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STORM WATER RUNOFF FROM GREEN RETAINING WALL SYSTEMS.

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Abstract

Like other innovative green technologies, green walls have the potential to mitigate urban flooding. This project was designed to evaluate the capacity of green wall systems to reduce stormwater runoff and mitigate urban flooding. Eighteen circular (7-foot diameter) green retaining wall systems were located on the SIUE campus, with six treatments arranged in a completely randomized design. Within a replicate, walls were either unplanted or planted with 5 *Sedum* species individually. Differences in stormwater runoff and runoff reduction were found between planted treatments and the unplanted control in September 2010, May 2011, and June 2011. A delay in runoff response also existed for the green walls following substantial precipitation. Our evaluation indicates that living retaining wall systems have the potential to reduce urban runoff and delay stormwater discharge.

Introduction

The city has become the hub of human activity. Only 28 percent of the U.S. population was found in metropolitan areas in 1910, but by 2000 80 percent resided in urban or suburban areas (6). The proliferation of impervious surfaces at the expense of permeable soil and beneficial vegetation increases stormwater runoff and flood potential. The isolated vegetation that does adorn lawns and parks is often exposed to increased levels of wind and sunlight, reducing potential precipitation interception (5). Vegetation or the lack thereof contributes significantly to urban hydrology. Vegetation can perform long-term and temporary storage of rainwater, moderate stormwater flow, and evapotranspire to cool the surrounding area. But in the urban landscape, plant cover is greatly diminished. With such a patchwork of impervious and pervious surfaces in an urban watershed, the routes of water as infiltration or groundwater recharge can be quite complex (9). Disconnecting or dividing impervious surfaces with patches of pervious ones would be one way to mitigate stormwater runoff. For example, water rerouted from a roof onto a lawn instead of directly onto a driveway may promote reduced runoff and increased infiltration and evapotranspiration (11). It is well understood that stormwater increases with the influx of buildings, roads, and parking lots, to name a few. Traditional rooftops can occupy over 40 percent of impermeable surface in a city, with almost all the falling precipitation ending up as stormwater runoff (10). Urbanization not only impacts the quantity of runoff, but also the quality of the water that enters our waterways. Roads and highways generate runoff, but the debris and exhaust associated with transportation often pollute that runoff. Air pollutants and other debris can collect on paved surfaces which can become concentrated in stormwater runoff during rain events—an occurrence known as the first flush phenomenon (1).

The necessity to address stormwater problems has led to the development of Sustainable Drainage Systems (SuDS) and Best Management Practices (BMPs) throughout Europe and the U.S. (7), as well as Low Impact Development (LID) which strives to mitigate stormwater on-site (4). Some commonly used BMPs include retention basins, detention basins, biofilters like grass swales, and wetlands (usually constructed), which function well where their application is practical and feasible. However in highly urbanized areas where space is prohibitively costly, solutions to stormwater problems must be more innovative. Technologies like green roofs and green walls, for example, focus on decentralizing stormwater runoff and promoting groundwater recharge while utilizing space that otherwise remains unused. Green roofs have received considerable research attention in Germany for several decades and more recently in the U.S. The research on green walls, on the other hand, is extremely limited. As a green technology, green walls could potentially address some of our urban hydrological problems.
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Green walls were first conceptualized and implemented in the Hanging Gardens of Babylon. Green walls are similar to green roofs in the use of hardy plants and media, but green walls are employed on building facades or along hilly urban terrain as living landscaping walls. Green walls, also known as vegetated or living walls, are designed to perform stormwater functions and alleviate the urban heat island effect. Currently, green wall design has diversified to include both green facades and living walls. Green facades generally utilize climbing or cascading plants along walls or separate structures like fences. Living walls can employ modular vegetation setups fixed vertically to a structure (8). A green retaining wall is a structure meant to stabilize a slope from subsidence while utilizing a block planting system that facilitates vegetation. The plants and media in a green retaining wall system promote interception, infiltration, and evapotranspiration while cooling and shading the surrounding urban microclimate. Green walls also have the benefit of aesthetic appeal, particularly to motorists and other passersby who might not otherwise see much vegetation in the city.

Despite limited research on green retaining walls, speculation can be made about plant selection, growth media, and stormwater performance based on the properties of other green technologies. Green retaining walls may perform similarly to green roofs, rain gardens, bioswales, and pervious pavement in reducing stormwater runoff. Some green roofs, in light and medium rain events, have been found to retain almost all rainfall and to delay peak runoff during heavy rainfalls (13). One study quantified the effectiveness of green roof systems on sloped roofs, commonly found in residential areas. The sloped green roofs retained 94.2% of rain water during light rain events (<0.2 cm), but only retained 63.3% during heavy events (>1 cm). This demonstrated that, once the material was fully saturated, additional rainfall primarily generated stormwater runoff. Additionally, water retention decreased as slope increased from 2 percent to 15 percent as well as from 2 percent to 25 percent (2). Green landscaping walls, which are usually employed at steep or near-vertical angles, may perform similarly to sloped roofs in some respects.

Vegetation and growing substrate are also important determinants of stormwater performance. Research on plant selection has largely been conducted in Germany, leaving the American Midwest with insufficient data (3). Stonecrops, of the genus Sedum, are drought-resistant succulent plants with shallow root systems that have already been found to thrive in green roof applications. Most species of *Sedum* originate from rocky outcrops, where they experience shallow soils and poor soil quality, full sunlight, highly variable daily temperatures, and frequent drought conditions (14). The physical properties of green retaining walls closely resemble these characteristics. There are alternatives to using Sedum, however their survivability is questionable. In a study of plant selection on green roofs, it was concluded that grasses promoted the most water loss, but succulents, like *Sedum*, survived drought conditions more easily. Overall, the use of a mix of species was recommended to maximize transpiration and plant survival (15). As such, we investigated several individual species of *Sedum* as well as a mixed Sedum treatment in our green wall study. Media depth is another important factor in the establishment of vegetation. The pockets of the green wall blocks might experience similar conditions as "extensive" green roof systems, in which the growing media is generally shallow (<20cm). Getter and Rowe recommend a media depth of at least 7.0 cm to facilitate successful establishment of *Sedum* species, likely due to moisture content, temperature fluctuations at varying depths (3). Regardless of vegetative cover, though, the properties and depth of the growing media play into the effectiveness of green walls to mitigate stormwater. VanWoert et al. argued that while vegetative cover plays an important role in erosion control and urban heat island effect reduction, the media is perhaps the most important factor regarding stormwater benefits (13). Fortunately media selection for green retaining walls is much less restricted than for green roofs, which usually require lightweight engineered material. We used coal bottom ash, a porous but heavy fill material for our green retaining wall systems.

Green wall systems have become an innovative way to green the urban environment. The study reported here involves a replicated experiment evaluating the storm water runoff of green retaining wall systems. Overall, the study will provide much-needed data for urban planning and serve as a foundation for further green wall research. The study will also contribute data on plant selection for green technologies in the Midwest. The purpose of this study was to evaluate the environmental benefits of green retaining walls on SIUE campus. To do so, differences in plant coverage and stormwater retention capabilities were determined for planted and unplanted walls. It was hypothesized that stormwater runoff from planted walls would be less than for unplanted walls and that different Sedum species would grow differently in the green wall systems.

Methodology

Our research began with the construction of eighteen circular plantable retaining wall systems. The green walls were located just north of Bluff (residence) Hall on the SIUE campus in 2007. The walls utilize a patented block design that provides a pocket for vegetation. Each wall was arranged with 5 circular tiers of blocks, staggered at each tier (Figure 1a, background). The core of each wall was filled with coal bottom ash donated by Ameren UE. Bottom Ash (80% by volume) blended with composted pinebark (20% by volume) was applied to the pocket of each block and along the top surface of each wall at 5 cm depth. Each green wall was constructed over an impermeable base layer with a single, central outlet to collect stormwater (Figure 1a, foreground). Installation of water collection units, 20.4 L buckets connected to the wall outlets with 3.8 cm PVC, was completed on June 28, 2010 (Figure 1b).

Five vegetative treatments and an unplanted "control," all with three replications, were arranged in a completely randomized design (Figure 1c). Each non-control wall was planted on July 1, 2007 with one of five *Sedum* species (*Sedum kamtschaticum*, *S. (Phedimus) takesimensis*, *S.*

spurium, *S.hybridum 'Immergrauch'*, or *S. cauticola*). *S. cauticola* plantings did not survive the first year, so that planting treatment was replanted with multiple *Sedum* species, including *S. spurium*, *S. sexangulare*, *S. cauticola*, *S. kamtschaticum*, and *S. album*. The walls were replanted on September 17, 2010 and May 5, 2011 with additional *Sedum* plugs to facilitate dense vegetative coverage. All *Sedum* plugs were provided by Jost Greenhouses.

Plant Coverage Measurements

Plant coverage of the green wall surface was quantified using a dot grid template with 4 cm-diameter holes, spaced 1.1 cm apart, arranged in 13 rows and 6 columns. Wall coverage was measured on the North, South, East, and West aspects for each treatment. For each aspect, the coverage template was clipped over the top block and allowed to drape over the side. The number of holes containing no vegetation were counted and recorded. Total green wall coverage was determined by adding together the empty spaces from all aspects. Percent coverage for each treatment was calculated using the equation [(312-#empty holes)/312]*100. For 100% coverage, there were no open holes and vegetation completely concealed the wall blocks and growth media. Coverage was measured at monthly intervals for each replicate wall throughout the growing seasons of the study period (8-10/10, 3-6/11).

Stormwater Measurements

The volumes of stormwater runoff following natural precipitation events were quantified using 20.4 L collection units. The water level for each treatment was determined using a metric ruler flush to the inside of the collection unit. The water level was used to calculate the runoff volume using the equation y=0.5456x (R^2=0.9992) for treatments with runoff depths less than 17.75 cm, or y=0.5756x (R^2=0.9942) for treatments with runoff depths greater than 17.75 cm. The previous equations were generated from a laboratory regression analysis of the collection units.

The volume in runoff was compared with the volume of precipitation to determine percent reduction. The percent reduction in stormwater runoff for each treatment was calculated using the equation $[(Vol_p-Vol_{gw})/Vol_p]*100$, where Vol_p was the volume of precipitation that fell over each 7-ft (2.13 m) diameter green wall and Vol_{gw} was the volume of stormwater runoff generated by each wall. The volume of rainfall would equal the volume of runoff for an impervious surface.

Data collection occurred promptly after each precipitation event. When rainfall occurred overnight, measurements were taken the next day. Substantially intense or long-duration events required multiple measurements. Official rainfall data was obtained from the SIUE Wastewater Treatment Plant, which records data for the National Weather Service on a daily basis. A precipitation event in this study consisted of at least 0.1 cm of precipitation falling within a 24-hour period. A heavy precipitation event consisted of greater than 1 cm of precipitation falling within a 24-hour period. Measured snowfall was converted to liquid precipitation (1 cm snow = 0.1 cm rain).

Data Analysis

For plant coverage data, a one-way ANOVA for a completely randomized design was used to test for differences between treatments and among treatments for each aspect. A Tukey's post-hoc test was then used to rank the differences at an alpha level of 0.05 (PROC GLM, SAS version 9.1).

For stormwater data, a one-way ANOVA for a completely randomized design was used to test for differences between treatments. A Tukey's post-hoc test was then used to rank differences at an alpha level of 0.1 (PROC GLM, SAS version 9.1). An alpha level of 0.1 was used in light of the low number of replicates, the large size of the green wall systems, the maximum capacity of the collection units being occasionally exceeded, and resulting additional experimental error.

Results and Discussion

From October 2010-June 2011 (excluding November-February), a total of 106.5 cm of liquid precipitation reached our study site. Thus, each green retaining wall received 3,807.8 L of rainfall. The month of April had the most precipitation, 20.2 cm, while October had the least, 2.5 cm (Figure 2a and 2b). April also had the greatest frequency of heavy precipitation (>1cm), 9 days, while October had only one day with heavy rain (Figure 2c).

Differences in plant coverage between treatments were found during the study period (Figure 3a). *S. kamtschaticum*, Mixed Sedum, and *S. spurium* (all > 50% coverage) had greater coverage than *S. hybridum 'immergrauch'* and *S. (Phedimus) takesimensis*, which were below 40 percent. Differences were also found in wall coverage for every month except September 2010 (Figure 3b, 4a, 4b, 4c). Coverage was the lowest for all treatments during March 2011, following winter foliage die-back.

For the entire study period, differences in volume of stormwater runoff as well as runoff reduction between treatments were not significant (Figure 5a). However, differences in runoff reduction between treatments were found for individual months including September 2010, May 2011, and June 2011 (Figure 5b). All treatments retained more than 75 percent of the 3,807.8 L of precipitation. In October, the green walls reduced runoff by 100%. The green walls retained less than 90% of precipitation during March and April 2011. In September, there was 14.6 cm of precipitation and five days with rain >1 cm. *S. (Phedimus) takesimensis* retained more stormwater than the unplanted control and *S. spurium* (Figure 6a). *S. (Phedimus) takesimensis* reduced runoff by more than 95 percent. The unplanted control and *S. spurium* reduced runoff by less than 90%. In May, there was 12.4 cm of precipitation and three days with rain >1 cm. *S. (Phedimus) takesimensis*, *S. spurium*, S. kamtschaticum, and Mixed Sedum retained more stormwater than the unplanted control (Figure 6b). *S. (Phedimus) takesimensis*, *S. spurium*, S. kamtschaticum, and Mixed Sedum retained more than 95percent of stormwater. The unplanted control retained less than 90 percent of stormwater. In June, there was 18.5 cm of precipitation and six days with precipitation >1 cm. *S. (Phedimus) takesimensis* retained more stormwater than the unplanted control and *S. spurium* (Figure 6c). *S. (Phedimus) takesimensis* reduced runoff by about 91percent while the unplanted control and *S. spurium* reduced runoff by less than 80 percent.

Stormwater runoff and runoff reduction did not seem to be impacted by plant coverage. *S. (Phedimus) takesimensis* performed best in June although *S. spurium*, S. kamtschaticum, and Mixed Sedum had the best coverage. Nonetheless, other characteristics of the plants may have led to the differences in stormwater runoff.

A delay in stormwater runoff was occasionally observed throughout the study. For certain events, generally >1cm, there was a noticeable lag in time between precipitation and runoff response for all green walls. However, the unplanted control wall generated runoff before the other treatments in some instances. For example, 3.0 cm of rain fell on 13 June 2011;

measurements were taken at 9 am, 3 pm, and 7 pm on June 14 to determine the volume of runoff in the stormwater collection units (Figure 7a). The control wall discharged a total of 39.2 L while *S. kamtschaticum* and *S. (Phedimus) takesimensis* discharged less than 5 L. The unplanted control had already discharged 30 percent, 12.1 L, of its runoff volume by 9 am (Figure 7b). By 3pm, however, *S. spurium*, *S. hybridum 'immergrauch,'* and Mixed Sedum had each discharged more than 5 L of stormwater, over 50 percent of their respective runoff volumes for that day. The control had discharged an additional 20.4 L, which was the maximum capacity of our collection units. At 7 pm, *S. spurium* had had discharged an additional 29percent of its runoff volume.

Conclusions

Our study demonstrates that green retaining walls may have the potential to substantially reduce stormwater runoff in urban environments. In May 2011, walls planted with *S. kamtschaticum*, *S. (Phedimus) takesimensis, S. spurium* and Mixed Sedum retained more stormwater than the unplanted control. In September 2010 and June 2011, walls planted with *S. (Phedimus) takesimensis* retained more stormwater than *S. spurium* and the control. These results show the importance of species selection to maximize the environmental benefits of green retaining walls.

Variation in runoff reduction was complex, as coverage changed throughout seasons and as the green walls continued to establish. In our study, *S. kamtschaticum*, Mixed Sedum, and *S. spurium* had greater coverage than *S. hybridum 'immergrauch'* and *S. (Phedimus) takesimensis.* Coverage and maximum growth of suitable species can influence evapotranspiration and microclimate temperature (Koehler et al., 2006). But differences in coverage did not seem to correlate with the differences in stormwater runoff. The ability of that species to cover the wall with vegetative cover may, overall, not be as indicative of stormwater benefits as other plant characteristics or the physical properties of the growing media (13). Future research in this area could focus on green walls with different aggregate materials. In addition, water quality studies could be conducted to determine any positive or negative effects of utilizing bottom ash as a growing media and backfill.

The key to managing urban stormwater is the comprehensive use of effective BMPs in stormwater management plans (12). Green retaining walls are innovative green technologies that may help mitigate stormwater runoff in spatially restricted metropolitan areas.

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Figure 1a. Each green wall is designed with an underlying impervious base layer (Foreground). Blocks are arranged in 5 staggered tiers (Background).

Figure 1b. The green retaining wall systems with 20.4 L collection units (May 2011).

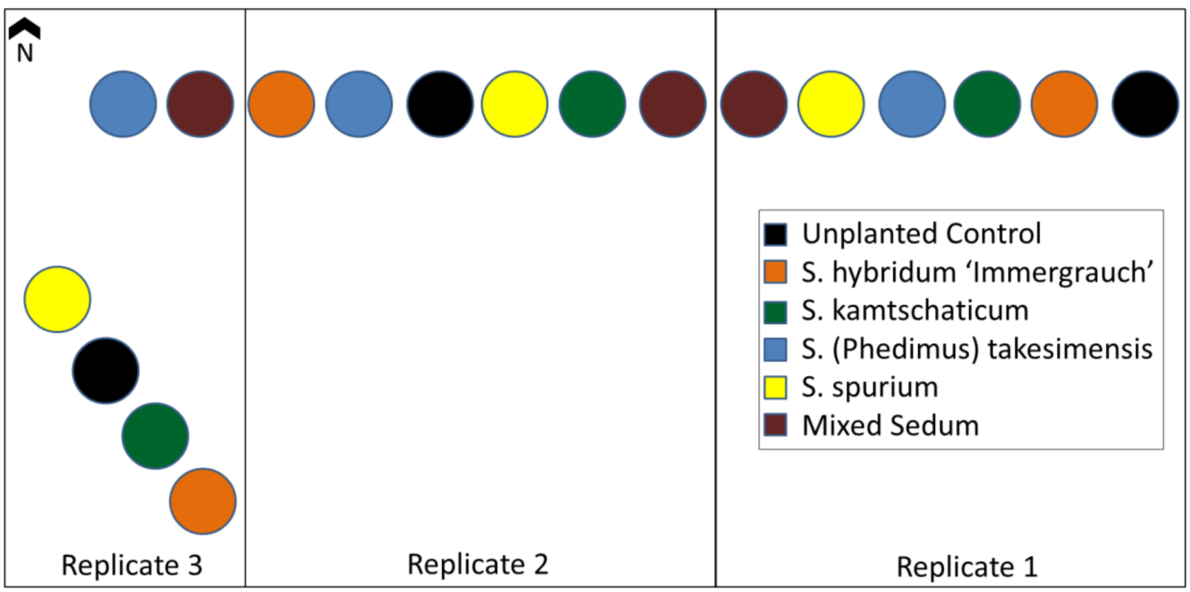

Figure 1c. The field site consisted of 18 green walls with three replicates of 6 treatments, including 5 planted treatments and an unplanted control.

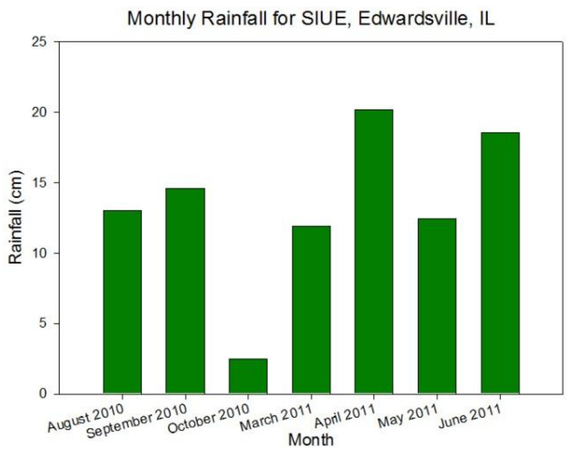

Figure 2a. Rainfall (cm) during months for which both coverage and stormwater were measured.

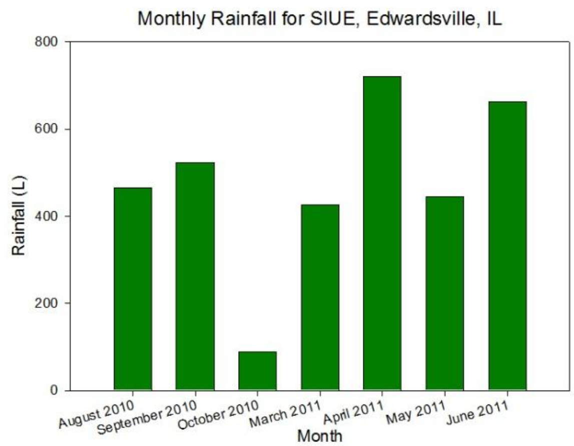

Figure 2b. Rainfall volume (L) falling over a representative 7-ft diameter green wall.

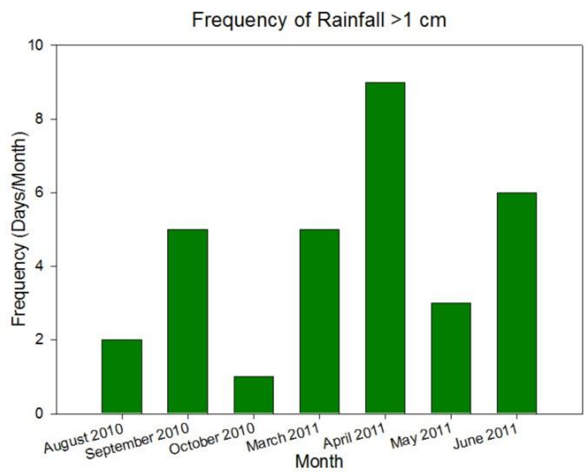

Figure 2c. Frequency of rainfall >1cm falling within a 24-hour period during each month.

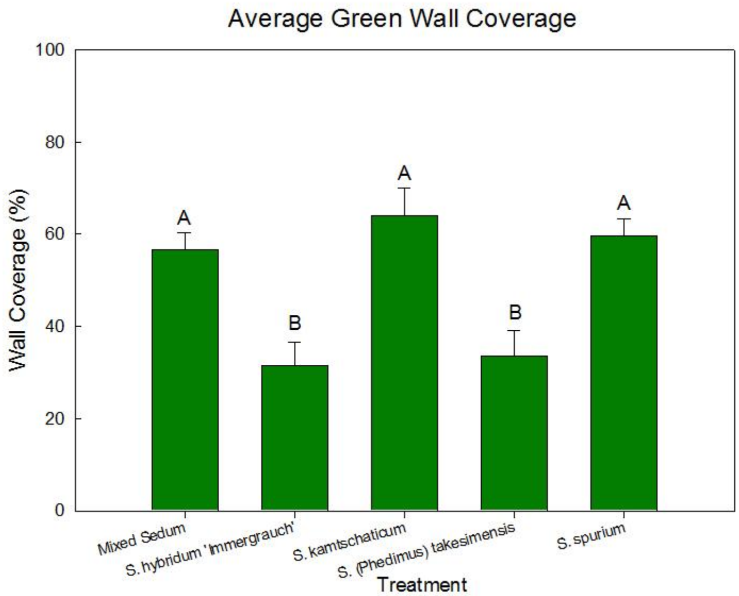

Figure 3a. Average percent plant coverage for study period (8-10/10, 3-6/11). Bars with different letters are significantly different within figure (α <0.05).

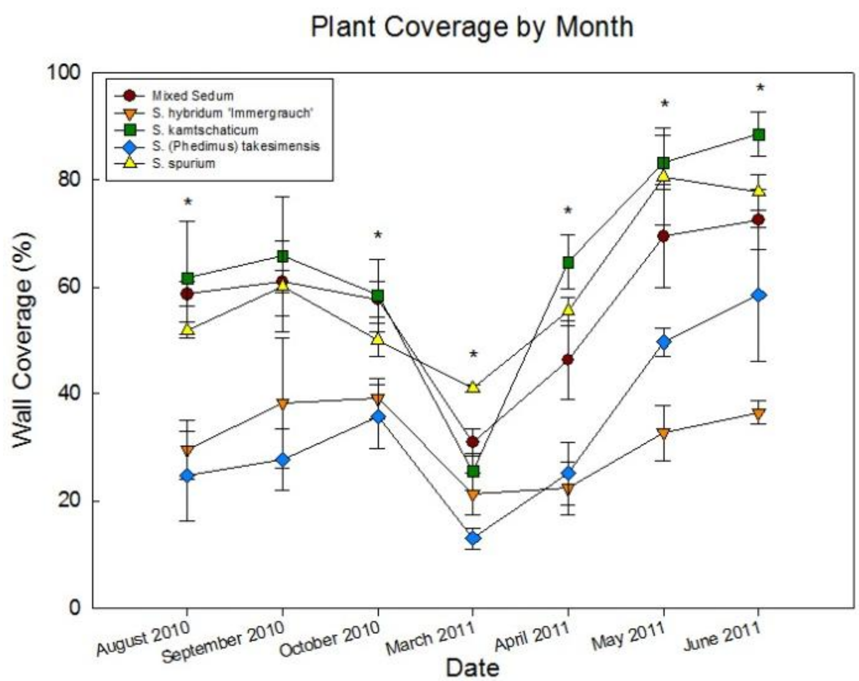

Figure 3b. The percent wall coverage for each treatment during the months for which both coverage and stormwater were measured. An asterisk indicates a difference between one or more means (α<0.05; Error Bars represent ± 1 SE)

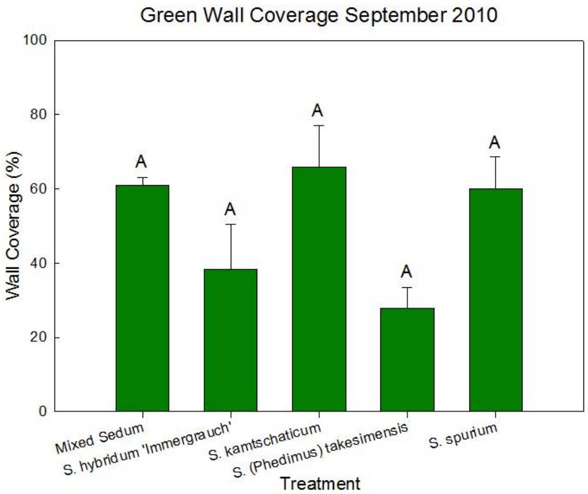

Figure 4a. Percent plant coverage on September 2010. Bars with different letters are significantly different within figure (α <0.05).

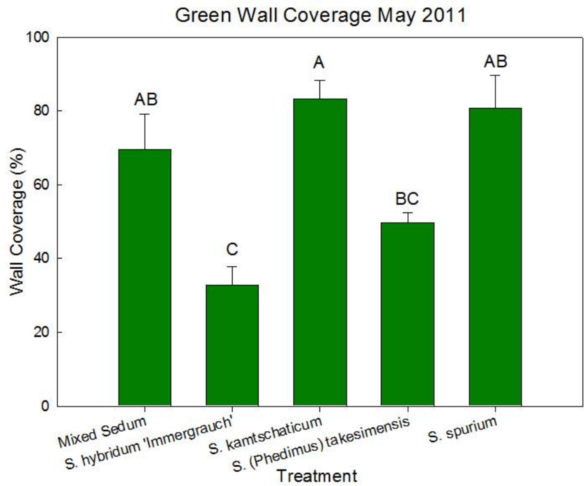

Figure 4b. Percent plant coverage on May 2011. Bars with different letters are significantly different within figure (α <0.05).

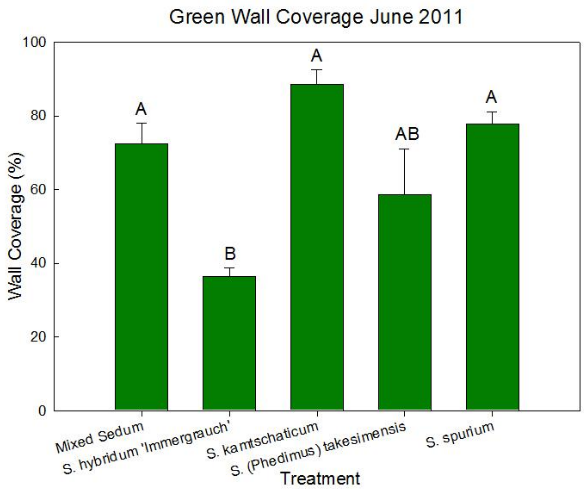

Figure 4c. Percent plant coverage on June 2011. Bars with different letters are significantly different within figure (α <0.05).

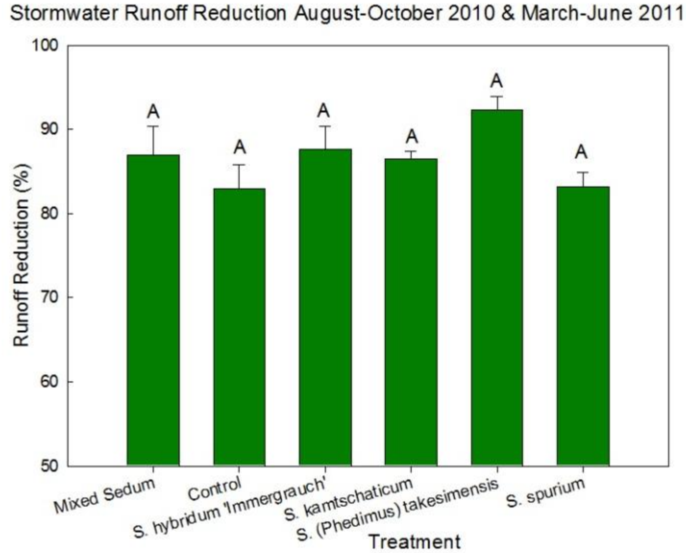

Figure 5a. Percent reduction in runoff for study period (8-10/10, 3-6/11). Bars with different letters are significantly different within figure (α <0.1).

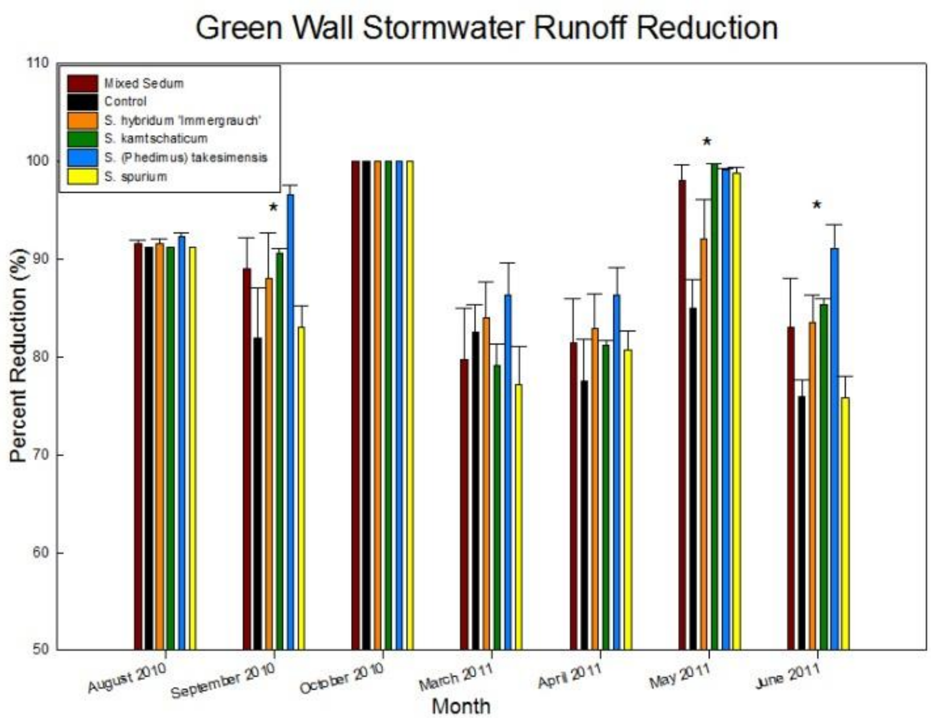

Figure 5b. Percent reduction in runoff for each treatment from 8/10-6/11. An asterisk indicates a difference between one or more means (α<0.1; Error Bars represent ± 1 SE).

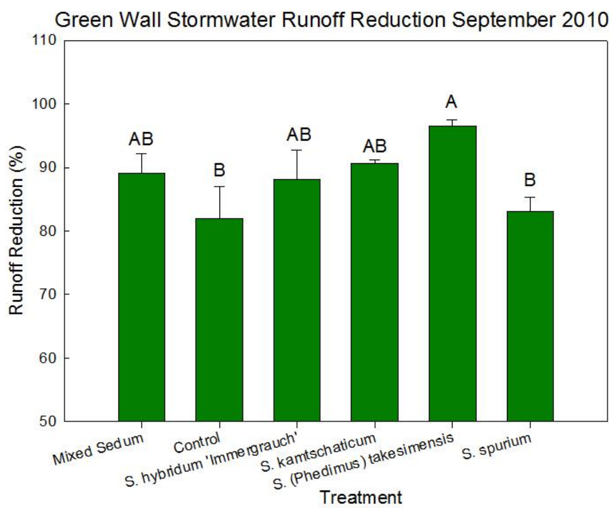

Figure 6a. Percent reduction in runoff for each treatment in September 2010. Bars with different letters are significantly different within figure (α <0.1).

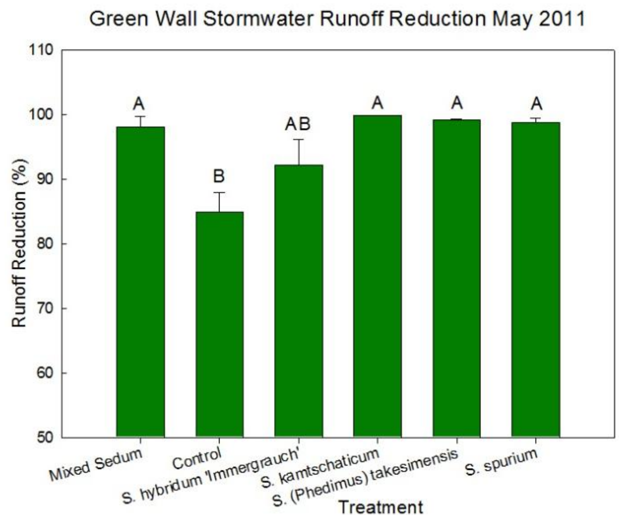

Figure 6b. Percent reduction in runoff for each treatment in May 2011. Bars with different letters are significantly different within figure (α <0.1).

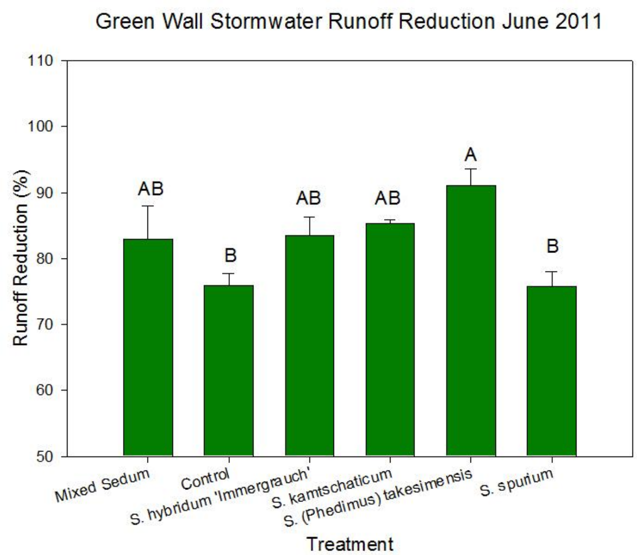

Figure 6c. Percent reduction in runoff for each treatment in June 2011. Bars with different letters are significantly different within figure (α <0.1).

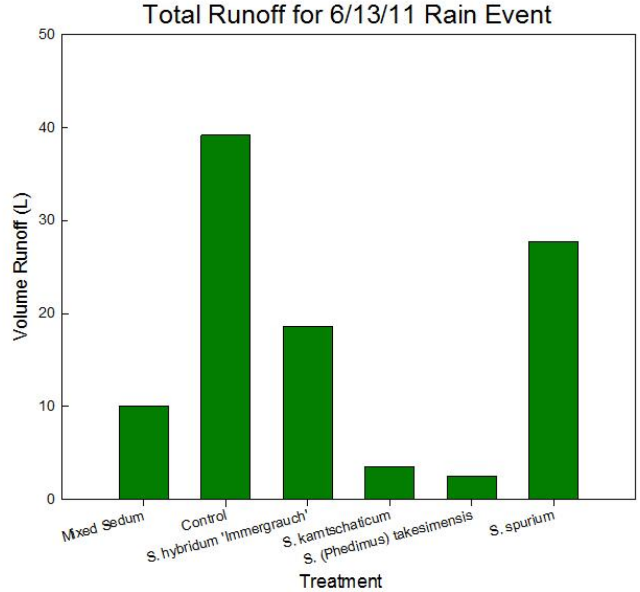

Figure 7a. Total runoff volume for 6/13/11 rain event (3.0 cm) on 6/14/11.

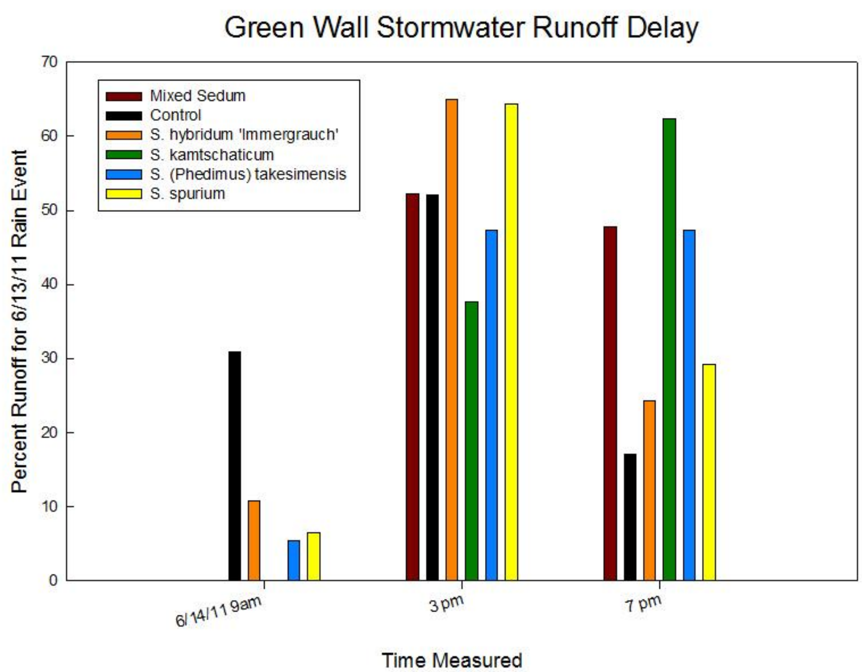

Figure 7b. Percent runoff volume discharged at 9 am, 3 pm, and 7 pm on 6/14/11.