Green Roof Substrate Composition Affects *Phedimus kamtschaticus* Growth and Substrate Water Content under Controlled Environmental Conditions

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Abstract. *Phedimus kamtschaticus* (Fischer) were grown in three experimental crushed brick-based green roof substrates (GRSs) with increasing organic matter (OM) content (10%, 20%, and 40% by volume) and a commercially available blend, Rooflite®, in single-pot replicates in a growth chamber for 6 months. Three unplanted replicates of each substrate were included in the design and received identical irrigation volumes as planted replicates. Three destructive harvests indicated that increased substrate OM increased plant root and shoot biomass; however, plants grown in Rooflite® demonstrated greater succulence in the second and third destructive harvests despite similar substrate OM content. By the end of the growth study, there was no difference in dry weight accumulation between the Rooflite® and 40% OM treatment despite the difference in succulence between the two treatments. Substrate volumetric water content (VWC) ranged from 22.5% to below 5% during three consecutive periods of imposed water stress with no differences in evapotranspiration (E_T), indicating plants were accessing substrate water previously assumed to be unavailable. Cumulative water loss (normalized for plant dry weight) indicated a likely shift into crassulacean acid metabolism (CAM) around 60-hour postirrigation. Planted treatments ($n = 6$) lost more water cumulatively ($P < 0.05$) compared with the unplanted controls ($n = 3$), although there were no differences in total water loss between substrate treatments.

As researchers continue to investigate the effects of various green roof components and system performance (Berndtsson et al., 2006; Getter et al., 2007; Getter and Rowe, 2008; Mentens et al., 2006; Molineaux et al., 2009; Rowe et al., 2006; Teemusk and Mander, 2007; VanWoert et al., 2005a), the total green roof area in North America increases (Erlachman and Peck, 2013). As the layer that supports the biological function of any green roof system, GRSs retain water for plant growth, allow air movement for root gas exchange, offer stability and structure for root anchoring, and provide nutrients for plant uptake. Although substrates retain a proportion of any rainfall (buffering immediate storm water runoff), plants provide the additional ecosystem service of storm water removal via transpirational water loss. In this way, water held in the GRS is taken up through the roots and cycled directly back into the atmosphere as water vapor, decreasing the water content of the GRS and allowing water retention

from the next rain event. Although water does leave the substrate through evaporative losses, Starry et al. (2014) demonstrated that with the exception of large (>62.5 mm) rain events, green roof platforms planted in *P. kamtschaticus* in the mid-Atlantic region were 30% more efficient at removing storm water through E_T compared with evaporation alone from unplanted platforms. This contradicted VanWoert et al.'s (2005a) conclusion that brown or unplanted experimental roof platforms were as effective at evaporating storm water as planted experimental platforms. Given plants' substantial influence on E_T water loss from a green roof system, the effects of GRS composition on plant growth and E_T should be investigated to enhance storm water retention predictions and inform green roof system design.

In general, any soilless substrate should be consistent in composition, free of pathogens and weed seed, and provide adequate water, air, and nutrients for plant survival and growth (Handreck and Black, 2007). In addition to these properties, GRS must also have an adequate bulk density to resist wind uplift without surpassing roof structural live load limits for the roof; they must also be engineered to rapidly drain to avoid

ponding. In the early 19th century, green roofs in Berlin did not use engineered media; rather, construction rubble was spread over tar paper roofs and the living systems developed overtime (Kohler and Poll, 2010). Modern GRS composition is largely based on recommendations in the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), the German landscape industry's guidelines for the design, planting, and maintenance of green roof systems. The FLL makes recommendations for particle size distribution and organic content as well as specific physical properties such as water holding capacity, bulk density, and total porosity (FLL, 2008).

Beyond the basic FLL recommendations, GRS composition varies internationally and regionally, usually due to raw material availability; however, the FLL recommendations have been adopted by municipalities and public entities around the world and applied to green roof components not considered in or by the FLL. North American GRS are largely composed of manufactured lightweight aggregates—usually slate, shale, or clay that has been kiln fired to create expanded mineral particles (Ampim et al., 2010). Particles of varying diameter are mixed together to achieve appropriate particle size distribution and physical properties such as water holding capacity, total porosity, and bulk density (Handreck and Black, 2007). Although the North American green roof industry largely uses manufactured aggregate for GRS, research from other countries indicates efforts to use lower carbon recycled or natural materials for the inorganic component of GRS. For example, New Zealand GRSs are largely composed of naturally occurring zeolite and volcanic rock (Fassman-Beck et al., 2013). A study based in northern Italy used a blend of locally available naturally occurring mineral materials as the extensive GRS (Nardini et al., 2012). Molineaux et al. (2009) reported in the United Kingdom, broken brick is a commonly used mineral portion of extensive GRSs. In Sweden, extensive GRSs were traditionally natural soil amended with naturally occurring lava or scoria, and Emilsson (2008) reported the results of a study using broken roof tiles as a component of extensive GRSs as an alternative to those mined minerals.

The organic content of GRS typically varies depending on the design intent of the green roof system; however, most ready-to-plant blends roughly follow the FLL guidelines of ≤ 65 g/L (FLL, 2008). This gravimetric recommendation is based on verification via loss on ignition. However, in practice, horticultural substrates are generally mixed volumetrically. The FLL guideline is a weight per volume metric—a value that could therefore vary widely depending on the bulk density of the blend if it is mixed volumetrically, as a typical horticultural substrate. Griffin (2014) demonstrated that given the differences in

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densities of the mineral and organic portions of GRS, a substrate could have up to 40% OM (volumetrically) and still fall within the FLL guidelines. Since OM provides cation exchange and water holding capacity, varying from the organic content of a GRS could have significant impacts on substrate water holding capacity, plant growth, and E_T .

Green roofs present a unique engineered environment for plants—a thin substrate layer requires a fibrous, nonaggressive root system to avoid compromising the integrity of the waterproof membrane of the roof; the reduced rooting zone also limits the volume of water that can be stored after rain events. Green roof plants must tolerate extreme diurnal temperature ranges, direct sun exposure, and high wind exposure. All these factors combine to provide a drought prone system even in climatic areas with relatively consistent rainfall. Although green roofs are most often found in urban areas, the environmental challenges they present to plants are in many ways comparable to deserts or rocky outcroppings, and the plants that are most often used in extensive green roof systems are succulent species

that have evolved physiological responses to extreme heat and drought conditions.

One such mechanism is a variation on the traditional C3 photosynthetic pathway termed the CAM. CAM allows for a water use efficiency, or the weight of plant material per volume of water used, 6-fold greater than C3 plants (Nobel, 1996) because carbon uptake occurs nocturnally. CAM plants are adapted to keep their stomata closed during the day to prevent water loss—carbon dioxide (CO_2) is sequestered at night when stomata open, and is stored as malic acid until sunrise. Even though stomata are closed during the day (primarily for water conservation), photosynthesis can continue during the day (albeit at a reduced rate) by converting the malic acid back into CO_2 for use in photosynthesis (Taiz and Zeiger, 2010). Various degrees of CAM expression exist—“CAM cycling” refers to the internal refixation of carbon stored as malic acid, whereas “CAM” indicates nocturnal carbon fixation via the enzyme phosphoenolpyruvate carboxylase with the potential for periods of stomatal opening at the beginning and end of the day. “CAM

idling” refers to stomatal closure for the entire 24-h day, where no new carbon is metabolized but malic acid is still created nocturnally via the recapture of respiratory CO_2 (Borland et al., 2011).

Starry et al. (2014) evaluated *P. kamtschaticus* for CAM metabolism and found it to be less drought resistant with less evidence of CAM metabolism than *Sedum album*, but did report some CAM activity for *P. kamtschaticus*. This supported Butler's (2011) findings that different succulents commonly found on green roofs can express variation in the extent to which they use CAM. Regardless of the photosynthetic pathway, the effects of GRS water availability on plant growth and E_T of green roof plants has not been studied in depth. In this study, the effects of substrate organic content on green roof plant growth and E_T were evaluated by growing *P. kamtschaticus* in four different substrates in a growth chamber for 16 weeks, culminating with a series of three stress (dry-down) periods where water was withheld for 12 d (after the first dry period) or 10 d (after the second dry period), to gain a better understanding of how substrate composition may affect the growth

Table 1. Plant growth data from three destructive harvests of pot-grown *Phedimus kamtschaticus* grown in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of OM plus an industry standard control (Rooflite™) in a growth chamber. Treatment means (n = 3) are shown for each plant growth parameter at each harvest day.

Treatment	Harvest one 15 July 2013					
	Aboveground fresh biomass ^z	Aboveground dry biomass ^y	Leaf area ^x	Belowground fresh biomass ^w	Belowground dry biomass ^v	Root length ^u
Control	6.48 a ¹ ± 0.76	0.54 a ± 0.03	71.03 a ± 7.08	1.92 ± 0.16	0.79 ± 0.20	2,342.67 ± 92.89
10% OM	1.76 ± 0.19	0.26 b ± 0.03	12.19 c ± 0.01	2.17 ± 0.36	0.91 ± 0.18	1,884.00 ± 64.71
20% OM	2.48 ± 0.13	0.35 b ± 0.03	23.16 bc ± 1.97	2.56 ± 0.29	1.17 ± 0.09	2,468.67 ± 74.09
40% OM	3.59 ± 0.26	0.39 ab ± 0.04	33.86 b ± 0.99	2.00 ± 0.30	0.90 ± 0.05	2,315.33 ± 92.32
Treatment	Harvest two 5 Sept. 2013					
	Aboveground fresh biomass ^z	Aboveground dry biomass ^y	Leaf area ^x	Belowground fresh biomass ^w	Belowground dry biomass ^v	Root length ^u
Control	17.68 a ± 1.09	1.02 ± 0.10	85.21 a ± 3.29	5.95 ± 0.51	2.48 ± 0.23	7,983.67 ± 80.83
10% OM	6.50 c ± 0.78	1.27 ± 0.07	34.35 c ± 0.21	7.15 ± 0.16	2.23 ± 0.29	5,882.67 ± 222.76
20% OM	10.8 b ± 0.67	2.38 ± 0.27	56.98 b ± 2.16	4.82 b ± 0.19	1.61 ± 0.21	7,547.02 ± 211.40
40% OM	18.43 a ± 0.60	5.95 a ± 0.51	101.62 a ± 1.10	5.48 ± 0.58	2.43 ± 0.23	8,572.70 ± 97.60
Treatment	Harvest three 14 Oct. 2013					
	Aboveground fresh biomass ^z	Aboveground dry biomass ^y	Leaf area ^x	Belowground fresh biomass ^w	Belowground dry biomass ^v	Root length ^u
Control	21.53 a ± 0.97	2.83 b ± 0.18	153.24 a ± 6.91	8.33 ± 0.83	3.94 ± 0.57	14,483.33 ± 1,332.47
10% OM	7.08 c ± 0.69	1.3 c ± 0.13	24.59 c ± 2.68	8.16 ± 0.1	2.48 ± 0.18	7,364.21 ± 413.02
20% OM	12.54 b ± 0.85	2.54 b ± 0.07	99.48 b ± 3.42	7.12 ± 1.28	2.90 ± 0.18	11,413.33 ± 1,315.35
40% OM	23.43 a ± 1.15	5.92 a ± 0.38	191.33 a ± 3.18	10.27 ± 0.9	4.58 ± 0.82	15,480.87 ± 758.57

OM = organic matter.

^zGrams.

^yGrams.

^xSquare centimeters.

^wGrams.

^vGrams.

^uMillimeters.

¹Lowercase letters designate significance at $\alpha = 0.05$.

Table 2. Particle size distribution of three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of OM plus an industry standard control (Rooflite™). Samples were oven-dried at 110 °C for 48 h before sieving using a Meinzer 11 shaker for 20 min and ASTM sieves 8, 16, 30, 45, 60, 100, and 200. Means (n = 5) are presented as percent weight of each diameter range per total sample weight.

ASTM sieve no.	Mesh size (mm)	10% OM percent	20% OM percent	40% OM percent SEM	Control percent
8	>2.360	56.85 ± 2.74	59.61 ± 2.65	61.20 ± 1.05	54.89 ± 0.54
16	1.180–2.360	10.14 ± 0.46	9.80 ± 0.57	9.72 ± 0.49	21.83 a ² ± 80
30	0.600–1.180	7.7 b ± 0.54	7.21 b ± 0.60	8.03 c ± 0.29	11.80 a ± 0.29
45	0.355–0.600	5.72 ± 0.37	6.03 ± 0.77	5.43 ± 0.34	4.37 ± 0.39
60	0.250–0.355	3.56 ± 0.25	3.32 ± 0.19	3.50 ± 0.25	2.1 b ± 0.19
100	0.150–0.250	6.26 ± 0.59	5.46 ± 0.43	5.86 ± 0.17	2.15 b ± 0.20
200	0.075–0.150	6.67 a ± 0.46	5.44 ab ± 0.20	3.79 b ± 0.61	1.52 c ± 0.16
Pan	<0.075	3.08 a ± 0.40	3.13 a ± 0.44	2.47 ab ± 0.06	1.35 b ± 0.27

OM = organic matter; ASTM = American Society for Testing Materials; SEM = scanning electron microscopy.

²Lowercase letters designate significance at $\alpha = 0.05$.

of green roof species and the consequent effects on storm water mitigation.

Our hypotheses were as follows:

1. H_0 : *P. kamtschaticum* root and shoot growth is unaffected by substrate OM content.

H_A : *P. kamtschaticum* root and shoot growth is affected by substrate composition, with 40% OM substrate producing greater root and shoot biomass than 20% and 10% OM content, due to the additional cation exchange and water holding capacity provided by the OM.

2. H_0 : GRS organic content will not affect evapotranspirational water loss from pots planted with *P. kamtschaticum*.

H_A : GRS organic content will affect evapotranspirational water loss from pots planted with *P. kamtschaticum*, since shoot growth is expected to increase with increasing proportions of OM, which should lead to greater leaf area and canopy volume and thus greater daily E_T .

Materials and Methods

Substrate preparation. In June 2012, a 60:40 crushed recycled brick:scoria mineral component was blended with mushroom compost (Frey Brothers, Lancaster, PA) in a drum mixer to create three different substrates on a volumetric (m^3/m^3) basis: 90 mineral:10 OM, 80 mineral:20 OM, or 60 mineral:40 OM. Enough of each blend was mixed to provide adequate amounts for platform-scale experiments, laboratory analyses plus 22 L which was stored in cold storage (4°C) in airtight containers. In addition to the experimental blends, 1.5-cubic yards of a ready-to-plant extensive GRS Rooflite™ manufactured by Skyland (Landenburg, PA) were purchased and stored in super sacks at the Research Greenhouse Complex (College Park, MD); 22 L of the Rooflite™ media was also placed in airtight containers in cold storage at 4°C for future use.

Growth chamber and destructive harvests. On 6 June 2013, a pot-scale growth chamber study was installed using these three experimental blends plus the Rooflite™

blend, using the substrate that had been in cold storage. Oyama pot-in-pots were used (AV Planters, San Lorenzo, CA) as previously described in Solano et al. (2012). In addition to the four planted treatments, three single-pot replicates of each substrate were left unplanted as a control treatment, and watered with all other replicates for the duration of the study. Fifteen single-pot replicates of each substrate were planted with one *P. kamtschaticum* plug from a 72-plug flat that had been rooted for about 1 year (Emory Knoll Farms, Street, MD). Before planting, the propagation media was completely washed from the plug roots. The Oyama container volume was 500 mL; the top container rested inside a separate container, allowing the measurement of leachate following irrigation events. Pots were watered with 100 mL (equivalent to 1.27-cm rainfall based on container surface area) every 3rd d, and leachate was immediately emptied from the bottom container to remove any excess water reserves for plants.

All pots were placed in a growth chamber at 29°C day, 16°C night, with a 12-h photoperiod at $1200\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (light

Fig. 1. In-pot volumetric water content for 500 mL containers planted with *Phedimus kamtschaticus* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) following the (A) first, (B) second, and (C) third 100-mL irrigation events imitating a 1.27 cm 1-h rain event. Means ($n = 6$) are shown for each treatment at each measurement interval.

Fig. 2. Water loss from containers planted with *Phedimus kamtschaticus* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry control (Rooflite™) normalized by total replicate leaf area in the (A) first, (B) second, and (C) third dry downs. Means ($n = 6$) are shown for each treatment at each measurement interval.

intensity) in a completely randomized design. Three single-pot replicates from planted treatments were harvested on three separate occasions (15 July, 5 Sept., and 14 Oct.) at 39, 91, and 130 d after planting, respectively. Root length, root fresh and dry weight, shoot fresh and dry weight, and leaf area were recorded at each harvest. Dry weights were obtained after drying all plant tissues at 40 °C in a Thelco Laboratory Oven (Precision Instruments, Winchester, VA); all fresh and dry weight measurements were recorded using a Mettler-Toledo PB3001-S balance (Mettler-Toledo, Inc., Columbus, OH).

Simulated drought periods. After the third destructive harvest, six single-pot replicates from each planted treatment plus three single-pot unplanted replicates remained in the growth chamber and were slowly rewatered by hand with 20 mL water every 12 min until each replicate had received 100 mL water to mimic a low-intensity 12.7-mm rain fall occurring over 1 h. Pot weights were recorded twice daily for 10 d. The resultant weight loss was attributed to E_T (planted replicates) and evaporation (unplanted replicates). The drying and rewetting process was performed three times, for three consecutive

periods of water stress. After the third dry down, all plants were destructively harvested as previously described. The media from each replicate was collected and oven-dried for 48 h at 105 °C in a Thelco Laboratory Oven (Precision Instruments) to obtain in-pot substrate VWC.

Data were analyzed using the MIXED procedure in SAS 9.3 and the LSMEANS statement; Scheffe's adjustment was used for multiple means comparisons for all data with $\alpha = 0.05$.

Results

Destructive harvests. There were no differences in belowground biomass dry weight for any of the harvests (Table 1); however, *P. kamtschaticus* leaf area was greater for plants grown in the Rooflite® blend for the first harvest but was not different from the 40% OM treatment for the second and third harvests. We note that this was a short-term laboratory experiment meant to tease out the effects of substrate OM immediately following green roof installation. In the field (i.e., plant roots not limited to a small volume of substrate in a pot), differences in belowground

biomass may be more evident. Plants grown in 20% OM substrate had less leaf area than those grown in 40% OM, but greater leaf area than those grown in 10% OM. This was expected given the benefits of increased water availability and nutrients with increasing proportions of OM.

Plants grown in 40% OM and Rooflite® had similar aboveground biomass fresh weights for the second and third harvests; however, plants grown in 40% OM had the highest total aboveground biomass dry weight for the second and third harvests (Table 1). These results indicate that plants growing in Rooflite® had higher water contents per gram dry weight (i.e., greater succulence) than plants growing in the 40% OM treatment. All harvests occurred the 3rd d following the most recent irrigation event, before being irrigated, so plants growing in 40% OM may have already used the available water, whereas plants growing in Rooflite® still had access to available water. It is important to note the differences in substrate particle size distribution between the experimental blends and the Rooflite® (Table 2). Although Rooflite® has fewer small-diameter particles compared with the

Fig. 3. Total cumulative water loss by *Phedimus kamschaticus* planted in three different experimental green roof substrates with increasing volumetric proportions (10%, 20%, or 40%) of organic matter plus an industry standard (Rooflite™) and unplanted pots with the same substrates. This represents the sum of averaged water loss after three separate 100-mL irrigation events, for a total of three simulated droughts. Means ($n = 6$ for planted and $n = 3$ for unplanted) are shown for each treatment. P values indicate significance at $\alpha = 0.05$.

experimental blends (<0.355 mm), it has a greater proportion of medium-diameter particles (0.355–2.36 mm), which would increase the water holding capacity of the substrate. Because all harvests occurred on the 3rd d following an irrigation event, differences in water availability between substrates could be the primary factor in the differences in succulence. However, since plants growing in the 40% OM treatment still had more dry weight accumulation on the second and third harvest dates, we suggest that dry weight accumulation may be less sensitive to water availability as the plants become more established.

Although the Rooflite® has similar gravimetric organic content to the experimental blends (Griffin, 2014), the volumetric proportion of OM for Rooflite is unknown. Nonetheless, the increased leaf area for plants grown in this standard industry blend for the first harvest may also be explained by the increased water availability as a function of particle size distribution (Table 2). The increased growth during the first 6 weeks of the study demonstrates that water availability may play a significant role in early plant establishment for *P. kamschaticus*. We note a primary limitation in this study is that substrate nutrient contents were not considered, and are likely at least partially responsible for differences in growth.

Simulated periods of water stress. Planted replicates lost more water than unplanted replicates over the course of the consecutive simulated dry periods (Fig. 3). This supports Starry's (2013) findings that planted green roof species do enhance storm water removal from roof substrates for all but large (>62.5 mm) rain events, despite the findings reported by VanWoert et al. (2005b), in which pots planted with mixed *Sedum* spp.

maintained a higher substrate VWC than unplanted pots.

The substrate VWC was calculated for each replicate by accounting for the final total plant fresh weight, substrate dry weight, and pot weight for each replicate over the course of the first simulated dry period (Fig. 1). Substrate VWC ranged from 22% to 25% down to 3.5% to 5% over the course of this first dry period (Fig. 1A). The VWC during the second imposed dry period ranged from 18%–22% to 4%–5% (Fig. 1B); although, the VWC during the third dry period ranged from 20%–23% to 2.5%–4% (Fig. 1C). The starting VWC was assumed to be container capacity for each substrate treatment, because each replicate produced leachate following each simulated rain event. The final VWC at the end of each dry down indicates the plants were able to remove nearly all of the water from each substrate, irrespective of OM content. These results are consistent with the findings of Bousset et al. (2011) in a drought-stress study of 15 temperate plant species; however, the VWC measurements were obtained using a handheld soil moisture meter instead of actual replicate weight. It is not known if the meter was calibrated to the specific GRS used in the study (Bousset et al., 2011), and the effects of root water on the handheld meter are unknown. The VWC values reported herein were extrapolated directly from dry weight of each replicate and thus are actual measurements of VWC.

Cumulative water loss for each dry period was normalized by total plant leaf area (Fig. 2D, E, and F). Normalized results indicate smaller plants may be more efficient at E_T and that biomass may not be as good of an indicator of water use compared with leaf area. Despite increased succulence in plants grown in Rooflite® and greater overall

biomass in plants grown in 40% OM, neither of these treatments showed more cumulative water loss than any other treatment. This implies that a green roof planted with larger plants may not be any more efficient at water cycling than a green roof planted with smaller plants, which could be a direction for future research. It is important to note that at the start of the simulated periods of drought, the canopies for all replicates covered the substrate surface of the pots.

Interestingly, the rate of water loss decreased after about 60 h for all three simulated dry periods, which may indicate plants had transitioned to CAM to conserve water. Comparing the timing with the in-pot VWC graphs show these transitions (points of inflection) occurred around 8% VWC during each dry down. Nevertheless, despite the extremely low-substrate VWC, the plants continued to transpire beyond this, albeit more slowly, further suggesting CAM activity—with stomata closed during the day, daytime water loss would be limited to evaporation and nocturnal water loss would be minimal during stomatal opening.

There were no differences in substrate VWC between treatments. Eksi et al. (2015) reported increased VWC with increasing volumetric proportions of OM in 0.65 m² experimental platforms. In a green roof tray-scale study, Nagase and Dunnett (2011) also found significant differences in substrate VWC with increasing volumetric proportions of OM in a brick-based green roof media. We hypothesize that differences in VWC between treatments may be detectable in a larger platform-scale study.

In-pot VWC fell below 5% for all treatments in all three dry downs. Griffin (2014) related substrate VWC with matric potential in an attempt to define plant available water and permanent wilting point for these same experimental GRS blends. Although the instruments used could not capture the entire water characteristic curve, the results herein support Griffin's conclusion (2014) that the range of plant available water for *P. kamschaticus* extends far beyond what has previously been assumed (Brady and Weil, 2000; Gliessman, 1998; Handreck and Black, 2007). Given that replicates were rewetted for three successive periods of water stress and each simulated drought showed in-pot VWCs below 5%, it cannot be assumed that permanent wilting point for *P. kamschaticus* is known. Defining the VWC corresponding to true permanent wilting point for succulent green roof species is another area for future investigation, as doing so would contribute to more accurate predictions of storm water mitigation potential.

All water lost from unplanted pots can be attributed to evaporation, whereas water lost from planted pots can be attributed to E_T , so water lost due to plant transpiration was extrapolated by subtracting the means of cumulative water loss of unplanted pots ($n = 3$) from the means of cumulative water loss from planted pots ($n = 6$), shown in Fig. 3. For all three consecutive dry periods,

means of transpirational water losses did not exceed means of evaporational water losses until 48 h after the start of the dry period.

Discussion

Increasing the volumetric proportions of OM in GRS results in plants with greater dry biomass, likely due to increased nutrients and water availability with increased OM; however, when compared with a commercially available substrate with similar gravimetric organic content but higher water holding capacity, only the 40% OM treatment yielded similar plant growth. Despite differences in volumetric organic content and porosity, substrate composition did not affect the total volume of water removed from the containers during three consecutive dry downs; rather, the presence of plants resulted in greater transpirational water use.

Perhaps the most interesting results of this experiment are the in-pot VWC reached during the course of the three dry periods, especially, when compared with cumulative water loss, which typically asymptoted at $\approx 8\%$ VWC for all three dry-down periods (and substrates). Nagase and Dunnett (2011) reported substrate VWC near 5% in a greenhouse study of brick-based GRSs mixed with increasing (0%, 10%, 25%, or 50%) volumetric proportions of OM: all treatments except the 50% OM fell below 5% VWC by 20 d after the start of the experiment. When relating VWC to water availability, permanent wilting point is assumed to be -1.5 MPa matric potential (Kiehl et al., 1992); however, Rodriguez (2009) demonstrated progressively unavailable water in horticultural substrates, leading to incipient water stress at pressures above -1.5 MPa. Regardless, the results herein demonstrate *P. kamtschaticus* may be accessing water previously assumed to be unavailable to plants.

Replicates in the study herein were certainly water stressed during the three consecutive periods of drought stress, but still did not reach permanent wilting point. Starry et al. (2014) reported decreased E_T in *P. kamtschaticus* at a VWC of $0.13 \text{ m}^3 \cdot \text{m}^{-3}$, and hypothesized that at lower water contents, water may not be readily available to plants, meaning E_T declines but still happening. We note the inherent ambiguity in the phrase “readily available”—is water that plants can access via CAM metabolism any less available than water that is accessed via C3 metabolism? These results indicate that *P. kamtschaticus* can access water previously assumed to be unavailable, or not readily available, to plants. Clarifying the true VWC range at which green roof plants can successfully move water will allow for better estimation of stormwater mitigation potential of

green roof systems and should be investigated more thoroughly.

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