American Ecological Engineering Society

Journal of Ecological Engineering Design
journals.uvm.edu/jeed

Research Paper

Evaluating Plant Coverage and Thermal Benefits of Green Walls for Sustainable Design

Mark Ostendorf[1], Susan Morgan[1], William Retzlaff[1], Serdar Celik[1]

[1]SIUE Living Architecture Regional Center of Excellence, Southern Illinois University Edwardsville, Edwardsville, Illinois, USA

Correspondence
Serdar Celik
SIUE Living Architecture Regional Center of Excellence
Southern Illinois University Edwardsville
Edwardsville, IL 62026, USA
Email: scelik@siue.edu

Received
February 11, 2024
Accepted
November 26, 2024
Published
April 10, 2025

Editors
Sara W. McMillan, Editor in Chief
Mauricio E. Arias, Associate Editor

The goal of this study was to evaluate the environmental benefits of green retaining walls at a higher education institution campus in a replicated experiment by quantifying the surface temperature of the green retaining wall block faces for one unplanted and 5 planted treatments. In addition, the study involves the comparison of green retaining wall systems planted on 4 different wall aspects (N, S, E, and W) with different species of *Sedum*. The study contributes data on plant selection for green wall and green roof design in the Midwest. According to this study, it was observed that planted green retaining walls may offer remarkable thermal benefits compared to retaining walls left unplanted. Significant differences in block surface temperatures among different treatments were observed. The study also found notable differences in percent plant coverage of planted treatments during an 11-month period. Further study could refine green retaining wall design by determining the thermal performance of green retaining walls over a longer time period, walls planted with other vegetated treatments, and walls filled with different fill materials.

Keywords Green infrastructure, Living wall, Thermal benefits, Urban heat island effect

Ostendorf M, Morgan S, Retzlaff W, Celik S. 2025. Evaluating plant coverage and thermal benefits of green walls for sustainable design. Journal of Ecological Engineering Design. https://doi.org/10.70793/jeed.21

> **Highlight**
> Experimental research on green retaining walls showed that the choice of plants and the coverage ratio play a significant role in thermal benefits of these sustainable designs.

1. Introduction

Metropolitan areas tend to exhibit the urban heat island effect (UHIE), the incidence of elevated temperature within developed areas (VanWoert et al. 2005). The elevated temperature is caused by a change in surface albedo and evaporative cooling. Surfaces can reflect a proportion of incident sunlight, a property known as albedo. Unfortunately, many impervious surfaces (i.e., asphalt pavement) instead absorb, store, and reradiate large quantities of solar radiation. Often by design, precipitation drains away quickly, leaving behind insufficient moisture for later evaporative cooling (Kleerekopper et al. 2012). There is also a general lack of moisture in urban areas that would be provided naturally by vegetation and water bodies (Sheweka and Magdy 2011).

Excessive urban heat results in higher energy loading for buildings and public health hazards. Warmer temperatures mean more frequent air conditioning use. Additional heat is generated anthropogenically by sources like HVAC (heating, ventilation, and air conditioning) systems, automobiles, industry, and homes (Sheweka and Magdy 2011). Anthropogenic activities that generate heat can also result in the influx of secondary air pollutants. The environmental effects of anthropogenic heating, however, may depend on the extent of urbanization (i.e., suburban area versus dense city center). The spatial distribution and, perhaps more importantly, the relative abundance of land cover types in a city tends to contribute to land surface temperatures and the urban heat island. Primarily, increased land surface temperature is attributed to the presence of buildings (Zhou et al. 2011). Other causes of the UHIE include deep urban canyons, microclimatic greenhouse effects, and building-induced wind obstruction. Wind velocity can be reduced by the presence as well as the geometry of buildings (Sheweka and Magdy 2011).

Addressing the warmer microclimate conventionally means increasing the use of air conditioning and expending more energy and money to maintain indoor air comfort. Fortunately, design opportunities exist to address and perhaps even prevent the UHIE, including the use of reflective surfaces, insulated building materials, and energy efficient heating and cooling systems. Kleerekopper et al. (2012) suggest 4 key design strategies to reduce urban heat islands: building form, shape, and density; building material color, composition, and permeability; preserved or introduced water bodies; and preserved or introduced vegetation. Specifically, buildings should be oriented with wind, shade, and seasonal factors in mind and built with properly colored and insulated materials to reduce heat gains. Vegetated surfaces can help improve the thermal performance of buildings by reducing the heat transfer. Both green roof and green wall applications can provide such benefits. According to a study by Fox et al. (2022), calculated thermal transmission through a living wall was 31.4% lower than the same façade without vegetation. Adding an air gap between the green layer and the vertical wall can enhance the thermal performance of the building (Khabaz 2023).

The relative abundance of vegetated land in a city is arguably the most important factor for UHIE mitigation (Zhou et al. 2011). The presence of plants not only moderates the UHIE through transpirative and shade-induced cooling, it also aides in the reduction of media erosion (VanWoert et al. 2005). Conventionally, this practice includes establishing lawns, small gardens, or isolated trees near buildings, in parking lot islands, and along sidewalks. Urban parks are also beneficial green spaces. City parks have become outdoor havens for city dwellers searching for comfortable and aesthetically pleasing retreats within the urban jungle. City parks can cool surrounding surfaces and air substantially. Unfortunately, benefits of green spaces are generally limited to their immediate area (Alexandri and Jones 2008). Certainly, greater expanses of vegetation would alleviate urban temperatures, but in dense metropolitan areas where buildings and pavement proliferate, setting aside space for conventional greenery is often impractical or impossible. Despite its particular vulnerability to the UHIE, high-density downtown property remains highly prized for development. Consequently, the aesthetics as well as the comfort of residents, motorists, pedestrians, and passersby seem to be forfeited for the sake of urban society.

With the issues of cost and space availability, innovative green infrastructure designs have emerged as prospective solutions to urban environmental problems. Two effective green design options to address the UHIE are green roofs and green walls. Green infrastructure designs have surfaced with the intent to reintroduce vegetation, reduce the UHIE, and minimize the need for air conditioning — all while utilizing available space more efficiently. Green infrastructure design has the added benefit of aesthetic appeal, particularly to people who might not otherwise see much vegetation in the city. The enhanced appearance of vertical greenery may even increase

Ostendorf M, Morgan S, Retzlaff W, Celik S. 2025. Evaluating plant coverage and thermal benefits of green walls for sustainable design. Journal of Ecological Engineering Design. https://doi.org/10.70793/jeed.21

worker productivity and alleviate mood. An increase in vegetation can reduce noise levels, a highly desirable benefit for city residents (Renterghem and Botteldooren 2009). These design options, many of which have surfaced from decades of product development and research in Germany, are receiving increasing interest in the United States.

One innovative green infrastructure is the green wall, first conceptualized thousands of years ago. Green walls famously adorned the Hanging Gardens of Babylon, one of the Seven Wonders of the Ancient World. Green walls are similar to green roofs or rain gardens in their use of specially selected plants and growing media, but green walls are employed along building façades and other built structures, along hilly urban terrain, or even as stand-alone walls. Green walls seek to provide human comfort and mimic naturally occurring vertically oriented environments: vines climbing tree trunks, plants clinging to cliff faces, succulents adorning rocky outcrops, etc. Green walls, also known as vegetated walls, living walls, or vertical greenery systems, are reputed to perform stormwater mitigation and purification, beautify urban hardscapes, and alleviate the UHIE (Manso et al. 2021, Ode et al. 2022, Wang et al. 2024). The outermost leaves of plants covering a green wall system can help reflect sunlight while the inner foliage can form layers of insulation. Green façades may also offer bioprotection for historic buildings (Sternberg et al. 2011) and serve as marketing tools to convey a greener image for companies and institutions (Weinmaster 2009). Green walls also contribute to stormwater retention. A recent study evaluated potential stormwater retention of a model living retaining wall system (Ostendorf et al. 2021). Different types of plants were found to perform better than the reference unplanted wall.

Living walls generally employ modular vegetation systems fixed vertically to a structure (Kontoleon and Eumorfopoulou 2010). Living walls are often used along building walls or fences or as stand-alone structures. Living walls can be subcategorized into modular walls, vegetated mat walls, biofiltration walls, and green landscape walls (Greenscreen 2010). Modular living wall systems are sometimes considered more comparable to terraced green roofs than to green façades (Köhler 2008). Vegetated mat walls feature a synthetic fabric able to support plants and usually require irrigation. Biofiltration walls are designed to improve air quality and regulate indoor air. Finally, green retaining walls, like traditional retaining walls, are designed to stabilize a slope from erosion and subsidence and create more developable space. Unlike standard retaining walls, however, green retaining walls utilize a modular system that facilitates vegetation. Green retaining walls, also referred to as living retaining walls or green landscape systems, are often employed to reduce noise levels (Greenscreen 2010), but they may also augment stormwater interception, infiltration, and evapotranspiration while cooling and shading surrounding microclimates (Ostendorf et al. 2021). The establishing root systems within a green landscaping wall may even serve as additional slope reinforcement (Stokes et al. 2008).

Despite the assumption that planted retaining walls provide thermal benefits, little scientific investigation has been conducted. Therefore, the purpose of this study was to quantify the differences in surface temperature between planted and unplanted retaining wall blocks. In addition, the study involved the comparison of green retaining wall systems planted with different species of *Sedum* on 4 different wall aspects (N, S, E, and W). The study will contribute data on plant selection for green wall and green roof applications in the Midwest. It was hypothesized that the block surface temperature of planted walls would be cooler than that of unplanted walls. It was also hypothesized that vegetative coverage of the planted walls would differ when planted with different *Sedum*. It was finally hypothesized that plant coverage would influence the wall block surface temperature.

2. Materials and Methods

2.1. Materials

To investigate the effect of sun position, this research began with the construction of 18 circular, plantable retaining wall systems (Figure 1). The green walls were located just north of Bluff (residence) Hall at Southern Illinois University Edwardsville, Edwardsville, United States. The walls utilized patented Hercules Mite™ modules that provide pockets for soil and vegetation. Each wall was arranged with 5 circular tiers of blocks, staggered at each tier (Figure 1a, background). Each green wall was approximately 213 cm (84 in) in diameter at the base, 168 cm (66 in) in diameter at the top, and approximately 69 cm (27 in) tall. The core of each wall was filled with coal bottom ash donated by Ameren. Bottom ash (80% by volume) blended with composted pine bark (20% by volume) was applied to the pockets of each block and along the top surface of each wall to a depth of 5 cm (2 in). Each green wall was constructed over an impermeable base layer (Figure 1a, foreground). The circular green wall systems were established in an area where no shade conditions existed from surrounding buildings or trees. The lawn surrounding the wall systems was mowed (typically weekly during the growing season) and trimmed at the base of the walls by Facilities Management. No supplemental irrigation was applied to the lawn surfaces surrounding the wall systems.

Fig. 1. Green retaining wall design. (a) Each green retaining wall system was designed with an impervious base layer (foreground). Blocks are arranged in 5 staggered tiers (background). (b) Each system was also fitted with 20.4 L stormwater collection units (June 2010).

Five vegetative treatments and an unplanted "control" wall, all with 3 replications, were arranged in a completely randomized design (Figure 2). Each wall was planted on July 1, 2007 with one of 5 *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 plugs containing multiple *Sedum* species, including *S. spurium, S. sexangulare, S. cauticola, S. kamtschaticum, S. rupestre* and *S. album.* All vegetated walls received supplemental plantings on 2010 September 17 and 2011 May 05 with additional *Sedum* plugs to facilitate dense vegetative coverage and to deter weed growth. All *Sedum* plugs were provided by Jost Greenhouses of St. Louis, Missouri, United States. No artificial irrigation was provided during establishment or during the study period. The green walls were fertilized on 2010 April 01, 2010 September 17, and 2011 March 31 with Woodace 18-5-10 long-term fertilizer. The walls and the areas surrounding the walls were regularly maintained and weeded with a lawn trimmer and a grass shear.

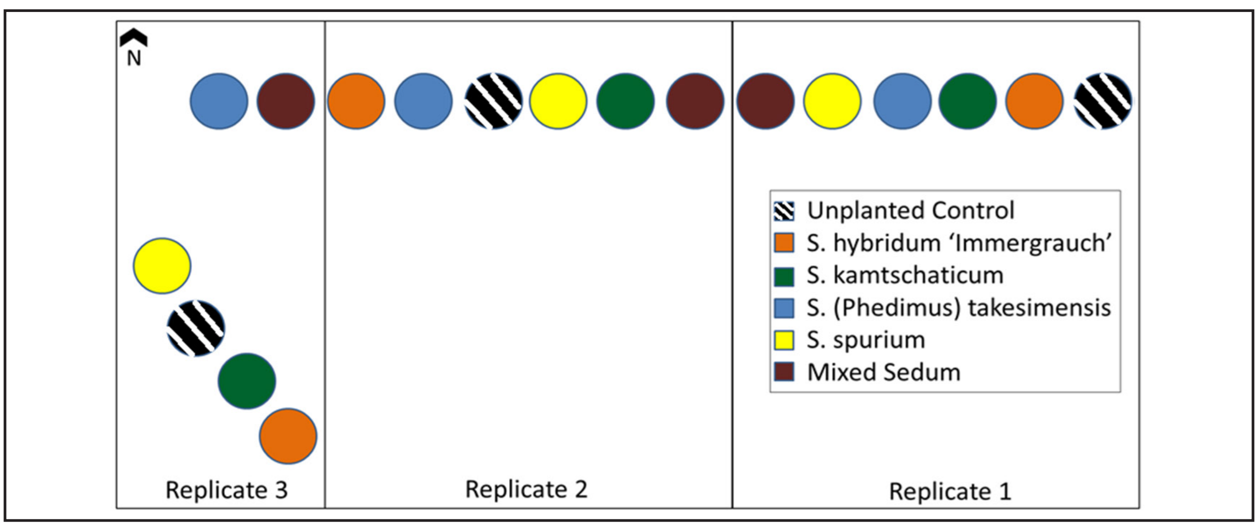

Fig. 2. The field site consisted of 18 green walls with 3 replicates of 6 treatments, including 5 planted treatments and an unplanted control.

2.2. Methods

2.2.1. 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 (Figure 3). The number of holes containing no vegetation was 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:

$$\%\ Plant\ Coverage = \frac{312-(\#\ of\ empty\ holes)}{312} \times 100 \quad (1)$$

For 100% coverage, there were no open holes and vegetation completely concealed the wall blocks and growth media partially or fully in each hole. Coverage was measured at monthly intervals for each replicate wall throughout the growing seasons of the study period, August through October 2010 and March through September 2011, resulting in 10 months of data collection.

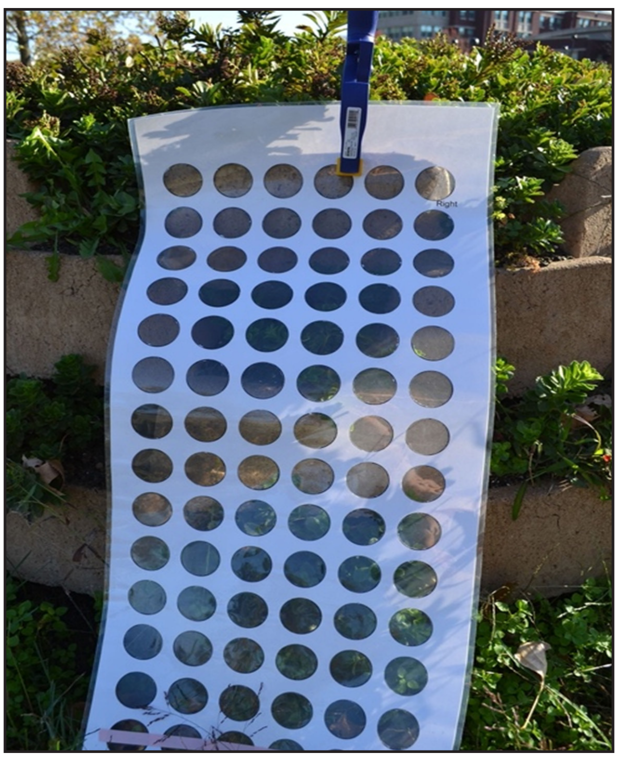

Fig. 3. Plant coverage was determined on each treatment aspect using a dot grid template.

Fig. 4. Surface temperatures of the block were recorded from each aspect with a non-contact infrared thermometer.

2.2.2. Surface Temperature Measurements

The surface temperatures of the green walls were measured using a digital non-contact infrared thermometer (Red Dragon GT1000). The infrared thermometer reads at a range of –20 °C to 270 °C and is accurate to ±2 °C. Block surface temperature was recorded for the middle block at the center of the surface (Figure 4). Surface temperature measurements were made on the north, south, east, and west aspects for each treatment. Midday thermal readings were made between the hours of 13:00 and 15:00 at semi-monthly intervals. Early morning and evening readings were made at dawn and just after dusk at monthly intervals. Data was collected from March 2010 to September 2011.

2.3. Data Analysis

For plant coverage data, a one-way analysis of variance (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 thermal 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).

To determine any relationship between thermal performance (at midday) and plant coverage of the green retaining wall systems, an analysis of covariance (ANCOVA) was conducted (PROC GLM, SAS version 9.1).

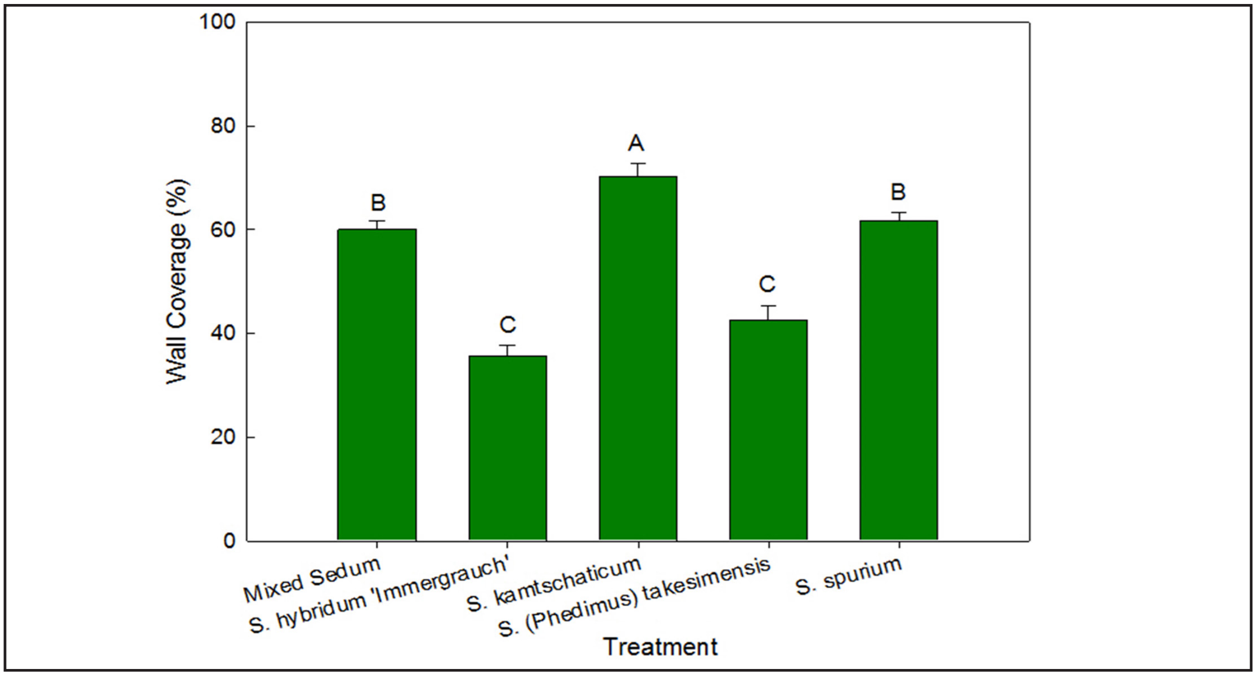

Fig. 5. Average growing season plant coverage for green wall systems for the entire study period (March 2010 – September 2011). Bars with different letters are significantly different (α <0.05, Error Bars represent +1 SE). (n=120; ANOVA DF, F-Value, and Pr>F reported in Table 1.)

3. Results

3.1. Plant Coverage

Differences in plant coverage between treatments were found when looking at the entire study period (August – October 2010, March – September 2011). Plant coverage ranged from about 35% to 70% (Figure 5). *S. kamtschaticum* had superior coverage (70%) compared to the other treatments. However, *S. spurium* and mixed *Sedum*, with 62% and 60% coverage, respectively, performed similarly, although statistically lower. *S. (Phedimus) takesimensis* and *S. hybridum 'Immergrauch'* with 42.5% and 36% coverage, respectively, performed significantly worse than the other species.

Differences in coverage were also found on a monthly basis for every month during the growing seasons except September 2010 (Figure 6). Coverage was <40% for all treatments except *S. spurium* (41%) in March 2011, following winter foliage die-back. Coverage was greatest (>50%) for all planted treatments excluding *S. hybridum 'Immergrauch'* between June 2011 and September 2011. Similar to analyzing the overall data, the monthly data generally showed *S. kamtschaticum* performed the best and *S. hybridum 'Immergrauch'* performed the worst.

Differences in plant coverage were also found between treatments along the 4 tested aspects for the study period (Figure 7). While *S. kamtschaticum* always performed well, other species performed equally well statistically except on the north aspect. *S. (Phedimus) takesimensis* and *S. hybridum 'Immergrauch'* performed worse than the others, except on the west aspect. On the west aspect, all plant species statistically performed

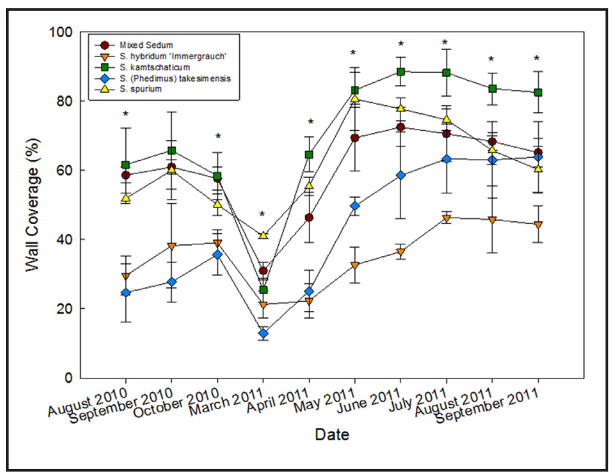

Fig. 6. Percent plant coverage for green wall systems for each month during the growing seasons (August 2010 – October 2010 and March 2011 – September 2011). An asterisk indicates a difference between treatments for that month (α <0.05, Error Bars represent ±1 SE). (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

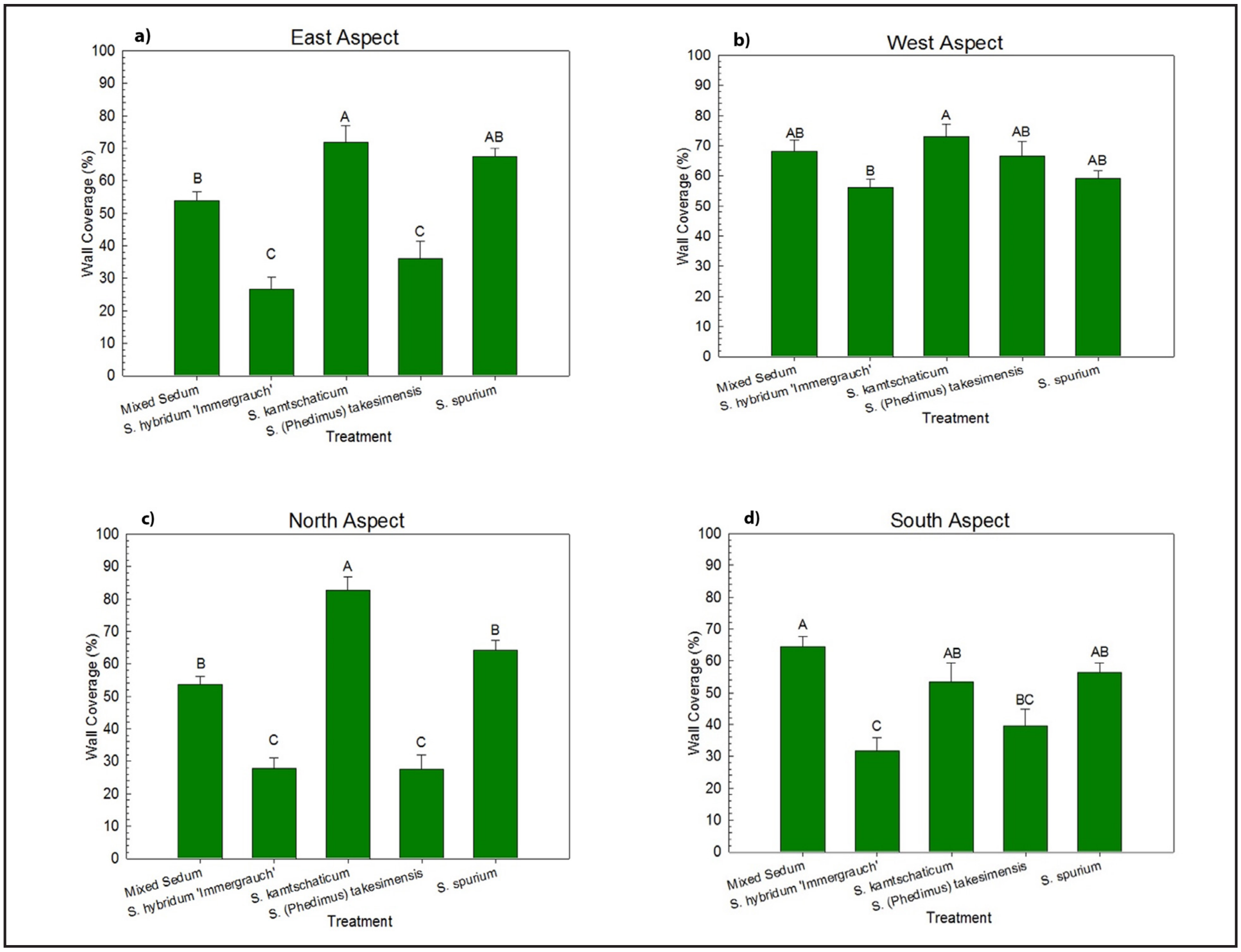

Fig. 7. Average plant coverage for green wall systems by aspect for entire study period (August 2010 through September 2011). Coverage on east (a), west (b), north (c), and south (d) aspects is shown separately. Bars with different letters are significantly different within each sub-figure (α <0.05, Error Bars represent +1 SE). n=30 for each aspect. (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

similarly, although the coverage was between 56% and 73%. The greatest coverage was *S. kamtschaticum* at 83% on the north aspect (Figure 7c). The lowest coverage was *S. hybridum 'Immergrauch'* and *S. (Phedimus) takesimensis* walls, both at 28%, on the north aspect.

3.2. Wall Surface Temperature

Differences in block surface temperatures were found at midday for the entire study period March 2010 through September 2011 (Figure 8). The block surface for *S. kamtschaticum,* mixed *Sedum,* and *S. spurium* were cooler on average at midday than the unplanted control. On average, the block surface for *S. kamtschaticum* at midday was 23.2 °C while the block surface for the control was 27.7 °C. No statistical differences in average block surface temperature were found between treatments in the morning or at dusk (Figures 9a and 9b).

Differences at midday were found between treatments on the west and south aspects. Statistical differences were not found at midday on the east or north aspects. Differences were also not indicated between treatments by aspect for morning or dusk measurements. For the west aspect at midday (Figure 10a), *S. kamtschaticum,* mixed *Sedum,* and *S. (Phedimus) takesimensis* were cooler than the unplanted control. On average, the block surface for *S. kamtschaticum* at midday was 23.2 °C. Block surface temperature for the control wall was 28.9 °C. For the south aspect (Figure 10b), the mixed *Sedum* wall was cooler than the unplanted control wall. On average, the block surface for mixed *Sedum* was 28.6 °C; it was 34.0 °C for the control wall.

Temporally, differences in midday block surface temperature between treatments were found during the spring and summer (Figure 11). No statistical differences

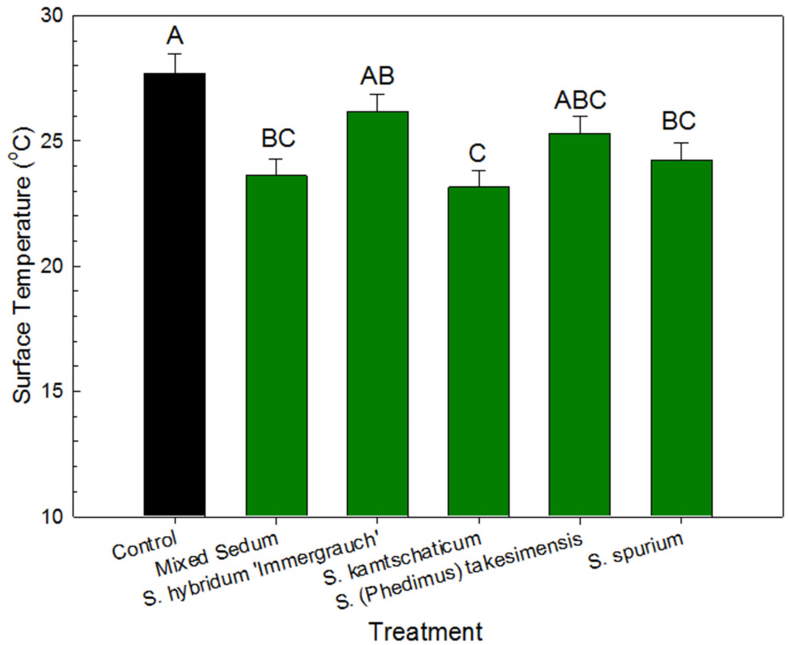

Fig. 8. Average block surface temperature (°C) for green wall systems at midday for the entire study period (March 2010 – September 2011). Bars with different letters are significantly different (α <0.05, Error Bars represent +1 SE). (n=336; ANOVA DF, F-Value, and Pr>F reported in Table 1.)

between treatments in midday block surface temperature were found for autumn or winter measurements. In the spring, midday block surface temperatures for *S. kamtschaticum,* mixed *Sedum,* and *S. spurium* were cooler on average than the unplanted control. On average, the block surface for *S. kamtschaticum* at midday was 23.6 °C while the block surface for the control was 29.3 °C. In the summer, midday block surface temperatures for *S. kamtschaticum,* mixed *Sedum, S. spurium,* and *S. (Phedimus) takesimensis* were cooler on average than the unplanted control. On average, the block surface for *S. kamtschaticum* at midday was 33.5 °C while the control was 40.3 °C.

Chronologically, midday block surface temperature differences between treatments were found in the spring and summer, but not the autumn or winter, of both 2010 and 2011 (Figure 12).

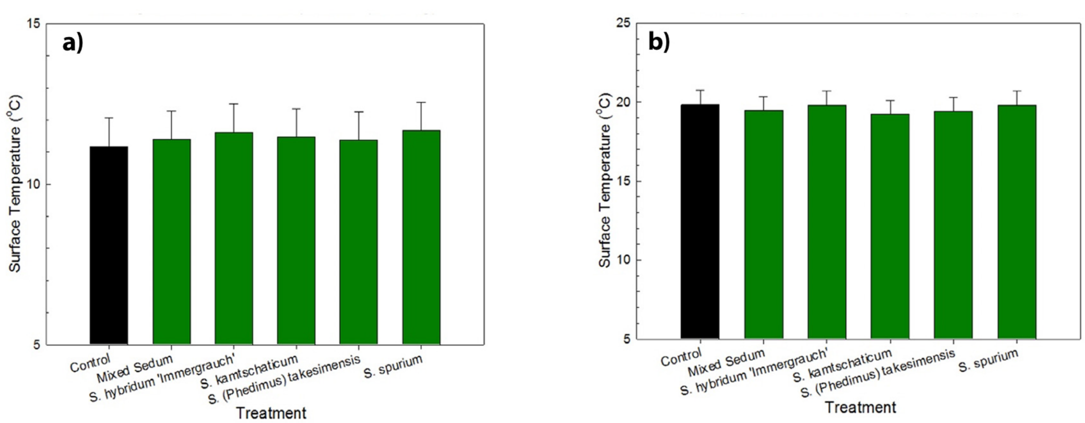

Fig. 9. Average block surface temperature (°C) in the morning (a) and in the evening (b) for the entire study period (March 2010 – September 2011). n=168 within each figure. (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

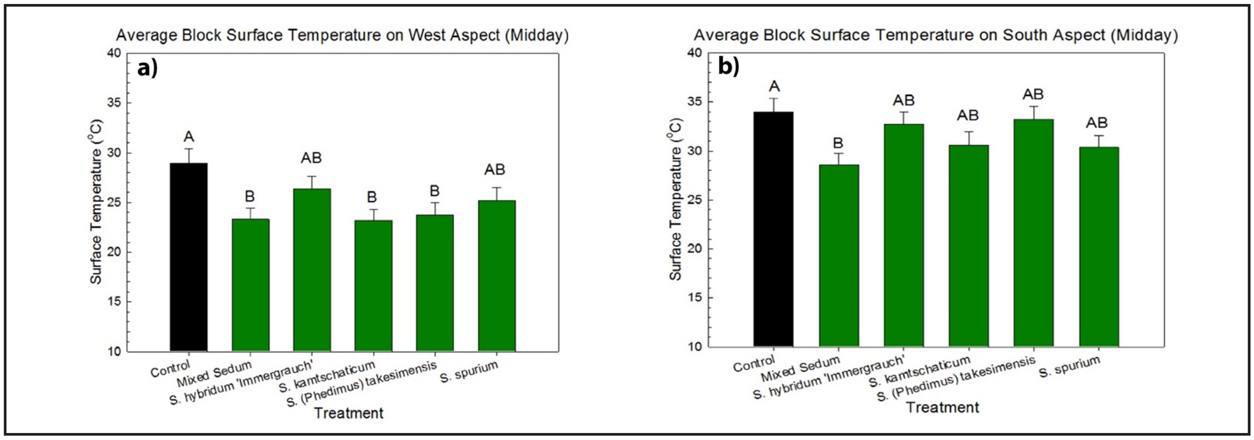

Fig. 10. Block surface temperature (°C) for green wall systems on the west (a) and south (b) wall aspects for the entire study period (March 2010 – September 2011). Bars with different letters are significantly different (α <0.05, Error Bars represent +1 SE). n=84 within each figure. (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

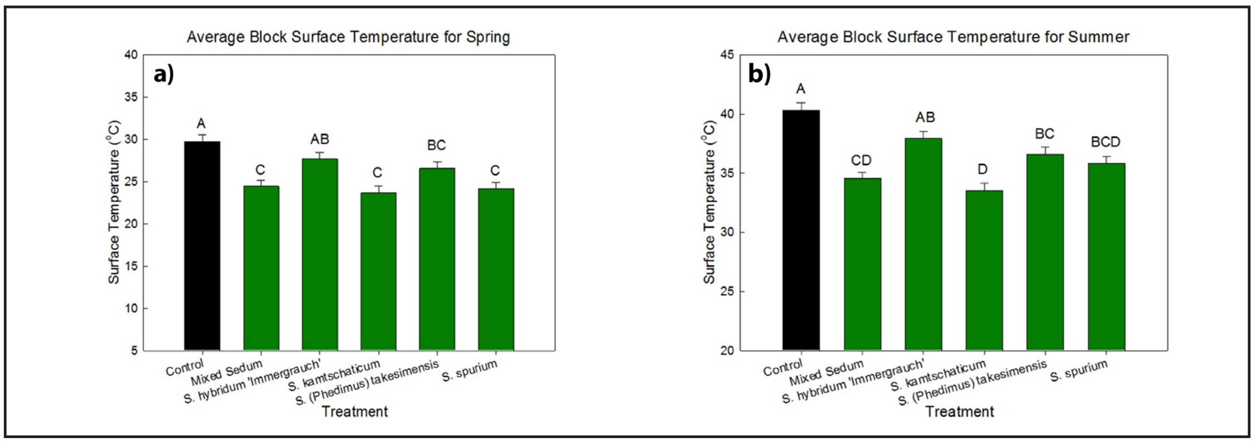

Fig. 11. Block surface temperature (°C) for green wall systems during spring (a) and summer (b) seasons at midday. Bars with different letters are significantly different (α <0.05, Error Bars represent +1 SE). n=120 spring, n=96 summer. (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

An analysis of covariance was performed to determine if plant coverage influenced the surface temperature of the green wall blocks, with an F-value of 44.46 and a P-value of <0.0001. The analysis of covariance indicated that plant coverage did in fact influence the surface temperature of the green retaining wall blocks (p <0.05).

4. Discussion

4.1. Plant Coverage

The treatment with the overall greatest percent plant coverage was *S. kamtschaticum* (70%). *S. kamtschaticum* had the greatest percent coverage on three aspects, east (72%), west (73%), and north (83%). Its performance may stem from its creeping growth habit, its ability to rapidly spread and fill an area, and its tolerance to rainy summers and frosty, rainy winters (Stephenson 1994). It has been found to survive during 80 days of drought in Michigan, United States (Snodgrass and Snodgrass 2006).

S. spurium also appeared relatively successful in covering the green walls (overall 62%). Other studies found *S. spurium* well-suited for green roof media (Getter and Rowe 2008, Wolf and Lundholm 2008), including a 16-month establishment study at Southern Illinois University Edwardsville (SIUE) (Kaufman 2008). Unfortunately, it did not fare well during the 2011 summer drought, when coverage diminished by 15% between July 2011 and September 2011.

One of the least successful treatments in terms of plant coverage was *S. hybridum 'Immergrauch'* with only 36% wall coverage on average. The treatment covered the top and pockets of the systems laterally and

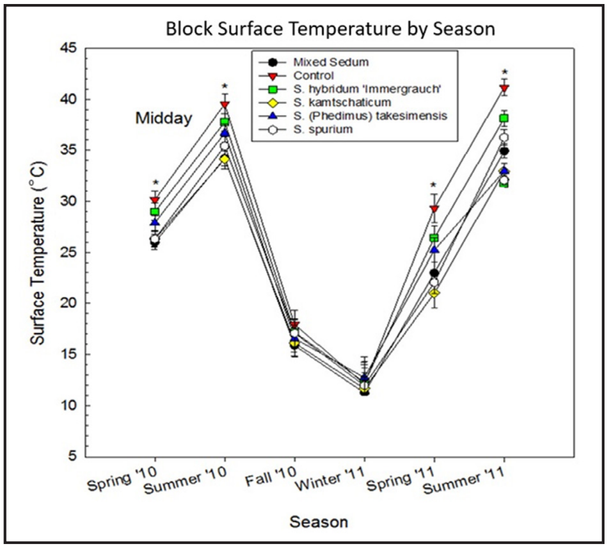

Fig. 12. Block surface temperature for treatments chronologically by season, as taken at midday. An asterisk indicates a difference between treatments for that season (α <0.05, Error Bars represent ±1 SE). (ANOVA DF, F-Value, and Pr>F reported in Table 1.)

even occasionally expanded into the adjacent ground-level soil, but did not grow very tall or tolerate adverse conditions very well. For example, over Winter 2010, coverage dropped below 30%. During the 2011 summer drought, *S. hybridum 'Immergrauch'* maintained a consistently low (<50%) plant wall coverage. In a green roof study at SIUE, complete failure of the *S. hybridum 'Immergrauch'* treatment occurred during the winter, likely due to the species' intolerance of winter shading (Gibbs-Alley 2008). In another SIUE study, *S. hybridum 'Immergrauch'* appeared to require at least 10 cm (4 in) of growing media to survive in a built-in-place green roof system; 5 cm of growing media appeared to be inadequate (Forrester 2007). The pockets of the Mite™ blocks are approximately 7.5 cm (3 in) deep, perhaps contributing to the subpar growth performance of *S. hybridum 'Immergrauch'*. This species would likely perform better in larger green retaining walls with deeper plant pockets.

Plant coverage varied noticeably throughout the study period. Influences on coverage include season, time since planting, and water availability. Winter foliage dieback affected all planted treatments. All planted treatments except *S. spurium* fell to <40% plant coverage by March 2011. Coverage measurements for *S. spurium* were relatively high (41%), likely because tall seed heads persisted throughout the majority of winter. Drought conditions from July 2011 to mid-September 2011 likely contributed to stagnation or slight decreases in plant coverage. Nonetheless, most treatments performed better in 2011 than in 2010, albeit 2010 data only includes August through October. As the plants continue to establish their root systems and spread vegetatively across the green wall surfaces, greater coverage is ultimately expected.

4.2. Wall Surface Temperature

Differences in block surface temperatures for the study period March 2010 through September 2011 were found only at midday. The block surface for *S. kamtschaticum,* mixed *Sedum,* and *S. spurium* planted walls were cooler on average at midday than the unplanted control. On average, the block surface for *S. kamtschaticum* at midday was 4.5 °C cooler than the control. In a United Kingdom study of green façades, an ivy-covered wall surface was 0.5 °C cooler on average than bare surfaces (Sternberg et al. 2011).

Differences at midday were found between treatments on the west and south aspects. For the west aspect, *S. kamtschaticum,* mixed *Sedum,* and *S. (Phedimus) takesimensis* were cooler than the unplanted control wall. On average the block surface for *S. kamtschaticum* at midday was 5.7 °C cooler than the block surface of the unplanted control for the west aspect. For the south aspect, the block surface for mixed *Sedum* was 5.4 °C cooler than that of the unplanted control.

Kontoleon and Eumorfopoulou (2010), in their summer study of green façades in northern Greece, found the surface of bare walls to be warmer than the wall sections covered by vegetation by 16.8 °C on the west aspect, 10.5 °C on the east aspect, 6.5 °C on the south aspect, and 1.7 °C on the north aspect. No differences between our treatments were found in the wall surface temperatures measured on the north and east aspects at the study-wide scale. However, this data incorporates temperatures taken during all seasons. Data from autumn and winter undoubtedly influence the overall averages. For instance, Perini et al. (2011) detected only a 1.2 °C – 2.7 °C difference in surface temperature between green façades and bare walls in a Netherlands study conducted during autumn. Consequently, many studies focus on determining thermal benefits during warmer spring and summer months while vegetation is actively photosynthesizing, evapotranspiring, and actively growing.

Climate impacts the performance of any living infrastructure system. The thermal performance results for this study in the United States Midwest, a humid continental climate, are similar to what Alexandri and Jones (2008) found for a south-facing wall in an urban canyon, for the cool continental climate of Moscow, Russia, where surface temperature decreases were 5.6 °C. A greater decrease, 14.3 °C, was found for the desert climate of Riyadh, Saudi Arabia.

Table 1 Descriptive statistics for each figure presented in the Results section (Figs. 5 through 12)

ANOVA for a Completed Randomized Experimental Design with 3 replicates as described in the Materials and Methods section

Fig. #	*DF*	*F-Value*	*Pr>F*	*Notes*
5	4	44.4	<.0001	-
6	4	6.59	0.0073	8/18/10
	4	3.61	0.0453	9/16/10
	4	4.72	0.0213	10/13/10
	4	14.27	0.0004	3/18/11
	4	11.96	0.0008	4/21/11
	4	9.92	0.0016	5/18/11
	4	9.14	0.0022	6/10/11
	4	5.31	0.0148	7/25/11
	4	3.51	0.0490	8/23/11
	4	4.04	0.0334	9/15/11
7	4	24.43	<.0001	East Aspect
	4	3.44	0.0102	West Aspect
	4	45.01	<.0001	North Aspect
	4	8.60	<.0001	South Aspect
8	5	5.9	<.0001	-
9A	5	0.04	0.9991	-
9B	5	0.08	0.9954	-
10A	5	3.2	0.0075	-
10B	5	2.54	0.0279	-
11A	5	9.96	<.0001	-
11A	5	16.93	<.0001	-
12	5	4.56	0.0005	Spring 2010
	5	5.72	<.0001	Summer 2010
	5	0.34	0.8877	Autumn 2010
	5	0.07	0.9971	Winter 2011
	5	6.16	<.0001	Spring 2011
	5	12.60	<.0001	Summer 2011

When the data were separated into seasons, differences were found between treatments for spring and summer, but not for autumn and winter. In the spring, midday block surface temperatures for walls planted with *S. kamtschaticum,* mixed *Sedum,* and *S. spurium* were cooler on average than the unplanted control. On average, the block surface for *S. kamtschaticum* planted walls at midday was 5.7 °C cooler than the block surface of the control. In the summer, midday block surface temperatures for walls planted with *S. kamtschaticum,* mixed *Sedum, S. (Phedimus) takesimensis,* and *S. spurium* were cooler on average than the unplanted control. The block surface for *S. kamtschaticum* at midday was 6.8 °C cooler than the block surface for the control.

On average for the study period, differences in block surface temperature between treatments were only found at midday. Differences between block surface temperatures were never found for morning measurements and rarely for evening thermal measurements. No differences were found for morning and evening measurements at the seasonal or study-wide scale. Some studies have observed differences at night. Di and Wang (1999) found, in their ivy-covered façade study, that the bare wall was 4 °C cooler than the vegetated façade at night. They attributed the difference to pronounced long-wave radiation from the brick surface. In another study, bare surfaces were 1 °C – 2 °C lower than the vegetated ones at night, also related to pronounced re-radiation of heat by the bare surface (Eumorfopoulou and Kontoleon 2009). In the present study, morning wall surface temperatures were always lower than dusk readings, as expected. Dusk wall surface temperatures were generally lower than midday readings. Midday and dusk measurements for winter 2011 were similar likely because of shorter daytime lengths and less time between midday and sundown for fluctuations in temperature to occur.

VanWoert et al. (2005) argued that vegetative cover plays an important role in erosion control and temperature moderation while growing media is perhaps the most important determinant of stormwater benefits. An analysis of covariance in this study indicated that coverage did, in fact, influence the capacity for the green retaining wall systems to moderate the surface temperature of the module face.

5. Conclusion

Green retaining walls, as examined in this study, may serve as an alternative urban heat island effect (UHIE) mitigation tool for urban areas. According to this study, it appears that, in the United States Midwest at least, planted green retaining walls may offer quantifiable thermal benefits compared to retaining walls left unplanted.

The choice of plant species affected the coverage and temperature of the retaining walls. In terms of plant coverage, certain *Sedum* treatments fared better than other planted treatments. In terms of block surface temperature, some *Sedum* treatments had cooler blocks than those of unplanted treatments. The ability of a vegetative treatment to cover a surface is often associated with better environmental performance, not to mention enhanced aesthetics and improved urban biodiversity. The assessment of plant coverage in this study revealed that *S. kamtschaticum* had better overall coverage (70%) than all other planted treatments.

Another purpose of green infrastructure is to reduce urban temperatures and suppress the urban heat island effect. It was found that certain planted treatments, *S. kamtschaticum,* mixed *Sedum,* and *S. spurium,* provided cooler block surface temperatures than the block of the unplanted control, though only at midday.

Further study could refine green retaining wall design by determining the thermal performance over a longer period of green retaining walls, walls planted with other vegetated treatments, and walls filled with different fill materials.

Acknowledgments

This project was a master's thesis project of Mark Ostendorf conducted under the direction of faculty in the SIUE Living Architecture Research Program. The faculty/student research group is thankful for the support of the Office of the Vice-Chancellor of Administration in approving the on-campus study-site location. We also thank the Department of Environmental Sciences and the SIUE Graduate School for the teaching assistantship for Mark that permitted him to conduct this study. We are forever indebted to Mark Woolbright, the inventor of the Hercules Living Wall Block, and to St. Louis Retaining Wall Company for the donation of project materials and project installation.

Author Contributions Statement

Conceptualization: WR, SM, SC; methodology: WR, SM, SC; data analysis: MO, SM, WR, SC; laboratory analyses: MO; writing original draft: MO; review/editing original draft: SM, WR, SC; investigation: MO, SC; resources: SM, WR, SC; data curation: WR, SC; supervision: SM, WR, SC; project administration: WR. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors have no conflict of interest to report.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request and at this link: https://doi.org/10.7910/DVN/TO0XHY

Related Publication Statement

Previous drafts of this manuscript were prepared as part of the master's thesis of the first author, Mark Ostendorf. The current manuscript, however, is a substantial synthesis of that thesis.

ORCID iDs

Mark Ostendorf
https://orcid.org/0009-0003-4641-4962

Susan Morgan
https://orcid.org/0000-0001-7610-4496

William Retzlaff
https://orcid.org/0009-0004-8751-3550

Serdar Celik
https://orcid.org/0000-0003-3607-6114

References

Alexandri E, Jones P. 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build Environ. 43:480-493. https://doi.org/10.1016/j.buildenv.2006.10.055

Di HF, Wang DN. 1999. Cooling effect of ivy on a wall. Experimental Heat Transfer. 12(3): 235–245. https://doi.org/10.1080/089161599269708

Eumorfopoulou EA, Kontoleon KJ. 2009. Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. Build Environ. 44:1024-1038. https://doi.org/10.1016/j.buildenv.2008.07.004

Forrester K. 2007. Evaluation of storm water runoff from a Midwest green roof system [master's thesis]. Edwardsville (IL): Southern Illinois University Edwardsville.

Fox M, Morewood J, Murphy T, Lunt P, Goodhew S. 2022. Living wall systems for improved thermal performance of existing buildings. Build Environ. 207A:108491. https://doi.org/10.1016/j.buildenv.2021.108491

Getter KL, Rowe DB. 2008. Media depth influences Sedum green roof establishment. Urban Ecosyst. 11:361-372. https://doi.org/10.1007/s11252-008-0052-0

Gibbs-Alley J. 2008. Evaluation of a green roof system with various growing media, sedum species, and fertilizer treatments [master's thesis]. Edwardsville (IL): Southern Illinois University Edwardsville.

Greenscreen. 2008. Introduction to green walls: Technology, benefits & design. [accessed 2021 Sep 7]. http://www.greenscreen.com/Resources/download_it/IntroductionGreenWalls.pdf

Kaufman SA. 2008. Plant species evaluation for extensive green roof applications in the Midwestern United States [master's thesis]. Edwardsville (IL): Southern Illinois University Edwardsville.

Khabaz A. 2023. Optimum thermal performance of green walls systems and design requirements against heat transfer of conventional external walls of low-rise concrete buildings in hot regions. Build Eng. 78:107654. https://doi.org/10.1016/j.jobe.2023.107654

Kleerekopper L, van Esch M, Salcedo TB. 2012. How to make a city climate-proof, addressing the urban heat island effect. Resour Conserv Recy. 64:30-38. https://doi.org/10.1016/j.resconrec.2011.06.004

Köhler M. 2008. Green facades – a view back and some visions. Urban Ecosyst. 11:423-436. https://doi.org/10.1007/s11252-008-0063-x

Kontoleon KJ, Eumorfopoulou EA. 2010. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Build Environ. 1287-1303. https://doi.org/10.1016/j.buildenv.2009.11.013

Manso M, Teotonio I, Silva CM, Cruz CO. 2021. Green roof and green wall benefits and costs: A review of the quantitative evidence. Renew Sust Energ Rev. 135:110111. https://doi.org/10.1016/j.rser.2020.110111

Ode Sang A, Thorpert P, Fransson AM. 2022. Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach. Front Ecol Evol. 10:804500. https://doi.org/10.3389/fevo.2022.804500

Ostendorf M, Morgan S, Celik S, Retzlaff B. 2021. Evaluating the stormwater retention of a living retaining wall system. J Liv Archit. 8(1):1-18. https://doi.org/10.46534/jliv.2021.08.01.001

Perini K, Ottelé M, Fraaij ALA, Haas EM, Raiteri R. 2011. Vertical greening systems and the effect on air flow and temperature on the building envelope. Build Environ. 46:2287-2294. https://doi.org/10.1016/j.buildenv.2011.05.009

Renterghem TV, Botteldooren D. 2009. Reducing the acoustical façade load from road traffic with green roofs. Build Environ. 44:1081-1087. https://doi.org/10.1016/j.buildenv.2008.07.013

Sheweka S, Magdy N. 2011. The living walls as an approach for a healthy urban environment. Enrgy Proced. 6:592-599. https://doi.org/10.1016/j.egypro.2011.05.068

Snodgrass EC, Snodgrass LL. 2006. Green roof plants: resource and planting guide. Timber Press Inc.

Stephenson R. 1994. Sedum: cultivated stonecrops. Timber Press, Inc.

Sternberg T, Viles H, Cathersides A. 2011. Evaluating the role of ivy (Hedera helix) in moderating wall surface microclimates and contributing to the bioprotection of historic buildings Build Environ. 46:293-297. https://doi.org/10.1016/j.buildenv.2010.07.017

Stokes A, Norris J, van Beek LPH, Bogaard T, Cammeraat E, Mickovski SB, Jenner A, Di Iorio A, Fourcaud T. 2008. How vegetation reinforces soil on slopes. In: Norris JE et al., editors. Slope stability and erosion control: ecotechnological solutions. Springer. https://doi.org/10.1007/978-1-4020-6676-4_4

VanWoert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT, Xiao L. 2005. Green roof stormwater retention: effects of roof surface, slope, and media depth. J Environ Qual. 34:1036-1044. https://doi.org/10.2134/jeq2004.0364

Wang A, Wang J, Zhang R, Cao SJ. 2024. Mitigating urban heat and air pollution considering green and transportation infrastructure. Transport Res A-Pol. 184:104079. https://doi.org/10.1016/j.tra.2024.104079

Weinmaster M. 2009. Are green walls as "green" as they look? An introduction to the various technologies and ecological benefits of green walls. J Green Build. 4:3-18. https://doi.org/10.3992/jgb.4.4.3

Wolf D, Lundholm JT. 2008. Water uptake in green roof microcosms: Effects of plant species and water availability. Ecol Eng. 33:179-186. https://doi.org/10.1016/j.ecoleng.2008.02.008

Zhou W, Huang G, Cadenasso ML. 2011. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. Landscape Urban Plan. 102(1):54-63. https://doi.org/10.1016/j.landurbplan.2011.03.009