Substrate loss is minimal in vegetated and un-vegetated extensive roof modules over a 14-month period

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Abstract

The presence of vegetation is thought to reduce loss of soil substrate after roof installation; however, few attempts have been made to quantify this effect. Twelve green roof modules placed at a 2% slope were used to quantify the effect of wind, precipitation intensity, vegetation and vegetation type on modular green roof substrate depth. The presence of vegetation reduced substrate loss immediately after installation of equipment, yet had little effect on substrate depth once the substrate had settled. Neither wind speed nor precipitation rate had a direct effect on substrate depth, although after some large rainfall events substrate depth increased due to media expansion caused by the retained water. Overall we observed negligible substrate depth decrease, regardless of vegetation presence, wind speed or precipitation intensity.

Keywords: roof substrate erosion, vegetated roof

Introduction

Research on green roofs has increased significantly in the past 20 years (Blank *et al.* 2013) as they can provide a range of environmental benefits (Oberndorfer *et al.* 2007; Rowe 2011). Green roofs reduce the amount of runoff coming from roof surfaces (Mentens, Raes & Hermy 2006; Bliss, Neufeld & Ries 2009; Volder & Dvorak 2013) as well as delay peak runoff during rain events (VanWoert *et al.* 2005; Bliss, Neufeld & Ries 2009; Burszta-Adamiak & Mrowiec 2013). Other benefits include improved runoff quality compared to standard roofs (Berndtsson, Emilsson & Bengtsson 2006; Berndtsson, Bengtsson & Jinno 2009; Gregoire & Clausen 2011), reduction in the urban heat island effect (Alexandri & Jones 2008), increased carbon sequestration (Getter *et al.* 2009), reduced energy demands of the building (Wong *et al.* 2003), and increased habitat for urban wildlife (Getter & Rowe 2006). Green spaces are also known to have positive sociological effects on humans (White & Gatersleben 2011).

Green roofs are generally divided into two categories: extensive and intensive. Extensive green roofs consist of shallow substrate (up to 10 cm depth) and are used mostly for their functional attributes. They are minimally irrigated and are planted with stress tolerant plants that rely mostly on rainwater. Intensive green roofs consist of much deeper substrate, are planted with larger plant species, and are typically irrigated. Intensive green roofs can be used as roof top gardens accessible to the public and usually require structural reinforcement. Retrofitting existing buildings with extensive green roofs is becoming an increasingly popular way to improve the building and local environment. Extensive green roofs are the most economical and practical type of retrofit because the building usually does not need structural reinforcement (Dunnett & Kingsbury 2004). A common technique for retrofitting is to use modular systems. Pre-assembled trays are installed on top of the waterproofing membrane on the roof in a grid-like fashion. Green roof modules contain all the profiles within each module and are a manageable option if moving and replacing certain areas of the roof or accessing the roof deck become necessary.

The loss of roof substrate over time through water and wind erosion, and the mitigating impacts of vegetation, has received little attention in green roof research. In natural systems precipitation is an important cause of soil erosion, and mostly occurring when the soil surface is bare and slopes are steep (Zuazo 2008). Wind is another contributor to soil erosion. Wind speed and turbulence, ground cover, surface roughness and soil structure, texture and moisture content are all important factors determining the extent of soil erosion due to wind (Chepil 1945). Erosion by wind is especially pronounced in areas with little vegetation and coarse soils (Breshears *et al.* 2003), as well as soils with low organic matter content (Liu *et al.* 2006). These conditions are typical of that experienced on an extensive, un-irrigated green roof, particular in drier climates.

Green roof substrate, especially substrate used on extensive types of green roofs, typically is coarse, mineral-based, and contains little organic matter. This allows the substrate to stay within weight restrictions while still being able to retain moisture to support plant life (FLLGuidelines 2002; Farrell *et al.* 2012). The coarseness of green roof substrate, combined with dry and hot summer months and greater wind speed atop roofs (Dunnett & Kingsbury 2004; Sutton 2008), causes extensive green roofs in the southern U.S. to resemble an environment typical of arid landscapes, where both wind and precipitation have strong eroding effects. The effects of precipitation and wind speed are not independent of each other, for example, precipitation and irrigation help reduce wind erosion by weighing down the soil and bonding soil particles to each other (Zobeck 1991). However, when precipitation exceeds the infiltration rate then surface runoff occurs leading to water erosion.

A pattern of less frequent but more intense rain events, as projected by global climate change (IPCC 2007; Groisman & Knight 2008), could increase water and wind erosion because, 1) larger, more intense, rain events will exceed the infiltration rate and cause increased water erosion, and 2) more intense and prolonged drying periods will lead to increased incidence of conditions that promote wind erosion. The lack of soil formation and/or sediment deposition atop a green roof means that any substrate lost must eventually be replaced, adding to the cost of green roof maintenance.

Installing vegetation to alleviate soil erosion is a widely used practice and has proven to be very effective as embankment plantings or for stabilizing riparian zones (Snelder & Bryan 1995). It has been suggested that in systems with low water input plants do not contribute much to the roof's cooling efficiency as most evaporative cooling comes from soil water evaporation rather than plant transpiration in such systems (Schweitzer & Erell 2014). However incorporating plants can reduce direct radiation input and optimize other benefits of the roof, such as storm water retention (Lundholm *et al.* 2010). In addition, plant roots and their exudates bind soil particles together and hold substrate in place which reduces vulnerability to both wind and water erosion (Gyssels *et al.* 2005), while surface roots and above ground vegetation slow down sediment flow (Van Dijk, Kwaad & Klapwijk 1996). Thus, the presence of plants can play an important role in maintaining substrate depth on the roof (Volder & Dvorak 2013). Maintenance of substrate depth directly contributes to both storm water mediation and energy usage reduction benefits of the substrate (Ouldboukhithine, Belarbi & Djedjig 2012; Morgan, Celik & Retzlaff 2013).

Our objective was to test whether the use of plants on green roof modules placed atop a rooftop on a 2% slope can help prevent or reduce substrate loss and if functional group composition (succulents, herbaceous, or mixed) has an effect on loss of substrate. We hypothesized that the presence of vegetation will significantly reduce substrate loss compared to an un-vegetated green roof. Second, we hypothesized that periods of higher wind speed or greater precipitation intensity will enhance substrate loss, and will enhance substrate loss more in un-vegetated modules than in vegetated modules.

Materials and Methods

EXPERIMENTAL DESIGN

Twelve extensive green roof modules were constructed on the roof of Texas A&M University's four-story Langford building in College Station, Texas (30° 37' 7.6"N, 96 20' 16.6"W). Six wood-framed boxes were constructed with each frame containing two TectaGreen green roof modules (Tecta America Corp®, Skokie, IL) for a total of twelve modules. Each module contained a layer of drainage cups filled with 2.54 cm of very coarse drainage substrate (Rooflite®drain) topped with a geotextile filter fabric (Tecta America Corp®, Skokie, IL) to keep growth substrate in place and prevent clogging of the drainage system. The top layer of the module consisted of 8.9 cm of growing substrate (Rooflite®extensive, Skyland USA LLC) (Figure 1). According to manufacturer specifications, this substrate has a 1–5 % proportion of silting components, 0.55–0.85 g cm⁻³ dry bulk density, 0.8–0.9 g cm⁻³ saturated bulk density, 60–75 % porosity, 15–25 % maximum water holding capacity, an air filled porosity at maximum water holding capacity of 50–60 % and a saturated hydraulic conductivity of 0.5–0.8 cm s⁻¹ (Rooflite 2013). The growing substrate meets the FLL Guidelines for extensive green roofs. Planting occurred on February 16, 2011. Three modules were left unplanted and used as a control. The other nine consisted of 3 different mixtures of plants, each replicated 3 times. Three modules contained succulents only and were planted with six plugs of *Bulbine frutescens*, six *Sedum mexicanum*, three *Malephora lutea*, six *Lampranthus spectabilis* 'Red Shift', four *Sedum kamtschaticum*, four *Sedum tetractinum*, and six *Phemeranthus calycinus* in each module. Three modules had a mix of succulents and herbaceous plants and consisted of six *Bulbine frutescens*, three *Graptopetalum paraguayense*, six *Stipa tenuissima*, six *Sedum Mexicanum*, three *Manfreda maculosa*, three *Lampranthus spectabilis* 'Red Shift', and six *Lupinus texensis*. The remaining three modules were planted with herbaceous plants only and consisted of three *Dichondra argentea*, three *Stemodia lanata*, six *Stipa tenuissima*, three *Myoporum parvifolium*, three *Manfreda maculosa*, and six *Lupinus texensis*. All plants were grown in 72-cell flats (3.8 cm x 3.8 cm x 5.7 cm deep) prior to planting. The modules were set at a 2 % slope facing southeast on top of the Langford building roof (four stories high) at the Texas A&M University campus in College Station, Texas. At the start of the experiment canopy coverage was approximately 50% (Figure 1b).

DATA COLLECTION & ANALYSIS

Three galvanized measurement rods (170 mm length) were installed in each module on May 25th, 2011 (Figure 1). Each rod had a wide metal base held in place by the weight of the substrate above it, preventing vertical movement of the rod. Rod installation and measurements began 3 months after planting the modules to allow plants to establish. During this period modules were watered weekly, however, after the experiment started supplemental irrigation was applied only once, on Aug 1, 2011 at 16.9 L m⁻² (equivalent to a 16.9 mm precipitation event) using a watering can. Each module received the same amount. Measurements were taken with a ruler by measuring the distance from top of the soil line to top of measuring rod to the nearest ½ mm. This length was subtracted from the entire length of the rod to determine substrate depth. An initial measurement was taken on May 25, 2011 and then once a week afterwards for two months. After this initial period, measurements were taken monthly from August 2011 through May 2012.

Figure 1. a) Cross section of the modules used in the study. Each module was 11 cm high and 61 cm wide. The rods were 170 mm in total length, depth of the growth substrate was 8.9 cm, and the geotextile filter fabric was installed over 162.6 cm³ drainage cups filled with expanded shale. Schematic is not to scale. Modified from Dvorak and Volder (2013), b) Photograph of an un-vegetated and vegetated module with rods installed.

Substrate depth on each date was calculated for each module by averaging the measurements from the three rods. Reductions in mean substrate depth were considered substrate loss, while increases in mean substrate depth represented substrate gain. Loss or gain rate (mm day⁻¹) were calculated as the amount of substrate loss or gain that occurred since previous measurement divided by the number of days since the previous measurement. Temperature, relative humidity,

solar radiation, wind speed, wind direction, and precipitation data was collected hourly using a weather station located on the same platform as the modules.

All statistics and analyses were performed using JMP 10 (SAS Institute Inc., Cary, North Carolina, USA) and SigmaPlot 9 (Systat Software Inc., San Jose, California U.S.A.). Differences in mean substrate loss or gain over the whole measurement period were analyzed using ANOVA. To assess the impact of wind speed and precipitation rate, data were analyzed using general linear regression with substrate loss or gain as dependent variable, vegetation presence and types as independent factors, and mean daily maximum wind speed during a time interval and mean daily precipitation during a time interval as co-variables.

Results and Discussion

There was no significant difference in substrate loss or gain over the full time period between the succulent, herbaceous, and mixed vegetation types ($P = 0.747$, data not shown), and thus we report only on the vegetated versus un-vegetated comparison. Vegetated (all vegetation types) and un-vegetated roofs did behave differently in the first three weeks after rod installation. In the first 3 weeks, substrate depth in vegetated modules was reduced less (1.1 mm reduction in depth) than in un-vegetated modules (5.7 mm reduction in depth). Once the substrate had settled after the rod installation disturbance (after June 15, 2011) there was no statistically significant difference in substrate depth reduction between vegetated (0.52 mm) and un-vegetated (0.88 mm) modules over a period of nearly a year (until May 22, 2012,). Thus, the presence of vegetation was helpful in reducing substrate depth reduction after initial rod installation, but appeared to have little effect once the substrate settled (Figure 2). Reductions in substrate depth can be caused by settling of particles (e.g., compaction or movement of finer particles down the profile) or actual loss of substrate through erosion. The presence of plants, and roots in particular, could reduce the rate of particle settling by maintaining a more porous structure through exudation of acidic and carbohydrate rich compounds such as mucilage (Czarnes *et al.* 2000; Bertin, Yang & Weston 2003; Gyssels *et al.* 2005). In addition, plants can modify the impact of wind and water erosion by altering velocity and by holding on to finer particles (Zuazo & Pleguezuelo 2008).

Figure 2. Substrate gain/loss of substrate-only (open circles) and vegetated modules (solid circles) through time. Dashed red line indicates the average loss in substrate and vertical bars indicate daily precipitation events. Red arrow and vertical bar indicate a manual irrigation event where 16.9 mm was applied with a watering can to keep plants alive. + indicates a statistically significant ($P < 0.05$) difference in substrate gain/loss rates between treatments.

Where we expected heavy precipitation events to decrease substrate depth by enhancing particle losses, it appears that large precipitation events during dry periods resulted in increased substrate thickness. Strong gains in substrate depth were observed on June 23, August 2, and September 22 when sizeable precipitation events (62.2 mm, 16.9 mm, and 35.6 mm respectively) occurred within 48 hours prior to substrate depth measurement. These large gains in substrate depth occurred only after precipitation events following a dry period (June–September, Figure 2), rather than after an even larger event when the substrate was already wet (104.4 mm, February 5) and other events in March. The modules were placed on a rooftop, thus it is unlikely that any real gains in substrate amount occurred; rather the initially dry substrate expanded and increased substrate depth. This explanation is supported by the lack of gain after the large event on February 5, when the substrate very likely was already fully expanded in response to frequent precipitation that month. It is also possible that as substrate shifted, some rods may have experienced disproportionate accumulation by chance, causing an average substrate gain while most other rods might have experienced soil loss. A closer analysis indicated that 85% of the rods gained substrate depth after these three precipitation events, supporting the idea of an overall swelling of the substrate, rather than accumulation on a few of the rods. In addition, the average standard deviation of erosion rate before and after the precipitation events was not significantly different, suggesting that the dataset did not become more variable after each of the three large precipitation events. Thus, the gain in substrate depth after large precipitation events was not driven by a few rods collecting a large amount of media; rather a majority of the rods did record a gain in substrate depth at a consistent rate.

When average daily wind speed and average daily precipitation rate over each measurement period were included in the model, we found a marginal interactive effect of average daily precipitation and average daily wind speed on erosion rate ($P = 0.050$, Table 1). This relationship was not affected by vegetation presence and showed a substrate gain during periods of sustained

high wind and high precipitation. Further analysis showed that this relationship was entirely driven by one event and there was no relationship between change in substrate depth and mean daily wind speed or mean daily precipitation when the period with the combined greatest wind speed and precipitation rate was excluded (Figure 3, Table 1). During this period of high wind, the modules received 62.2 mm of precipitation in an 8-hour period after a prolonged dry period, likely leading to swelling of the initially dry substrate and a gain in substrate depth as the substrate saturated. It is important to note that detailed analysis showed that there was still no effect of wind speed (either average or average daily maximum) or vegetation presence on substrate loss when only periods with no precipitation were taken into account (Table 2). Thus, even under dry conditions, wind speed and vegetation did not strongly impact substrate depth gain or loss.

Figure 3. Effect of a) average daily precipitation, and b) average daily maximum wind speed on substrate gains and losses. Panel c) shows the relationship between average daily precipitation and average daily maximum wind speed. The point with 7.8 mm average precipitation and 3.3 m s⁻¹ average daily average wind speed is designated as exceptional in Table 2, where 62.2 mm of precipitation fell over an 8-hour period less than 24 hours prior to the measurement.

We found that vegetation did not strongly affect changes in substrate depth after the initial substrate settling subsided. However, after three months of plant establishment and when initially installing the rods, it was more difficult to insert rods in the planted modules due to resistance from plant roots. The presence of an established root system can help reduce the loss of soil, while the tops shelter the substrate from wind and precipitation impact (Gyssels *et al.* 2005). It is

possible that most fine particles were lost during plant installation and when the measurement rods were installed, reducing the impact of the plants. It has been observed that finer particles are eroded away at a greater rate than larger particles (Gonzalez-Hidalgo, Echeverria & Vallejo 1999). In dry soils typical of deserts, which are somewhat similar to green roof substrates, fine particle loss due to wind erosion is common (Gilette *et al.* 1980; Goudie 2008). Although we did not find noticeable changes in substrate depth after initial reductions in substrate depth due to instrument installation, we did observe that the top part of the substrate profile became mostly composed of larger soil particles through time. This can happen without a marked change in soil depth as most fine particles are generally located between coarser particles. It is possible that some resorting may have occurred where finer particles were moved downward in the soil profile. In addition, our modules were placed at a shallow slope of 2 %. It is likely that vegetation would have had a greater impact on preserving substrate depth if the slope were steeper which would have accelerated water related erosion.

Table 1. Statistical analysis of the presence/absence of vegetation, daily average wind speed (m s^{-1}) and average precipitation rate (mm day^{-1}) for the preceding interval on green roof substrate loss or gain. *P* values <0.05 are printed in bold. See figure 3 for exception (3.3 m s^{-1} average wind speed, and 7.8 mm day^{-1} precipitation).

	Includes all events		Exception removed		No precipitation	
	F ratio	<i>P</i> > F	F ratio	<i>P</i> > F	F ratio	<i>P</i> > F
Vegetation	0.08	0.779	0.05	0.829	0.09	0.762
Wind	1.97	0.162	2.68	0.103	0.99	0.322
Vegetation x Wind	0.17	0.683	0.13	0.722	0.08	0.782
Precipitation	1.65	0.200	1.36	0.246	NA	NA
Vegetation x Precipitation	0.04	0.841	0.01	0.914	NA	NA
Wind x Precipitation	3.90	0.050	0.01	0.919	NA	NA
Vegetation x Wind x Precipitation	0.01	0.909	0.00	0.956	NA	NA

Conclusion

The presence of plants initially helped to reduce the effects of substrate disturbance but did not affect substrate depth changes thereafter. There was a temporary gain in substrate depth when data were collected immediately after large precipitation events following dry periods, but surprisingly there was no effect of wind speed on substrate depth during periods with little or no precipitation.

Substrate lost from a green roof can create a problem, from a maintenance standpoint, if too much substrate is lost. In our 14-month study we found no additional benefits of vegetation presence on maintaining substrate depth after installation. However, our data suggest that established vegetation can preserve substrate depth during periods of disturbance, for example when maintenance takes place.

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