids between pavers rather than through the paver itself. Permeable pavers are separated by joints filled with highly porous aggregate or by gaps between interlocking bricks (Alsubih, Arthur, Wright, & Allen, 2017). These joints allow water to percolate between the bricks, entering the soil and recharging the groundwater. Permeable pavement allows approximately 8% to 60% of the inflow to pass through to underlying media (Walker, 2013). In contrast pervious pavers provide a range of infiltration rates of approximately 40% to 93% (Mullaney & Lucke, 2014).

2.2.2. Vegetated Green Infrastructure. Vegetated green infrastructure uses the same methods of infiltration, retardation, and storage as non-vegetated green infrastructure; however, vegetated green infrastructure incorporates plants into the design to achieve the goal of stormwater runoff reduction and pollution mitigation. Plants can also utilize the stormwater via transpiration to grow, adding to the removal of water from the subsurface and reconnecting the water-soil-atmospheric components of the water cycle in urban environments. Rain gardens, bioswales, constructed wetlands, and green roofs are all examples of commonly used vegetated green infrastructure techniques that use plants as bioretention to mitigate stormwater and pollution. The differentiating factor between these techniques is how much water can be stored in the designed bioretention area and what type of vegetation is used. Rain gardens are typically designed as 7 to 20 percent the size of the impervious surface generating the runoff, four to eight inches deep, and must be grown in depressional landscaped areas (Tennis, Leming, & Akers, 2004), (Gardens, 2018). Also rain gardens are typically used in smaller residential applications, and use water-tolerant native plant species to mitigate stormwater (Gardens, 2018), (NRCS, 2005). Bioswales are much larger than rain gardens, are often parabolic or trapezoidal in shape and are typically found near large parking lots and roadways (NRCS, 2005a). Swales vary greatly in size but are typically designed to convey a 10-year rainstorm, or about 4.3 inches of rainfall in 24 hours (NRCS, 2005a). Constructed wetlands are even larger than bioswales, are used to treat as well as store stormwater and are generally built in floodplains with soil- or gravel-based horizontal flow system and natural vegetation (Scholz, 2015).

2.3. GREEN ROOFS

Green roofs are best described as vegetated rooftops that are designed to retain and capture rainfall within the green roof media that is used for plant growth. Green roofs are typically constructed in a layered system with root barriers, drainage material, a filter layer, media, and vegetation atop roofing material. The design and construction of green roofs can vary greatly based on the building owner's needs as well as the structural capabilities of the building it resides on. Often green roofs fall into two main categories: extensive, which have a soil media depth of 3 inches or less, and intensive, which have media depths greater than 3 inches. Since extensive green roofs have only 3 inches or less of media, only shallow rooting vegetation such as Sedum or native grasses can be used to cover the green roof. However, since intensive green roofs can be much deeper, the limiting factor of vegetation usage is based on climate and structural support capabilities (Weiler & Scholz-Barth, 2009).

2.3.1. Intensive Green Roof Cost and Construction. Intensive green roofs are solely defined based on soil media depth. The media depth of an intensive roof can vary substantially to accommodate a range of vegetation, such as small plants to large fully grown trees, and allow access for human use. It is hard to retrofit an existing rubber roof with an intensive green roof because often the design of the green roof is a major structural component of the building. The weight of an intensive green roof depends on factors such as soil type, amount of vegetation, type of vegetation, soil water content, and pitch of the roof. Typical weights of intensive green roofs range from 30 to 100 pounds per square foot dry (Archtoolbox, 2020). The cost of a green intensive green roof also varies greatly and depends on factors like area of vegetation, type of vegetation, structural reinforcements, amount of soil used, as well as associated operation and management costs. The material cost alone can range from $20 per square foot to more than $200 per square foot (Reggev, 2019).

2.3.2. Extensive Green Roof Cost and Construction. Extensive green roofs require less structural support, and it is easier to retrofit existing roofs with green roof material. Usually extensive roofs are not meant to be used for human activity, rather just used for the ecosystem services as well as stormwater and heat island mitigation benefits. Extensive green roofs require less material, are generally lighter than their intensive counterparts, and require little to no operation and maintenance costs. Extensive green roofs typically weigh between 10 and 30 pounds per square foot and cost approximately $10 to $50 per square foot (Archtoolbox, 2020), (Reggev, 2019).

2.3.3. Green Roof Ecosystem Services. Green spaces in urban environments significantly improve human health and provide abundant ecosystem services. These ecosystem services include: provisioning services, any type of benefit to people that can be extracted from nature; regulating services, any basic service provided by the ecosystem that makes life possible for people; cultural services, any non-material benefit that contributes to the development and cultural advancement of people; and supporting services, any fundamental process in nature (Federation, 2020). Green roofs provide many of these services in urban environments; however, one of the biggest hindrances to vast green roof implementation is the cost associated with construction and management of green roofs, which is solely borne by the building owner. Many of the benefits that green roofs provide are societal and environmental benefits that are not monetized to offset the costs incurred from the construction; however, economic incentives such as tax incentives and LEED certification points can be used to offset the capital and construction costs incurred by green roof building owners by adding a quantifiable value to the ecosystem services provided by the roof.

2.3.3.1. Provisioning services. The United Nations developed seventeen Sustainable Development Goals (SDGs) in 2015 to address the growing environmental and societal issues impacting future sustainability (United Nations, n.d.a). Eleven of these goals focused on creating sustainable cities to accommodate for future population growth. The growing population in urban environments has influenced a critical need to create provisioning systems that can potentially sustain food production in the urban environment. Cities and urban areas are often referred to as "food deserts", or areas that have limited access to supermarkets, supercenters, grocery stores, or other sources of healthy and affordable food (United States Department of Agriculture, 2019). In the U.S. alone, the USDA's Economic Research Service previously identified more than 6,500 food desert tracts (Dutko, Ver Ploeg, & Farrigan, 2012). These food deserts are often found in low-income neighborhoods within urban areas.

Clinton et al. (Clinton et al., 2018) suggests that pre-existing vegetated areas in the urban environment have the potential to produce 100–180 million tons of food annually; however, many heavy metals such as zinc, lead, zirconium, and copper are often found in urban soils that are of primary concern in food production in cities, mostly due to their potential human toxicity (Ma, Yang, Li, & Wang, 2016). Green infrastructure techniques are being used to add green space for safe food production in many large cities that have food deserts. Several studies have effectively grown tomato (*Solanum lycopersicum*), bean (*Phaseolus vulgaris*), cucumber (*Cucumis sativus*), pepper

(*Capsicum annuum*), basil (*Ocimum basilicum*), and chive (*Allium schoenoprasum*) on both extensive and intensive green roofs (Ouellette, Waltersº, & Middenº, 2013), (Whittinghill, Rowe, & Cregg, 2013). There are several obstacles pertaining to the design and composition of green roof media that must be overcome before this production system can be more widely used. The limitations of green roof media use for food production include having required nutrients, an adequate water holding capacity, as well as sufficient media depth for root growth. Designing green roof media to optimize these soil properties could help increase the feasibility and popularity of using green roofs provisioning potential as a solution to food deserts.

2.3.3.2. Regulating services. All parts of the water cycle are disrupted in urbanized environments due to the impervious materials used. Precipitation is unable to infiltrate or be removed from the ground via evapotranspiration (ET) due to impervious surfaces. ET is the cumulative process in which water is removed from the ground through evaporation within soils and the transpiration of vegetation. Impervious surfaces do not allow plants to grow and transpire groundwater from the soil and block the sun from warming the soil, inhibiting evaporation at shallow depths. Evapotranspiration is a critical component to the water cycle and has been shown to have cooling effects in areas through latent heat dissipation. Research suggests that increasing vegetation in urban settings can decrease ambient air temperatures by 2-4°C (Taha, 1997). In addition to less vegetation, urban areas have low albedos because of the dark construction materials used in the built environment. Roofs and pavements in urban areas account for approximately 60% of urban surfaces (Akbari et al., 2007). Several studies have shown that urban areas can reverse the UHI effect by increasing albedo of roof and pavements (Akbari et al., 2007). Climate-regulating services are provided by green roofs through potential urban heat island mitigation. Green roofs provide a vegetated area in urbanized settings that both decreases albedo and allows for evaporative cooling effects.

2.3.3.3. Cultural services. The impact of green spaces in urban environments on human mental health is becoming an increasingly popular topic. Traditionally the urban environment is associated with chronic stress, insufficient physical activity, and exposure to anthropogenic environmental hazards (Braubach et al., 2017). The World Health Organization (WHO) suggests that green spaces in urban environments promote physical activity and can help alleviate mild depression and reduce physiological stress indicator (World Health Organization, n.d.a). Engemann et al (Engemann et al., 2019) assessed the impact of green space on psychiatric disorder development in children. Results of the study found that the presence of high levels of green space during childhood are associated with a lowered risk of psychiatric disorders later in life.

Reconnecting human activity with nature in a traditionally built environment not only helps individual health, but also positively impacts the health of the community. Green spaces provide an aesthetically pleasing setting that creates opportunity for social engagement as well as recreational opportunity (Nutsford, Pearson, & Kingham, 2013). The amount of green spaces in an urban environment; however, is predominantly located in white and more affluent neighborhoods. Often low-income neighborhoods and communities of color have relatively poor access to safe and well-maintained parks and other types of open space (Wolch, Byrne, & Newell, 2014). The presence of green space like trees, parks, and other natural areas have also been shown to help decrease the occurrences of violent crimes in urban environments; however, it can also have negative impacts in low-income neighborhoods through gentrification (Shepley, Sachs, Sadatsafavi, Fournier, & Peditto, 2019).

2.3.3.4. Supporting services. Green roofs provide water-cycling-supporting services by reconnecting the water cycle in the urban environment. Urban environments pave over and build on pervious land with materials that are impervious. In doing so, water that falls on urban surfaces cannot be recharged into the ground as in natural areas and becomes overland flow into nearby water bodies. This change in land use and water flow has been shown to directly impact nearby receiving water bodies by altering stream hydrographs and geomorphology (Finkenbine, Atwater, & Mavinic, 2000). An investigation conducted by the U.S. Geological Survey studied the impact of urbanization on peak discharge rates on water bodies. The Salt Creek in Illinois observed an increase of discharge rates by about 100 percent from about 1,000 cubic feet per second (ft^3/s) to about 2,000 (ft^3/s) after urbanization of the watershed (Konrad, 2003). Not only does the volume of urban runoff increase due to impervious surfaces, but the time at which the peak flow occurs is shortened. An increase of impervious surfaces by 10 - 20% doubled peak flows associated with the 1.5 to 2-year recurrence intervals for most urban watersheds, which increases the potential to destabilize nearby streams (Bledsoe & Watson, 2000). The degree of perviousness also influences channel geometry and flow regimes in an urban watershed. Typically, areas with high perviousness are observed to have smaller stream channels, and channels deepen to accommodate larger flows as watersheds becomes urbanized (Bledsoe & Watson, 2000). In research conducted by Neller (Neller, 1988), the rate of channel bank erosion of geographically similar urban and rural channels was compared. The rate of channel bank erosion of an urban channel was found to be 3.6 times greater than that of a nearby rural channel.

Green roofs introduce pervious areas back into urbanized areas through rain harvesting and providing space for infiltration of rainwater. The vegetation component of green roofs also provides additional rainwater storage by transpiring rainwater captured in green roof media. Extensive and intensive green roofs have grown in popularity over the years as an effective stormwater BMP because rainwater that falls atop roofs gets captured in the green roof media, which results in stormwater flow attenuation and increases the lag time of the peak discharge. Many studies have shown that green roofs can reduce 40% to 100% of precipitation depending on green roof design and climatic conditions (Carter & Jackson, 2007), (VanWoert et al., 2005), (DeNardo, Jarrett, Manbeck, Beattie, & Berghage, 2005). Precipitation retention depends on several key factors of green roof design including media water holding capacity, media depth, climatic conditions, vegetation, and slope of roof (Getter, Rowe, & Andresen, 2007), (Sims et al., 2016), (Berndtsson, 2010).

2.4. HYDROGEL

Hydrogels are comprised of hydrophilic polymer chains that have the ability to hold large amounts of water. The negative charge of the carboxylic acids along the length structure of the hydrogel polymer creates a strong bond with the hydrogen atoms of water molecule and studies have shown that some hydrogels can absorb as much as 600 times their original volume of water (V. Wong, 2007). Hydrogels can be designed specifically to respond to a variety of physical and chemical stimuli to control the amount of water absorption as well as the amount of water desorption and can also reabsorb water after completely drying from a saturated state (Ahmed, 2015).

Hydrogel's ability to absorb copious amounts of water has made it a popular additive for different medical, environmental, and common household products. Hydrogel additives are used in pharmaceuticals, drug delivery systems, regenerative medicines, tissue engineering, biomedical applications, agriculture, medical adhesives, and even diaper materials (Ahmed, 2015). When used in agricultural applications, acrylamide is often added to the hydrogel polymer. Hesie et al (Heise et al., 2019) found that polyacrylamide hydrogel amendments increased water content of a sandy soil by 70%. In agricultural applications hydrogel can be synthesized to create specially design polymers that contain nutrients needed to promote plant growth. One study synthesized acrylic phosphorus-containing hydrogels which improved water retention as well as sorption of nutrients (Olekhnovich, Baidakova, Uspenskii, Slobodov, & Uspenskaya, 2016).

PAPER

I. SOIL-WATER-ENERGY BUDGET OPTIMIZATION FOR GREEN ROOFS

ABSTRACT

At present, one limitation to achieving more widespread use of extensive green roofs is a lack of definitive models that comprehensively quantify and predict the collective water-energy benefits of green roofs under different climatic conditions and green roof media designs. Without accurate valuation, implementation considerations are incomplete in terms of the positive value for the owner and the greater urban area. This research investigates the properties of green roof media that influence the water holding capacity, climate-specific evapotranspiration predictions, crop coefficients, and nutrient leaching characteristics of extensive green roofs under both lab and field conditions. Two commercially available green roof media, Arkalyte and GAF, were used in this study. A novel, in-vitro, nutrient-leaching method was developed to assess different green roof media's nutrient-leaching patterns and predict nutrient-leaching behavior in field-scale applications. The thermal performance of different green roof media designs was also examined by evaluating the field capacity and the crop coefficient in a set of field mesocosms. Hydrogel was added to green roof media in both the in-vitro and field investigations to evaluate the effect of media amendments on water retention, nutrient-leaching, and energy dissipation through evapotranspiration in green roof media under different climatic conditions.

A comparison of nutrient-leaching results from the in-vitro nutrient-leaching method and a previous 9-month field-scale analysis indicates a linear relationship; therefore, the developed in-vitro leaching method can be used to reflect field-scale nutrient leachability and water-retention performance of green roof media. The hydrogel amended green roof media resulted in a significant decrease in concentrations of total nitrogen, total organic carbon, and total phosphorus in green roof leachate. The hydrogel amendment also increased the water retention of Arkalyte and GAF green roof media by 4% to 26%. Accurate assessment of green roof media design properties are essential to maximize water retention in the media, subsequently providing substantial energy dissipation in the urban setting, and concurrently limit nutrient run-off and eutrophication of urban waters and downstream water bodies.

1. INTRODUCTION

1.1. THE URBAN CLIMATE

The global population is currently growing at a pace that will result in 8 billion inhabitants by 2023, and according to the United Nations, the urban population globally is growing disproportionately day by day (Roser, 2013).This increase in urban population causes a need for urban areas to increase in density and sprawl into previously undeveloped land. The expansion of impervious urban areas into undeveloped land disrupts the natural water cycle, impacting urban hydrology, urban climatology, and overall human health (Capps, Bentsen, & Ramírez, 2016). This concurrent population growth and urbanization is reflected in both the National Academy of Engineering's

Grand Challenges initiatives to restore and improve urban infrastructure and access to clean water (Engineering, n.d.a), as well as the Millennium Development Goals to ensure environmental sustainability (World Health Organization, 2018).

Urbanization leads to increased water-quality degradation, increased potential for disease transfer, and urban and downstream flooding (Walsh et al., 2005). In many large cities around the U.S., combined sewer overflow (CSO) systems are used to convey excess stormwater in the urban environment, which mixes with raw, untreated sewage that discharges to nearby urban waters. The U.S. Environmental Protection Agency (EPA) changed NPDES regulation standards to eliminate CSO usage and many urban areas in the U.S. have entered consent decrees with the EPA to find alternate ways to mitigate pluvial flooding (EPA, n.d.a). Approximately 860 communities with a total population of about 40 million people have CSO systems (EPA, n.d.a). Occurrences and cost associated with pluvial flooding are expected to increase in severity as a result of concurrent climate change and urbanization (Houston et al., 2011).

Urbanization also causes a phenomenon known as the Urban Heat Island (UHI). The UHI effect is created through three primary phenomena: increased short-wave radiation adsorption, increased energy retention capacity in built materials, and decreased evapotranspiration in the disrupted urban-water cycle. Dark materials that absorb short-wave radiation are used in urban development and energy is then released as long wave radiation by these materials, causing surface temperatures in urban areas to increase (Grimmond, 2007). Albedo is the material property that describes a materials ability to absorb solar radiation from the sun. Typically, rural areas have higher albedos than urban environments and can reflect more incoming solar radiation (Alberti, 2008). The addition of green spaces and high-albedo materials have been shown to decrease urban temperatures (Akbari, Pomerantz, & Taha, 2001). Susca et al (Susca et al., 2011), determined a 2°C temperature difference between the most vegetated areas and the least vegetated areas of four areas in New York City. Several investigations have concluded that the mitigation potential of high-albedo material is dependent on factors including building characteristics, urban environment, meteorological and geographical conditions (Yang, Wang, & Kaloush, 2015). The impact of the built environment on increased ambient air temperatures is also intensified due to the disruption of the water cycle in urban setting. Evapotranspiration (ET) cooling effects are eliminated in urban settings without vegetation. ET is a natural process commonly associated with vegetated areas that quantifies the amount of water removed through evaporation and transpiration of vegetation. The mass of water removed as vapor, or ET, can be converted into energy using the latent heat of vaporization, or the energy required to vaporize free water.

The impacts of UHI are profound in terms of social and financial costs. Recent investigations revealed UHI increased demand of 1-1.5 gigawatts of electricity in downtown Los Angeles, equating to $100 million annually. Mitigation of UHI could reduce municipal energy usage for cooling by 20%, saving over $10 billion annually in energy cuts across US (Akbari et al., 2001).

1.2. GREEN ROOFS BENEFIT IN THE URBAN ENVIRONMENT

Green roofs are a green infrastructure technique that has gained attention in recent years as a potential cost-effective way to mitigate pluvial flood risk, improve urban water quality, and mitigate UHIs. Green roofs are used to introduce green space back into the built environment to provide stormwater infiltration, thereby reducing stormwater runoff and decreasing the volume of water rapidly sent to nearby waterways during pluvial flooding. The amount of precipitation that is retained in the green roof media is dependent on factors such as thickness of the green roof media, its water content, roof slope, size of precipitation event, precipitation distribution during study periods, and climate (G. K. Wong & Jim, 2014). A wide range of stormwater retention rates have been determined based on these green roof design parameters (Hilten, Lawrence, & Tollner, 2008).

The same natural processes that green roofs use to capture, and store stormwater are used in urban developments to reconnect aspects of the water cycle in urban environments, are also simultaneously used to combat the UHI effect. Latent energy dissipation, through water vaporization of stored water, is a powerful cooling benefit in the urban environment that has been quantified for green roofs in many studies (Santamouris, 2014). Santamouris et al 2014 (Santamouris, 2014), reviewed several investigations that quantified latent heat dissipation of green roofs under differing design characteristics and found energy dissipation to range from 26 to 600 Watts per square meter. Water content and temperature are the driving factors that impact the amount latent heat a green roof can provide.

Several numerical and conceptual models have been developed to model the amount of evapotranspiration and energy dissipation green roofs provide (Xiong & Qiu, 2011), (Jahanfar, Drake, Sleep, & Gharabaghi, 2018). Typically, green roof models estimate ET using the FAO Penman-Monteith method, which uses metrological data to empirically approximate the amount of evapotranspiration that a vegetated area can provide, and then relate this to latent heat dissipation through the latent heat of vaporization of water. In a study by Li et al. 2014 (Li et al., 2014), the impacts of UHI mitigation by green roofs were modeled and results suggested that surface UHI could be reduced by 1 °C in the Baltimore-Washington metropolitan if about 30% of the roof areas were converted to green roofs. Li et al 2014, noted the main factor noted for UHI mitigation efficacy was maintaining soil moisture, but a study to improve moisture retention in roof media has not been investigated as an approach to improve green roof application for UHI mitigation.

1.3. GREEN ROOFS LIMITATIONS

Green roofs need media that is sufficiently fertile to sustain vegetation requiring available nutrients. Nitrogen, potassium, and phosphorous are common macronutrients in fertilizers present in commercial green roof media to promote plant growth. Water that is not retained in the green roof media can leach nutrients and organic carbon from the media to the urban watershed. Eutrophication is observed in many urban waters and connected downstream costal water systems, and the impacts from green roofs are not well understood, considered, or quantified. Numerous studies have investigated nutrient concentrations in green roof leachate in both field and lab applications (Morgan, Celik, & Retzlaff, 2013), (Buffam & Mitchell, 2015). Factors that impact stormwater retention, including media type, media depth, amount of precipitation, and vegetation, also impact nutrient concentration in green roof runoff (Whittinghill, Rowe, Andresen, & Cregg, 2015), (Carpenter, Todorov, Driscoll, & Montesdeoca, 2016); however, water-quality impacts of variable green roof media have not been well characterized, and no standardized testing of media for nutrient leaching has been developed.

The factors that impact the ET performance of green roofs include climatic conditions like solar radiation, wind speed, precipitation, and temperatures which can significantly vary depending on the geographic location, and media water holding capacity is also a prime factor in the green roof water balance. The variability of climatic conditions in urban environments presents a significant challenge when designing and selecting green roof materials to provide ET for UHI mitigation. Stovin et al 2012 (Stovin et al., 2012), notes that the prediction of green roof water-retention performance requires accurate meteorological data relating to ET under both well-watered and moisture-stressed conditions, and further research is needed to refine the predictive value of the model in response to specific plant, substrate, or other climatic factors.

1.4. COMPREHENSIVE GREEN ROOF MODEL AND DESIGN GUIDANCE

Green roofs provide many benefits to both the built urban environment and natural environment. Ecosystem services and traditional roof services that green roofs provide include: natural habitat creation, increased roof life expectancy to buildings, urban heat island mitigation, energy savings to the building, reduced air pollution, and reduced energy demands. To improve efficacy and implementation of green roof design, comprehensive valuation is needed. The UHI mitigation benefits of green roofs have not been thoroughly quantified and the potential negative impacts, such as increased nutrient addition to urban streams, have not been integrated into green roof media design. This research aims to examine the impact of green roof media design on green roof performance factors such as runoff reduction, UHI effect mitigation, nutrient leaching, water holding capacity, crop coefficients, and potential evapotranspiration to provide recommendations and guidance for the design of green roofs in different geographical regions.

This research attempts to address the absence of green roof design guidance by better understanding the relationships between soil-water-energy nexus in green roof systems and assist in efforts to optimize nutrient and water retention in green roofs in varying climates. The impact of green-roof-media design is investigated through development of in-vitro- and field-scale experiments and measurement of hydro-thermal benefits and nutrient leaching under a variety of climate conditions, media types, and amendments. Nutrient leaching and water retention properties of green roof media were examined in controlled in-vitro investigations and field capacity and potential evapotranspiration properties of green roof media were examined in field investigations. The in-vitro investigations focused on developing a methodology that can rapidly and accurately test green roof media's potential nutrient leaching and water retention in a full-scale green roof application. Also investigated in the in-vitro portion of this research is the impact of hydrogel granule amendments on nutrient leaching and water retention properties of green roof media. The field investigation portion of this research focuses on using hydrogel amendments to influence field capacity and potential evapotranspiration properties of green roof media. Data collected and interpretation provided unique insight into the thermal benefits of different media amendments, media water holding coefficient of green roofs, and developed a standardized method to collect and test green roof leachate.

2. MATERIAL AND METHODS

2.1. GREEN ROOF MEDIA AND CHARACTERISTICS

In this study two types of commercially available green roof media were tested in both field and in-vitro applications. The first media type tested was Arkalyte, an 80/20 composition of heat-expanded clay rock/composted pine bark, which had aged in ambient conditions, one year prior to the initial investigation. The second type of media tested was GAF GardenScapes^{TM} media, a blend of lightweight rock, organics, and carbon additives. The effect of amendments on hydro-thermal properties of green roofs was also investigated through the addition of hydrogel (HG) granules. HG is a highly hydrophilic material that is a common additive in the agricultural industry, medical applications, and in diaper material to increase the water absorption capacity of materials (V. Wong, 2007).

2.2. IN-VITRO WATER QUALITY COLUMNS

The water quality of different green roof media mixtures and compositions was studied using in-vitro simulated rainfall events. Seven testing columns were constructed from 30 cm diameter polyvinyl chloride (PVC) cylinders enclosed at the bottom using a cut 1.3 cm thick PVC sheet. A 0.64 cm barbed tube fitting was drilled into the bottom of the testing cylinders to allow for runoff collection from a drain hole. Leachate was collected in bottles attached to the testing cylinders drain hole via tubing and stored for water-quality analyses. To replicate rainfall events similar to that of South-Central Missouri, deionized water as fed into the system 10 times at a rate equivalent to a 25.4 mm 1-year, 30-minute rainfall event, per NOAA Technical Paper No. 40, via plastic tubing attached to a spray nozzle above each cylinder (Hershfield, 1961). The tubing system was set in parallel, distributing an equivalent rate of flow to each of the seven test cylinders. In the first series of rainfall events, six of the seven cylinders were filled with green roof liners comprised of a plastic root guard between two layers of fabric filter material and 7.5 cm of commercially available media, measured gravimetrically for consistency. Non-amended GAF and Arkalyte green roof media were tested and conducted in triplicate. The seventh testing column was a control column and was lined at the bottom of the cylinder with only white thermoplastic polyolefin (TPO) roofing. After 10 rainfall events the Arkalyte and non-amended GAF media were removed from the testing cylinders For the second series of 10 simulated rainfall events the testing cylinders were relined with fresh green roof liners and filled 7.5 cm deep with 5% and 10% HG-amended GAF green roof media.

Runoff samples collected from each rainfall event were then analyzed for the following water-quality parameters: total phosphorus (TP), total nitrogen (TN), and total organic carbon (TOC). Using Hach Method 8190 for a Hach DR/1900 Spectrophotometer, total phosphorus was measured, following EPA Method 365.2 for freshwater samples. Testing for TN and TOC was completed using a Shimadzu TOC-L TOC analyzer with standard catalyst per 720°C catalytic thermal decomposition/chemiluminescence and 680°C combustion catalytic oxidation methods, respectively. Known quality control standards for TP, TN, and TOC were prepared and analyzed with the runoff samples for each respective chemical analysis procedure. The mass of TN, TP, and TOC leached out per area of green roof for each 25.4 mm rainfall event was calculated for each green roof media mixture. Mass per area of each green roof media was then calculated by dividing the area of each column.

2.3. WATER ENERGY BALANCE

To investigate the thermal properties of different roofing materials the Emerson Hall rooftop on the Missouri University of Science and Technology (Missouri S&T) campus located in Rolla, MO was divided into three sections, one-third green roof, one-third black ethylene propylene diene monomer (EPDM) rubber roof, and one-third white thermoplastic polyolefin (TPO) with each area approximately 370 square meters (Gibler, 2015). Sixteen thermocouples were used in various locations in the investigation area to record thermal data at 0.6 m above the roof surface, at the roof surface, and on the underside of the concrete slab of the roof (sub-slab). The thermocouples placed at 0.6 m above the roof surfaces were shrouded by white, schedule 40, polyvinyl chloride (PVC) to shield the thermocouples from damage by incoming solar radiation.

During the field investigation portion of this study, green roof media's thermal properties were examined with the addition of HG granules in roof-top green roof mesocosms. The green roof mixtures were tested in eight Green Roof Block™ (GRB) load cells as modular green roof trays, 2 feet by 2 feet (60.8 cm by 60.8 cm) atop Emerson Hall. Four of the eight GRB load cells were filled 10 cm deep with GAF media, and four were filled 10 cm deep with Arkalyte media. Two GRB load cells of each media type were left unplanted, and two GRB load cells of each media type are planted with drought tolerant plants and a Midwest Mix of different Sedum species from Jost Greenhouse, St. Louis MO (Gibler, 2015). This experimental design is a continuation of

Gibler et al. 2015, however for this specific study one hundred grams of dehydrated HG granules were added to the four GRB load cells containing Arkalyte media. The data from the GRB load cells and meteorological weather station was integrated in a MATLAB numerical model, which computed ET of the GRB load cells and crop coefficients for each media type (Gibler, 2015).

2.4. GREEN ROOF FIELD CAPACITY

The soil property known as field capacity is interchangeably used with the terms water holding capacity and water retention capacity (Rai, Singh, & Upadhyay, 2017). The ability for green roof media to retain water is the dominant characteristic that affects potential ET. Water must be present in any media for actual ET to occur. Increasing the field capacity of green roof media increases the amount of water that can be stored within the green roof media, which provides more water to be evapotranspired and providing more energy dissipation potential. The impact of HG granules on the field capacity was investigated in both field and in-vitro column tests. HG was added only to the GAF media in the in-vitro investigation and only in the Arkalyte media GRBs in the field investigation.

The field capacity of GAF media and HG-amended GAF media in in-vitro rainfall events was calculated by weighing each test cylinder before and after the simulated rainfall events, and storage is calculated. The field study included gravimetric assessment of water content of the GRBs as weight were continuously recorded by a National Instruments CompactRIO that recorded real-time continuous measurements averaged on five-minute intervals. Storage of each green roof GRB is calculated by the difference in tray weights after precipitation events and tray weights of dry media right after instillation on the roof.

2.5. METEROLOGICAL DATA

Evapotranspiration is heavily dependent on climatic conditions; therefore, accurate climatological data is imperative to calculate potential ET using the Penman-Monteith method (Penman, 1948), (Penman, 1963), (Monteith, 1965). To accurately quantify the amount of potential ET on the green roof at Missouri S&T, local weather parameters were collected from a weather station adjacent to the green roof mesocosms. The experimental design is a continuation of Gibler et al. (Gibler, 2015). In brief, the weather station included an anemometer fixed 2 meters above the green roof surface, a hygrometer 1 meter above the green roof surface, a pyranometer, and thermal couples. The meteorological data was collected and stored via Sutron 9210 Datalogger for convenient manual download.

2.6. ET MODELING

An ET modeling code developed by Gilber et al. 2015 (Gibler, 2015),was used to facilitate the computational processing of a large amount of real-time meteorological and load cell data, calculate green roof characteristics (e.g., storage), and estimate potential evapotranspiration using the FAO Penman-Monteith equation. The code was also used to fit crop coefficients (Kc) for green roof media using data from March 2016 to December 2016. Although 5-minute data were collected, FAO Penman-Monteith modeling of potential ET is not realistic for time periods shorter than one hour (Allen, Pereira, Raes,

& Smith, 1998); therefore, meteorological data for all potential ET calculations were averaged over a one-hour period and load cell data was also averaged over one hour to minimize noise and synchronize data for comparison to calculated reference evapotranspiration. Since the Penman-Monteith equation does not use precipitation or thermal data to calculate evapotranspiration, thermocouple data and precipitation data were used in their original 5-minute interval format.

3. RESULTS AND DISCUSSION

3.1. WATER RETENION AND NUTRIENT LEACHING

3.1.1. Runoff Reduction. After 10 rainfall events a total of 254 mm of simulated rainfall was applied to the green roof media columns. Of the 254 mm applied rainfall, 251.5 mm of runoff was observed from the control cylinder. The HG amendment had an impact on precipitation retention in the green roof media as compared to the non-amended versions of green roof media. The percentage of rainfall stored (percent retention) obtained in this study from the non-amended green roof media 53% retention for GAF media and 37% retention for Arkalyte media and were similar to those found in literature. In studies such as Gibler et al. 2015 (Gibler, 2015) and Morgan et al. 2013 (Morgan et al., 2013), 10-cm deep green roofs retained approximately 50-60% of precipitation. The GAF-10% HG mixture retained the highest percentage of rainfall (71% of the total simulated rainfall), and the GAF-5% HG mixture retained approximately 64% of the total simulated rainfall. These retention rates are slightly higher than the non-amended green roof media storage values. The increase in percent retention for GAF media from the HG amendment was 11% for 5% HG, and 18% for 10% HG.

Table 1. Percent storage (water retention) for each green roof media mixture from in-vitro column tests.

Media type	***Percent retention***
GAF	**53%**
Arkalyte	**37%**
GAF-5%HG	**64%**
GAF-10%HG	**71%**

3.1.2. Nutrient Leachate Characteristic Curve. Results from in-vitro column testing for the green roof media indicate that HG-amended GAF media decreased the mass of all nutrients tested in green roof leachate as compared to the mass of non-amended GAF media. The cumulative mass flux of TN leached over the entire in-vitro investigation after 10, 25.4 mm rainfall events, averaged 31.4 g/m^2 or non-amended GAF media, 12.5 g/m^2 for GAF with 5% HG, 11.2 g/m^2 for GAF with 10% HG, and 7.0 g/m^2 for the Arkalyte media. Results indicate that the 5% HG reduced the amount of TN mass in the leachate by approximately 60% while the 10% HG reduced the TN mass in the leachate by approximately 65%. Results for the cumulative TN mass per each rainfall event were used to create a TN leaching curve for each media mixture shown in Figure 1.

A similar leaching trend was found for TOC and TP; however, unlike TN, the results show that the mass of both constituents were lowest in the 10% HG amended media. The cumulative average TOC mass ranged from 48.8 g/m^2 for the non-amended GAF green roof media, 17.8 g/m^2 for the Arkalyte media, 10.5 g/m^2 for GAF media with 5% HG, and 9.9 g/m^2 for GAF media with 10% HG. These results indicate that the 5% and 10% HG-amended GAF media reduced the TOC mass by 79% and 80%, respectively, from the total mass leached from non-amended GAF media. The 5% and 10% HG amended media mass of TOC were 40% and 45% lower than the cumulative mass produced in Arkalyte media's leachate. Cumulative TP mass in green roof media leachate for this investigation were as follows: 0.915 g/m^2 for non-amended GAF media, 0.580 g/m^2 for Arkalyte media, 0.405 g/m^2 for 5% Hydrogel amended GAF, 0.396 g/m^2 for 10% HG-amended GAF. The 5% HG and the 10% HG TP leachate mass were both approximately 57% lower than the non-amended GAF media leachate mass. Figure 1. below show the results for the TN, TOC, and TP leachate mass during the entire study period of in-vitro rainfall events. Table 2. summarizes the reduction in nutrient concentrations and runoff amount for each green roof media mixture compared to the non-amended GAF media.

Table 2. Summary of nutrient mass retention.

Media Type	*% Retention TN*	*% Retention TOC*	*% Retention TP*
Arkalyte	**78%**	**64%**	**38%**
GAF-5%HG	**60%**	**79%**	**57%**
GAF-10%HG	**65%**	**80%**	**57%**

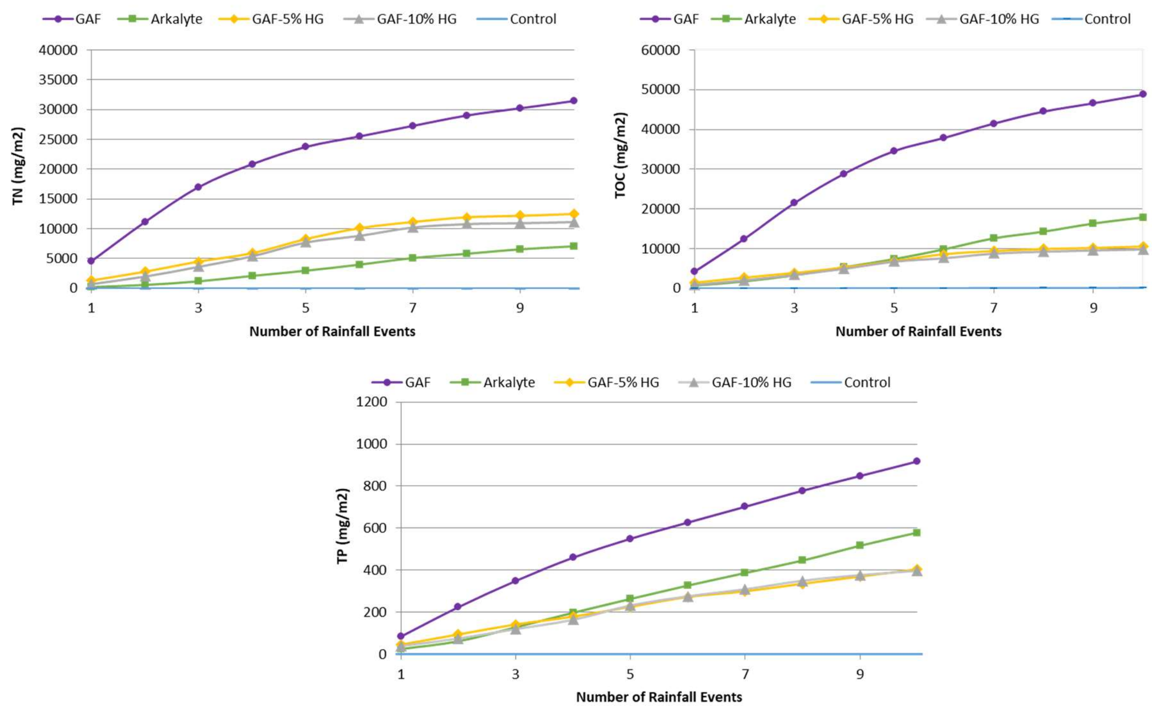

Figure 1. Cumulative TN, TOC, and TP mass leaching in the in-vitro column tests for GAF and Arkalyte media as well as hydrogel (HG) amended GAF media. Data is average of n=3, except control.

3.1.3. "First Flush" Nutrients. The in-vitro investigation used fresh GAF green roof media. In contrast the Arkalyte media, had previously been exposed to ambient conditions for approximately a year during a previous green roof study (Harper, Limmer, Showalter, & Burken, 2015). Unlike the study conducted by Harper et al. 2015 (Harper et al., 2015), the in-vitro column test captured all leachate, including initial leaching of TN, TP, and TOC concentrations in the green roof media leachate during the first few simulated rainfall events. This "first flush" is very apparent in the non-amended GAF green roof media, but is not present in leachate results from the HG-amended GAF media mixtures or Arkalyte media (Figure 2).

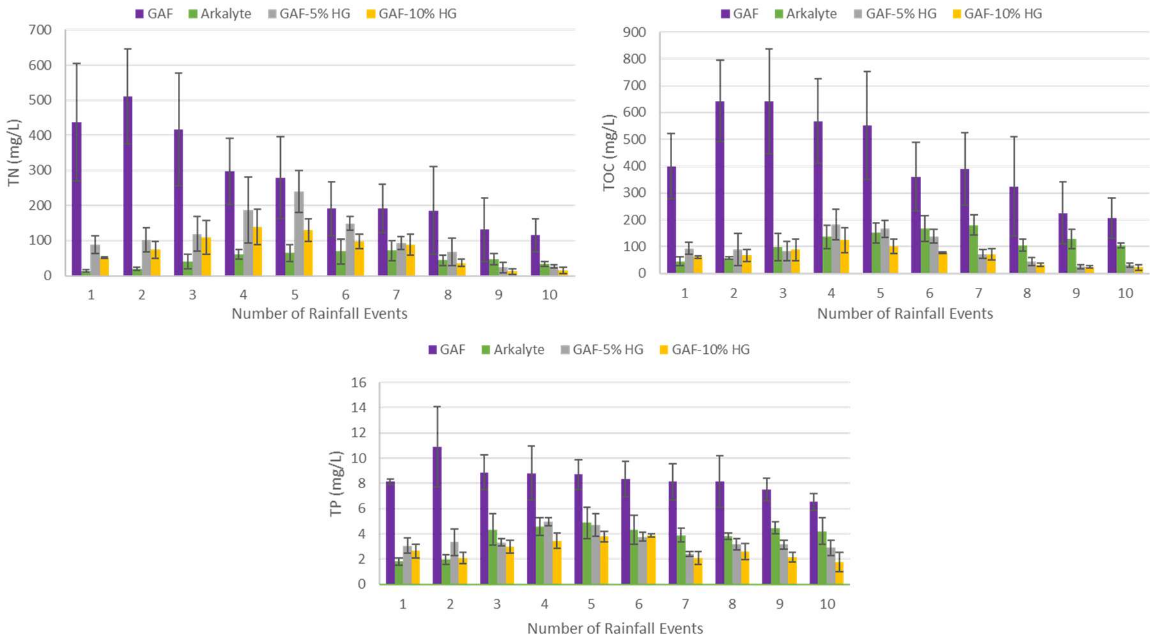

Figure 2. Nutrient concentration per simulated rainfall in-vitro column tests for GAF and Arkalyte media, and hydrogel (HG) amended GAF media. Each data point is average of 3 samples. Error bars represent 95% confidence interval.

The change in mass loading rates for the GAF media further indicates a "first flush" of nutrients in early rainfall events (Table 3). The mass loading rate for TN in GAF media leachate changes from 186.5 $mg/m^2/mm$ for the first simulated precipitation event to a rate of 250.4 $mg/m^2/mm$ for the second precipitation event. After the second rainfall event the mass loading rate continues to decline after each rainfall event till the rate begins to reach a point of steady state of approximately 48.8 to 46.9 $mg/m^2/mm$. Similar trends were observed in the TOC and TP data (Tables 3-5).

Both HG-GAF mixtures changed the mass loading dynamics of the original GAF media by reducing the magnitude of the first flush of TN, TP, and TOC. The peak mass loading concentrations of TN in the GAF leachate were reduced by 63% and 64% by the

5% Hydrogel mixture and the 10% Hydrogel mixture, respectively. TOC peak mass loading concentrations decreased by approximately 80% for both the 5% HG mixture and the 10% HG mixture. TP mass loading concentrations were also impacted by the Hydrogel mixtures. The 5% HG mixture reduced the peak concentration by approximately 65% and the 10% HG mixture reduced the peak concentration by 50%, while precipitation retention was highest in the 10% hydrogel as noted above.

HG also changed the timing of the peak concentration of nutrient leaching under rainfall event as compared to the original GAF media. Typically, the non-amended GAF green roof media had peak TN, TP, and TOC concentrations occur after the second or third rainfall event. In addition to decreasing peak concentrations, the 5% HG-amended GAF media had peak concentrations of TN later in the rainfall events, and less of a 'first flush' occurrence. Peak concentrations occurred between the 3rd to 6th precipitation events, spreading out the impacts over a longer period, and at notably lower peak concentrations. Mass loading rate for each constituent after each rainfall event are shown in Tables 3-5. The dual impacts of decreasing peak concentrations and distributing the loading to the receiving watershed over more events will have notable benefits and aid in the watershed assimilating the nutrient load and attenuating the downstream eutrophication potential.

The Arkalyte media tested did not show a high nutrient mass loading rate initially; however, there was a gradual increase of nutrient mass loading rates in the leachate over the course of the in-vitro column tests, similar to the HG-amended GAF mixtures. Peak concentrations of mass loading occurred after the seventh rainfall event for TN and TOC, whereas the peak concentration for TP occurred after the fourth rainfall event, as shown in Tables 3-5.

Table 3. Summary of mass loading concentrations of TN of in-vitro column tests for GAF, Arkalyte, and HG-amended GAF media. Bold value is the peak concentrations.

TN ($mg/m^2/mm$)

Rainfall Number	GAF	Arkalyte	GAF with 5% HG	GAF with 10% HG
1	186.5	7.82	53.2	31.0
2	**250.4**	13.7	56.3	48.3
3	**229.6**	24.0	67.0	64.1
4	151.8	35.7	55.4	**69.7**
5	113.3	34.3	**93.4**	**90.8**
6	69.5	**39.8**	**72.1**	43.8
7	69.6	**43.7**	41.2	55.3
8	68.5	28.2	30.8	22.2
9	48.8	30.0	9.98	5.81
10	46.9	19.0	11.9	7.23

Table 4. Summary of mass loading concentrations of TOC of in-vitro column tests for GAF, Arkalyte, and HG-amended GAF media. Bold value is the peak concentrations.

TOC ($mg/m^2/mm$)

Rainfall Number	GAF	Arkalyte	GAF with 5% HG	GAF with 10% HG
1	170.4	25.7	56.2	37.1
2	**314.8**	41.1	49.0	44.1
3	**354.2**	59.7	46.2	52.3
4	291.1	80.4	54.1	**62.6**
5	224.2	80.5	**65.0**	**71.0**
6	130.8	**97.0**	**67.5**	34.5
7	142.3	**109.1**	31.9	45.7
8	120.0	67.0	20.4	19.5
9	84.2	82.1	9.92	12.1
10	84.4	59.4	14.8	10.3

Table 5. Summary of mass loading concentrations of TP of in-vitro column tests for GAF, Arkalyte, and HG-amended GAF media. Bold value is the peak concentration.

TP ($mg/m^2/mm$)

Rainfall Number	GAF	Arkalyte	GAF with 5% HG	GAF with 10% HG
1	3.48	1.03	1.83	1.61

Table 5. Summary of mass loading concentrations of TP of in-vitro column tests for GAF, Arkalyte, and HG-amended GAF media. Bold value is the peak concentration (cont.).

2	**5.32**	1.41	1.84	1.37
3	4.90	2.62	**1.87**	1.77
4	4.36	**2.71**	1.47	1.73
5	3.53	2.59	1.85	**2.66**
6	3.03	2.49	1.83	1.72
7	2.96	2.35	1.06	1.31
8	3.02	2.35	1.43	1.60
9	2.80	2.70	1.36	1.07
10	2.66	2.39	1.34	0.79

3.1.4. Field and In-vitro Column Test Comparison. The previous study conducted by Harper et al. 2015 (Harper et al., 2015), investigated the nutrient leaching characteristics of GAF and Arkalyte green roof media in ambient conditions assessed on a rooftop setting. The study ranged over a 9-month period, which included prolonged dry periods as well as periods of frequent heavy rainfall. While the climate conditions and experimental arrangements of the rooftop and in-vitro studies were dissimilar, the type and depth of the media evaluated was consistent and leachate constituent testing was completed in both studies.

Results in Figure 3 show the leaching characteristics of the two media was comparable between the field and the controlled laboratory setting, with GAF having the higher leachable TN, TP, and TOC over time, versus the aged Arkalyte. The leaching profile in the Harper et al study and the laboratory study were normalized for the total precipitation events, demonstrated in the linear comparisons of nutrient leaching between the roof top and laboratory study. The total mass per area of TN, TP, TOC leached in the 9 month roof top study and the laboratory study did vary, as would be expected in the differing temperatures, including freeze-thaw events, the substantial difference in the length of the study, the inclusion of initial precipitation and leaching events in laboratory study with the high leaching concentration, and most notably the differences in precipitation intensity, frequency and duration see SI. Harper et al 2015 (Harper et al., 2015), did not capture the 'first flush' events that were captured in the laboratory investigation. The concentrations of TN, TOC, and TOC from the in-vitro investigation were consistently higher than results from similar field investigations, which can be expected from the consistent intensity of the precipitation events, and the capture of all leached nutrients.

The primary finding is that the differences between the two media in the 9-month field test and the rapid controlled test were consistent and linear, thereby giving confidence that the controlled, rapid screen can provide an assessment of expected field performance in terms of comparing media in terms of nutrient leachability and water retention. The controlled laboratory studies are also more reproducible and comparable from different sites and for different media design studies. Uncontrolled field-testing is inherently irreproducible between differing locations and temporal scales, and field trials are also more time and resource consuming.

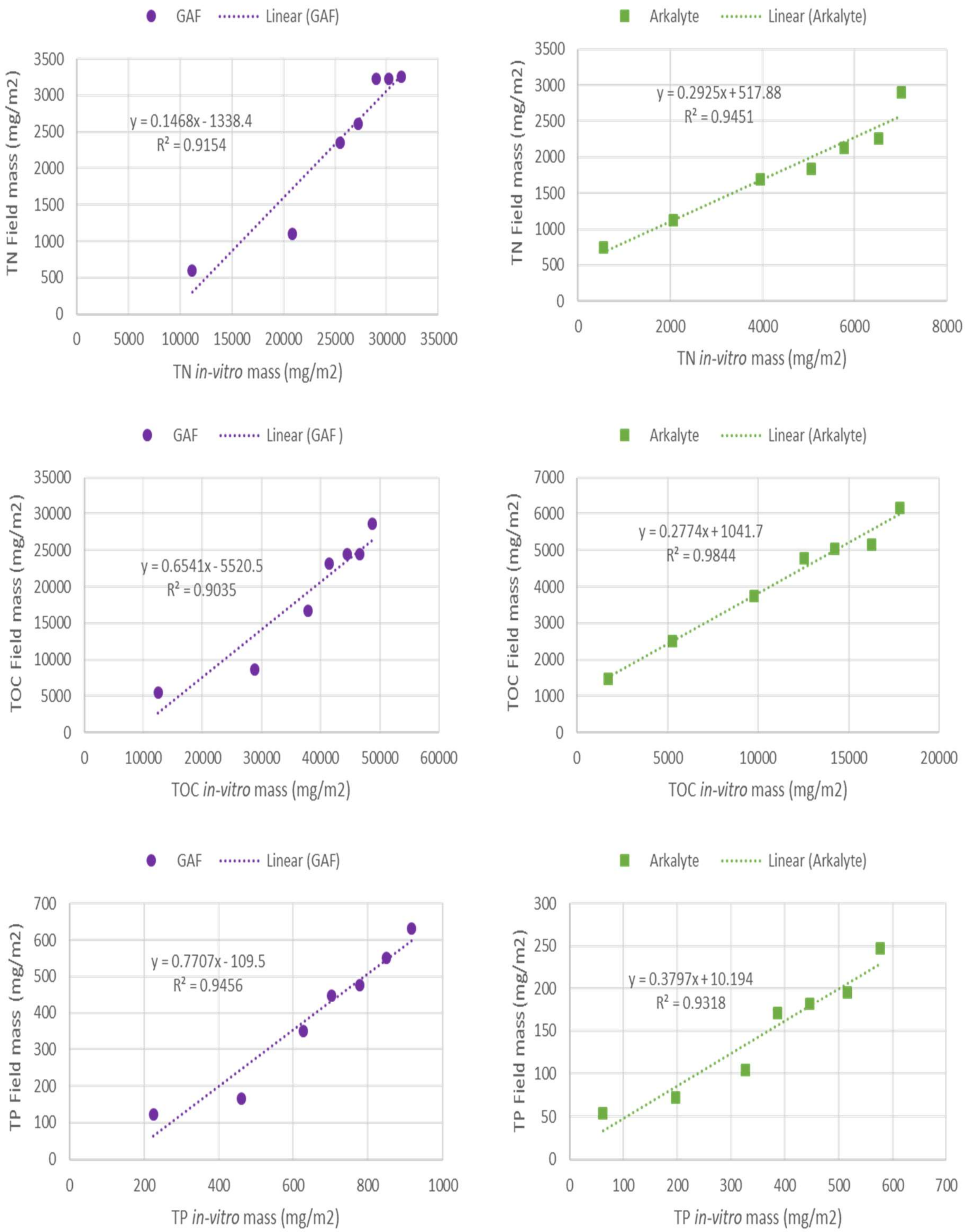

Figure 3. Comparison of leaching from ambient rooftop study (y axis) and standardized laboratory testing done in-vitro (x-axis).

3.2. ENERGY ANALYSIS

3.2.1. Green Roof Field Capacity and Potential ET. The amount of water that is available for potential ET is a significant factor when determining the amount of cooling a specific green roof design can provide. The real-time saturation of the green roof GRBs was determined from the results of continuous load cell monitoring and precipitation data from the rooftop weather station. The instantaneous saturation of the green roof media is calculated by taking a ratio of the fixed saturated weight and the instantaneous weight of each individual green roof GRB. The instantaneous saturation of unplanted green roof media atop Missouri S&T's Emerson Electric Hall is compared between March 1, 2016 and December 1, 2016 in Figure 4. Prior to July 13, 2016 the Arkalyte media in the field GRBs did not contain HG. The rain events captured by the roof prior to this date, which resulted in completely saturated green roof media, occurred on March 17, 2016, March 26, 2016, April 2, 2016, April 13, 2016, May 2, 2016, and July 4, 2016. After addition of HG, rain events that completely saturated the green roof media occurred on July 15, 2016, August 5, 2016, August 15, 2016, September 2, 2016, September 12, 2016, and September 17, 2016. The rainfall during this time period varied in intensity, duration, and drying time between rainfall events. Results from this investigation indicate that HG added to the Arkalyte media increased the water storage by 4% to 26% as compared to the non-amended Arkalyte condition. This additional water storage provided by the HG amendment increases the volume of water captured in the green roof media, which is available to be evapotranspired later during dry conditions, increasing the amount of potential ET and cooling potential.

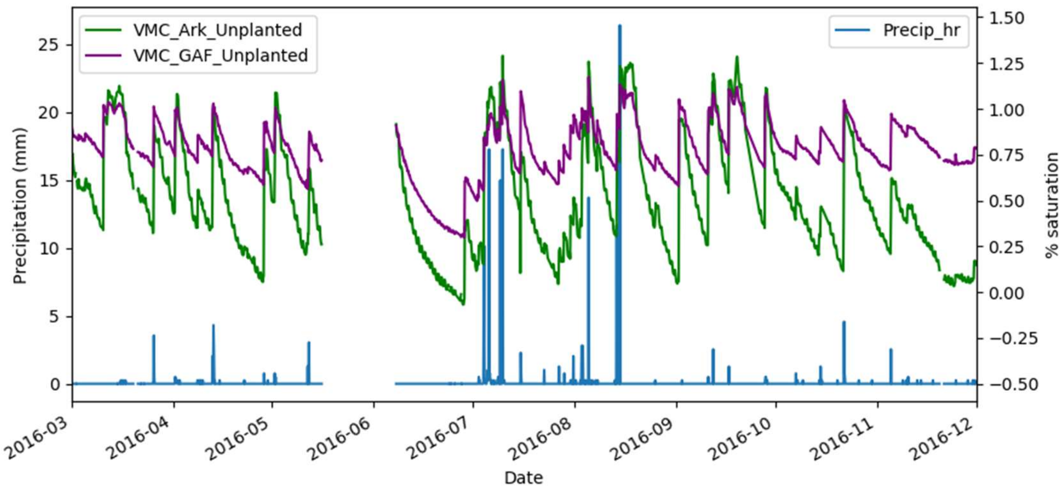

Figure 4. Instantaneous precipitation (mm) and green roof media saturation of unplanted conditions March 1, 2016 through December 1, 2016, Missouri S&T's Emerson Electric Hall.

3.2.2. Crop Coefficients and Reference. The real-time saturation data also indicates that both conditions of HG-amended Arkalyte media and non-amended Arkalyte media loses significant water content during dry periods. The saturation content Arkalyte media attains during dry periods is close to 0% saturation for both non-amended and HG amended, meaning the media frequently evapotranspired all stored water captured after rainfall events. The GAF GRB data has a much higher saturation baseline indicating that the media retains 50% to 75% of soil moisture that is trapped within the green roof media after rainfall events. Water trapped within the green roof media is not readily available for evapotranspiration therefore less actual ET can be attained from GAF media. Crop coefficients (K_c) are used in the Penman-Monteith equation to adjust potential ET values based on the media and type of vegetation used; this adjusted ET is known as actual ET.

The crop coefficients for the unplanted conditions of GAF and Arkalyte media were calculated by the ET model code on a monthly basis for March 2016 through October 2016 and are listed in Table 6. Based on results from the real-time saturation data and calculated crop coefficients it can be determined that the Arkalyte media will result in greater ET than the GAF media due to higher K_c values and increased water retention. The addition of HG in July 2016 does not have a notable effect on the Arkalyte media calculated K_c value indicating that the HG amendment does not impede the evaporation of stored water in the media, while it does increase the water holding capacity of the media.

Table 6. Calculated crop coefficients for Arkalyte and GAF green roof media in unplanted conditions. Not applicable=NA.

Month	*Year*	*GAF Unplanted*	*Arkalyte Unplanted*
3	2016	0.26	0.71
4	2016	0.21	0.61
5	2016	0.13	0.56
6	2016	0.19	0.38
7	2016	0.25	0.58
8	2016	0.30	0.58
9	2016	0.25	0.51
10	2016	0.11	0.47
11	2016	NA	NA
12	2016	NA	NA

3.2.3. Urban Heat Island Mitigation. One of the biggest challenges of quantifying green roofs impact on the UHI effect is accurately calculating the amount of ET and resulting energy dissipation. Few models have been able to accurately calculate ET and energy dissipation and relating it to rooftop temperatures. Figure 5 below shows the interaction between water availability, potential ET, and the thermal differences between each roofing material. On June 4, 2016 a 10 mm rainfall was recorded locally. On June 8th, after the rainfall event, thermal data on each roof indicates the green roof had the lowest peak surface temperature and the black roof having the highest peak surface temperature. The recorded temperature of the green roof was 30°C, which is approximately 17°C cooler than the black membrane roof and 11°C cooler than the white TPO roofing. No precipitation events occurred in Rolla until July 5, 2016. During this dry period, predicted evapotranspiration (ETo in mm/hr) generated by the ET modeling code is calculated while the temperature differential between the roofing material decreases as the water content of the media is exhausted. The ETo indicates that the green roof is removing the stored water from the media, concurrently as less water is available to be evapotranspired, the green roof surface temperature begins to increase. Over a 10-day period, the green roof surface temperature eventually increases to the point that has a relatively similar surface temperature as the black membrane and white membrane roofing material. The temperature differential between the black and green roofs is 4°C on June 19, 2016.

The latent heat flux generated through ET is calculated by multiplying the volume of precipitation removed via ET by the latent heat of vaporization of water (2,260 kJ/kg). Multiplying the latent heat flux by the area of the green roof yields the total amount of energy dissipated by the green roof. The total energy dissipated by the latent heat flux for 9.0 mm of precipitation evapotranspired over the 10-day period was 55 MJ/m2.

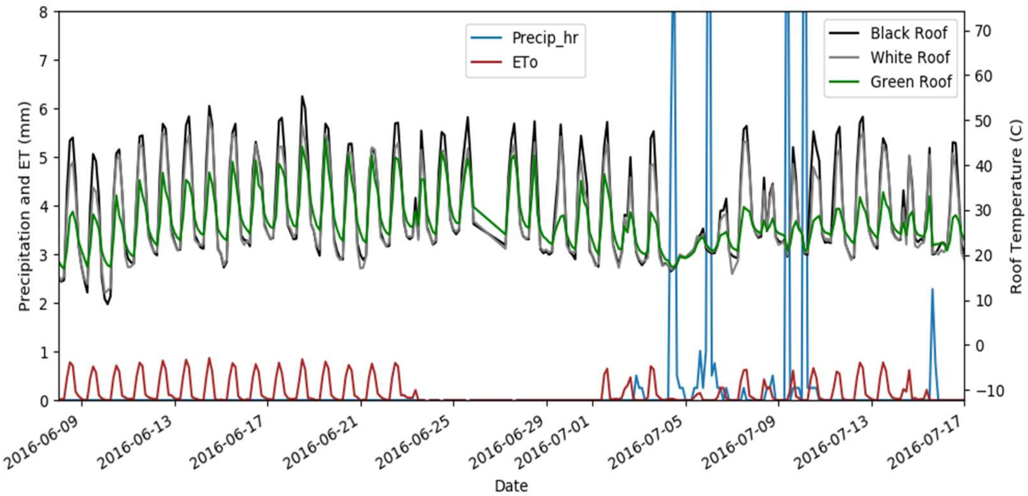

Figure 5. Thermal comparison of green, black (EDPM), and white (TPO) rooftop surface temperatures with ET and precipitation.

4. CONCLUSIONS

4.1. SUMMARY OF FINDINGS

This work demonstrates the ability and establishes methodology to quantifiably assess green roof media in rapid testing in a controlled setting, which can allow for assessment of multiple media in parallel, for water and nutrient management. Testing both the magnitude and lability of nutrient leaching properties of green roof media was demonstrated, thereby establishing a protocol for screening green roof media. With an established screening protocol for comparing media hydrologic and nutrient-retention performance, design optimization of green roof media can be undertaken with quantifiable comparisons and targeted performance standards, as desired in the design of green infrastructure. Amending of the media for specific enhancement of media performance characteristics was also clearly demonstrated, including concurrent increase in water retention and decreasing leaching of nutrients, for the benefit of both water quality and to remedy urban flooding.

The concentrations of TN, TOC, and TP from the in-vitro investigation were consistently higher than results from similar lab and field investigations, as would be expected with the first flush inclusion and the high intensity of the precipitation events used the in the rapid screening. The relative performance compared to field testing was consistent with previous field studies, demonstrating that the rapid screening protocol can be used to evaluate the relative performance of various green roof media's or novel media designs to improve performance of green roof media for specific desired outcomes. In terms of the benefit of the design approached trialed in this test, HG improved all targeted parameters, retaining 25% and 39% more water at 5 and 10% HG amendment, and significantly reducing TN, TOC, TP. Amendment strategies to design improved media characteristics were successful, decreasing the mass of all nutrients tested in green roof leachate by 57% to 80% with as little as a 5% addition of HG to GAF media. Mass of TN, TOC, and TP in leachate was reduced, as was the volume of roof runoff generated, thereby having a multiplicative benefit on total mass loading to local waterbodies and alleviating both urban flooding and water-quality issues.

This investigation also successfully investigated the relationship of water retention and green roof media properties as it relates to thermal performance of green roofs. The field investigation of this study indicated that HG amendment increased field capacity of Arkalyte media by 4% to 26%; however it did not impact the rate at which water was evapotranspired as shown by the crop coefficients of each condition. By investigating and manipulating the water retention properties of green roofs, optimization recommendations of green roof media design can be made based on the geographical location of a prospective green roof.

Linking meteorology and roof media characteristics allows for projecting comprehensive benefits of green roof applications. Future linking of projected meteorology for a location with typical meteorological year data can allow for efficient design to meet performance standards of green roofs to achieve specific targets of improving hydrologic performance of green roofs and remedy the broken urban water cycles resulting in a profound impact on urban heat islands.

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SECTION

3. CONCLUSIONS AND RECOMMENDATIONS

3.1. CONCLUSIONS

A standardized in-vitro screening method for green roof water retention and nutrient loading was developed as a result of this work. Nutrient loading results from the controlled, designed screening method were similar to nutrient loads from a 9-month field investigation indicating that the developed testing method can be used to forecast nutrient loading and water retention performance of green roof media. The green roof screening method design also allowed for multiple types and mixture of green roof media to be tested simultaneously for water retention and nutrient loading. The interaction of the energy dissipation and water retention as it relates to ambient green rooftop temperatures is better understood as a result of this study as well. Using real-time meteorological and load cell data the changes in green roof surface temperatures were shown to change with the amount of water availability within the green roof media. Crop coefficients of different green roof media mixtures were also determined to investigate the water removal properties of green roof media through evapotranspiration of stored water. This study illustrates the need to comprehensively link the soil-water-energy interactions of green roof media design with meteorological conditions to obtain optimal hydrologic and thermal performance of green roofs.

3.2. RECOMMENDATIONS

3.2.1. Nutrient Loading. From the results of this research it is apparent that HG has a significant beneficial impact on the concentration of nutrients in the green roof media leachate. When designing a green roof media with HG, understanding the optimal percentage by weight of HG is essential to achieving the desired results. Additional ratios of green roof media and HG should be tested to find the point at which the least amount of nutrient leaching occurs or when adding additional HG no longer have an effect on nutrient concentrations. Kuoppamaki et al. (Kuoppamäki, Hagner, Lehvävirta, & Setälä, 2016) showed that biochar amendments to green roof media also has an impact on nutrient loading. Other materials such as zeolites, and expanded limestone should be investigated to determine which material is best at reducing nutrient loading while maintaining economic viability. The in-vitro rapid testing process enables multiple media compositions to be tested under the same conditions at the same time. The in-vitro rainfall events could simultaneously investigate different amendment nutrient leaching response based on the chosen rainfall. The method developed to rapidly test leaching characteristic of nutrients can be easily modified to test other variables that effect nutrient loading like different media depths and duration between rainfall events.

3.2.2. Additional ET Investigations. HG could be added to GAF media used in the field portion of this investigation to have a more complete idea as to how HG performs in different green roof media. Through the crop coefficients and percent saturation data it was determined that GAF green roof media did not evapotranspire stored water readily. Investigating if the addition of hydrogel changes this property of the GAF media as it did for Arkalyte media would be interesting and beneficial. Such comparisons could have broader implications on driving forces of ET in green roof media by comparing the different amendments impacts with the green roof media itself.

3.2.3. Water-Quality Amendment Field Investigation. Total nitrogen, total phosphorus, and total organic carbon water-quality samples should be taken from the HG amended GRBs in field. In previous work by Harper et al and Gibler et al, water-quality samples were taken from non-mended GAF and Arkalyte media. Results from that previous work were used in this study to test the validity of the rapid testing nutrient leaching results. Adding HG to fresh green roof media in a field application can also be used to verify the results obtained in the nutrient leaching lab tests for the HG amended conditions. The results from this investigation would further confirm the validity of the rapid nutrient leaching testing method, verifying that the method can be used to project field leaching values in a controlled setting before an actual green roof is built.

3.2.4. HG. Using HG as a green roof amendment is relatively new and only a few investigations use this amendment. Deska et al. (Iwona Katarzyna Deska 2020), found that increasing the percentage by weight of HG decreases the effectiveness of the water holding capacity when considering longer-term dry periods. More studies should be done to observe how long HG's water retention capabilities last and if the amount of water the amendment holds over time changes due to degradation on both field as well as lab conditions. In the field sunlight and freeze-thaw events can cause significant weathering to materials, it would be interesting to observe if the green roof media can decrease the rate of HG degradation from the weathering process. Another important investigation that should be done is assessing what the potential by-products of HG are and if any are of environmental or human health concern.

Overall, investigating these additional recommendations will add to this body of work and contribute needed knowledge to advance the effective and expanded use of green roof and green infrastructure approaches for the benefit of urban waters. The collective valuation of green roof and green infrastructure applications will also help to improve implementation, and increase the use of economic vehicles such as subsidies, incentives and fee reductions to aid in offsetting the cost to building owners for the collective benefit of society and community.

APPENDIX A.

SUPPLEMENTAL IN-VITRO RESULTS

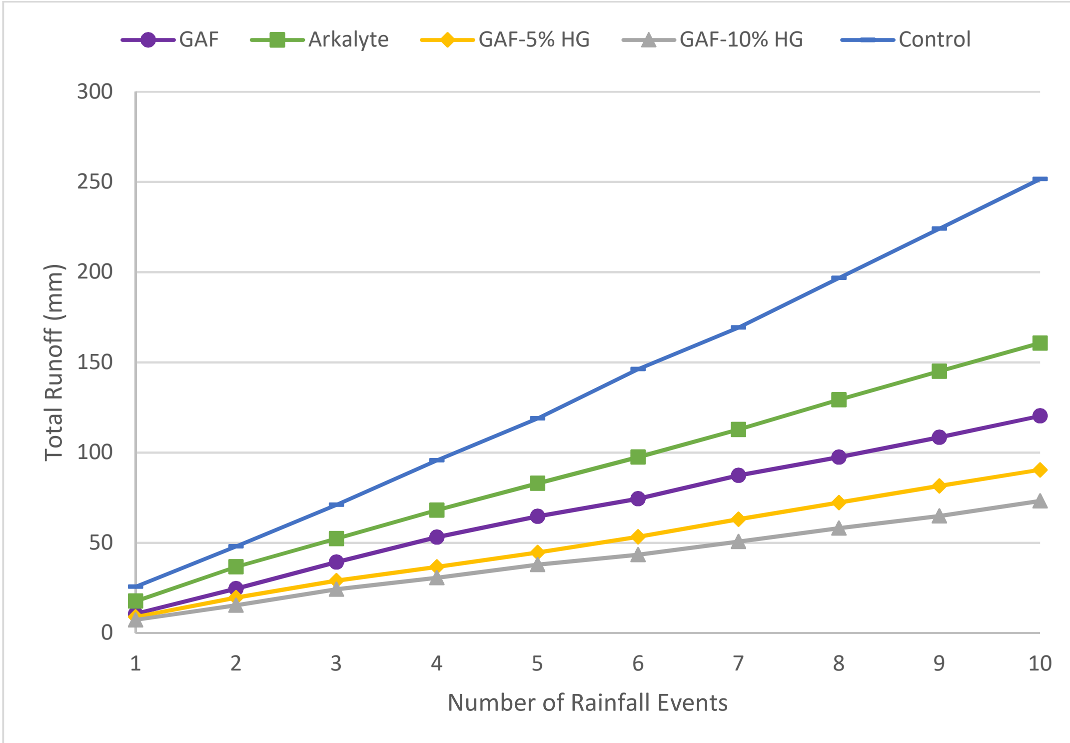

Figure A.1. Cumulative runoff (mm) observed from in-vitro column tests for GAF, Arkalyte, and HG amended GAF media. Data is average of n=3, except control.

APPENDIX B.

SUPPLEMENTAL IN-VITRO INVESTIGATION PHOTOS

Figure B.1. Green roof runoff collected after Rainfall Event #2.

Figure B.2. Green roof runoff collected after Rainfall Event #10.

APPENDIX C.

GREEN ROOF LEACHATE SIGNIFICANCE

```
 Tukey multiple comparisons of means
  95% family-wise confidence level

Fit: aov(formula = Concentration ~ Soil.Type, data = dataTN)

$Soil.Type
                       diff        lwr        upr     p adj
5.HYDRO-10.HYDRO    33.00770  -37.45521 103.470618 0.6150413
ARKALYTE-10.HYDRO  -29.82763  -93.77168  34.116423 0.6182948
GAF-10.HYDRO       177.37993  113.43587 241.323978 0.0000000
ARKALYTE-5.HYDRO   -62.83533 -129.02372   3.353049 0.0693193
GAF-5.HYDRO        144.37222   78.18384 210.560605 0.0000006
GAF-ARKALYTE       207.20756  148.00687 266.408245 0.0000000
```

```
 Tukey multiple comparisons of means
  95% family-wise confidence level

Fit: aov(formula = Concentration ~ Soil.Type, data = dataTOC)

$Soil.Type
                       diff       lwr      upr     p adj
5.HYDRO-10.HYDRO    18.99977 -65.24164 103.2412 0.9356275
ARKALYTE-10.HYDRO   47.76263 -28.68520 124.2105 0.3669466
GAF-10.HYDRO       331.67963 255.23180 408.1275 0.0000000
ARKALYTE-5.HYDRO    28.76286 -50.36816 107.8939 0.7794645
GAF-5.HYDRO        312.67986 233.54884 391.8109 0.0000000
GAF-ARKALYTE       283.91700 213.14006 354.6939 0.0000000
```

```
 Tukey multiple comparisons of means
  95% family-wise confidence level

Fit: aov(formula = Concentration ~ Soil.Type, data = dataTP)

$Soil.Type
                       diff        lwr      upr     p adj
5.HYDRO-10.HYDRO   0.3424271 -0.5439146 1.228769 0.7460787
ARKALYTE-10.HYDRO  0.9411877  0.1223235 1.760052 0.0173326
GAF-10.HYDRO       5.2689655  4.4501012 6.087830 0.0000000
ARKALYTE-5.HYDRO   0.5987607 -0.2458633 1.443385 0.2568670
GAF-5.HYDRO        4.9265385  4.0819145 5.771162 0.0000000
GAF-ARKALYTE       4.3277778  3.5542619 5.101294 0.0000000


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```

Figure C.1. Tukey multiple comparisons of means for green roof media leachate.

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