ABSTRACT

Title of Document: A COMPARISON OF ORGANIC MATTER AMENDMENTS FOR USE IN EXTENSIVE GREEN ROOF SUBSTRATES

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Organic matter is important for water retention and nutrient availability in green-roof systems. Yet few quantitative green-roof studies provide data for various sources of organic matter (OM). Coconut coir (CC), rice hulls (RH), SmartLeaf® (SL), and mushroom compost (MC) were used as green roof substrate amendments. The effects of OM on water-holding capacity, nutrient availability and plant establishment were measured. Growth of *Phedimus kamtschaticus* was greater with MC or SL compared to CC or RH. Substrate moisture and nutrient availability were significantly affected by OM source during an 8-month rooftop experiment and a 6-month growth chamber study. Coconut coir showed high moisture retention, low nutrient availability and low aboveground biomass, indicating that nutrient availability is crucial to successful

plant growth and establishment on a green roof. Composted materials such as MC and SL that have higher levels of available nutrients, promote better growth than unprocessed materials like RH and CC.

A COMPARISON OF ORGANIC MATTER AMENDMENTS FOR USE IN EXTENSIVE GREEN ROOF SUBSTRATES

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
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Dedication

This work is dedicated to my mother, Dr. Susan Barton,

who inspires me as a scientist, as a horticulturist, and as a person.

Acknowledgements

Thank you to all my friends and family who supported me throughout this process. Without you, I would have given up long ago. Thank you to my committee, Dr. John Lea-Cox, Dr. Andrew Ristvey, and Dr. Steve Cohan who stood by me through the many twists and turns of this project. All three collaborated to provide me with invaluable advice and insights without which this project could not have been completed.

Ed Snodgrass, Dominique Bayne, and the rest of the staff at Emory Knoll Farms provided me with the plants for this research in addition to great advice and insights into green roofs during my time as an intern there.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Literature Review

1.1 Green roof background information

1.1.1 Green roof definition and benefits

Green roofs are roof systems designed to support the growth of plants while primarily mitigating stormwater runoff. A green roof is an assembly of components that combines to provide a range of ecosystem services not offered by traditional roofing options. The components of a green roof can include: a structural roofing deck, waterproofing layer, root barrier, moisture storage layer, drainage layer, filter fabric, growing media, and plant materials (Emory Knoll Farms 2012).

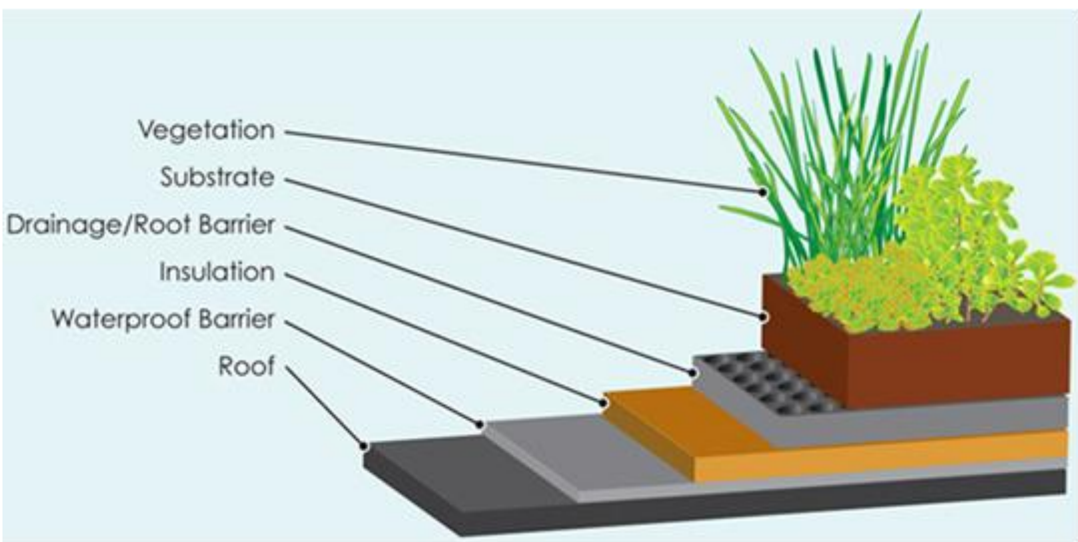

Figure 1.1 Diagram of an extensive green roof (Greensulate LLC. 2015)

Green roofs fall into two major categories: intensive and extensive roofs. An intensive roof can also be described as a roof garden with a layer of growing media, generally greater than 15.2 cm in depth (Getter and Rowe 2006). The name “intensive” refers to the fact that these roofs require greater inputs, in terms of irrigation and maintenance. These roofs generally can support greater plant diversity with species ranging from annual accent plants to large trees and shrubs. Intensive roofs are often designed as green spaces that are accessible to the public. An extensive green roof is thinner and designed primarily to provide ecosystem services. Because the growing media on extensive roofs is typically less than 15.2 cm (Getter and Rowe 2006), they weigh less and require fewer structural modifications to existing roof structures.

Green roofs provide two main benefits: ecosystem services and economic benefits. Ecosystem services include mitigation of stormwater runoff, urban heat island reduction, and increased biodiversity (Getter and Rowe 2006). Economic benefits incorporate increased lifespan of the roofing membranes (US General Services Administration 2011) building insulation (Oberndorfer et al. 2007) and reduction of impervious surface fees (District of Columbia Water and Sewer Authority 2015). It should be noted that ecosystem services also provide direct economic benefits to owners as well as society.

The reduction in stormwater runoff is one of the most significant ways for a green roof to contribute to environmental, economic and ecosystem health. Research shows that green roofs can typically retain between 45% and 76% of annual stormwater events, dependent largely on climate and rainfall intensity (Berghage et al. 2009; Starry 2013). A summary of German green roof studies conducted between 1987 and

2003 showed that extensive green roofs retained between 42% and 81% of rainfall compared to the retention of between 9% and 38% for non-greened roofs (Mentens et al. 2006). Runoff begins when the substrate reaches its field capacity (Bengtsson et al. 2005). This field capacity can be significantly influenced not only by substrate physical properties and depth, but also by climate, season and rainfall intensity (Berndtsson 2010). Multiple studies have quantified the effect of rainfall intensity on the ability of a green roof to retain water; these studies indicate that as rainfall intensity increases the percent of rainfall retained decreases (Carter and Rasmussen 2006; Gardiner and Windhager 2008; Starry 2013; Villarreal and Bengtsson 2005). The quantity of water retained can also be affected by substrate composition, depth, plant species, slope, and roof age (Berndtsson 2010). Green roofs do not completely stop stormwater runoff from roof surfaces but they do improve urban water runoff, allowing them to more closely approximate the natural water balance of soil conditions (Berndtsson 2010).

Green roofs also provide a reduction in temperature both for the roof surface and for the surrounding microclimate (Ouldboukhitine et al. 2014). This temperature reduction provides significant economic benefits through an increase in longevity of roofing membranes. Additionally, in the case of buildings with a large green roof footprint, the lower temperatures provide a reduction in the cost of cooling the building. One study compares air temperatures inside two buildings with comparable insulation, one with a green roof and one without. The building with the green roof experienced indoor temperatures of 30 °C (86 °F) for only 5% of a three day period compared to 15% for the unplanted roof (Niachou et al. 2001). In a Mediterranean summer, temperatures for a green roof at the underlying asphalt layer were consistently cooler by around 25 °C (77 °F) than at the asphalt layer of a bare roof (Theodosiou et al. 2013). Reduced temperature fluctuations give green roof membranes an average lifespan of 40 years, more than double the average lifespan for conventional roofing membranes (US General Services Administration 2011).

Vegetated roofs provide habitat to otherwise barren roofscapes that allow biodiversity in urban areas (Williams et al. 2014). In surveying European green roof research, Dvorak and Volder (2010) found reference to green roofs supporting butterflies, birds, spiders, and other macroinvertebrates in addition to many plant species, some of which were endangered (Dvorak and Volder 2010). A study of green roofs in Chicago showed green roofs supported bees in large enough communities to provide pollination to green roof plants (Ksiazek et al. 2012). However, it is important to assess these benefits with some caution. While green roofs do provide a significant increase in habitat when compared with conventional roofs, the comparison to ground-level green space and the ability of green roofs to provide habitat corridors is still under-researched (Williams et al. 2014).

1.1.2 Current state of the green roof industry

The green roof industry in North America is experiencing significant growth. In 2013, there were 6,421,538 ft^2 of installed green roofs reported from 950 projects, 10% more than reported in 2012 ("2013 Annual Green Roof Industry Survey" 2014). Four of the ten United States metro regions with the greatest amount of new green roof square footage installed in 2013 are in the Mid-Atlantic region: Washington D.C. (2,100,000 ft^2), New York City (650,000 ft^2), Philadelphia (300,00 ft^2), and Baltimore (200,00 ft^2) ("2013 Annual Green Roof Industry Survey" 2014).

This growth is due in part to the environmental and economic benefits mentioned above. Green roofs can be considered a fiscally sound investment due to increased lifespan of roofing materials and with reduced pay-back periods taking advantage of current subsidy programs. Green roof membranes are expected to last for 30 to 50 years (US Environmental Protection Agency n.d.). A report from the USGS on the benefits and challenges of green roofs weighs positives such as stormwater reduction, energy savings, real estate value and community effects compared to installation, maintenance, and replacement costs. Typically this results in a return on investment of between 4.3% and 5.9% depending on the location in the US and the size of the green roof (US General Services Administration 2011).

Growth of the green roof industry is also due in part to legislation, rebates and fees that increase incentives for green roof installation. Subsidies and rebates are one time financial benefits that help to defray installation costs. The 2014-2015 green roof rebate program from the District Department of the Environment in Washington, DC provides grants of $10 to $15 per square foot to subsidize green roof installation on residential, commercial, and institutional buildings (“Green Roofs in the District of Columbia” n.d.). Anne Arundel County (MD) offers credit of up to $10,000 against property taxes for approved stormwater management, which includes the use of vegetated roofs (Anne Arundel County Office of Planning and Zoning 2010). In Philadelphia, business owners can receive a credit of up to $100,000 against their taxes for installing a green roof (Philadelphia Industrial Development Corporation n.d.).

A reduction in stormwater fees can have a substantial economic impact over the lifetime of the roof, as these fees are likely to continue to increase. In Washington DC, residential and non-residential customers pay an impervious surface area charge, which goes to funding the Clean Rivers Project (District of Columbia Water and Sewer Authority 2015). In 2015, the charge amounts to about $2,700 for ¼ acre of impervious surface per year, which represents an increase of 15.4% from 2014 (District of Columbia Water and Sewer Authority 2015). This charge can be lowered by installing a green roof, which reduces the impervious area on the site.

1.2 Green roof substrates

1.2.1 Performance expectations

Typical substrates (or growing media) are made up of five basic components: mineral particles, organic matter, water, air, and living organisms (Handreck and Black 2002). Varying ratios of combined components contribute to the physical, chemical and biological properties that define the functionality of the substrate, developed for specific goals or an intended purpose. In the case of green roofs, the substrates must be light weight, be efficient in absorbing and retaining water, be able to drain excess water, provide anchorage for plants, and provide nutrients to enhance plant growth (Getter and Rowe 2006; Nagase and Dunnett 2011; Snodgrass and Snodgrass 2006).

Specific proportions and types of these components can aid in the initial and long-term performance of a green roof.

1.2.2 Mineral component

The inorganic component, i.e. mineral particles of a green roof substrate can consist of expanded clay, expanded shale, expanded slate, sand, crushed brick, or a combination of any of these components (Fassman et al. 2010). The physical properties, the size and arrangement of mineral particles, help to define the pore spaces of the substrate. Large particles leave big pore spaces through which water quickly drains. Smaller particles leave smaller pore spaces that retain water and reduce water flow through the substrate profile (Handreck and Black 2002). Suitable particle distribution balances large and small particles to create a substrate with enough air space to provide oxygen to the roots and enough small pores to maintain an adequate available water supply (Nelson 2003).

1.2.3 Organic component

The amount and type of organic matter affects the function of a green roof by contributing to the structure and porosity of the media, increasing the water–holding capacity, increasing the cation exchange capacity (CEC), affecting substrate pH and nutrient availability essential for plant growth (Allison 1973). A high ratio of organic matter provides more nutrients and greater water-holding capacity, but can contribute significantly to overall weight and can be associated with subsidence of the media.

Lower organic percentages reduce weight but may cause stress due to lack of nutrients and lower water-holding capacity (Fassman et al. 2010)

The CEC and pH have a large influence on the ability of the substrate to provide nutrients to plants. A high CEC allows cations to adsorb to the surface of soil particles, minimizing the amount of nutrients lost through leaching (Taiz and Zeiger 2010), although this does not apply to anions like nitrate and phosphate. Availability of different nutrients changes as pH changes. The optimum availability for most nutrients in substrates is typically found between pH 6 and 7 (Handreck and Black 2002).

Recommendations for the addition of organic matter added to green roof media are vague and are given in both weight and volume proportions. The FLL (German Landscape Research, Development, and Construction Society) recommends ≤ 65 g/l of organic matter ***by mass*** for an extensive green roof (FLL 2008). The Auckland Regional Council recommends 5% to 20% ***by volume*** with higher percentages aiding in plant success but adding to the weight load of the roof (Fassman et al. 2010). Because different types of organic matter have different bulk densities (Handreck and Black 2002), the conversion between gravimetric and volumetric ratios can result in very different amounts of organic matter being incorporated, depending on which recommendation is followed.

Types of organic matter vary significantly in physical and chemical composition. They fall into two broad categories: composted, having undergone a thermophilic and aerobic stabilization process (Raviv 2005), and uncomposted materials. The green roof community uses a variety of organic matter both in commercial installations and in research projects. Some composted materials used include mushroom compost (Griffin 2014), composted yard waste (Young et al. 2014), vermicompost (Carter and Jackson 2007), and composted pine bark (Fassman et al. 2010). Some uncomposted materials used include coconut coir (Fassman et al. 2010) rice hulls, and sphagnum peat moss (Bousselot et al. 2011).

Although extensive research has been conducted on nutrient content in green roof runoff and leachate (Beck et al. 2011; Bliss et al. 2009; Teemusk and Mander 2007), few studies have focused on nutrient dynamics within the roof system (Ampim et al. 2010). Essential nutrients enter a plant when they are absorbed from the soil solution as ions by the roots (Handreck and Black 2002). These essential nutrients are nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (Brady 1974). Nutrients are used by the plant for various biological functions such as energy storage, building proteins, or maintaining cell turgor (Taiz and Zeiger 2010).

1.2.4 Water and air

Adequate access to water and air are critical for success of plants. Water is required for the functioning of plants at a cellular level. During photosynthesis, plant stomata open to take in carbon dioxide, water is transpired in this process, cooling the leaf. Plants must have regular access to sufficient volumes of water to replace what is lost

(Taiz and Zeiger 2010). The water held in the substrate combined with dissolved salts comprises the soil solution, which supplies the plant with nutrients (Brady 1974). Roots need access to oxygen in order to maintain metabolic activity and growth (Bunt 1988). Amount of water and air are largely defined by pore size, which in turn is controlled by the types and ratios of mineral components and organic matter.

1.2.5 Living organisms – organic matter decomposition

The biological component of growing media is the biotic community supported within the substrate (Handreck and Black 2002). Organic matter added to a substrate provides microorganisms to establish a nutrient cycle (Bunt 1976). Decomposition of organic matter includes the physical and chemical processes involved in breaking the material down into smaller particles and eventually into its elemental chemical constituents (Aerts 1997). Microorganisms, both bacteria and fungi, participate in biotic decomposition by breaking down the organic matter through physico-chemical methods, thereby releasing nutrients (Brady 1974). This process releases inorganic compounds such as ammonium, phosphate, carbon dioxide and water (Aerts 1997).

Rate of organic matter decomposition is controlled by three distinct factors: physico-chemical properties of the substrate, environmental influences, and types of organisms participating in the decay process (Daubenmire and Prusso 1963). Limited research has yet been conducted on the decomposition rates of organic matter on green roofs. Because deserts have scarce water and high temperatures, decomposition studies conducted in desert environments can help to explain what might occur under green roof conditions. Desert studies show that when the water supply is limited, microbial activity can be constrained to biotic pulses following rain events (Collins et al. 2008). Speed of decomposition is strongly affected by temperature as decay rate increases at higher temperatures as long as water is present (Daubenmire and Prusso 1963). The influence of a combination of these two factors, increased rainfall and higher temperatures, mean that decomposition is not equivalent throughout the year. Climates bring seasonality to decomposition that should be considered when determining rates of organic decay (Daubenmire and Prusso 1963).

1.3 Selecting organic matter for a green roof

1.3.1 Selection criteria

Types of organic matter can vary significantly in physical and chemical composition. In addition to selecting an organic material based on all the functional characteristics (physical, biological, and chemical) mentioned before, one should take into account continuity of supply and cost of the material (Handreck and Black 2002), stability (FLL 2008) , maturity (Dunnett and Kingsbury 2004), and environmental considerations (Boldrin et al. 2010).

Not all organic matter used in green roof falls within the ideal range for nutrient availability so the pH of inorganic and organic components should be considered along with the ideal pH range for the chosen plants. Organic matter is often added to the substrate in a composted form because mature compost has high nutrient content and is more stable than uncomposted materials (Ampim et al. 2010). Finally, one should consider the potentially detrimental materials that can be found in organic materials such as herbicide or pesticide residues, or weed seeds (Fassman et al. 2010) and the potential for leachate with high concentrations of dissolved nutrients (Beck et al. 2011; Teemusk and Mander 2007).

1.3.2 The organic matter used in this research

Four substrates were selected for this study considering the above criteria.

1) Mushroom compost is a byproduct of the mushroom industry. Some components of mushroom substrate include straw, poultry manure, peat moss, and cocoa hulls ("Information on the Benefits and Uses of Mushroom Compost" n.d.). The carbon nitrogen ratio (C:N) of mushroom compost is within the ideal range for compost at 13:1 (Fidanza and Beyer 2005). Particle size distribution of mushroom compost in southern Pennsylvania was found to be 91% ≤ 3/8”, with ≈8% between 3/8 and 5/8”, and 1% from 5/8 to 1” (Fidanza et al. 2010). The same study found an average pH of 6.6 with a range of 5.9 to 7.8.

2) Coconut coir is a natural byproduct created when processing coconut husks. It consists of a mix of mesocarp pith tissue and short fibers (Abad et al. 2002). It has been used as an alternative to peat within the nursery industry (Peat Research and Development Centre 1994; Vavrina and Armbrester 1996). While coconut coir consistently has high water holding capacity, other physical and chemical properties of coir (pH, CEC, EC, C/N) can be highly variable depending on the source of the coconuts, ratio of pith tissue to fiber, processing method, and stockpiling period. (Abad et al. 2002).

3) Composted yard waste is typically processed by municipalities. SmartLeaf®, a product produced by the City of College Park, MD, consists of composted grass, leaves, flowers, weeds and wood pruning material (Public Works Department College Park Maryland n.d.). After collection, these materials are composted in windrows reaching temperatures of 60°C (140°F), which kills weeds and pathogens. The compost is screened to remove large particles over ½" and has a pH of between 7.4 and 8 (Public Works Department College Park Maryland n.d.).

4) Rice hulls are available in large volumes because they are a waste product of the rice milling industry. Rice hulls do not have a high water-holding capacity when used whole but can improve aeration of a substrate (Handreck and Black 2002). They can be or ground to various particle sizes, which increases water-holding capacity (Evans et al. 2011). Parboiled rice hulls (PBH) have been investigated for use in horticultural propagation at Purdue and at the University of Arkansas (Currey et al. n.d.; Evans 2008). Rice hulls have a low CEC and decompose slowly (Evans 2008) due to a high lignin content.

1.4 Green roof substrate standards

Despite the importance of substrate on green roof performance, standards and information for substrates are often superficially discussed in small sections of manuals and reviews (Ampim et al. 2010). The composition of many commercial substrates is considered to be proprietary (Emilsson 2008; Nagase and Dunnett 2011; Olszewski and Young 2011). This leaves designers, installers, and building owners with few options to make thoroughly informed decisions, based upon type and ratios of substrate components. In research applications, the proprietary nature of substrates leads to inconsistencies and limited scope of inference.

Different organizations provide varying standards for substrate qualities such as particle size and percent of organic matter. The United States Department of Agriculture, International Soil Science Society, American Society for Testing Materials, the Massachusetts Institute of Technology, and the Forschungsgesellschaft Landschaftsentwichlung Landscaftsbau (FLL) all have different standards for particle size distribution (Griffin 2014). As previously mentioned, discrepancies between volumetric and gravimetric proportions of substrates can lead to a wide range of substrate functionality while remaining within the stated standards (Friedrich and Buist 2008).

1.5 Research objectives and hypotheses

The goal of this research was to better understand the role different types of organic matter play within a green roof substrate, in regard to maximizing the potential for successful plant establishment.

I hypothesized that, in general, the type of organic matter would have an effect on the growth of green roof plants during their establishment period. The basis of this hypothesis is the contribution of different OM types to water-holding capacity and nutrient availabilities. I also hypothesized that different types of organic matter would decompose at different rates. Specific hypotheses are given for each experiment in the following chapters. To test these hypotheses, I conducted experiments under controlled growth chamber conditions and in a replicated study on a third floor roof at the University of Maryland, College Park.

Chapter 2: A Comparison of Organic Matter Source: Rooftop Experiment

2.1 Introduction

2.1.1 Green roof definition and benefits

Green roofs are roof systems designed to support the growth of plants while primarily mitigating stormwater runoff. A green roof is an assembly of components that works to provide ecosystem services not offered by traditional roofing options. The components of a green roof can include: a structural roofing deck, waterproofing layer, root barrier, moisture storage layer, drainage layer, filter fabric, growing media, and plant materials (Emory Knoll Farms 2012). Green roofs fall into two major categories: intensive and extensive roofs. An intensive roof can also be described as a roof garden with a layer of growing media, generally greater than 15.2 cm in depth (Getter and Rower 2006). An extensive green roof is thinner and designed primarily for ecosystem services. Because the growing media on extensive roofs is typically less than 15.2 cm (Getter and Rower 2006), they weigh less and require fewer structural modifications to existing roof structures. Green roofs provide two main categories of benefits: ecosystem services and economic benefits. Ecosystem services include mitigation of stormwater runoff, urban heat island reduction, and increased biodiversity (Getter and Rower 2006). Economic benefits incorporate increased lifespan of the roofing membranes (US General Services Administration 2011), building insulation (Oberndorfer et al. 2007) and reduction of impervious surface fees

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2.1.2 Green roof substrates

Typical substrates (or growing media) are made up of five basic components: mineral particles, organic matter, water, air, and living organisms (Handreck and Black 2002). Varying ratios of components combined, form the physical, chemical and biological properties that define the functionality of the substrate, developed for specific goals or an intended purpose. In the case of green roofs, the substrates must be light weight, be efficient in absorbing and retaining water, be able to drain excess water, provide anchorage for plants, and provide nutrients to enhance plant growth (Getter and Rower 2006; Nagase and Dunnett 2011; Snodgrass and Snodgrass, 2006).

Specific proportions and types of these components can aid in the initial and long-term performance of a green roof. The amount and type of organic matter affects functionality by contributing to the structure and porosity of the media, increasing the water–holding capacity, increasing the cation exchange capacity (CEC), affecting the pH, and storing nutrients essential for plant growth (Allison 1973). A high ratio of organic matter provides more nutrients and greater water-holding capacity but can contribute significantly to overall weight and can be associated with subsidence of the media. Lower organic percentages reduce weight but may cause stress due to lack of nutrients and lower water-holding capacity (Fassman et al. 2010). Recommendations for the addition of organic matter added to green roof media are vague and are given in both weight and volume proportions The FLL (German Landscape Research, Development, and Construction Society) recommends ≤ 65 g/l of organic matter *by mass* for an extensive green roof (FLL 2008). The Auckland Regional Council recommends 5% to 20% *by volume* with higher percentages aiding in plant success but adding to the weight load of the roof (Fassman et al. 2010). Because different types of organic matter have different bulk densities (Handreck and Black 2002), the conversion between gravimetric and volumetric ratios can mean largely different amounts of organic matter being incorporated, depending on which recommendation is followed.

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2.1.3 Substrate standards

Despite the importance of substrate on green roof performance, standards and information for substrates are often superficially discussed in small sections of manuals and reviews (Ampim et al. 2010). The composition of many commercial substrates is considered to be proprietary (Emilsson 2008; Nagase and Dunnett 2011; Olszewski and Young 2011). This leaves designers, installers, and building owners with few options to make thoroughly informed decisions, based upon type and ratios of substrate components. In research applications, the proprietary nature of substrates leads to inconsistencies and limited scope of inference.

2.1.4 Objectives and hypotheses

The goal of this research was to better understand the functions that different types of organic matter provide to green roof substrates, with regard to maximizing the potential for successful plant establishment and better predict the long-term functioning of organic material. It was hypothesized that,

1. H_O: Percent volumetric water content will be equal for each of the four treatments (type of OM used in substrate).

   H_A: Percent volumetric water content will not be equal for each of the four treatments (type of OM used in substrate).

2. H_O: Plant growth will be equal for each of the four treatments (type of OM used in substrate) due to water availability.

   H_A: Plant growth will not be equal for each of the four treatments (type of OM used in substrate) due to water availability.

2.2 Materials and methods

2.2.1 Substrate development

Four types of organic matter (OM), each with different physical and chemical properties were selected, based on industry use as a component or part of a mix of components in green roof substrates. These four types of OM (see Appendix A for OM analyses) were mushroom compost (Hy-Tech Mushroom Compost, Inc.; West Grove, PA), coconut coir (Maryland Plant & Supplies, Inc.; Rosedale, MD), SmartLeaf® (Public Works Department, City of College Park, MD), and rice hulls (Riceland Foods, Inc.; Stuttgart, AZ).

The substrates were created by combining a special batch of M2 green roof substrate (Stancills Inc., Perryville, MD), which initially had 0.5% organic matter by mass (compared to 3.9% in a typical batch of M2), with one of each of the OM components (see Appendix A for substrate analyses). An unknown amount of Osmocote® was initially present in the M2. Because substrates were installed outside (often above 70° F) in moist conditions for eleven months before initiation of this study, it is likely that soluble macronutrients were mostly leached or volatilized during this time. Each OM component was separately combined with the M2 substrate in a small cement mixer, with additional mixing done by hand, to produce a 20% OM : 80% M2 (v/v) mixture.

2.2.2 Experimental design

Green roof modules (LiveRoof®, Spring Lake, MI) were filled with each substrate mix, and placed on the 3rd floor roof of the Plant Sciences Building at the University of Maryland, College Park in March of 2013. For each treatment, 42 modules, each 61.0 cm x 30.5 cm x 8.3 cm (L×W×H, 15338 cm^3) and approximately 15.3 liters in volume, were filled with one of the four substrates for a total of 168 experimental units. Of these, half were planted with 3 plugs each of *Phedimus kamtschaticus* (Fisch. & C.A.Mey.), formerly *Sedum kamtschaticum*, (Emory Knoll Farms, Street, MD) and half were left unplanted. The modules were arranged in a randomized complete block design in 7 blocks, each having 3 replicates of both planted and unplanted modules per each of the 4 OM treatments. The design was oriented along an east to west pattern to block for a sunlight / temperature gradient (Fig. 2.1).

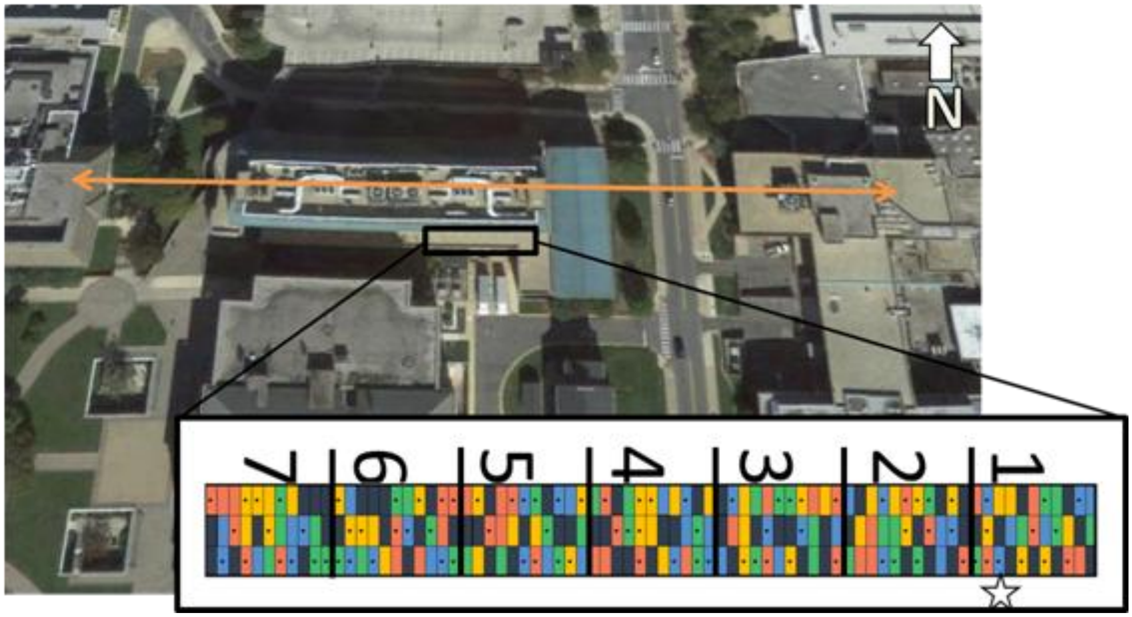


Figure 2.1 Overview of the rooftop study site on the Plant Sciences Building third floor roof in College Park, MD. The call-out image shows blocking design. Type of organic matter is represented by color (coconut coir = blue, rice hulls = red, SmartLeaf® = green, mushroom compost = orange), presence/absence of a dot indicates planted/unplanted respectively; and dark gray squares indicate modules not used in the experiment. The orange arrow indicates the track of the sun in relation to the planting site.

2.2.3 Litter bags

Litter bags were installed into the modules to more closely monitor organic matter decomposition. Construction, installation, processing and results of this litter bag study are discussed in detail in chapter 4.

2.2.4 Rooftop conditions

A weather station (Decagon Devices, Inc., Pullman, WA) consisting of a PAR (photosynthetically active radiation) sensor, ECRN-100 rain gauge, anemometer (wind speed and direction), leaf wetness sensor, and a temperature/RH sensor monitored environmental data at the University of Maryland Research Greenhouse, 0.9 km from the roof site. These sensors were connected to an EM50 data logger, with sensor data measured every minute and logged on a 5-minute basis, to provide climatic data.

The ECRN-100 rain gauge collected precipitation data in mm per 5 minute period. Separate precipitation events were defined by at least a 5-hour period in which no rain was recorded. Duration was defined as the total number of minutes that precipitation was recorded. Total storm precipitation was the total mm recorded within a single event. Intensity was the total storm precipitation divided by the total duration of the storm (in hours). Precipitation events were separated into three categories: small (up to 7.8 mm/hour), medium (7.9 mm/hour – 12.7 mm/hour), and large (12.8 mm/hour and above).

Four GS3 sensors (Decagon Devices, Inc.) were placed in randomly selected modules for each treatment and measured electrical conductivity, substrate temperature and soil moisture. GS3 sensors were inserted horizontally into the litter bags at a 5 cm depth (Fig. 2.2). This substrate data was measured every minute and the average logged every 15 minutes, by connecting the GS3 sensors to EM50R data loggers (Decagon Devices, Inc.).

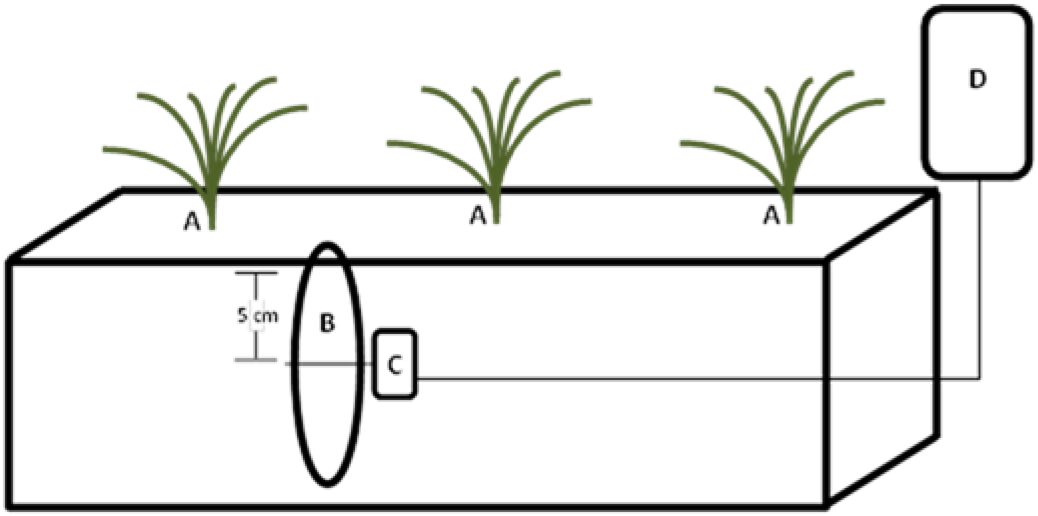


Figure 2.2 Diagram representing location of plants (A), litterbag (B), GS3 sensor (C), and EM50 node (D).

2.2.5 Harvesting and processing

Biomass data was collected during the second year of plant growth, from February to September of 2014. Plants were harvested (from individual modules) from the roof on 5/15/2014, 7/16/2014, and 9/24/2014 at 102, 164 and 234 days after study initiation, and kept in refrigerated storage (1.6 C) until processed (described below). At each harvest, one module per treatment per block (n=7 per OM treatment) was sampled from both planted and unplanted treatments (n=56). A photograph was taken of each planted module from a fixed position using a gantry and each plant was measured to record its aboveground canopy diameter.

Plants were removed from the module and roots were rinsed twice successively. During each washing, the plants were submerged and gently agitated to remove media while minimizing fine root loss. Water was changed regularly and loose roots were collected and kept together with the plant. Plants were laid out to air dry. After 5 days, roots and shoots were separated and weighed to determine fresh weight. The total number of shoots per plant were counted and the leaves were removed from 10 random shoots. Leaf area for these ten shoots were measured using a leaf area meter (LI-3100C, LI-COR, Lincoln, Nebraska) and multiplied by the number of shoots to estimate whole plant leaf area. All roots and shoots were then dried until weights stabilized (typically after 14 days) in a drying oven (Model 1690, VWR International, Radnor, PA), maintained at a constant 50 C. Sample dry mass was determined upon cooling after removal from oven.

2.2.6 Statistical analysis

All treatment effects were calculated using a multiple means comparison adjusted with the Tukey-Kramer HSD method. Statistical analysis was conducted using JMP (JMP®, Version *10 Pro).*

2.3 Results

2.3.1 Volumetric water content

Substrate volumetric water content was analyzed from three selected medium intensity rain events. These events were early (5/15/2014), middle (7/8/2014), and late (9/2/2014) in the study period. Table 2.1 gives descriptive details of these events. All three events were selected because they had similar intensities (8.3-8.9 mm/hour), although the first rain event was longer and had greater total precipitation than the other two events. Figure 2.3 gives a visual representation of the three rain events. In these graphs, data from planted and unplanted treatments were averaged over substrate type (coconut coir, CC; rice hulls, RH; mushroom compost, MC; SmartLeaf®, SL). Figure 2.4 shows all precipitation events for the entire year in order to give context to the three selected events. The first rain event, the event with the greatest volume, showed a different infiltration and accommodation curve than the following two events, which were more similar in total precipitation volume and time.

Except for the time period between the 2nd and 6th hour of the first rain event, CC maintained the highest average VWC.

Table 2.1 Descriptive details of selected rain events shown in Figure 2.3

Rain Event	Date	Duration (hours)	Average Antecedent % VWC	Intensity (mm/hr)	Total Precipitation (mm)
1	5/16/14	7.33	12.9	8.3	61.0
2	7/8/14	1.08	12.9	8.9	9.6
3	9/2/14	0.58	18.6	8.6	5.0

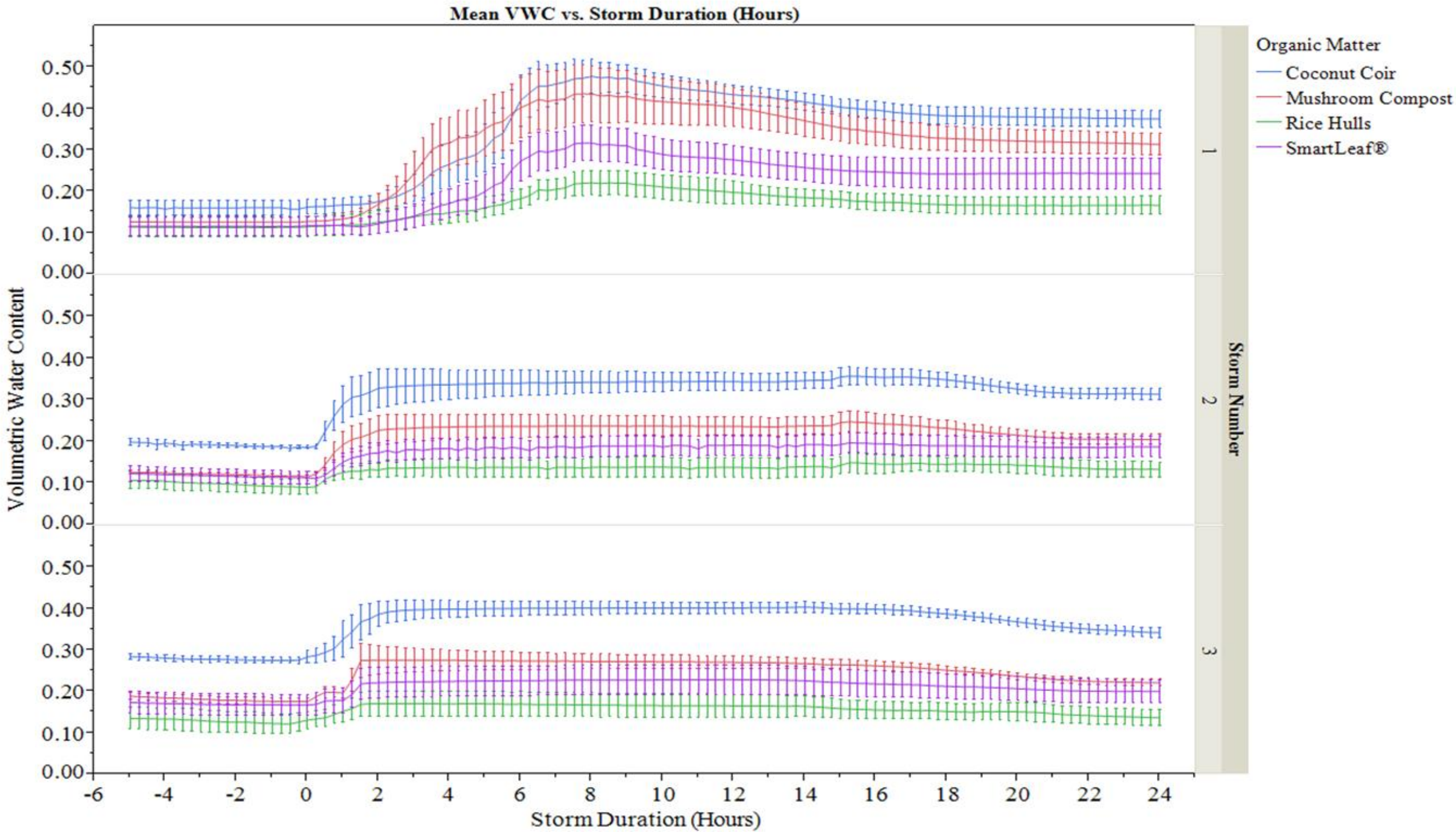


Figure 2.3 A, B, and C Volumetric water content from three separate rain events during the study period (A: Storm 1 - 5/15/2014, B: Storm 2 – 7/8/2015, C: Storm 3 – 9/2/2014). Vertical lines represent standard error for VWC value at each time point

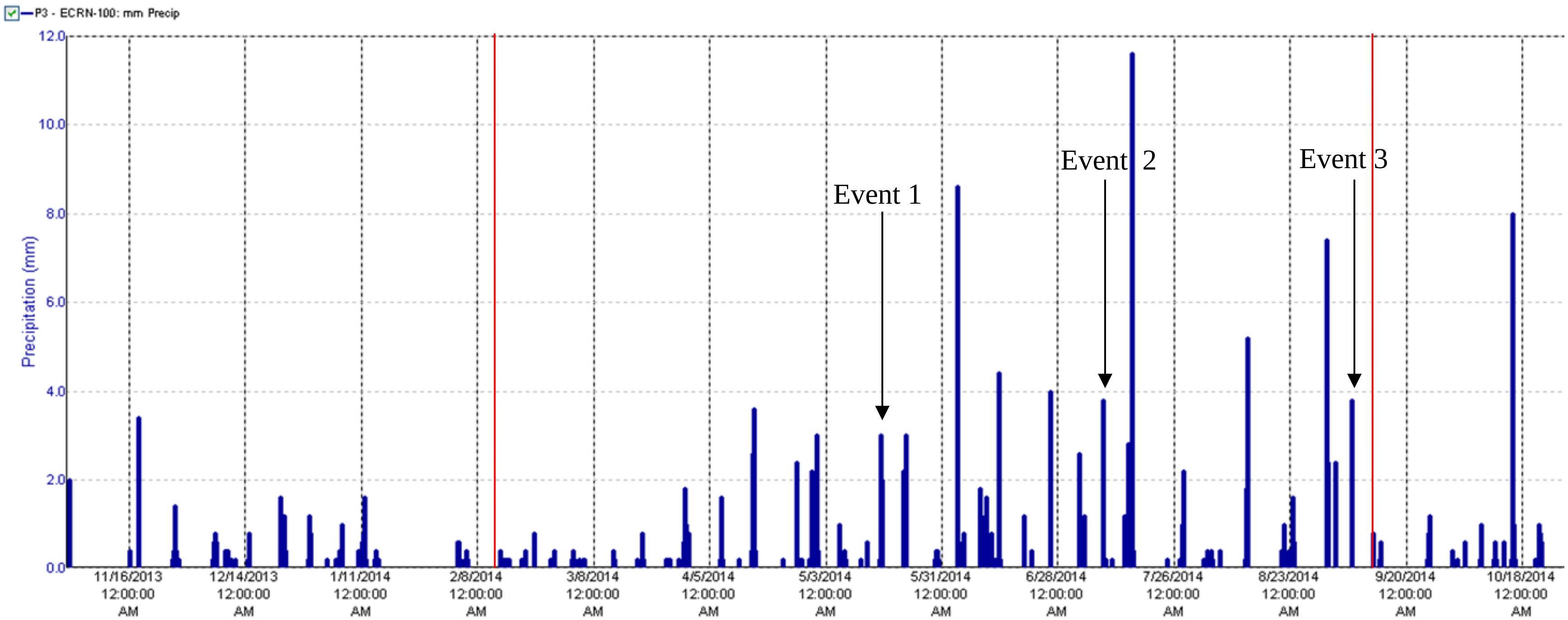


Figure 2.4 Precipitation depths for one year from 11/1/2013 to 10/28/2014. The arrows indicate the three rain events shown in Fig. 2.3 Beginning and end of the study period is indicated by red lines

Table 2.2 Change in % VWC (Δ %VWC) and standard error during the first 6 hours of each rain event. Letters indicate significant treatment effects within each rain event.

Substrate	Rain Event 1	Rain Event 2	Rain Event 3
Coconut Coir	25.9 ± 4.6[a]	15.3 ± 2.7[a]	12.5 ± 1.1[a]
Rice Hulls	7.0 ± 1.1 [b]	4.6 ± 1.2 [b]	7.6 ± 2.1[ab]
SmartLeaf®	15.8 ± 2.7 [ab]	6.9 ± 1.0 [ab]	5.8 ± 1.1 [b]
Mushroom	27.7 ± 7.1[a]	11.9 ± 2.9 [ab]	9.8 ± 1.7 [ab]

The change in % VWC (Δ %VWC; Table 2.2) represents the total water gained in the substrate during the first 6 hours of each rain event. The gain was highest overall for the first rain event.

Figure 2.5 shows the relative VWC of each substrate treatment at t=-1, the antecedent moisture content; t=6, saturation; and t=24, after significant runoff. For the first rain event there was no significant difference between treatments in terms of antecedent moisture content. For the following two events, CC modules had higher antecedent moisture content than any other treatment. Time after 24 hours shows the greatest level of distinction between treatments. CC modules had the highest VWC, except in the first rain event where it was no different than modules with MC. RH modules consistently had the lowest VWC. Generally, the trend was that modules with MC and SL were intermediary in VWC between the other two.

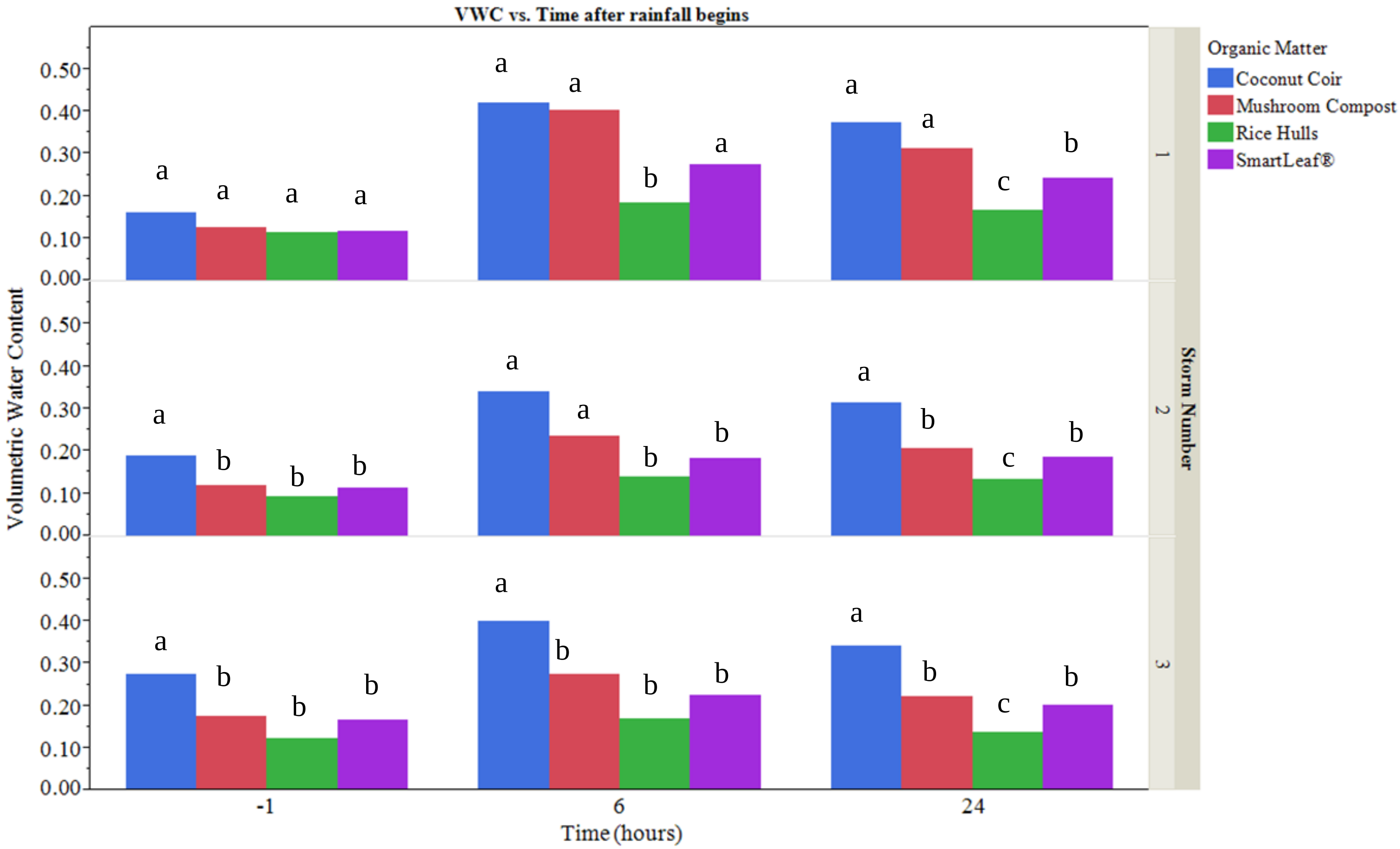


Figure 2.5 Comparison of volumetric water content 1 hour before each event started, 6 hours after rain started, and 24 hours after rain started for each of the three rain events (Event 1 – 5/15/2014, Event 2 – 7/8/2014, Event 3 – 9/2/2014). Letters indicate significant differences at each time within event.

Table 2.3 gives descriptive details for two rain events that occurred less than 12 hours apart. Figure 2.6 shows the VWC for the same events. In these graphs, planted and unplanted modules are shown separately. The order of VWC was the same during this rain event as during the rain events shown in Figure 2.3. The infiltration curve was smoother for planted modules, showing that periods of more intense precipitation caused a less dramatic effect on the VWC of the planted module.

Table 2.3 Descriptive details of rain events shown in Figure 2.6

Date	Start Time	Duration (hours)	Average Antecedent % VWC	Intensity (mm/hr)	Total Precipitation (mm)
5/21/14	6:10 PM	0.58	15.2	9.3	5.4
5/22/14	5:35 AM	0.67	23.5	16.2	10.8

The antecedent VWC shown between t=-6 and t= 0 is lower for the planted treatment than for the unplanted treatment. Between t=12 and t=14 (Fig. 2.6), the difference in dry down between planted and unplanted treatments was seen. A sharper dry down curve, indicating significant leaching, was seen in the unplanted treatment compared to the gentler slope of the planted treatments. The two SL sensors were more variable than the two replications in other treatments, leading to a high standard error.

Treatment differences between planted and unplanted modules can also be seen in Figure 2.7. This graph shows the mean VWC of each plant treatment (planted or unplanted) at noon for each date during the study period (2/3/2014 – 9/24/2014). Mean VWCs for both treatments were similar, with VWC for unplanted modules slightly lower, until late march. Treatment differences were largest in May and noticeably decreased by September.

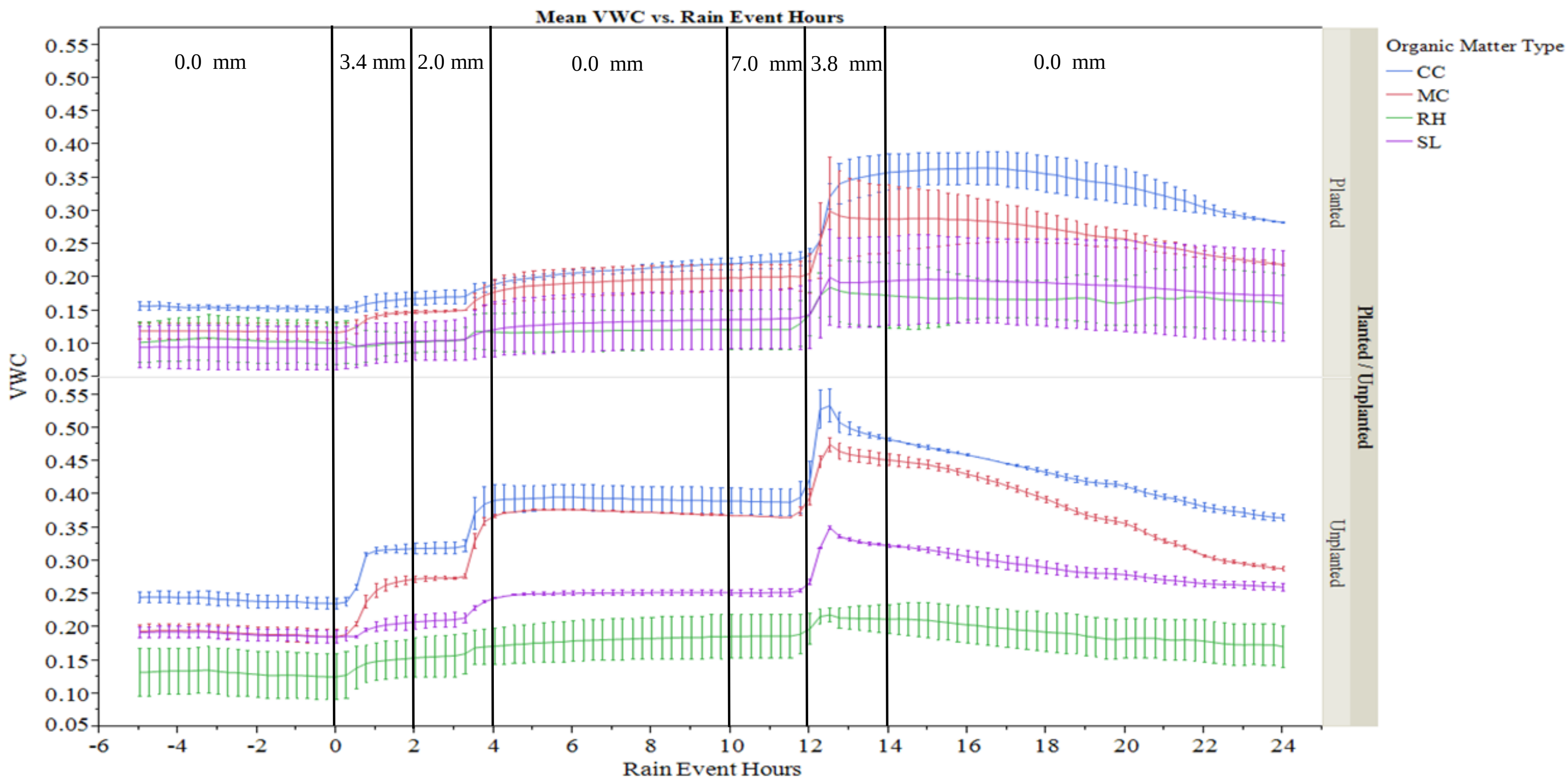


Figure 2.6 Volumetric water content from a rain event with two separate periods of intense precipitation. Numbers, in mm, along the top of the graph show depth of precipitation in each time period separated by long vertical lines. Data from planted modules is shown in the top graph while data from unplanted modules is shown in the bottom graph. Short vertical lines represent standard error for each organic matter treatment.

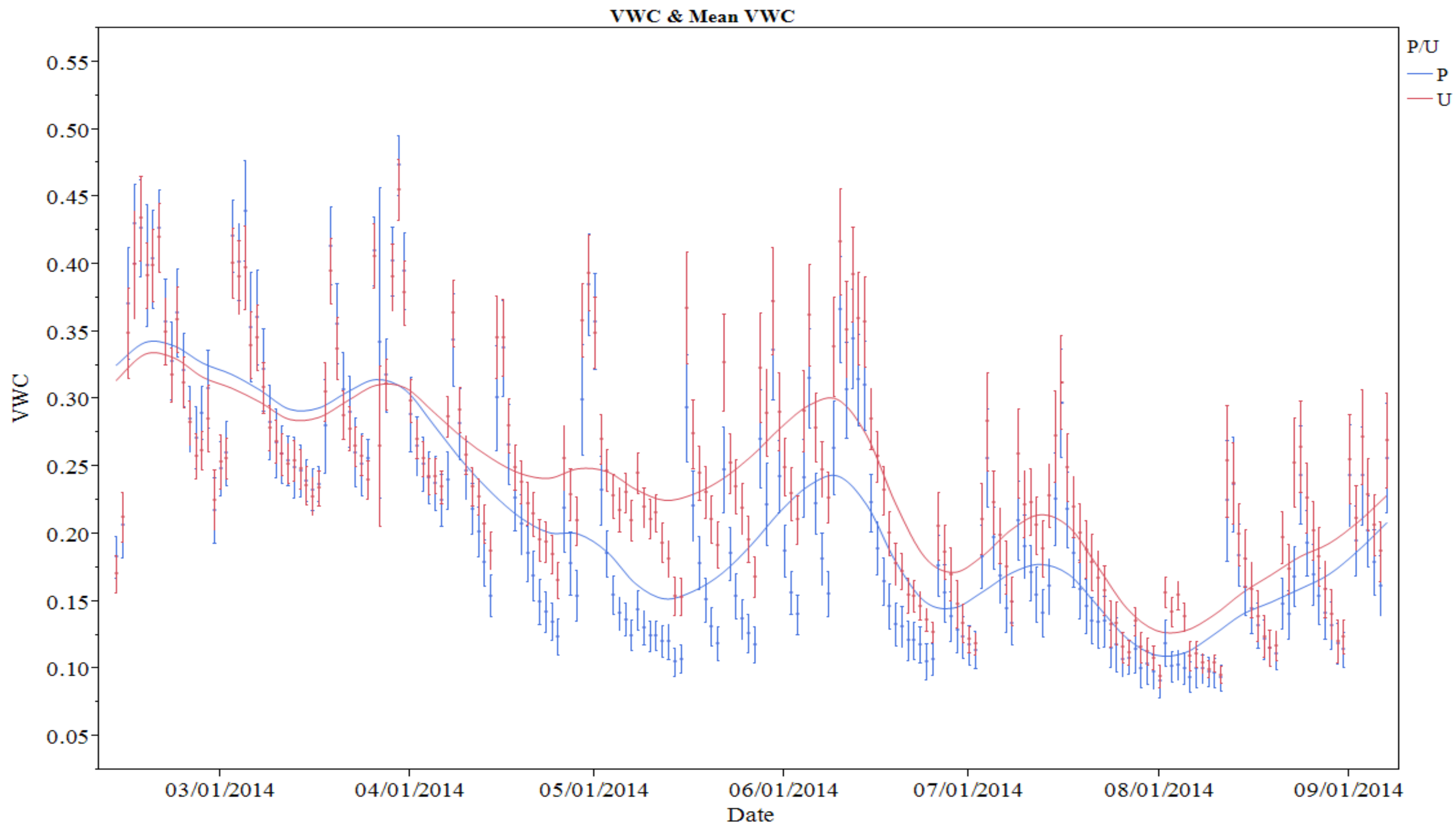


Figure 2.7 Volumetric water content of all modules at noon each day during the study period (2/3/2014 – 9/24/2014). Means are averaged across different OM types to show planted (P, in blue) and unplanted (UP, in red) treatment differences. Vertical bars indicate standard error for each treatment (P or UP) on each date.

2.3.2 Plant growth

Table 2.4 shows the biomass of roots of *Phedimus kamtschaticus* from each harvest. Table 2.5 shows shoot biomass and extrapolated leaf area, again from each harvest. Generally, plants from CC modules were intermediate in size between those from RH modules and those from MC or SL modules. At the first harvest, plants grown in RH modules had significantly lower root mass, shoot mass and leaf area. At the second harvest, there were no significant differences in root mass or leaf area but plants grown in RH modules had significantly lower shoot mass than those grown in MC and SL modules. At the third harvest, shoot dry masses of plants grown in MC modules (18.8 g) and SL modules (17.5 g) were significantly higher than for plants grown in CC modules (12.7 g) and RH modules (10.2 g). Throughout the entire study, there were no significant differences between growth of roots for plants grown in MC, SL, or CC modules and no significant differences between growth of shoots or leaf area for plants grown in MC or SL modules.

Treatment differences were also visually apparent. Figure 2.8 shows photographs of representative modules from the final harvest in September 2014. Plants grown in CC and RH modules were smaller and had more visible necrosis on leaf margins. Plants grown in SL and MC modules were larger and show less leaf necrosis. Photographs in Figures B1 – B4 in Appendix B show the progression of plant growth and change in each treatment throughout the experiment.

Table 2.4 Biomass and standard errors of *Phedimus kamtschaticus* dry root mass (g) for each organic matter treatment at each harvest. Letters indicate significant treatment effects (α = 0.05) within harvest. An expanded table of growth metrics is available in App. B.

Substrate	Harvest 1 (5/15/2014)	Harvest 2 (7/16/2014)	Harvest 3 (9/24/2014)
	Root Mass	Root Mass	Root Mass
Coconut Coir	18.8 ± 1.7 [a]	23.2 ± 1.7 [a]	26.4 ± 1.6 [a]
Rice Hulls	13.2 ± 1.1 [b]	17.9 ± 1.7 [a]	16.9 ± 1.1 [b]
SmartLeaf®	19.9 ± 0.6 [a]	23.7 ± 1.4 [a]	27.3 ± 1.3 [a]
Mushroom	19.6 ± 1.3 [a]	22.5 ± 1.8 [a]	27.8 ± 2.0 [a]

Table 2.5 Biomass and standard errors of *Phedimus kamtschaticus* Leaf area (cm^3/cm^3) and dry shoot mass (g) for each organic matter treatment at each harvest. Letters indicate significant treatment effects (α = 0.05) within harvest. An expanded table of growth metrics is available in Appendix B.

Substrate	Harvest 1 (5/15/2014)		Harvest 2 (7/16/2014)		Harvest 3 (9/24/2014)	
	Leaf Area	Shoot Mass	Leaf Area	Shoot Mass	Leaf Area	Shoot Mass
Coconut Coir	1100.2 ± 90.1 [bc]	11.9 ± 0.8 [a]	1191.9 ± 85.5 [a]	16.4 ± 1.1 [ab]	694.4 ± 87.3 [b]	12.7 ± 1.1 [b]
Rice Hulls	891.5 ± 70.4 [c]	8.4 ± 0.5 [b]	1074.2 ± 102.8 [a]	12.2 ± 1.1 [b]	672.5 ± 32.9 [b]	10.2 ± 0.6 [b]
SmartLeaf®	1380.0 ± 51.8 [ab]	13.4 ± 0.4 [a]	1373.9 ± 85.3 [a]	18.5 ± 1.0 [a]	1000.7 ± 80.8 [a]	17.5 ± 0.9 [a]
Mushroom	1476.1 ± 119.7 [a]	14.1 ± 0.8 [a]	1370.1 ± 82.3 [a]	19.2 ± 1.5 [a]	1223.4 ± 90.7 [a]	18.8 ± 1.4 [a]

Figure 2.8 Representative images selected from the final harvest in September. Some necrotic margins can be seen in all images with more visible in the first two, coconut coir and rice hulls.

2.4 *Discussion and conclusions*

2.4.1 Volumetric water content

Graphs and analysis of volumetric water content throughout this experiment showed treatment differences both for water infiltration and ability to hold water. It is important to note that there was no supplementary watering during this experiment; this is especially interesting when compared with the growth chamber experiment described in the following chapter which followed a regular watering regime.

Modules with CC had the highest VWC at most points during the analyzed storm events while modules with RH had the lowest VWC. This trend existed in both planted and unplanted treatments and indicates that type of organic matter had an impact on a green roof's ability to absorb and retain water.

A possible explanation for the fact that the VWC for MC modules exceeded VWC for CC modules between t=2 and t=6 during the first rain event is that CC rewets more slowly than MC. The antecedent moisture content was lower for CC before the first rain event than for the following events, so this effect was not repeated. Afterwards, as seen in the graphs (Fig. 2.3) coconut coir modules consistently had a higher antecedent VWC than the other organic matter treatments. This suggests that the media amended with CC had the capacity to hold more water even when the change in VWC was insignificant compared to the change in VWC for MC or SL as seen in Event 1.

Treatment differences in average VWC between planted and unplanted modules are plainly seen in Figs. 2.6 and 2.7. In Fig. 2.6 antecedent VWC was lower for planted modules than for unplanted modules, likely due to plant water use in the planted modules. There are several possible explanations for the dynamic differences seen in wetting and drying curves. Plant canopy intercepts precipitation limiting both the total amount of water that reaches the surface of the substrate and the time it takes water to reach the surface. This allowed water to infiltrate into the substrate at a slower pace and likely permitted less runoff. In planted modules VWC also decreased at a slower rate suggesting that plants decelerated the movement of water though the module, or increased the capture of rain water in the module. Unplanted modules show noticeable leaching once they have reached saturation during the second precipitation event shown in Figure 2.6.

Figure 2.7 gives a visual perspective of VWC over the entire study period. This allows seasonal differences to become apparent. When plants were dormant, VWC was nearly equal for planted and unplanted treatments. When plants began to leaf out in April, differences between planted and unplanted treatments increased. The differences were most pronounced during spring when plant growth rate was highest. The difference then decreased towards the end of the season as plants began to enter dormancy. Both Figs. 2.6 and 2.7 provide evidence to support the idea that plants are important to overall stormwater retention capacity and evapotranspiration.

2.4.2 Plant growth

All four organic matter treatments achieved the minimum in supporting the survival and growth of plants through two full seasons of growth. Treatment differences were most pronounced in shoot dry mass, indicating that type of organic matter has an effect on the ability of the plants to spread and achieve coverage of a roof surface. Plants grown in SL and MC modules were larger and more robust than plants grown in RH and CC modules indicating possible nutritional differences between the OM amendments.

An interesting trend was seen from the differences between root growth and shoot growth. Plants grown in MC, SL, or CC showed no significant difference in root dry mass. However, there were significant differences in shoot dry mass and leaf area, which changed over the course of the experiment.

2.4.3 Conclusions

This experiment demonstrated that type of organic matter had an effect on green roof performance in two key ways: rain water retention and facilitating healthy plant growth. While CC had a high propensity to hold water, this was not always reflected in increased aboveground biomass or leaf area. MC and SL held more water than rice hulls and were associated with a significant increase in plant growth. This indicates another quality of OM type, such as nutrient content and availability, might be playing a role in plant establishment. The images taken during the experiment showed symptoms of potential nutrient deficiencies (Lea-Cox 1999) associated with plants grown in CC or RH modules.

As noted earlier, the experiment also demonstrated that plants have an important role to play in stormwater retention which supports previous work comparing planted and unplanted platforms (Starry, 2013). Rice hulls can be considered the least successful organic component as these modules had the lowest VWC and lowest plant mass throughout the experiment. A substrate that can retain water and support significant plant growth can maximize the effectiveness of the roof system. The growth chamber experiment discussed in the following chapter helps in understanding the growth differences shown in different treatments, especially between plants grown in CC, MC, or SL modules.

Chapter 3: A Comparison of Organic Matter Source: Growth Chamber Experiment

3.1 Introduction

3.1.1 Green roof definition and benefits

Green roofs are roof systems designed to support the growth of plants while primarily mitigating stormwater runoff. A green roof is an assembly of components that works to provide ecosystem services not offered by traditional roofing options. The components of a green roof can include: a structural roofing deck, waterproofing layer, root barrier, moisture storage layer, drainage layer, filter fabric, growing media, and plant materials (Emory Knoll Farms 2012). Green roofs fall into two major categories: intensive and extensive roofs. An intensive roof can also be described as a roof garden with a layer of growing media, generally greater than 15.2 cm in depth (Getter and Rower 2006). An extensive green roof is thinner and designed primarily for ecosystem services. Because the growing media on extensive roofs is typically less than 15.2 cm (Getter and Rower 2006), they weigh less and require fewer structural modifications to existing roof structures. Green roofs provide two main categories of benefits: ecosystem services and economic benefits. Ecosystem services include mitigation of stormwater runoff, urban heat island reduction, and increased biodiversity (Getter and Rower 2006). Economic benefits incorporate increased lifespan of the roofing membranes (US General Services Administration 2011), building insulation (Oberndorfer et al. 2007) and reduction of impervious surface fees

(District of Columbia Water and Sewer Authority 2015). It should be noted that ecosystem services also provide direct economic benefits to owners as well as society.

3.1.2 Green roof substrates

Typical substrates (or growing media) are made up of five basic components: mineral particles, organic matter, water, air, and living organisms (Handreck and Black 2002). Varying ratios of components combined, form the physical, chemical and biological properties that define the functionality of the substrate, developed for specific goals or an intended purpose. In the case of green roofs, the substrates must be light weight, be efficient in absorbing and retaining water, be able to drain excess water, provide anchorage for plants, and provide nutrients to enhance plant growth (Getter and Rower 2006; Nagase and Dunnett 2011; Snodgrass and Snodgrass, 2006).

Specific proportions and types of these components can aid in the initial and long-term performance of a green roof. The amount and type of organic matter affects functionality by contributing to the structure and porosity of the media, increasing the water–holding capacity, increasing the cation exchange capacity (CEC), affecting the pH, and storing nutrients essential for plant growth (Allison 1973). A high ratio of organic matter provides more nutrients and greater water-holding capacity but can contribute significantly to overall weight and can be associated with subsidence of the media. Lower organic percentages reduce weight but may cause stress due to lack of nutrients and lower water-holding capacity (Fassman et al. 2010). Recommendations for the addition of organic matter added to green roof media are vague and are given in both weight and volume proportions The FLL (German Landscape Research, Development, and Construction Society) recommends ≤ 65 g/l of organic matter *by mass* for an extensive green roof (FLL 2008). The Auckland Regional Council recommends 5% to 20% *by volume* with higher percentages aiding in plant success but adding to the weight load of the roof (Fassman et al. 2010). Because different types of organic matter have different bulk densities (Handreck and Black 2002), the conversion between gravimetric and volumetric ratios can mean largely different amounts of organic matter being incorporated, depending on which recommendation is followed.

Types of organic matter vary significantly in physical and chemical composition. They fall into two broad categories: composted, having undergone a thermophilic and aerobic stabilization process (Raviv 2005), and uncomposted materials. The green roof community uses a variety of organic matter both in commercial installations and in research projects. Some composted materials used include mushroom compost (Griffin 2014), composted yard waste (Young et al. 2014), vermicompost (Carter and Jackson 2007), and composted pine bark (Fassman et al. 2010). Some uncomposted materials used include coconut coir (Fassman et al. 2010) rice hulls, and sphagnum peat moss (Bousselot et al. 2011). In addition to selecting an organic material based on all the functional characteristics (physical, biological, and chemical) mentioned before, one should take into account continuity of supply and cost of the material

(Handreck and Black 2002), stability (FLL 2008), maturity (Dunnett and Kingsbury 2004), and environmental considerations (Boldrin et al. 2010).

Although extensive research has been conducted on nutrient content in green roof runoff and leachate (Beck et al. 2011; Bliss et al. 2009; Teemusk and Mander 2007), few studies have focused on nutrient dynamics within the roof system (Ampim et al. 2010). Essential nutrients enter a plant when they are absorbed from the soil solution as ions by the roots (Handreck and Black 2002). These essential nutrients are nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (Brady 1974). Nutrients are used by the plant for various biological functions such as energy storage, building proteins, or maintaining cell turgor (Taiz and Zeiger 2010).

3.1.3 Substrate standards

Despite the importance of substrate on green roof performance, standards and information for substrates are often superficially discussed in small sections of manuals and reviews (Ampim et al. 2010). The composition of many commercial substrates is considered to be proprietary (Emilsson 2008; Nagase and Dunnett 2011; Olszewski and Young 2011). This leaves designers, installers, and building owners with few options to make thoroughly informed decisions, based upon type and ratios of substrate components. In research applications, the proprietary nature of substrates leads to inconsistencies and limited scope of inference.

3.1.4 Objectives and hypotheses

The goal of this research was to understand the functions that different types of organic matter provide within a green roof substrate, to maximize the potential for successful plant establishment and to better predict the long-term functioning of organic material. It was hypothesized that type of organic matter would have an effect on the growth and performance of green roof plants during their establishment period, based on different water-holding capacities and nutrient availabilities. This research compared the success of plants grown in four different substrate mixes during a simulated 6-month spring establishment period, by comparing biomass and tissue nutrient content while continuously monitoring volumetric water content under strictly controlled environmental conditions.

1. H_O: Percent volumetric water content will be equal for each of the four treatments (type of OM used in substrate).

   H_A: Percent volumetric water content will not be equal for each of the four treatments (type of OM used in substrate).
2. H_O: Plant growth will be equal for each of the four treatments (type of OM used in substrate), due to adequate water availability.

   H_A: Plant growth will not be equal for each of the four treatments (type of OM used in substrate) due to inadequate water availability.
3. H_O: Tissue nutrient content will be equal for each of the four treatments (type of OM used in substrate), due to adequate nutrient availability.

   H_A: Tissue nutrient content will not be equal for each of the four treatments (type of OM used in substrate) due to inadequate nutrient availability.

3.2 *Materials and Methods*

3.2.1 Substrate development

Four types of organic matter (OM), each with different physical and chemical properties were selected based on industry use, as a component or part of a mix of components in green roof substrates. These four types of OM were mushroom compost (Hy-Tech Mushroom Compost, Inc.; West Grove, PA), coconut coir (Maryland Plant & Supplies, Inc.; Rosedale, MD), SmartLeaf® (Public Works Department, City of College Park, MD), and rice hulls (Riceland Foods, Inc.; Stuttgart, AZ).

The substrates were created by combining a special batch of M2 green roof substrate (Stancills Inc., Perryville, MD), which initially had 0.5% organic matter by mass (compared to 3.9% in a typical batch of M2), with each one of the selected OM components (see Appendix Figs. A1-A7 for media analyses). An unknown amount of Osmocote® was initially present in the M2. Because substrates were stored outside (often above 70° F) in moist conditions for more than sixth months, it is likely that macronutrients were either leached or volatilized by the time these mixtures were created. Each OM component was separately combined with the M2 substrate in a small cement mixer with additional mixing done by hand, to produce a 20% OM: 80% M2 (v/v) mixture.

3.2.2 Experimental design

Two flats of *Phedimus kamtschaticus*, formerly *Sedum kamtschaticum*, plugs (Emory Knoll Farms, Street, MD) were placed into a growth chamber in November 2013 to break dormancy for this experiment. On 30 March, 2014 after plugs broke dormancy and showed significant growth, the roots of each plug were rinsed with water to remove any propagation media. Plugs were separated into three blocks by fresh weight (Block A 3.0g – 5.0g; Block B 5.1g – 6.9g; Block C 7.0g – 9.0g) and planted in 11.4 cm polypropylene pots (Myer Industries, Middlefield, OH), filled with the four substrate mixtures. Each block of plants was arranged in a randomized complete block design within the chamber.

Twenty four Echo-5TM sensors (Decagon Devices, Inc., Pullman, WA) were inserted in 24 pots (2 sensors randomly assigned to 2 pots per treatment per block), to monitor substrate volumetric water content (VWC) and temperature within the root zone. Small slits for the sensors were made in one side of the pot and the sensor was inserted sideways into the root zone at 5cm depth (see Fig. 3.1). These slits were then sealed with duct tape, to ensure no water leaked from the slits. Sensor readings were calibrated based on the four individual substrates (Appendix D).

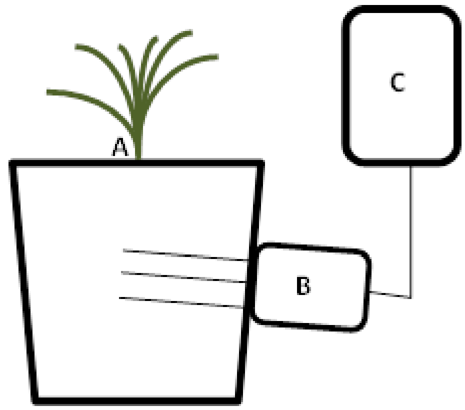


Figure 3.1 Diagram representing location of (A) plant, (B) 5 TM sensor, and (C) EM50R node

3.2.3 Growth chamber conditions and watering regime

Temperature and photoperiod settings for the growth chamber were changed once per month, to reflect monthly averages and mimic Mid-Atlantic weather conditions from recent years (Table 2.1). Temperatures for the chamber were determined from an analysis of weather data from July, 2010 to October, 2012 collected from a weather station at the University of Maryland Research Greenhouse complex. Photoperiod settings were calculated from sunrise and sunset times for College Park, MD taken from Weather Underground (www.wunderground.com).

The watering regime was devised to provide adequate water content for plant growth while also entering stress conditions commonly found on green roofs. Initially, plants were watered with 30 mL every 3 days. Watering was then decreased to once per week in order to better match water scarcity common on green roofs. At this frequency, plants spent too long under water stress conditions for treatment differences to be visible. Therefore watering was adjusted such that plants were watered to saturation with 100 mL of water every 5 days; this regime was continued until termination of the experiment. Figures C1 – C4 track VWC during this period and show a visual representation of the changes in watering regime.

Pots were not fertilized as one of the experimental objectives was to compare native nutrient availabilities between each OM treatment.

Table 3.1 Temperature and photoperiod settings used for growth chamber experiment.

Month	Lights On	Lights Off	Day Temp (C)	Night Temp (C)
April	6:32 AM	7:45 PM	15.8	12.1
May	5:58 AM	8:13 PM	22.2	17.8
June	5:45 AM	8:32 PM	26.1	21.1
July	5:56 AM	8:29 PM	29.4	24.4
August	6:21 AM	8:00 PM	27.2	22.8
September	6:49 AM	7:17 PM	23.3	19.4
October	7:18 AM	6:30 PM	16.1	12.2

3.2.4 Harvesting and processing

Plants were sampled at four times during the experiment. Initial plant samples were collected when the plugs were first transplanted on 3/30/14 (n=24). Two pots per treatment per block (n=6 per OM) were sampled (n=24) at each successive harvest dates (6/5/2014, 8/1/2014 and 10/1/14 at 67, 124 and 185 days after planting). A photograph was taken of each pot from a fixed position using a gantry. A key was then used to determine likely nutrient deficiencies (Lea-Cox 1999). Each plant was measured to record its aboveground canopy width and height at each harvest date. The width was taken at the widest point of each plant and the height was measured from the substrate surface to the uppermost tip of the plant without stretching.

Plants were removed from the module and roots were rinsed twice successively. In each washing, the plants were submerged and gently agitated to remove media while minimizing fine root loss. Water was changed regularly and loose roots were collected and kept together with the plant. Plants were then laid out to air dry.
The following day, roots and shoots were separated and weighed to determine fresh mass. All leaves were removed and leaf area measured using a leaf area meter (LI-3100C, LI-COR, Lincoln, Nebraska). All roots and shoots were then oven-dried until weights stabilized (typically after 7 days) in an oven (Model 1690, VWR International, Radnor, PA) maintained at a constant 50 C. Sample dry mass was determined upon cooling after removal from oven.

Tissue samples from the final harvest were analyzed (JR Peters Laboratory, Allentown, PA) for nutrient concentration. A total of 24 samples (4 OM × 3 reps × 2 plant structures) from the final harvest (on 10/01/14) were analyzed. Roots and shoots were taken from the plant with the largest dry mass, the smallest dry mass, and the plant with the dry mass closest to average. The results from the laboratory were reported as concentration in either ppm or percent. Nutrient contents were calculated from these results, as shown in Fig. 3.2, to normalize differences in nutrient concentration due to the growth differences (root and shoot dry mass) between treatments (Ristvey et al., 2007).

Nitrogen Content

$$= \frac{percent\ N}{100} \times dry\ mass\ \ mg$$

Sodium Content

$$= \frac{ppm\ Na}{1000000} \times dry\ mass\ \ mg$$

Figure 3.2 Equations for calculating nutrient content from nutrient concentration values. The equations used for N and Na represent those used to respectively calculate values reported as nutrient percent and as ppm.

3.2.5 Statistical analysis

All treatment effects were calculated using a multiple means comparison adjusted with the Tukey-Kramer HSD method. Statistical analysis was conducted using JMP (JMP®, Version *10 Pro*).

3.3 Results

3.3.1 Plant growth

As the experiment progressed, treatment differences became visually apparent. Figures 3.3 to 3.5 show photographs of representative plants from each treatment (coconut coir, CC; rice hulls, RH; mushroom compost, MC; SmartLeaf®, SL) at each harvest. Significant differences were observed between treatments in root and shoot dry mass at the second and third harvests (Table 3.2).

The most distinct differences were shown in shoot dry mass (Fig. 3.6). Plants grown in RH-amended substrate consistently had the lowest shoot mass throughout the experiment. By the third harvest there were significant differences between shoot dry mass for MC and SL (1.6 and 1.7g, respectively) and the smaller plants grown in CC and RH substrates (0.8g and 0.6g; Table 3.2). Though plants grown in CC substrates had lower shoot dry mass, the root dry mass was not significantly different than those of plants grown in SL substrate and were significantly larger than those of plants grown in MC substrate. Every plant not destructively harvested survived until the end of the experiment.

Figure 3.3 Representative photographs selected from the first harvest in June. Yellowing and necrotic leaf margins can be seen in the rice hulls photograph.

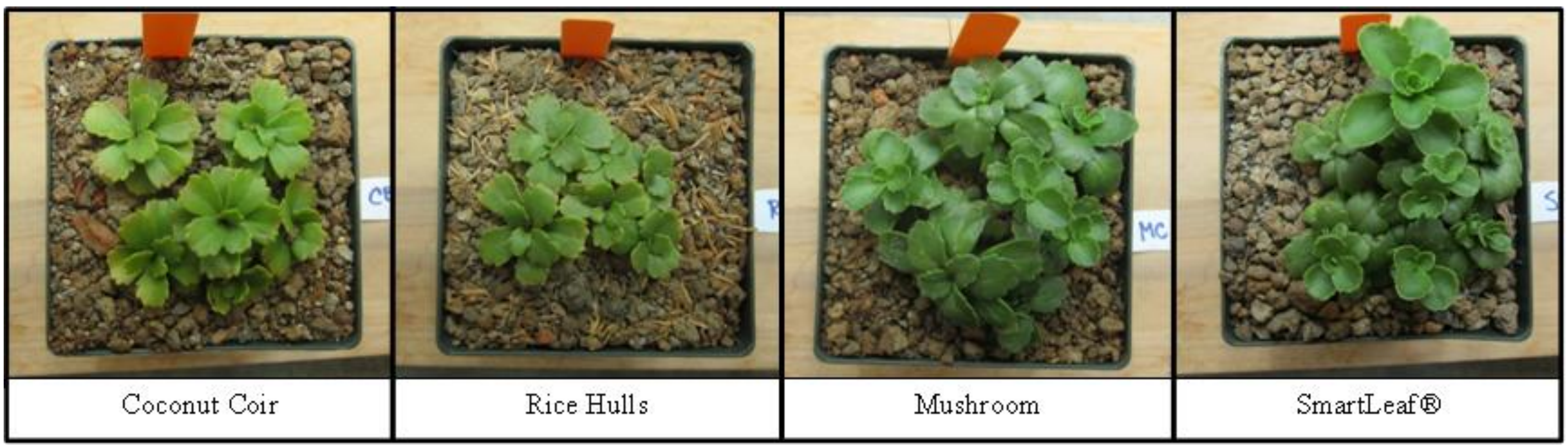


Figure 3.4 Representative photographs selected from the second harvest in August. Yellowing and necrotic leaf margins can be seen in the coconut coir and rice hull photographs.

Coconut Coir	Rice Hulls	Mushroom	SmartLeaf®

Figure 3.5 Representative images selected from the final harvest in October. Necrotic leaf margins and downward cupping can be seen in the coconut coir and rice hull images

Table 3.2 Average biomass (grams) and standard errors of *Phedimus kamtschaticus* for each organic matter treatment at each harvest. Letters indicate significant treatment effects ($\alpha = 0.05$) within each harvest in the same column

	Harvest 1 (6/5/2014)		Harvest 2 (8/1/2014)		Harvest 3 (10/1/2014)	
OM Type	Root Mass	Shoot Mass	Root Mass	Shoot Mass	Root Mass	Shoot Mass
Coconut Coir	1.3 ± 0.1^{a}	0.5 ± 0.1^{a}	1.9 ± 0.1^{a}	0.7 ± 0.1^{ab}	2.0 ± 0.2^{a}	0.8 ± 0.1^{b}
Rice Hulls	1.2 ± 0.1^{a}	0.4 ± 0.1^{a}	1.5 ± 0.2^{b}	0.5 ± 0.0^{b}	1.5 ± 0.1^{b}	0.6 ± 0.1^{b}
SmartLeaf®	1.4 ± 0.2^{a}	0.5 ± 0.1^{a}	1.3 ± 0.1^{b}	0.9 ± 0.1^{ab}	1.7 ± 0.2^{ab}	1.7 ± 0.2^{a}
Mushroom	1.1 ± 0.1^{a}	0.5 ± 0.1^{a}	1.2 ± 0.1^{b}	1.1 ± 0.1^{a}	1.5 ± 0.1^{b}	1.6 ± 0.2^{a}

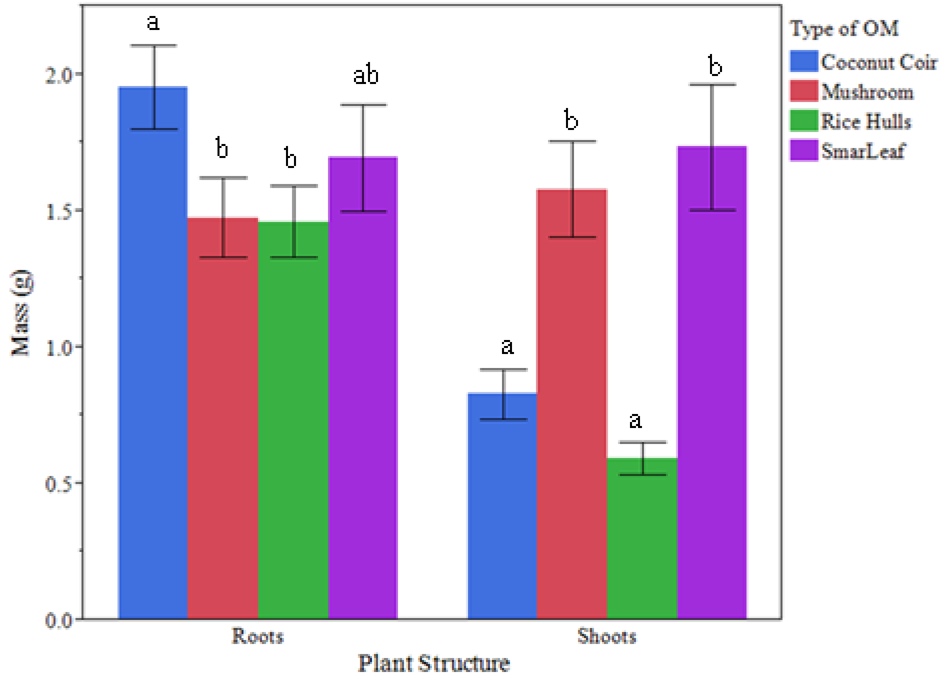


Figure 3.6 Average dry root and shoot biomass (grams) of *Phedimus kamtschaticus* for each organic matter treatment at the October harvest. Bars represent standard error and letters indicate significant treatment effects (α = 0.05) within roots or shoot dry mass.

3.3.2 Volumetric water content

Graphs showing continuous substrate volumetric water content (VWC) for each treatment over the course of the entire experiment (Fig. B1 A-D), and additional graphs focused on the three watering cycles surrounding each harvest (Figs. B2-B4) can be found in Appendix C.

Substrate VWC was analyzed for three dry-down periods over a course of 15 days surrounding each harvest date, in order to ascertain any differences in plant-available water. Substrates amended with RH, MC, and SL were not significantly different in percent volumetric water capacity (% VWC) at any harvest (Table 3.3).

Table 3.3 Effect of organic matter type on percent volumetric water content (% VWC). Low indicates the antecedent moisture content (% VWC 1 hour before rewetting). High indicates the subsequent moisture content (% VWC 1 hour after rewetting). Each value represents an average of sensors (n=6) over three watering cycles. Letters indicate significant treatment effects (α = 0.05) within each harvest in the same column.

	Harvest 1 (5/30/2014 - 6/15/2014)		**Harvest 2 (7/22/2014 - 8/7/2014)**		**Harvest 3 (9/19/2014 - 10/4/2014)**	
OM Type	Low	High	Low	High	Low	High
Coconut Coir	8.0 ± 0.7^{a}	28.2 ± 1.6^{a}	5.9 ± 0.7^{a}	24.5 ± 1.4^{a}	8.8 ± 0.8^{a}	25.5 ± 1.8^{a}
Rice Hulls	5.0 ± 0.3^{b}	19.3 ± 0.7^{b}	4.5 ± 0.3^{a}	18.2 ± 0.7^{b}	5.6 ± 0.3^{a}	19.2 ± 1.1^{ab}
SmartLeaf®	5.9 ± 0.5^{ab}	17.0 ± 0.6^{b}	5.7 ± 0.6^{a}	16.7 ± 0.7^{b}	6.6 ± 0.5^{a}	19.7 ± 0.4^{ab}
Mushroom	5.5 ± 0.4^{ab}	13.6 ± 0.7^{b}	4.8 ± 0.4^{a}	14.9 ± 0.8^{b}	5.6 ± 0.4^{a}	16.9 ± 0.8^{b}

Substrate amended with CC consistently had the highest percent VWC (Table 3.3). These differences were more pronounced at high %VWCs following watering. The change in percent VWC (Δ %VWC; Table 3.4) represents the total water lost during a 5 day dry-down period around each harvest. SL and MC pots showed an increase in Δ % VWC over the course of the experiment. Table 3.5 shows total water lost from each treatment over equivalent time periods, to see if there were any changes in physical properties over the course of the experiment.

Table 3.4 Effect of organic matter type on change in percent volumetric water content (Δ %VWC) within harvest. Changes are averaged from three 5 day dry-down periods. Letters indicate significant treatment effects ($\alpha = 0.05$) within each harvest in the same column

Substrate	Harvest 1	Harvest 2	Harvest 3
Coconut Coir	19.7 ± 1.3^{a}	17.6 ± 1.1^{a}	19.7 ± 1.3^{a}
Rice Hulls	13.7 ± 0.7^{b}	13.3 ± 0.8^{ab}	13.9 ± 1.0^{ab}
SmartLeaf®	10.5 ± 0.7^{bc}	10.3 ± 0.8^{b}	13.3 ± 0.6^{ab}
Mushroom	7.8 ± 0.8^{c}	9.7 ± 1.1^{b}	11.9 ± 1.0^{b}

Table 3.5 Effect of organic matter type on total water loss (mL) within harvest. Changes are averaged from three 5 day dry-down periods. Letters indicate significant treatment effects ($\alpha = 0.05$) within each harvest in the same column.

Substrate	Harvest 1	Harvest 2	Harvest 3
Coconut Coir	137.7 ± 9.2 [a]	122.9 ± 8.0 [a]	137.7 ± 9.2 [a]
Rice Hulls	96.0 ± 5.2 [b]	93.4 ± 5.6 [ab]	97.3 ± 7.0 [ab]
SmartLeaf®	73.7 ± 4.8 [bc]	71.9 ± 5.7 [b]	93.1 ± 4.2 [ab]
Mushroom	54.4 ± 5.4 [c]	67.7 ± 7.6 [b]	83.5 ± 6.8 [b]

Upon further analysis, an increase in dry root mass as Δ % VWC increased was noted for plants grown in substrate amended with MC (Fig. 3.7). Plants grown in substrate amended with SL show a similar trend between the second and third harvest. The relationship shows both Δ %VWC and dry root mass increasing over the course of the experiment.

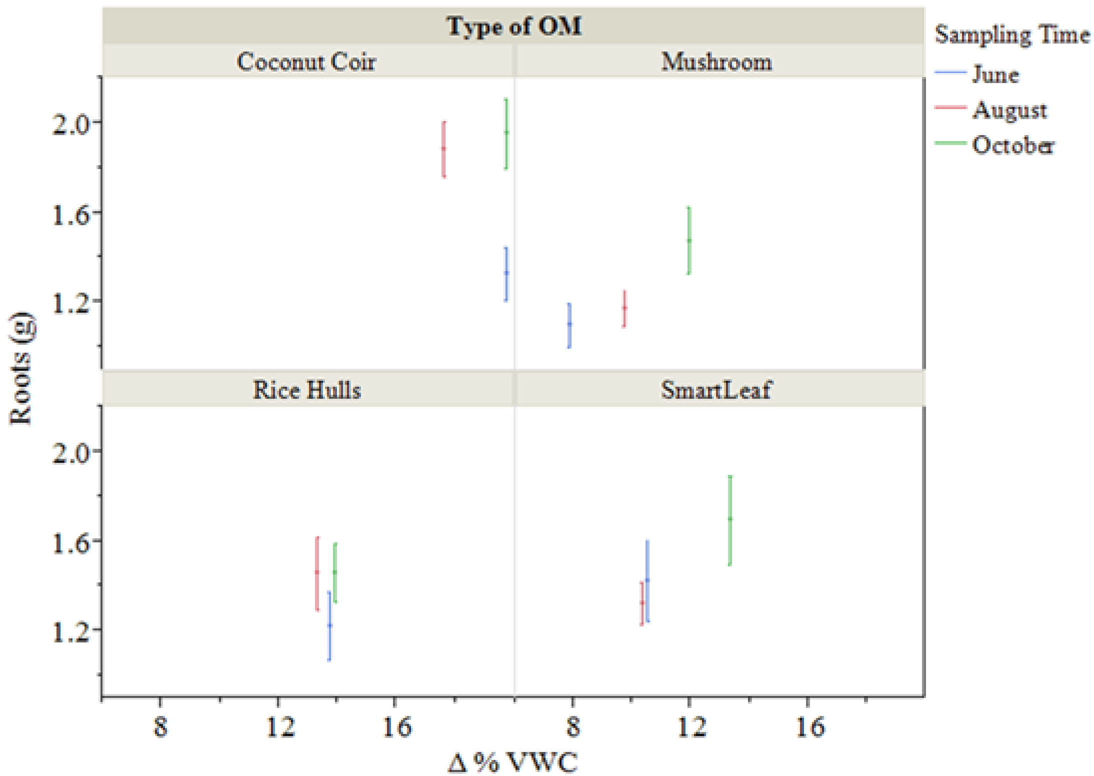


Figure 3.7 Relationship between dry root mass and Δ %VWC. The dot represents the average value and bars represent standard error.

3.3.3 Plant tissue analysis

At the third harvest, significant differences were found in nitrogen and potassium content in the shoots (Figs. 3.8 A, B). Plants grown in M2 substrate amended with MC or SL had higher nitrogen (Fig. 3.5A) and potassium (Fig 3.5B) contents than the other two organic matter treatments. Plants grown in substrates amended with CC or RH showed symptoms of potassium deficiency (Figs. 3.3-3.5), including necrotic leaf margins and downward leaf cupping (Lea-Cox 1999) with the deficiency beginning by the first harvest for plants grown in rice hull substrate (Fig. 3.3). Roots showed no significant difference in nutrient content for any of the macronutrients. Full nutrient analysis results can be found in Appendix C, Table C2.

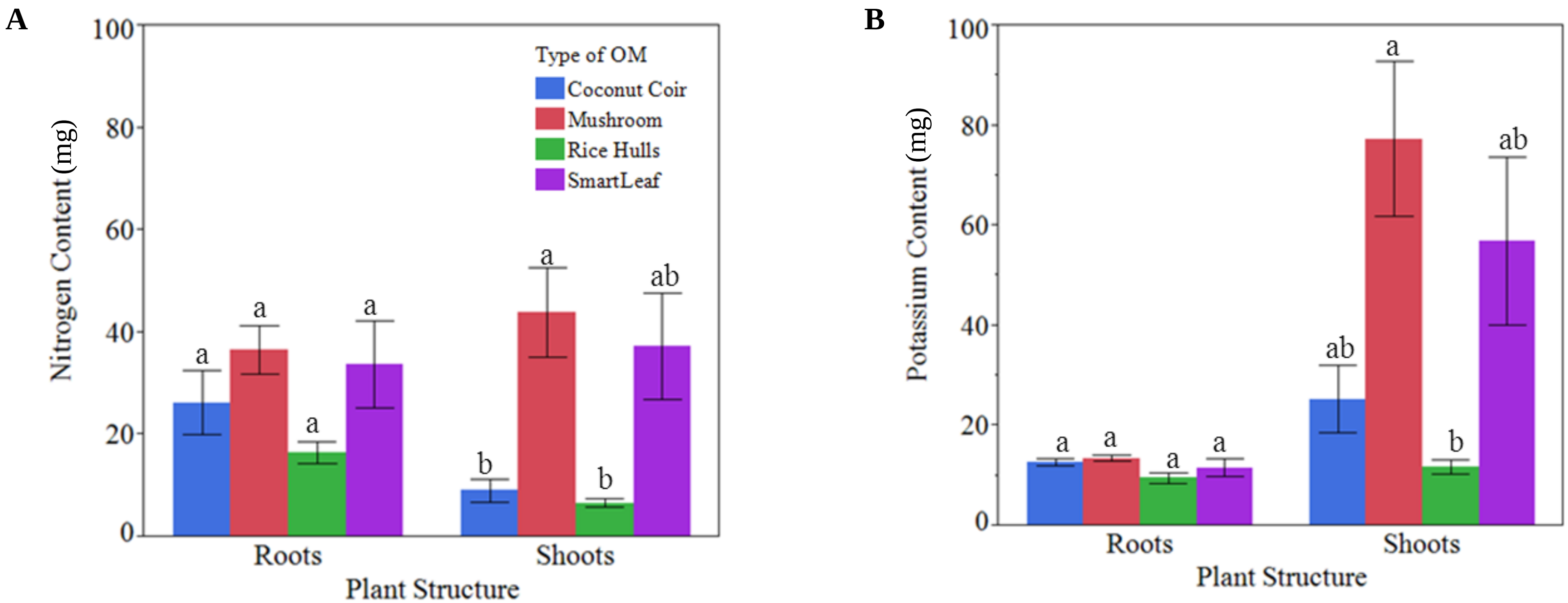


Figure 3.8 Average (A) nitrogen content (mg) and (B) potassium content (mg) of *Phedimus kamtschaticus* for each organic matter treatment at the final harvest. Bars represent standard error and letters indicate significant treatment effects ($\alpha = 0.05$) within plant structure. Appendix Table B1 shows additional nutrient analysis results.

3.4 Discussion and Conclusions

3.4.1 Plant growth

The results of this growth chamber experiment can be thought of as representative of the first six months in the establishment of a green roof. Because there was no plant mortality except in the case of destructive harvest, all types of organic matter can be considered to have achieved the minimum of supporting plant survival.

Over the course of the experiment, differences between OM treatments became progressively more pronounced. By the second harvest, 124 days after the start of the experiment, plants in the MC and SL organic matter treatments were larger (Table 3.2) and showed nutritional differences (Fig. 3.4) compared to plants grown in the CC and RH organic matter treatments. By the third harvest (Fig. 3.5), 185 days after the start of the experiment, these differences in shoot dry mass had become significant (Figs. 3.6A, B). Since there were few differences in substrate VWC, it is likely that these significant differences in shoot dry mass were due to nutritional deficiencies, rather than from any water limitation. The comparatively high root to shoot ratio of plants grown in CC substrate also provides an indication of plant response to nutrient deficiencies. Plants had access to adequate VWC, but limited nutrients. The higher root to shoot ratio indicates that the plants shifted resources to root growth in order to forage for nutrients.

3.4.2 Volumetric water content

Volumetric water content (% VWC) routinely dropped to between 4.5% (for RH) and 5.9% (for CC) throughout the experiment despite plants being watered to saturation every 5 days. Starry (2013) showed that water use efficiency declines rapidly for *Phedimus kamtchaticus* below 8% VWC and 6% VWC is the wilting point. Plants grown in MC or SL thrived, despite frequently dropping below this apparent wilting point. This provides evidence to support the idea that *Phedimus kamtschaticus* is most likely a CAM-cycler, being able to switch between C3 and CAM metabolism, depending upon water availability (Starry et al., 2014)

CC consistently had the highest VWC of all substrates, but did not show increased growth or improved plant health with this additional available water. Plants grown in RH showed the nutrient deficiency symptoms and low shoot mass similar to CC but pots were not significantly different in %VWC from pots amended with MC or SL.

CC also had the highest change in total water loss, despite the low growth rate of plants in this treatment. Total water loss was attributed to evaporation from the substrate surface as well as plant water use through transpiration. Smaller plants typically use less water than large plants, so it could be concluded that the large amount of water lost from CC is due to an inability of this substrate to retain water, perhaps combined with a higher percentage of exposed substrate that contributed to higher evaporative losses. What these results do show is that water availability was not the determining factor in limiting plant growth with this particular CC formulation.

3.4.3 Nutrient content

Differences in tissue nutrient content between treatments support the differences seen in plant growth during this experiment. By the third harvest, plants grown in substrate amended with MC or SL had more than twice the amount of potassium and more than four times the amount of nitrogen than plants grown with CC or RH amendments (Fig. 3.8A, B). The striking visual differences shown in Fig. 3.5 illustrate the potassium deficiency symptoms exhibited by plants grown in substrates amended with CC or RH. Given the general deficiency of nitrogen and other cations with these types of organic matter, it is evident that the plants had nutrient deficiencies that were expressed primarily as potassium deficiency.

3.4.4 Conclusions

This is the first study, to our knowledge, that provides definitive data to illustrate that *Phedimus kamtchaticus* not only thrives at lower VWC, but more importantly, shows that adequate nutrient availability, influenced by organic matter type, is essential to optimize plant growth in the critical months following transplanting. This indicates that success of a green roof during this critical establishment period is likely dependent in part on the type of organic matter used.

All of the plants not destructively harvested survived, indicating that all four types of organic matter have potential for green roof applications. We found that MC or SL incorporated as single OM amendments are more effective materials for adding to a green roof substrate than CC or RH. While coconut coir has a high ability to hold water, it does not have the nutrient content necessary for plant establishment.

The possibility of maximizing organic matter benefits by mixing different types of organic matter offers interesting opportunities for future research. A mixture of locally available neighborhood compost mix, like SL, combined with a waste product like CC might offer a sustainable way to achieve high nutrient availability and high water holding capacity.

Chapter 4: Critical assessment of the litter bag method for use on green roofs

4.1 *Review of the litter bag method*

The litter bag method is a classic technique used in ecological studies to quantify the breakdown rate of organic matter (Aerts 1997; Blair and Crossley Jr, 1988; Falconer, Wright, and Beall, 1933; John, 1980; Schaefer et al., 1985). Measured amounts of organic material or “litter” are sealed into nylon bags or metal baskets. These are then either buried in the soil or left on the soil surface exposed to field conditions. The bags are removed at specific intervals and the remaining organic matter is weighed to measure the rate of decomposition.

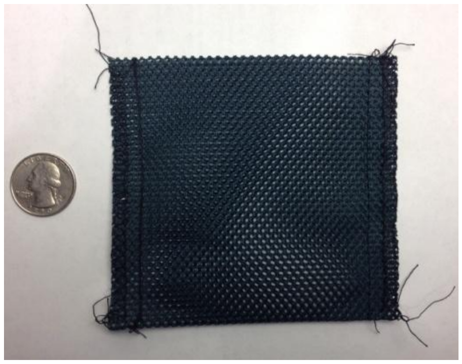
The mesh diameter of the bag can inhibit some forms of decomposition. Some fungal hyphae (John, 1980) and macro fauna (Cotrufo et al., 2010) cannot penetrate bags with small mesh sizes. Despite this factor, the litterbag remains an accepted experimental method; its simplicity and low cost make the litter bag method a standard in ecological research (Robertson et al., 1999).

4.2 *Materials and methods*

4.2.1 Construction

Fabric litter bags were made from polyester mesh (Rootmaker® products company, LLC) to more closely monitor organic matter decomposition. Bags (2mm mesh size) were pre-cut and pre-sewn to 10.2 cm x 10.2 cm (L×W), as shown in Figure 4.1.

A)



B)

Figure 4.1 (A) Polyester mesh litter bag (2 mm mesh size) before filling with quarter shown for size reference. Litter bags after filling before being installed on the roof (B).

Each bag contained 73.1 g of M2 (approximately 100 mL by volume). In order to maintain the ratio of each OM type to M2 (v/v), the incorporated weight for each type of organic matter was different. The fresh weights used for each OM are listed in Table 4.1. After filling, the fabric bags were stapled closed and were placed into small plastic containers to catch any matter lost in moving the bags for installation in the planted roof modules. Any material lost from the bag was collected and processed to determine moving loss for each replicate bag.

Table 4.1 Fresh and oven-dry mass of organic matter included in the litter bags.

OM Type	Fresh Mass	Oven-dry Mass
Coconut coir	7.22 g	1.70 g
Rice hulls	2.78 g	2.65 g
SmartLeaf®	13.76 g	6.60 g
Mushroom compost	8.75 g	3.89 g

4.2.2 Installation

The litter bags were installed on the roof on February 2, 2014 in 168 modules, 84 planted and 84 unplanted. Litter bags were inserted vertically into a hole dug in the substrate directly between two plants. The bottom of the bag was placed in contact with the base of the module (Fig. 4.2).

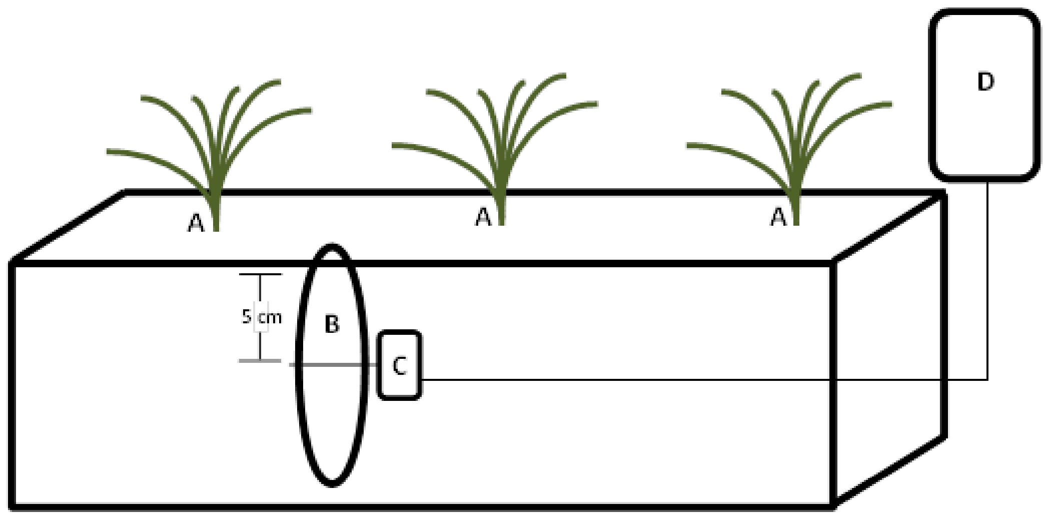


Figure 4.2 Diagram representing location of plants (A), litterbag (B), GS3 sensor (C), and EM50R node (D); (Decagon Devices, Inc., Pullman WA).

4.2.3 Harvesting and processing

At each harvest, 5/15/2014, 7/16/2014, and 9/24/2014 (102, 164 and 234 days after installation), litter bags were removed from the planted modules by digging down on each side of the bag between two of the plants (Fig. 4.3), cutting the roots as close to the bag as possible and brushing excess substrate from the outside of the bag. Bags were then transported to a lab and then cut open completely, to ensure that no substrate or roots were left inside. Roots were separated from each substrate, weighed, and dried in an oven maintained at a constant 50 C. Litter bags were extracted from unplanted modules and excess substrate brushed off; bags were similarly processed in the lab, to ensure no substrate was left inside.

Figure 4.3 An example of a planted module in May 2014; the black rectangle indicates approximate location of litter bag

Substrate contents of litter bags from both planted and unplanted modules were dried in an oven (Model 1690, VWR International, Radnor, PA) maintained at 50 C. When dry weights stabilized, each sample was weighed and ashed in a muffle furnace (Model 650-126, Fisher Scientific, Waltham, MA) at 550 C for 5 hours (see Appendix C for ashing procedure). Samples were then re-weighed after ashing. The ashed weight was subtracted from oven dry weight to determine amount of organic matter burned off.

4.3 Issues with litter bag use

4.3.1 Mesh size

The 2 mm mesh used for the experiment was too large and allowed too much material to be lost by sifting out of the bag during transport, or washing out of the bag during the time in the roof module. A preliminary study showed that up to 1/3 of the mass of SmartLeaf® was lost between construction of the litter bag, moving the bag to the roof, and determining organic percentage through ashing. The collection and quantification of "moving loss" material was an attempt to correct for this error but could not account for the large amount of material that could have been lost through sifting once buried in the modules or during early rainfall.

The size of the mesh intentionally allowed roots to grow into the bag. Because the ashing procedure cannot determine origin of organic matter, it is crucial to separate all roots from litter bag contents before ashing. Also, some short fibers included in coconut coir were almost impossible to distinguish from the roots of *Phedimus kamtschaticus*. It is likely that more error was introduced with this substrate during the separation of treatment organic matter from plant roots.

4.3.2 Organic matter variability

The same preliminary study also found that variability of the organic material sometimes masked any decomposition or treatment effect. Through the process where SmartLeaf® lost 1/3 of its mass, the other three organic materials appeared to gain mass during handling. The mass of each type of organic matter used was different in order to maintain the volumetric ratio of 20 mL OM to 80 mL M2, despite the organic materials having different bulk densities. Fresh organic material, as opposed to oven dried was used to maintain any biotic communities within the material. This added a level of variability to the mass, as each type of organic matter had different water-holding capacity.

Because of the variability and moving loss issues in the preliminary study, the procedure for moving and processing litter bags was carefully examined and modified to identify and correct for potential areas of organic matter loss. In early stages of the second experiment, handling loss was quantified by subtracting the measured quantity lost in moving, from the remaining amount of organic material determined through ashing, from the average weight initially included in the bag. Despite the procedural changes, this handling loss, which already accounted for moving loss, was 14% for rice hulls, 27% for mushroom compost, and 42% for SmartLeaf® while coconut coir appeared to gain mass by 24%, most likely by including substrate particles in the root mass.

These issues of large mesh size and organic matter variability, means that any data taken from the litter bag portion of this experiment unfortunately had little validity.

4.4 Suggestions for future research

Litter bags were constructed from a polyester mesh fabric with 2 mm openings and were 10.2 cm x 10.2 cm (L×W). Using a much finer material, such as tea bags or nut milk bags which have openings closer to 0.3 mm, would minimize the amount of organic matter that could sift out of the bag or be washed out with rainfall. Mixing the organic matter with the inorganic green roof substrate M2, allowed the bag to function like the rest of the module but limited the total amount of organic material that could be included.

Using a larger amount of organic matter would help to limit some of the issues with variability. More successful results could be achieved if the organic matter was added with a more consistent volume. Adding the organic matter according to oven-dry mass would eliminate the variability in initial moisture content and hopefully standardize the results.

Chapter 5: Conclusions

Organic matter (OM) is important to the functioning of a green roof, a fact reflected in many standards and guides for green roofs (Fassman et al. 2010; FLL 2008). As the green roof industry grows nationwide, it is logical and important to evaluate the role that organic matter plays in enhancing the water and nutrient retention, and overall performance of green roofs. This research provides some initial data that evaluates these metrics for four locally-available types of organic matter in the mid-Atlantic region. To summarize, we asked several key questions.

① **Do different types of organic matter affect the success of plant establishment?**

② **If so, can we begin to understand how these different organic matters affect green roof water and nutrient dynamics, especially during the critical period of establishment?**

To answer these broad questions, two experiments were conducted comparing coconut coir (CC), rice hulls (RH), mushroom compost (MC), and SmartLeaf® (SL) organic matter amendments. These types could be further grouped into two categories: uncomposted (coconut coir and rice hulls) and composted (mushroom compost and SmartLeaf®). In the first longer-term (rooftop) experiment, was conducted over an 8-month period on a 3rd floor rooftop exposed to the elements. While coconut coir has a high propensity to hold water, this was not always reflected in increased aboveground biomass or leaf area. Mushroom compost and SmartLeaf® held more water than rice hulls and were associated with a significant increase in plant growth. Nutritional differences were indicated by the images but not confirmed.

Stormwater retention was influenced by the type of organic matter treatment and by whether the module was planted or unplanted. In the case of planted modules, the effect of organic matter type can be considered not only in terms of the physical water holding abilities of the organic material, but also as a function of the ability of an organic material to increase plant growth and therefore increase transpiration potential.

The rooftop experiment answered Question ①. Yes, type of organic matter has an effect on plant growth and establishment success. We concluded that mushroom compost and SmartLeaf® appeared to be more effective organic matter amendments than coconut coir and rice hulls. However, these results did not really allow us to understand *why* these organic matter amendments were more effective in promoting growth.

In a subsequent, controlled growth chamber experiment we sought to explain the physical and chemical properties of each organic matter type that contributed to optimized plant growth and successful establishment of *Phedimus kamtschaticus.* There were obvious differences in plant size, which became significant over the course of the experiment. The growth chamber study confirmed the trend shown in the rooftop experiment of reduced plant growth in coconut coir or rice hull substrates compared to increased plant growth in mushroom compost or SmartLeaf® substrates. VWC was highest in coconut coir substrates and lower in the other three treatments. There were significant differences between nitrogen and potassium contents in aboveground biomass; plants grown in mushroom compost substrate had the highest nutrient contents, plants grown in rice hulls had the lowest, and plants grown in coconut coir or SmartLeaf® were in between.

The growth chamber experiment confirmed the results from the rooftop experiment, and provided insight into Question ②. From this controlled study, it is clear that type of organic matter impacts both the water holding capacity of the substrate and the growth of plants during the establishment period. In this experiment, nutrient availability was clearly the limiting factor in plant growth. We suspect that differences in plant growth seen in the rooftop experiment were also due to nutritional deficiencies, rather than water availability. This is strong evidence to support the use of composted organic materials, which in this case provide higher nutrient availability to plants during the initial growth period.

These experiments provided some valuable insights into the functioning of different types of organic materials on green roofs and posed interesting questions for future research:

How does the composition of the organic matter affect nutrient content and availability? Why do uncomposted materials provide less available nutrient content than composted materials?

The C/N ratio of the different types of organic matter likely plays a role in the answer to this question in addition to the amounts of lignin and cellulose. Also, further exploration of the availability of potassium and nitrogen (and the interaction of these nutrients) might provide additional insight into optimizing growth in green roof substrates.

This study demonstrates the importance of selecting an appropriate organic matter amendment to enhance green roof performance, not only in terms of nutrient availability but also on substrate water retention capacity. Because the composition of many commercially available substrates is considered proprietary information (Emilsson 2008; Nagase and Dunnett 2011; Olszewski and Young 2011), it is difficult for designers, installers, scientists, and property owners to make informed choices about different substrate compositions. These issues are compounded by the discrepancy in standards between substrates where organic matter is added proportionally *by volume* and substrates where organic matter is added proportionally *by mass*. Although we did not study the effects of incorporating different rates of organic matter, this should be further investigated, to inform the industry and provide better guidance for formulating better standards. The industry, guided by designers and consumers, continues to search for ways to diversify the plant palette used on green roofs. It is therefore important to consider the role type of organic matter can play in successful establishment and green roof health, to provide support for a wider range of plants, especially those less inherently adapted to green roof conditions.

Choice of organic matter type is important to defining the way a green roof system will function. Many types of organic matter have potential for green roof applications and more research will continue to illuminate the best choices. Considering physical properties, nutritional content, and source will allow selection of the most effective organic matter type.

Appendix A: Media Analysis

A.1.1 M2 Composition and analysis

M2 is a green roof substrate (Stancills Inc., Perryville, MD) composed of shale coarse, clay fines, organic matter, and Osmocote® (1 lb per cubic yard). The M2 used in these experiments was analyzed (Figs. A1 and A2) and found to have 0.5% by mass organic matter because low organic material was requested. An analysis of typical M2 conducted for Stancills Inc. (Figs. A.3 a-c) showed 3.9% by mass organic matter.

A.1.2 Organic matter composition and analysis

A media analysis was conducted on each type of organic matter. Results are included as Figs. A4 – A7.

SOIL ANALYSIS REPORT

Analytical Method(s): Mehlich 3

Date Received: 10/31/2014 **Date Of Analysis:** 11/03/2014 **Date Of Report:** 11/04/2014

Sample ID Field ID	Lab Number	Organic Matter			Phosphorus				Potassium		Magnesium		Calcium		Sodium		pH		Acidity	C.E.C
		%	Rate	ENR lbs/A	Mehlich 3 ppm	Rate	Reserve ppm	Rate	K ppm	Rate	Mg ppm	Rate	Ca ppm	Rate	Na ppm	Rate	Soil pH	Buffer Index	H meq/100g	meq/100g
M2	07011	0.5	VL	54	41 MD = 47	M			119 MD = 75	VH	94 MD = 74	H	614 MD = 51	M	40	L	6.8		0.1	4.5

Sample ID Field ID	Percent Base Saturation					Nitrate		Sulfur		Zinc		Manganese		Iron		Copper		Boron		Soluble Salts		Chloride		Aluminum
	K %	Mg %	Ca %	Na %	H %	NO_3N ppm	Rate	S ppm	Rate	Zn ppm	Rate	Mn ppm	Rate	Fe ppm	Rate	Cu ppm	Rate	B ppm	Rate	SS ms/cm	Rate	Cl ppm	Rate	Al ppm
M2	6.8	17.4	68.2	3.9	2.9			29	H	2.4	M	24	H	170	VH	2.1	H	2.1	H					

Values on this report represent the plant available nutrients in the soil. Rating after each value: VL (Very Low), L (Low), M (Medium), H (High), VH (Very High). ENR - Estimated Nitrogen Release. C.E.C. - Cation Exchange Capacity.

Explanation of symbols: % (percent), ppm (parts per million), lbs/A (pounds per acre), ms/cm (milli-mhos per centimeter), meq/100g (milli-equivalent per 100 grams). Conversions: ppm x 2 = lbs/A, Soluble Salts ms/cm x 640 = ppm.

This report applies to sample(s) tested. Samples are retained a maximum of thirty days after testing.

Analysis prepared by: A&L Eastern Laboratories, Inc.

by: Pauric McGroary

Pauric McGroary

Figure A.1 Soil analysis (Mehlich 3 method) of M2 green roof media (no supplementary organic material) (A&L Eastern Laboratories 2014)

TEST	RESULTS	NORMAL RANGE
pH	6.89	5.20 - 6.30
Soluble Salts ms/cm EC	1.27	0.75 - 3.50
Nitrate ppm NO3-N	115.65*	35.00 - 180.00
Ammonium ppm NH4-N	0.57	0.00 - 20.00
Phosphorus ppm P	1.14*	5.00 - 50.00
Potassium ppm K	63.04	35.00 - 300.00
Calcium ppm Ca	159.73	40.00 - 200.00
Magnesium ppm Mg	25.62	20.00 - 100.00
Sulfur ppm S	49.74*	50.00 - 250.00
Boron ppm B	0.26	0.05 - 0.50
Iron ppm Fe	0.24*	0.30 - 3.00
Manganese ppm Mn	0.01*	0.02 - 3.00
Copper ppm Cu	0	0.00 - 0.50
Zinc ppm Zn	0.01*	0.30 - 3.00
Molybdenum ppm Mo	0*	0.01 - 0.10
Aluminum ppm Al	0.54	0.00 - 0.00
Sodium ppm Na	24.24	0.00 - 0.00
Chloride ppm Cl	48.07	0.00 - 0.00

Figure A.2 Media analysis (distilled water) of M2 (no supplementary organic material) (JR Peters Laboratory, 2014)

Green Roof Media Analysis

Results on dry weight basis unless specified otherwise

Analysis	Units	Result	FLL Guidelines for Multi Course Extensive Sites[1]
Particle Size Distribution (See accompanying report)			
≤ 0.05 mm *(Fll reference value based on < 0.06 mm)*	mass %	6.3	≤ 15
Denisty Measurements			
Bulk Density (dry weight basis)	g/cm^3	0.79	—
Bulk Density (dry weight basis)	lb/ft^3	49.11	—
Bulk Density (at max. water-holding capacity)	g/cm^3	1.21	—
Bulk Density (at max. water-holding capacity)	lb/ft^3	75.47	—
Water/Air Measurements			
Moisture	mass %	18.2	—
Total Pore Volume[2]	Vol. %	59.2	—
Maximum water-holding Capacity	Vol. %	42.4	35 - 65
Air-Filled Porosity (at max water-holding capacity)	Vol. %	16.8	≥ 10
Water permeability (saturated hydraulic conductivity)	cm/s	0.059	0.001 - 0.12
Water permeability (saturated hydraulic conductivity)	in/min	1.394	0.024 - 2.83
Organic Measurements			
Organic matter content	mass %	3.9	—
Organic matter content	g/L	31.0	≤ 65

GR01B Multi Course Extensive

[1]Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL). 2008. Guidelines for the Planning Execution and Upkeep of Green-Roof Sites

[2]Total pore volume determined using measured particle density instead of assumed particle density as specified in FLL

Figure A.3 M2 green roof media analysis (Agricultural Analytical Services Laboratory 2014)

Green Roof Media
Particle Size Distribution

Particle Size Analysis		Sum of particles less than size specified				
Diameter -mm-	%		Diameter -mm-	Diameter -in-	Sieve size	% sum of particles
< 0.002	2.5	<	0.002	---	---	2.5
0.002-0.05	3.7	<	0.05	---	---	6.3
0.05-0.25	4.4	<	0.25	0.0098	60 mesh	10.7
0.25-1.0	14.8	<	1.0	0.0394	18 mesh	25.5
1.0-2.0	15.2	<	2.0	0.0787	10 mesh	40.7
2.0-3.2	12.0	<	3.2	0.125	1/8 inch	52.7
3.2-6.3	33.0	<	6.3	0.250	1/4 inch	85.7
6.3-9.5	14.0	<	9.5	0.375	3/8 inch	99.7
9.5-12.5	0.3	<	12.5	0.500	1/2 inch	100.0
> 12.5	0.0					

Figure A.4 M2 particle size distribution table (Agricultural Analytical Services Laboratory 2014)

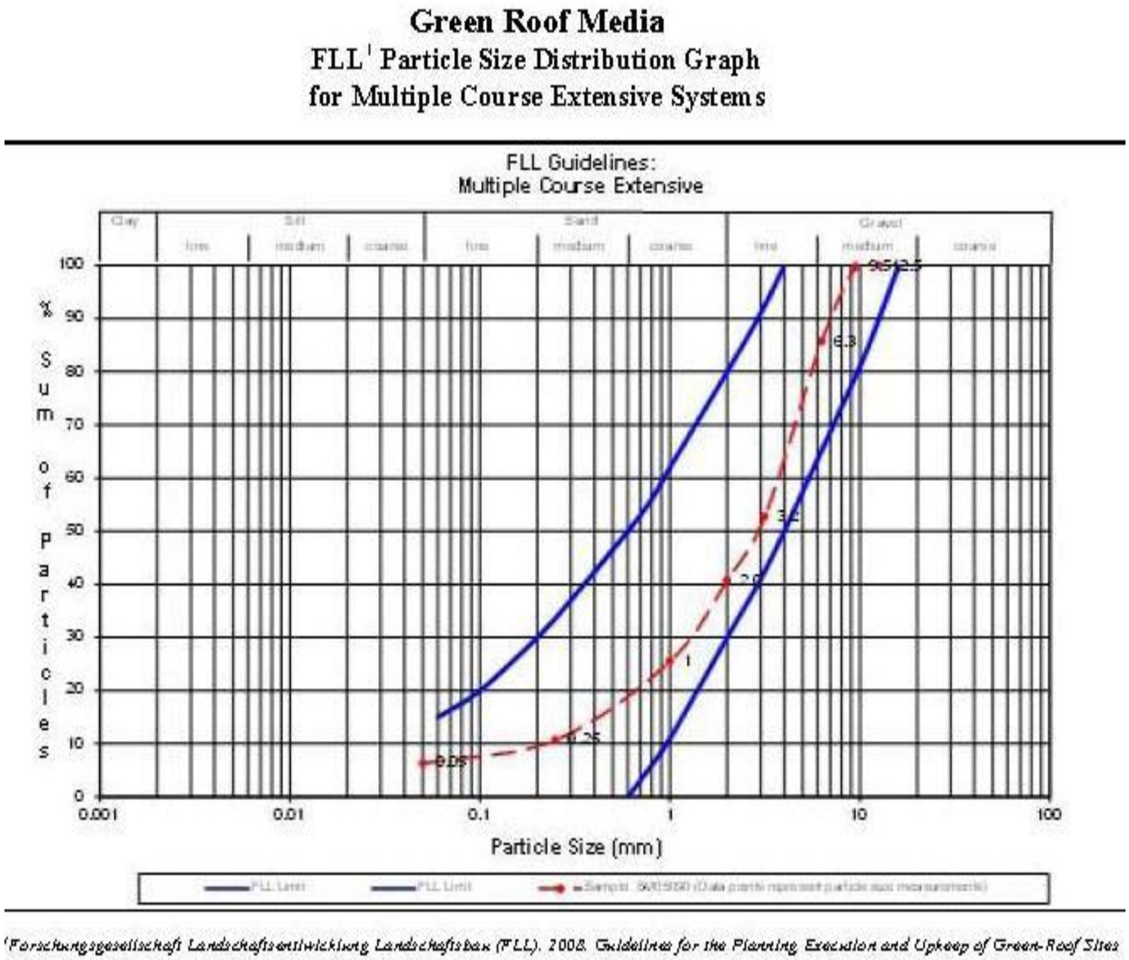


Figure A.5 M2 particle size distribution graph (Agricultural Analytical Services Laboratory 2014)

TEST	RESULTS	NORMAL RANGE
pH	6.3	5.20 - 6.30
Soluble Salts ms/cm EC	0.84	0.75 - 3.50
Nitrate ppm NO3-N	1.51*	35.00 - 180.00
Ammonium ppm NH4-N	1.51	0.00 - 20.00
Phosphorus ppm P	2.57*	5.00 - 50.00
Potassium ppm K	192.66	35.00 - 300.00
Calcium ppm Ca	1.68*	40.00 - 200.00
Magnesium ppm Mg	1.59*	20.00 - 100.00
Sulfur ppm S	4.12*	50.00 - 250.00
Boron ppm B	0.1	0.05 - 0.50
Iron ppm Fe	0.14*	0.30 - 3.00
Manganese ppm Mn	0*	0.02 - 3.00
Copper ppm Cu	0.01	0.00 - 0.50
Zinc ppm Zn	0.01*	0.30 - 3.00
Molybdenum ppm Mo	0*	0.01 - 0.10
Aluminum ppm Al	0.35	0.00 - 0.00
Sodium ppm Na	38.83	0.00 - 0.00
Chloride ppm Cl	212.42	0.00 - 0.00

Figure A.6 Media analysis (distilled water) of coconut coir (JR Peters Laboratory, 2014)

TEST	RESULTS	NORMAL RANGE
pH	6.13	5.20 - 6.30
Soluble Salts ms/cm EC	0.34*	0.75 - 3.50
Nitrate ppm NO3-N	4.31*	35.00 - 180.00
Ammonium ppm NH4-N	0.82	0.00 - 20.00
Phosphorus ppm P	20.31	5.00 - 50.00
Potassium ppm K	110.14	35.00 - 300.00
Calcium ppm Ca	1.69*	40.00 - 200.00
Magnesium ppm Mg	4.58*	20.00 - 100.00
Sulfur ppm S	2.83*	50.00 - 250.00
Boron ppm B	0.04*	0.05 - 0.50
Iron ppm Fe	0.25*	0.30 - 3.00
Manganese ppm Mn	1.58	0.02 - 3.00
Copper ppm Cu	0.05	0.00 - 0.50
Zinc ppm Zn	0.12*	0.30 - 3.00
Molybdenum ppm Mo	0.01	0.01 - 0.10
Aluminum ppm Al	0.14	0.00 - 0.00
Sodium ppm Na	2.43	0.00 - 0.00
Chloride ppm Cl	26.27	0.00 - 0.00

Figure A.7 Media analysis (distilled water) of rice hulls (JR Peters Laboratory, 2014)

TEST	RESULTS	NORMAL RANGE
pH	7.93	5.20 - 6.30
Soluble Salts ms/cm EC	13.36*	0.75 - 3.50
Nitrate ppm NO3-N	76.85*	35.00 - 180.00
Ammonium ppm NH4-N	71.42*	0.00 - 20.00
Phosphorus ppm P	10.51	5.00 - 50.00
Potassium ppm K	3062*	35.00 - 300.00
Calcium ppm Ca	559.22*	40.00 - 200.00
Magnesium ppm Mg	283.05*	20.00 - 100.00
Sulfur ppm S	1566*	50.00 - 250.00
Boron ppm B	0.45	0.05 - 0.50
Iron ppm Fe	1.94	0.30 - 3.00
Manganese ppm Mn	0.99	0.02 - 3.00
Copper ppm Cu	1.02*	0.00 - 0.50
Zinc ppm Zn	0.57	0.30 - 3.00
Molybdenum ppm Mo	0.36*	0.01 - 0.10
Aluminum ppm Al	1.38	0.00 - 0.00
Sodium ppm Na	443.61	0.00 - 0.00
Chloride ppm Cl	500.22	0.00 - 0.00

Figure A.8 Media analysis (distilled water) of mushroom compost (JR Peters Laboratory, 2014)

TEST	RESULTS	NORMAL RANGE
pH	8.04	5.20 - 6.30
Soluble Salts ms/cm EC	0.84	0.75 - 3.50
Nitrate ppm NO3-N	37.24*	35.00 - 180.00
Ammonium ppm NH4-N	1.78	0.00 - 20.00
Phosphorus ppm P	4.12*	5.00 - 50.00
Potassium ppm K	166.98	35.00 - 300.00
Calcium ppm Ca	48.37	40.00 - 200.00
Magnesium ppm Mg	14.87*	20.00 - 100.00
Sulfur ppm S	5.31*	50.00 - 250.00
Boron ppm B	0.49	0.05 - 0.50
Iron ppm Fe	0.52	0.30 - 3.00
Manganese ppm Mn	0.1	0.02 - 3.00
Copper ppm Cu	0.06	0.00 - 0.50
Zinc ppm Zn	0.06*	0.30 - 3.00
Molybdenum ppm Mo	0.05	0.01 - 0.10
Aluminum ppm Al	1.34	0.00 - 0.00
Sodium ppm Na	19.29	0.00 - 0.00
Chloride ppm Cl	97.62	0.00 - 0.00

Figure A.9 Media analysis (distilled water) of SmartLeaf® (JR Peters Laboratory, 2014)

Appendix B: Chapter 2 Supplementary Tables and Figures

B.1.1 Plant Growth

Table B1 provides an expanded set of growth metrics for *Phedimus kamtrschaticus* from the rooftop experiment,

Figures B1 to B4 illustrate the visual progression of plant growth over the course of the experiment.

Table B.1 Average growth metrics and standard errors of *Phedimus kamtschaticus* for each organic matter treatment at Harvest 1 (5/15/2014), Harvest 2 (7/16/2-14), and Harvest 3 (9/24/2014). Because roots and shoots were not separated immediately after harvest, there was some loss of water from shoots before fresh shoot mass was obtained. OM Types: coconut coir (CC), rice hulls (RH) SmartLeaf® (SL), and mushroom compost (MC). Letters indicate significant treatment effects ($\alpha = 0.05$) within harvest.

OM Type	Harvest	Diameter (cm)	Fresh Root Mass (g)	Fresh Shoot Mass (g)	Oven Dry Root Mass (g)	Oven Dry Shoot Mass (g)	Leaf Area (cm^3/cm^3)
CC	1	20.7 ± 0.6 [ab]	42.8 ± 4.4 [ab]	75.6 ± 6.1 [bc]	18.8 ± 1.7 [a]	11.9 ± 0.8 [a]	1100.2 ± 90.1 [bc]
RH	1	19.5 ± 0.7 [b]	32.5 ± 2.6 [b]	56.5 ± 3.8 [c]	13.2 ± 1.1 [b]	8.4 ± 0.5 [b]	891.5 ± 70.4 [c]
SL	1	21.6 ± 0.2 [a]	48.6 ± 1.2 [a]	87.9 ± 4.7 [ab]	19.9 ± 0.6 [a]	13.4 ± 0.4 [a]	1380.0 ± 51.8 [ab]
MC	1	22.8 ± 0.4 [a]	47.8 ± 2.2 [a]	100.8 ± 7.2 [a]	19.6 ± 1.3 [a]	14.1 ± 0.8 [a]	1476.1 ± 119.7 [a]
CC	2	21.1 ± 0.7 [a]	59.2 ± 4.7 [a]	107.1 ± 6.5 [a]	23.2 ± 1.7 [a]	16.4 ± 1.1 [ab]	1191.9 ± 85.5 [a]
RH	2	19.9 ± 0.8 [a]	44.1 ± 4.0 [a]	76.7 ± 10.1 [b]	17.9 ± 1.7 [a]	12.2 ± 1.1 [b]	1074.2 ± 102.8 [a]
SL	2	21.8 ± 0.3 [a]	56.4 ± 3.0 [a]	122.5 ± 7.5 [a]	23.7 ± 1.4 [a]	18.5 ± 1.0 [a]	1373.9 ± 85.3 [a]
MC	2	22.0 ± 0.5 [a]	52.9 ± 4.5 [a]	127.8 ± 4.9 [a]	22.5 ± 1.8 [a]	19.2 ± 1.5 [a]	1370.1 ± 82.3 [a]
CC	3	20.5 ± 0.6 [bc]	65.1 ± 4.7 [a]	67.2 ± 8.1 [b]	26.4 ± 1.6 [a]	12.7 ± 1.1 [b]	694.4 ± 87.3 [b]
RH	3	19.2 ± 0.4 [c]	41.3 ± 2.5 [b]	57.8 ± 2.0 [b]	16.9 ± 1.1 [b]	10.2 ± 0.6 [b]	672.5 ± 32.9 [b]
SL	3	21.6 ± 0.5 [ab]	65.6 ± 3.9 [a]	96.0 ± 7.9 [a]	27.3 ± 1.3 [a]	17.5 ± 0.9 [a]	1000.7 ± 80.8 [a]
MC	3	22.8 ± 0.6 [a]	65.9 ± 4.8 [a]	122.0 ± 8.7 [a]	27.8 ± 2.0 [a]	18.8 ± 1.4 [a]	1223.4 ± 90.7 [a]

Figure B.1 Images A and B show the progression of one module of plants grown in coconut coir from October of 2013 to May of 2014. Images B, C, and D show representative plant growth from the coconut coir treatment each harvest.

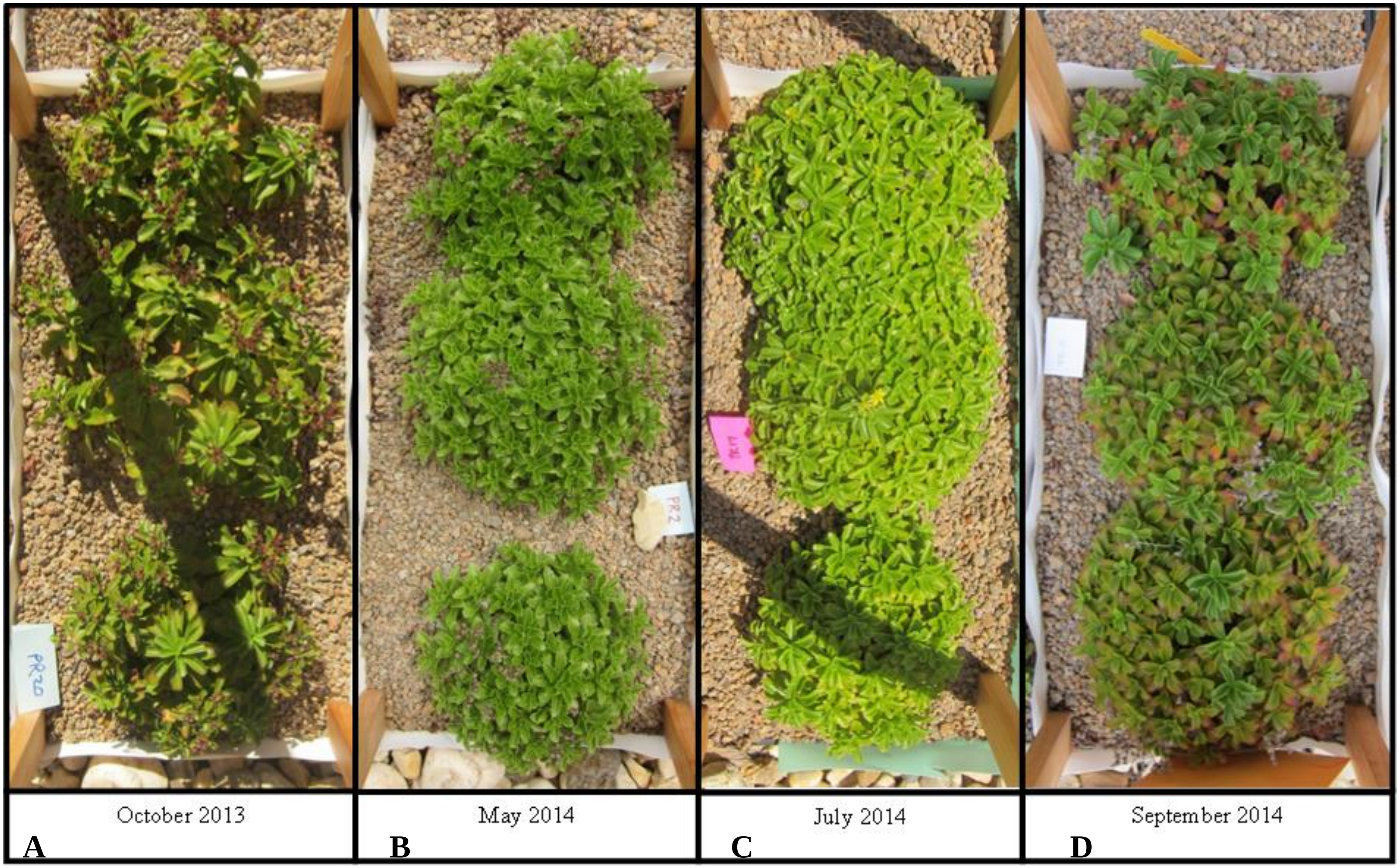


Figure B.2 Images A and B show the progression of one module of plants rice hulls from October of 2013 to May of 2014. Images B, C, and D show representative plant growth from the coconut coir treatment each harvest.

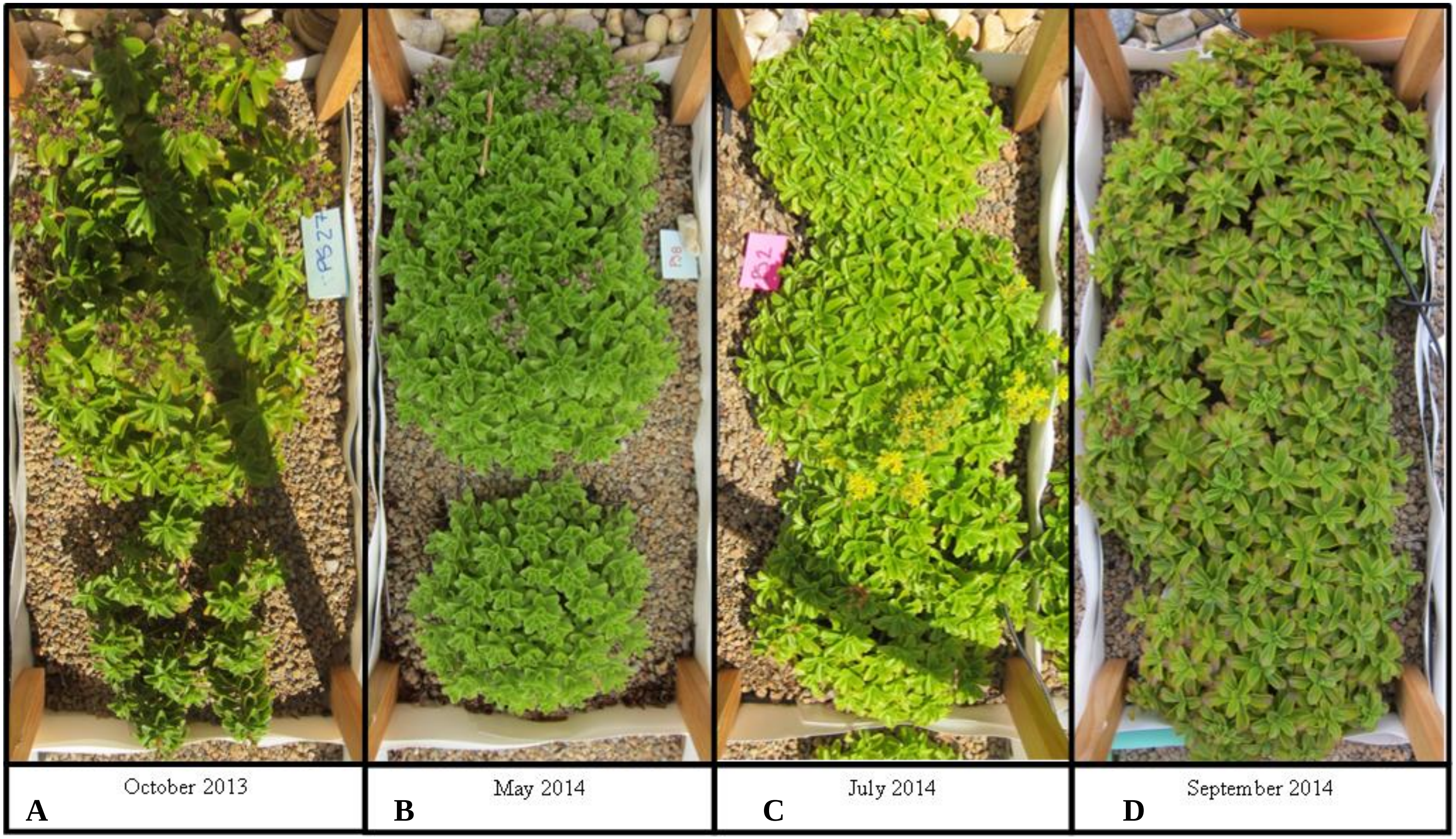


Figure B.3 Images A and B show the progression of one module of plants SmartLeaf® from October of 2013 to May of 2014. Images B, C, and D show representative plant growth from the coconut coir treatment each harvest.

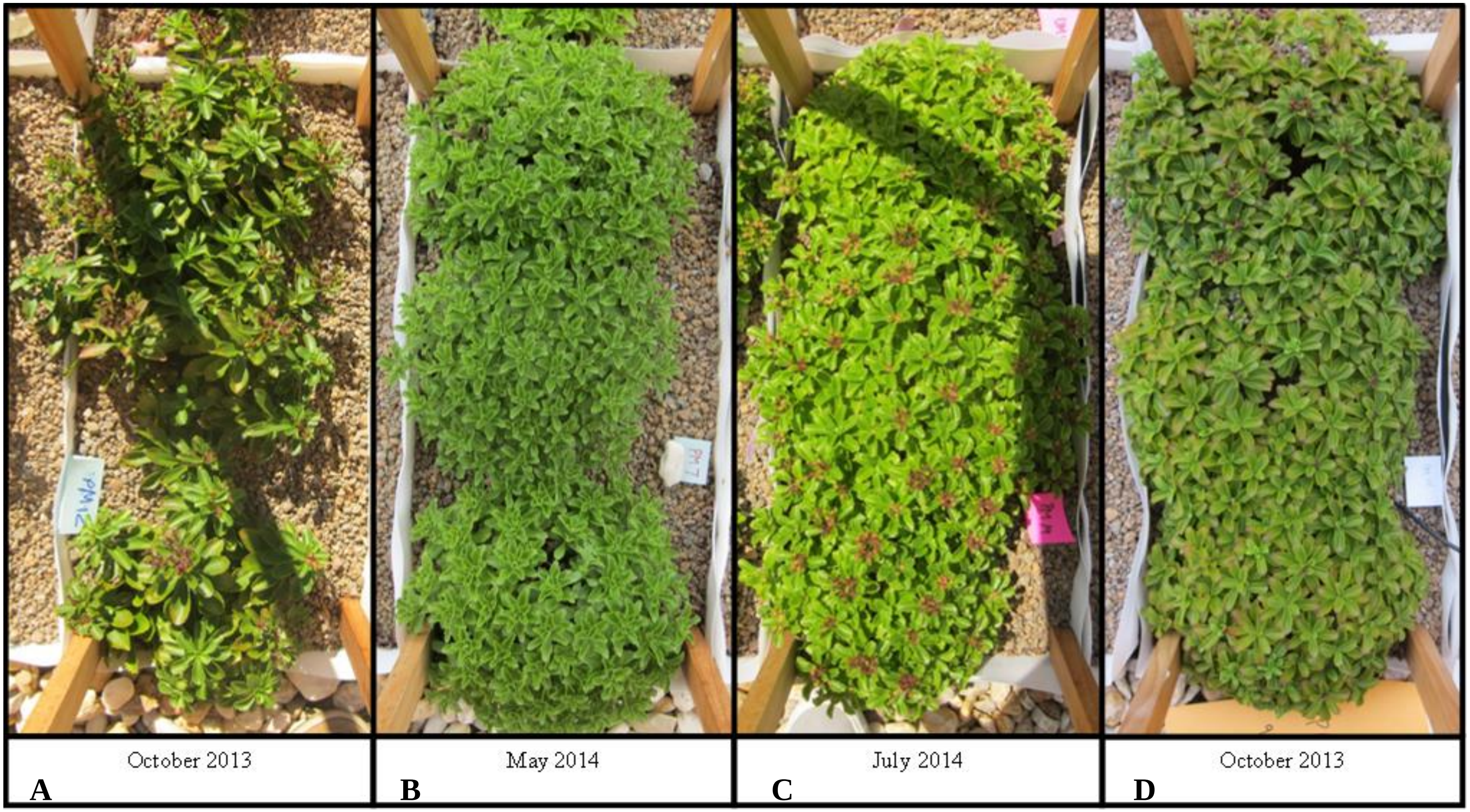


Figure B.4 Images A and B show the progression of one module of mushroom compost from October of 2013 to May of 2014. Images B, C, and D show representative plant growth from the coconut coir treatment each harvest.

Appendix C: Chapter 3 Supplementary Tables and Figures

C.1.1 Volumetric water content

Percent volumetric water content (% VWC) was measured continuously throughout the experiment using 5TM sensors (Decagon Devices Inc., Pullman, WA). Figures C.1 to C.4 show this continuous % VWC for each of the four organic matter treatments over the course of the entire experiment Figures C6 – C7 focus on the three watering cycles surrounding each harvest.

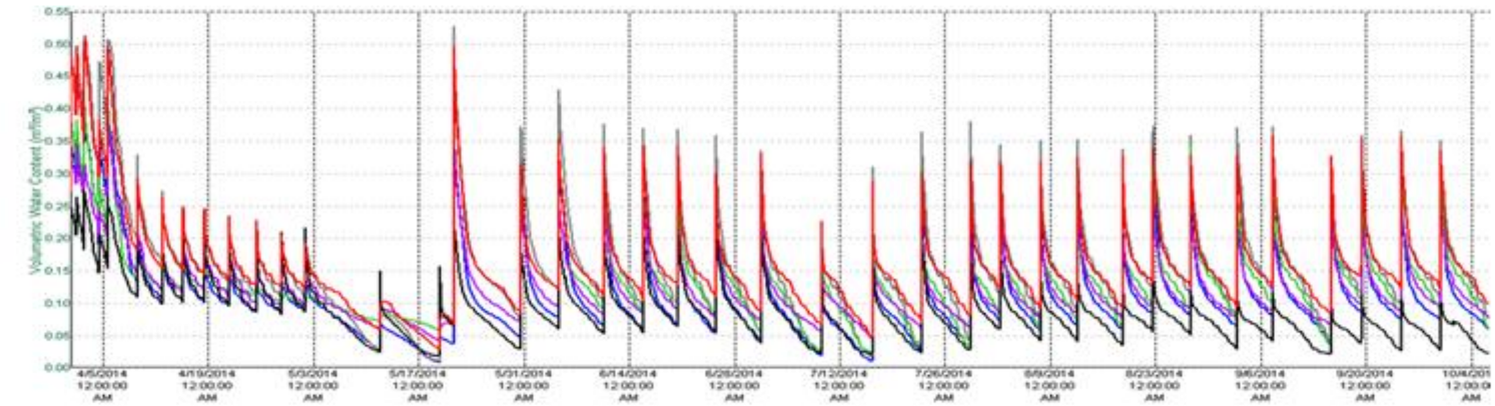


Figure C.1 Volumetric water content of pots filled with coconut coir substrate over the course of the growth chamber experiment (3/31/14 to 10/6/14).

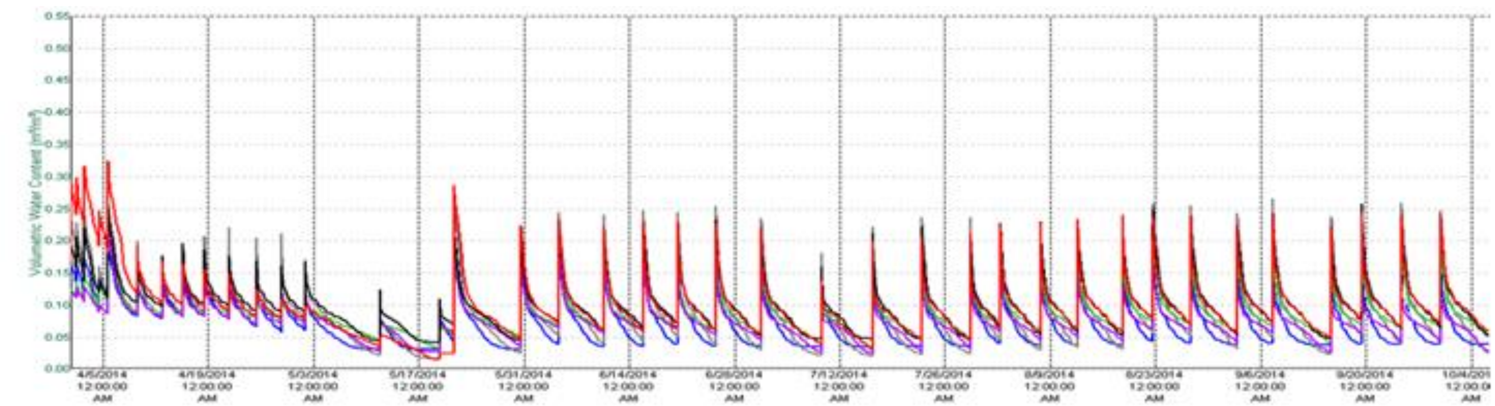


Figure C.2 Volumetric water content of pots filled with rice hull substrate over the course of the growth chamber experiment (3/31/14 to 10/6/14).

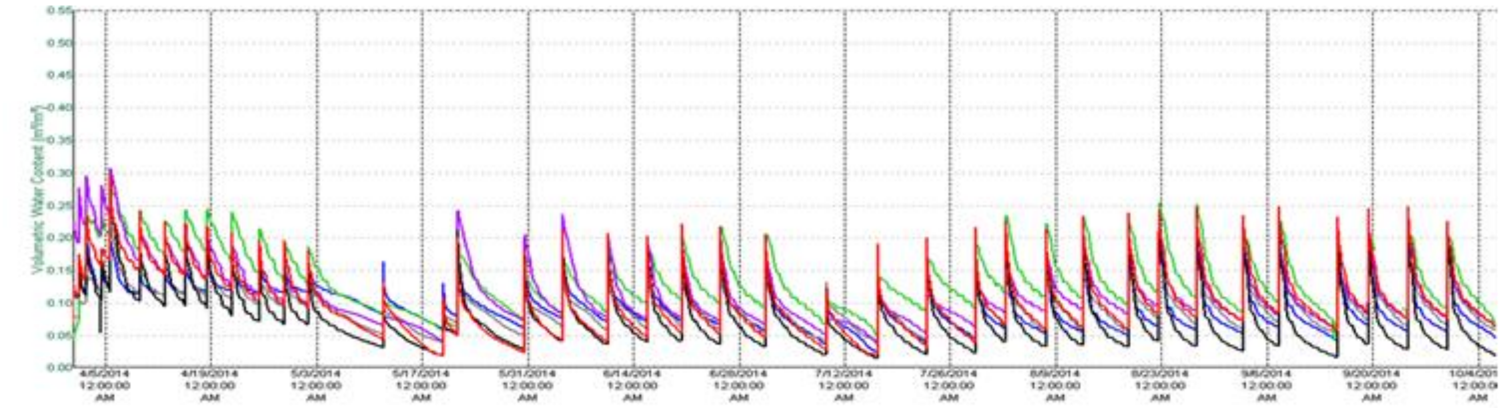


Figure C.3 Volumetric water content of pots filled with SmartLeaf® substrate over the course of the growth chamber experiment (3/31/14 to 10/6/14).

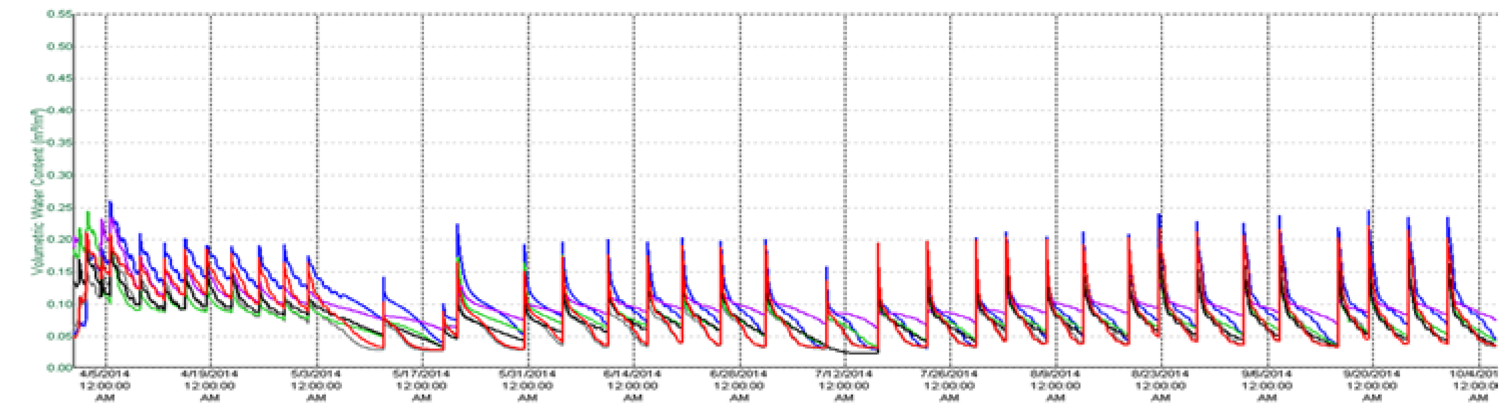


Figure C.4 Volumetric water content of pots filled with mushroom compost substrate over the course of the growth chamber experiment (3/31/14 to 10/6/14).

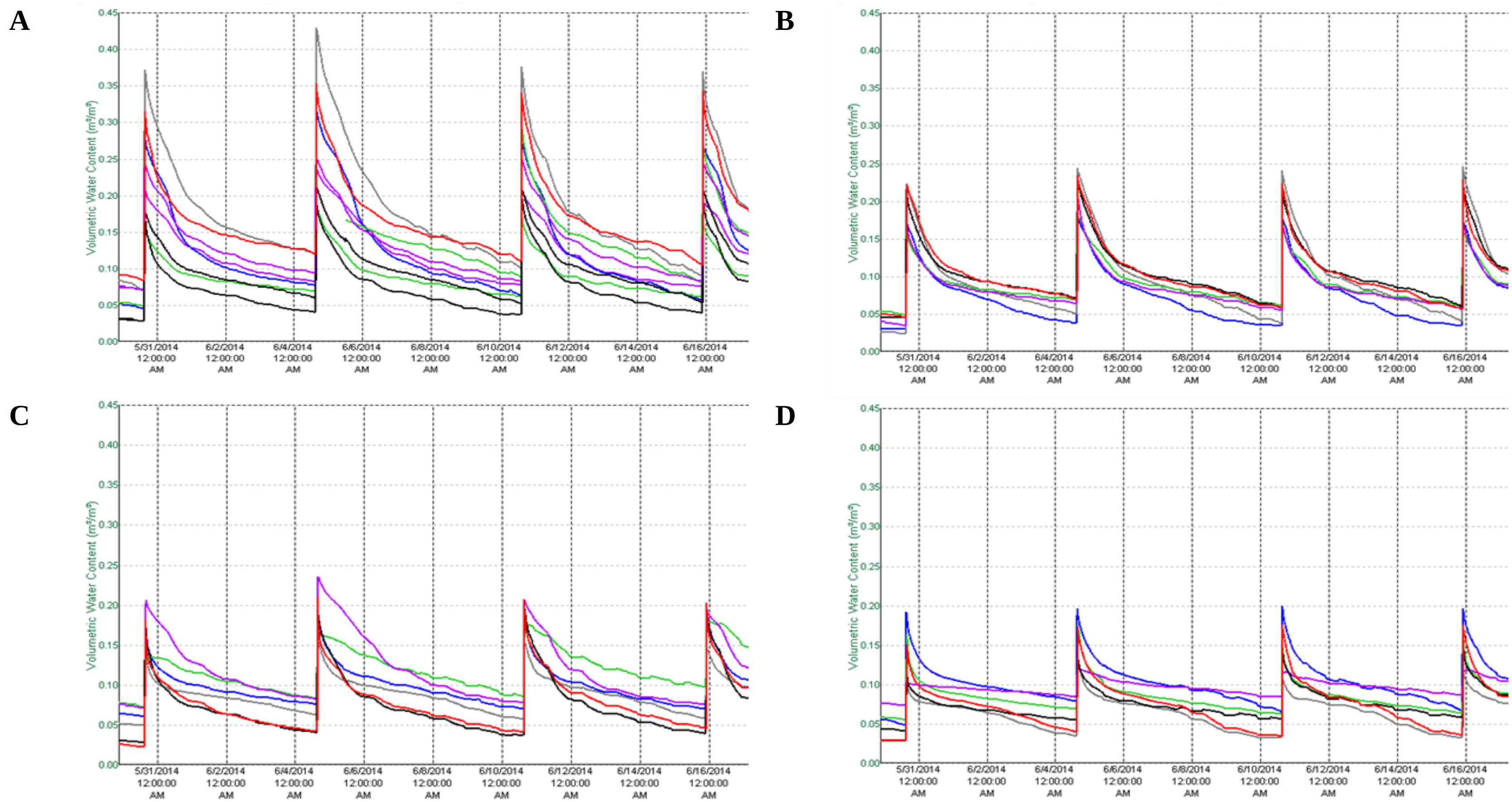


Figure C.5 A-D Volumetric water content of (A) coconut coir, (B) rice hull, (C) SmartLeaf®, and (D) mushroom compost pots before and after first sampling date (6/5/2014).

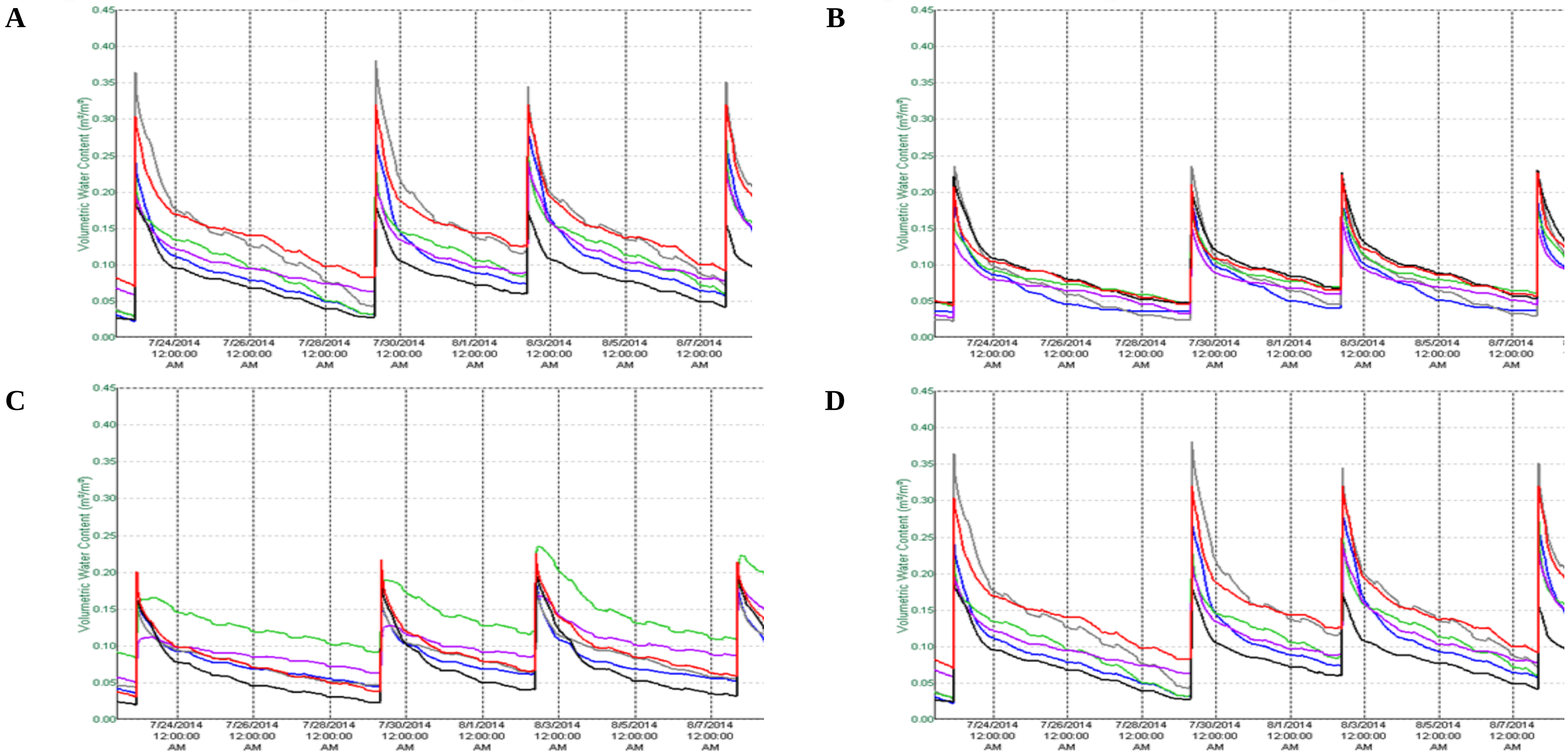


Figure C.6 A-D Volumetric water content of (A) coconut coir, (B) rice hull, (C) SmartLeaf®, and (D) mushroom compost pots before and after second sampling date (8/1/2014).

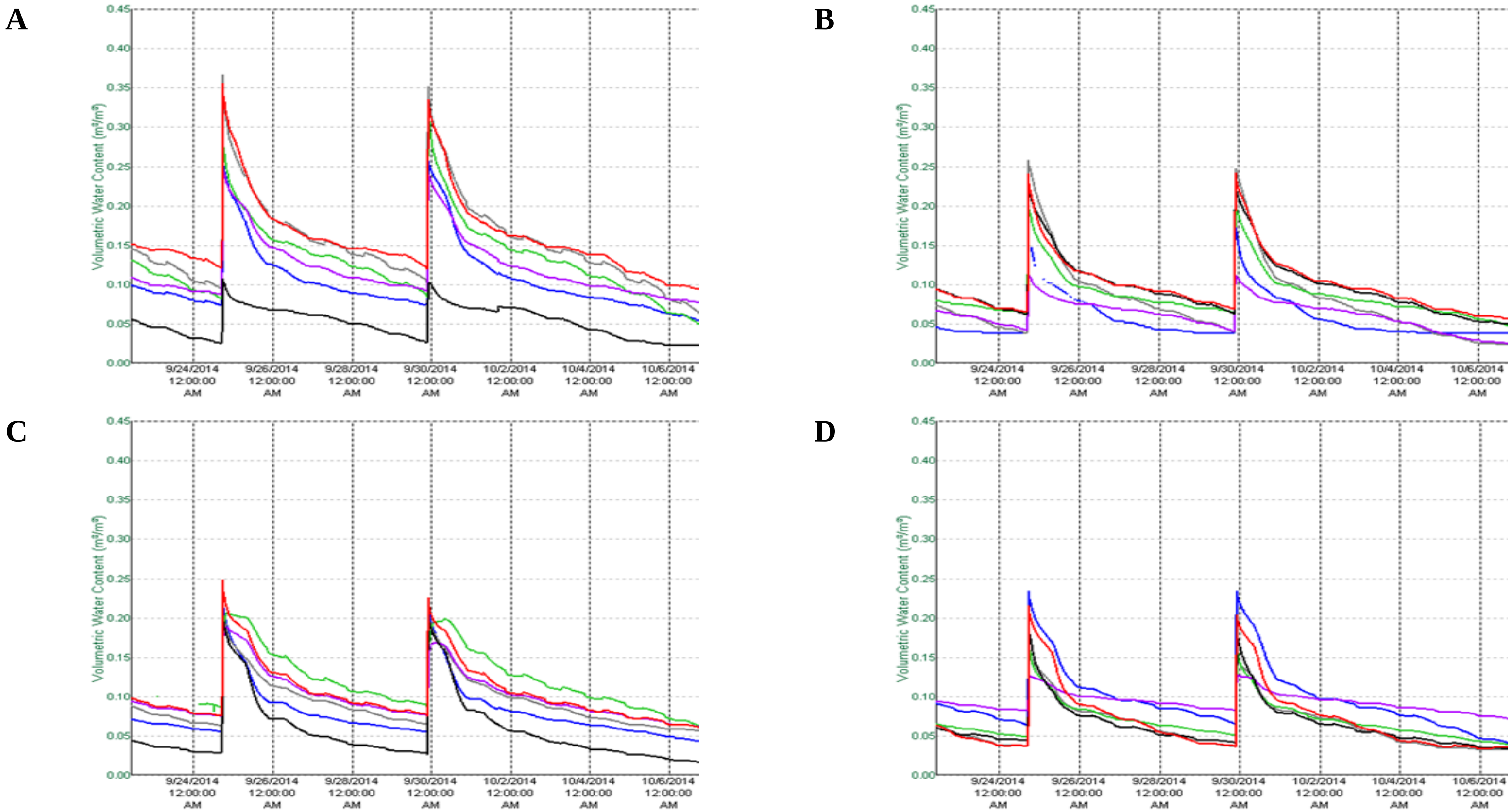


Figure C.7 A-D Volumetric water content of (A) coconut coir, (B) rice hull, (C) SmartLeaf®, and (D) mushroom compost pots before and after third sampling date (10/1/2014).

C.1.2 Nutrient content and concentration

Tissue samples from the final harvest were analyzed (JR Peters Laboratory, Allentown, PA) for nutrient concentration (Table C2). A total of 24 samples (4 OM × 3 reps × 2 plant structures) from the final harvest (on 10/01/14) were analyzed Nutrient contents (Table C1) were calculated from these results, as shown in main text Fig. 2.2, to normalize differences in nutrient concentration due to the growth differences (leaf area, root and shoot dry mass) between treatments (Ristvey et al. 2007).

Table C.1 A,B Nutrient **content** of *Phedimus kamtschaticus* from the third harvest. OM Types: coconut coir (CC), rice hulls (RH) SmartLeaf® (SL), and mushroom compost (MC). Letters indicate significant treatment effects (α = 0.05) within the same plant structure.

A

OM Type	Plant Structure	Calcium (mg)	Chloride (mg)	Magnesium (mg)	Manganese (mg)	Nitrogen (mg)	Phosphorus (mg)	Potassium (mg)	Sodium (mg)
CC	Shoots	28.9 ± 3.9[a]	30.7 ± 7.1[a]	3.9 ± 1.1[a]	0.1 ± 0.0[a]	9.1 ± 2.3 [b]	2.9 ± 0.4[a]	25.4 ± 6.8 [ab]	0.6 ± 0.1[a]
RH	Shoots	26.0 ± 1.7[a]	18.1 ± 3.6[a]	2.8 ± 0.2[a]	0.1 ± 0.0[a]	6.7 ± 0.9 [b]	4.0 ± 0.2[a]	11.8 ± 1.5 [b]	0.4 ± 0.1[a]
SL	Shoots	48.9 ± 14.1[a]	44.1 ± 13.6[a]	8.9 ± 2.7[a]	0.1 ± 0.0[a]	37.4 ± 10.4[ab]	5.1 ± 1.4[a]	57.0 ± 16.8[ab]	1.1 ± 0.4[a]
MC	Shoots	44.6 ± 8.2[a]	36.0 ± 8.6[a]	8.5 ± 1.6[a]	0.1 ± 0.0[a]	44.0 ± 8.8[a]	5.2 ± 0.9[a]	77.4 ± 15.4[a]	0.9 ± 0.1[a]
CC	Roots	34.0 ± 5.5[a]	7.5 ± 0.7[a]	4.6 ± 0.7[a]	0.1 ± 0.0[a]	26.3 ± 6.3[a]	3.1 ± 0.4[a]	12.8 ± 0.4[a]	2.0 ± 0.4[a]
RH	Roots	24.7 ± 2.7[a]	5.5 ± 0.7[a]	3.2 ± 0.5[a]	0.1 ± 0.0[a]	16.5 ± 2.1[a]	2.6 ± 0.4[a]	9.6 ± 0.4[a]	1.1 ± 0.1[a]
SL	Roots	35.3 ± 6.2[a]	8.7 ± 2.6[a]	4.1 ± 0.8[a]	0.1 ± 0.0[a]	33.9 ± 8.5[a]	3.7 ± 0.6[a]	11.7 ± 0.6[a]	2.5 ± 0.6[a]
MC	Roots	37.7 ± 5.3[a]	5.1 ± 0.5[a]	4.1 ± 0.6[a]	0.1 ± 0.0[a]	36.6 ± 4.8[a]	4.2 ± 0.6[a]	13.6 ± 0.6[a]	2.4 ± 0.3[a]

B

OM Type	Plant Structure	Aluminum (mg)	Boron (mg)	Copper (mg)	Iron (mg)	Molybdenum (mg)	Zinc (mg)
CC	Shoots	0.02 ± 0.01[a]	0.05 ± 0.01 [b]	0.01 ± 0.00 [b]	0.0 ± 0.0[a]	0.00 ± 0.00 [b]	0.00 ± 0.00[a]
RH	Shoots	0.01 ± 0.00[a]	0.04 ± 0.01 [b]	0.01 ± 0.00 [b]	0.1 ± 0.0[a]	0.00 ± 0.00 [b]	0.00 ± 0.00[a]
SL	Shoots	0.04 ± 0.01[a]	0.17 ± 0.04[a]	0.02 ± 0.01[ab]	0.1 ± 0.0[a]	0.01 ± 0.00[ab]	0.00 ± 0.00[a]
MC	Shoots	0.05 ± 0.03[a]	0.09 ± 0.01[ab]	0.04 ± 0.00[a]	0.0 ± 0.0[a]	0.01 ± 0.00[a]	0.00 ± 0.00[a]
CC	Roots	1.82 ± 0.45[a]	0.06 ± 0.01[a]	0.11 ± 0.01[a]	0.5 ± 0.1[a]	0.00 ± 0.00[a]	0.00 ± 0.00[a]
RH	Roots	0.70 ± 0.16[a]	0.04 ± 0.00[a]	0.05 ± 0.00 [b]	1.1 ± 0.2[a]	0.00 ± 0.00[a]	0.00 ± 0.00[a]
SL	Roots	1.65 ± 0.27[a]	0.08 ± 0.01[a]	0.05 ± 0.01 [b]	0.8 ± 0.2[a]	0.01 ± 0.00[a]	0.00 ± 0.00[a]
MC	Roots	1.10 ± 0.21[a]	0.05 ± 0.00[a]	0.08 ± 0.01[ab]	0.9 ± 0.3[a]	0.01 ± 0.00[a]	0.00 ± 0.00[a]

Table C.2 A,B Nutrient **concentration** of *Phedimus kamtschaticus* from the third harvest. OM Types: coconut coir (CC), rice hulls (RH) SmartLeaf® (SL), and mushroom compost (MC). Letters indicate significant treatment effects (α = 0.05) within the same plant structure.

A

OM Type	Plant Structure	Aluminum (ppm)	Boron (ppm)	Calcium %	Chloride (ppm)	Copper (ppm)	Iron (ppm)	Magnesium %
CC	Shoots	24.5 ± 1.4	53.1 ± 4.9	3.3 ± 0.3	33945.3 ± 2117.1	15.9 ± 2.1	32.5 ± 2.1	0.4 ± 0.0
RH	Shoots	16.5 ± 0.7	61.0 ± 2.2	4.2 ± 0.5	27895.0 ± 2043.9	16.9 ± 0.7	31.4 ± 2.3	0.4 ± 0.0
SL	Shoots	21.1 ± 6.8	109.9 ± 2.8	3.2 ± 0.1	28591.0 ± 1929.6	16.0 ± 1.0	54.4 ± 5.7	0.6 ± 0.0
MC	Shoots	29.4 ± 8.1	61.0 ± 11.1	2.9 ± 0.2	22920.0 ± 334.7	24.4 ± 2.6	54.9 ± 1.6	0.6 ± 0.0
CC	Roots	853.7 ± 102.2	28.6 ± 0.7	1.6 ± 0.0	3677.7 ± 219.7	55.6 ± 9.5	436.2 ± 68.0	0.2 ± 0.0
RH	Roots	472.4 ± 70.3	29.4 ± 3.3	1.7 ± 0.1	3749.0 ± 164.1	38.9 ± 5.1	369.5 ± 79.3	0.2 ± 0.0
SL	Roots	1036.5 ± 105.2	48.2 ± 4.3	2.2 ± 0.1	5173.7 ± 288.4	31.6 ± 3.3	713.5 ± 79.4	0.3 ± 0.0
MC	Roots	704.7 ± 35.1	35.3 ± 2.9	2.5 ± 0.0	3360.3 ± 236.4	48.7 ± 5.3	516.7 ± 26.6	0.3 ± 0.0

B

Type of OM	Plant Structure	Manganese (ppm)	Molybdenum (ppm)	Total Nitrogen %	Phosphorus %	Potassium %	Sodium (ppm)	Zinc (ppm)
CC	Shoots	57.1 ± 5.5	1.3 ± 0.4	1.0 ± 0.1	0.3 ± 0.0	2.8 ± 0.2	671.0 ± 71.1	21.0 ± 2.4
RH	Shoots	61.4 ± 4.6	3.0 ± 0.9	1.1 ± 0.0	0.7 ± 0.1	1.9 ± 0.2	546.2 ± 83.7	17.4 ± 3.2
SL	Shoots	59.3 ± 5.8	6.4 ± 0.6	2.5 ± 0.3	0.3 ± 0.0	3.7 ± 0.2	679.1 ± 131.6	43.0 ± 3.3
MC	Shoots	58.2 ± 7.5	5.8 ± 0.1	2.9 ± 0.2	0.3 ± 0.0	5.1 ± 0.4	563.5 ± 43.5	42.0 ± 2.3
CC	Roots	54.9 ± 2.6	2.4 ± 0.4	1.2 ± 0.1	0.2 ± 0.0	0.6 ± 0.1	967.8 ± 73.2	81.2 ± 11.5
RH	Roots	70.6 ± 6.9	3.5 ± 1.0	1.1 ± 0.1	0.2 ± 0.0	0.7 ± 0.0	779.2 ± 58.7	31.4 ± 2.6
SL	Roots	81.2 ± 2.8	6.7 ± 0.5	2.1 ± 0.3	0.2 ± 0.0	0.7 ± 0.1	1554.0 ± 197.8	47.0 ± 2.9
MC	Roots	82.5 ± 8.5	6.2 ± 0.0	2.4 ± 0.3	0.3 ± 0.0	0.9 ± 0.1	1585.3 ± 218.2	63.1 ± 4.9

Appendix D: Sensor calibration

D.1.2 Procedure

Sensor Calibration Protocol, Elizabeth Barton, written 8/10/2012, updated 2/19/2014

Modified from the Homogenized Substrate Method (Decagon Devices, Inc.)

1. Weigh empty 1000 mL and record mass
2. Fill beaker with substrate packed to approximate field bulk density
3. Weigh filled beaker and record mass
4. Insert sensor one into the substrate with the tines down avoiding any air gaps between sensor tines and substrate as much as possible
5. Use ECH2O Utility (Decagon Devices Inc., Version 1.72) to measure raw sensor output in m^3/m^3 and record sensor reading
6. Repeat steps 4 and 5 with sensors 2 and 3
7. Empty substrate into plastic tub, add an arbitrary amount of water, mix thoroughly
8. Pack substrate back into the beaker to the same volume
9. Repeat steps 3-8 until substrate is saturated
10. Follow calculations and calibration equation instructions from "Calibrating ECH2O Soil Moisture Sensors" (Cobos and Chambers 2010)

D.1.2 Calibration results

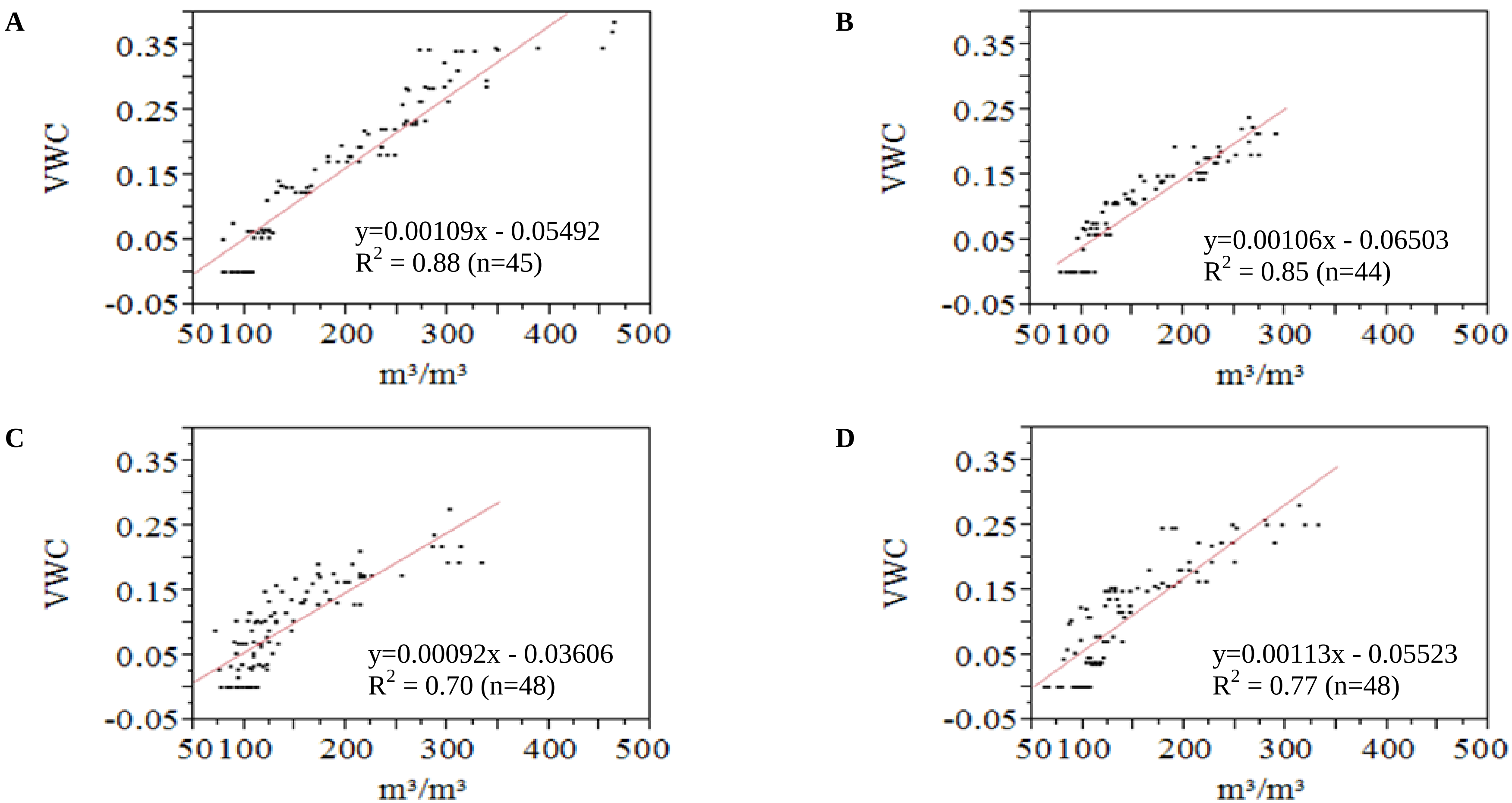


Figure D.1 Linear bivariate fit of calibration results for GS3 sensors for (A) coconut coir, (B) rice hulls, (C) SmartLeaf®, (D) mushroom compost

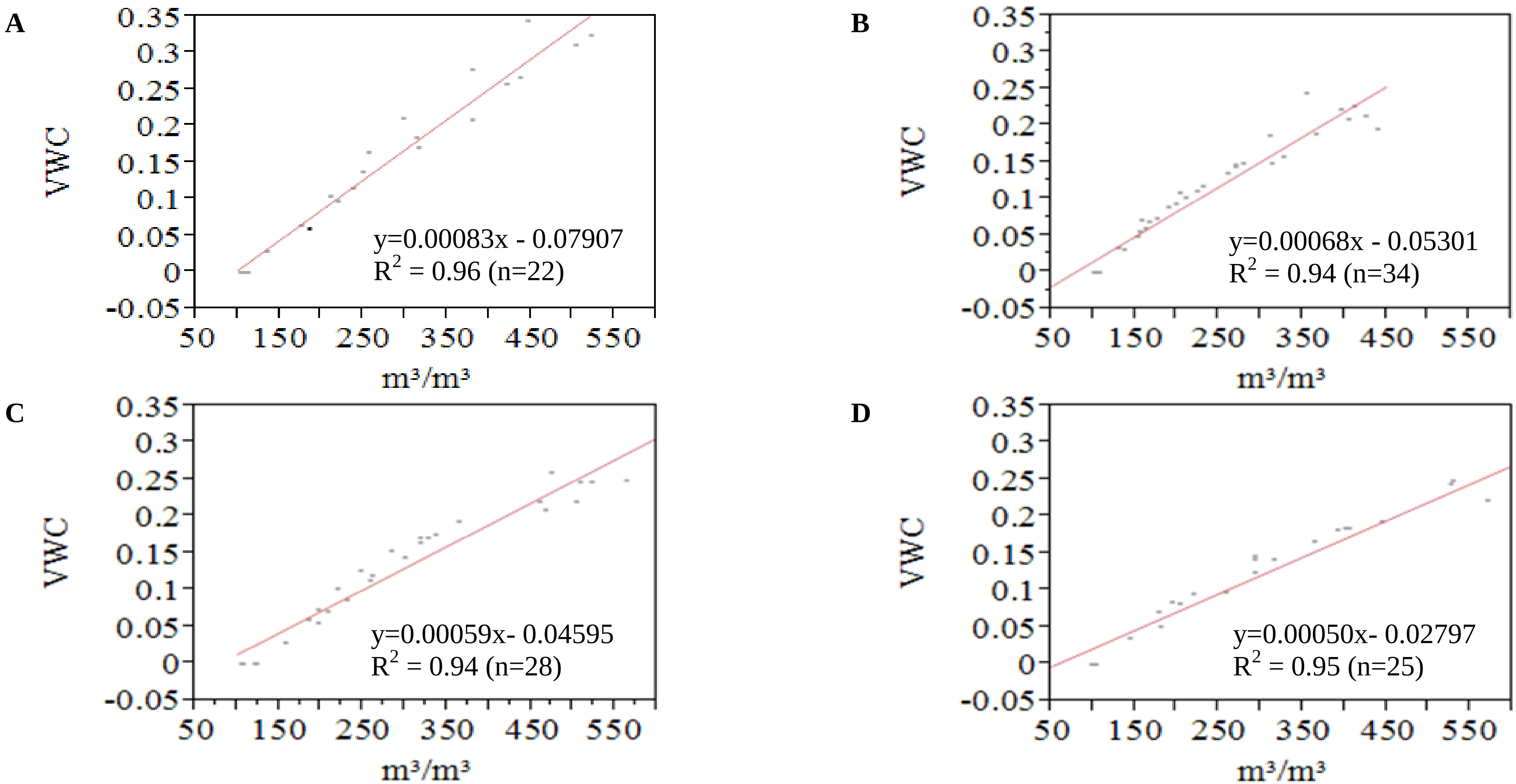


Figure D.2 Linear bivariate fit of calibration results for 5TM sensors for (**A**) coconut coir, (**B**) rice hulls, (**C**) SmartLeaf®, (**D**) mushroom compost

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