ABSTRACT

Title of Document: DESIGN AND PERFORMANCE OF A WETLAND-INSPIRED GREEN BULKHEAD AND A GRASSLAND-INSPIRED GREEN WALL

Lela Stanley, M.S., 2015

Directed By: Professor Patrick C. Kangas, Department of Environmental Science and Technology

Green walls are technologies that provide benefits to the human, natural, and built environments including building shading and cooling, aesthetics, and habitat. Using natural ecosystems as templates, it should be possible to design green walls to provide enhanced ecological functions and play a role in urban reconciliation ecology. This thesis describes the design and performance of two types of green wall drawing inspiration from Mid-Atlantic ecosystems. The first, a wall modeled on Chesapeake Bay brackish marshes, was operated in the Baltimore Harbor for five months and successfully replicated some conditions of wetlands including supporting the growth of native macrophytes throughout the growing season. Notably, this model is the first functional green wall designed for an urban waterfront. The second design tested native grass survival in a dry grasslands-inspired green wall model. In this model, which was moisture-limited with a very shallow substrate, both planted grass species gave way to an invasion of volunteer species.

DESIGN AND PERFORMANCE OF A WETLAND-INSPIRED GREEN BULKHEAD AND A GRASSLAND-INSPIRED GREEN WALL

By

Lela Stanley

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2015

Advisory Committee:
Professor Patrick C. Kangas, Chair
Professor Andrew H. Baldwin
Associate Professor David R. Tilley
Dr. Peter I. May

Dedication

To Frank and Sherman.

Acknowledgements

Grateful thanks go to my committee members for their guidance and support; to Gary Seibel and the Project Development Team; to the Living Classrooms Foundation for the use of their bulkhead space; to Dr. Martin Rabenhorst for providing IRIS tubes and advice; and to Tim Williamson and Nick Ray for advice and encouragement. My sincere thanks also go to the Department of Environmental Science and Technology, for the financial support that made this thesis possible.

Table of Contents

List of Tables

List of Figures

Chapter 1: **Overview**

Green walls are a rapidly growing technology that depending on design specifics can cool and insulate the building envelope, provide habitat for plant, arthropod, and bird species, support food production, recycle graywater, and provide social and psychological benefits to their users. However, many gaps exist in the use of green walls in ecological design. For instance, an untapped area that presents great potential for green wall development exists in many cities in the form of urban waterfront walls. Additionally, little green wall research has been done to date to establish locally appropriate native plant species for use in the Mid-Atlantic region, or to test the ability of drought-tolerant species to the challenging conditions of green walls.

This thesis describes the design and assesses the performance of two green wall models, focusing on plant success, soil parameters and/or system water dynamics to characterize them. Elements common to these two designs included a vertical zigzag pattern of irrigation drainage through the walls, designed to increase retention time, and the unconventional use of natural sediment. This latter design choice was made in part to provide a natural seed bank. Both wall designs were also characterized by notably shallow substrate.

Chapter 1 describes the design and performance evaluation of a new green bulkhead prototype: a green wall model informed by the function and zonation of native Chesapeake brackish marshes. Green bulkhead plant performance, water flows and retention, and soil parameters were assessed and compared to reference marsh plants and literature values. This proof of concept demonstrated that some species of native wetland plants could be supported in a green wall model in the Baltimore Harbor, although plant success was highly variable between species in the single model described here, and that green walls mounted on waterfront walls (bulkheads) could slow and store water flowing through them.

Chapter 2 describes a grassland-inspired green wall designed to test the survival of native grasses, and emergence of volunteer vegetation species, in water-stressed wall habitat with limited substrate. Two grasses commonly found in serpentine barrens ecosystems were chosen, on the rationale that species capable of thriving in barrens would be suited to the harsh conditions of this green wall design. Over the 2014 summer growing season, however, these species generally failed to thrive and yielded to a profusion of volunteer weed species.

Chapter 2: **Design and Performance of a Wetland-Inspired Green Bulkhead**

Introduction

In 2010, global urban areas occupied some 3% of the world's land (Liu et al. 2014); by 2030, the world is projected to add at minimum another 430,000 km^2 of urban land - an area larger than the state of California (Seto et al. 2011). This process of urbanization alters and destroys local ecosystems through a host of effects ranging from surface paving, shifts in hydrology, and subsequent soil microbial alterations, to habitat loss and fragmentation, driving changes in species composition, richness, and behavior; concentrated pollutant loading in faster-flowing, channelized stormwater; the development of an urban heat island effect; sound and light pollution; and a psychological toll exacted from city dwellers (Pickett et al. 2001, Groffman et al. 2003, Carter and Butler 2008, Lundholm and Richardson 2010, Roe et al. 2010, Kowarik 2011). Along urban waterfronts, natural shorelines are drastically altered through the addition of seawalls or bulkheads (Chapman 2006), with consequences for ecological function.

Developing approaches to reducing these problems and rendering cities less ecologically harmful as well as better places to live is essential, considering the extent of the globe undergoing urbanization. The concept of ecological reconciliation proposed by Rosenzweig (2003) offers a template for such improvement. In this paradigm, anthropogenic landscapes may be altered to support more species while not compromising their use to humans. As cities grow, productive natural landscapes are replaced with biologically inert, impermeable structures. These, however, have an enormous vertical surface area compared to their footprint. High-rise building wall areas can total twenty times or more that of their roofs (Dunnett and Kingsbury 2008). More conservatively, Köhler (2008) estimates overall urban wall area available and appropriate for modification to be double that of its footprint. Drawing information and inspiration from analogous natural systems (e.g. Lundholm and Richardson 2010, Francis and Lorimer 2011), this space presents great potential for ecological engineering: modifying or designing outright walls and other vertical areas to support life and provide ecological services that benefit both their environment and human users. The practice of designing green façades and living walls is one example of this approach.

Green façades and living walls rely on the cultivation of plants along a vertical built surface to achieve societal and ecological benefits. Like green roofs, these technologies (here collectively termed green walls) are methods of reversing some of the effects of urbanization by rendering permeable some of the built environment's impermeable skin (Ottelé 2011). Compared to green roofs, the benefits provided by green walls are less well studied (Köhler 2008) but appear to be considerable, albeit highly variable, depending on local climate, plant choice, and wall design. They may be categorized generally into benefits to the building envelope itself and to local ecosystems and human populations.

Building envelope benefits of green walls include thermal regulation, notably cooling (Perini et al. 2011), and shielding of the building envelope from ultraviolet light (Dunnett and Kingsbury 2008). The cooling and insulating effects of wall greenery via evapotranspiration, direct shading, and landscape albedo alteration have been extensively investigated (Cameron et al. 2014) and are often used to justify green wall development (though see Hunter et al. 2014).

Ecosystem and social benefits of green walls form a diverse group. Green wall plants reduce air pollution by trapping dust and particulate matter (Joshi and Ghosh 2014). Selecting food plants for green walls contributes to local food security (Köhler 2008). Although the ability of green walls to promote biodiversity is widely touted, few studies have actually investigated this; however, Matt (2012) and Chiquet et al. (2013) found higher numbers and diversity of invertebrates and birds, respectively, using green walls than using bare walls. Green wall plantings can be used for water recycling; Loh (2008) notes that in Australia many interior green walls are irrigated with recycled gray or blackwater, The muffling properties of soil or substrate and plant tissues can produce measurable reductions in noise pollution (Azkorra et al. 2015). Finally, the driving reason behind most green wall installations is the visual and aesthetic enhancement they provide (Hopkins and Goodwin 2011).

Green wall research has grown rapidly in recent years (Köhler 2008) but is still in its relative infancy compared to green roof design. An untapped resource for green wall creation exists in the form of retaining walls, seawalls, and bulkheads around urban waterways (Francis and Lorimer 2011, Dyson and Yocom 2015). These areas exist in every coastal and harbor city and in every city with a significant river. They can represent significant real estate in the midst of densely developed areas. Francis and Hoggart (2008) found 28 ha of contiguous retaining wall along the River

Thames in London. Similarly, a University of Maryland study (P. Kangas, pers. comm.) found 0.6 ha of bulkhead area in the Baltimore Inner Harbor that was available for green wall modification.

Despite this abundance of space, no published studies to date report successful development of green wall type infrastructure for waterfront walls. Dyson and Yocom's (2015) review of ecological design for urban waterfronts discusses two attempts, in Seattle and on the Cuyahoga River, to foster plant growth on retaining walls using planter baskets. Both attempts failed, due to wave action sweeping sediment and/or plants from baskets. Approaches to modifying the built structures of retaining walls to provide habitat for local marine biodiversity have been tested in England, Australia, and Italy, with some success (reviewed in Chapman and Underwood 2011, Francis and Hoggart 2008, Perkol-Finkel et al. 2012). However, these approaches focused on physically modifying seawalls, making them less useful for retrofitting existing retaining walls, and were limited to mimicking the conditions of rocky intertidal habitats.

The evident lack of recognition of waterfront walls as viable locations for ecological design and restoration is especially curious considering the functions and value of the original ecosystems that occupied those spaces. Pre-urbanization, areas now occupied by ports and heavily developed harbors were extremely productive riparian systems and wetlands whose loss exacerbates the negative effects of urbanization (see e.g. Everard and Moggridge 2012). As a class, wetlands provide enormous ecosystem services. They are high primary producers that sequester carbon, support fisheries and waterfowl populations, and provide other wildlife habitat, as well as recreational and tourism opportunities (Millennium Ecosystem Assessment 2005). Wetlands trap and remove sediment and contaminants, including nutrients and heavy metals, from the water column (Mitsch and Gosselink 1993). In coastal areas, salt marshes and mangrove forests provide protection from storms by absorbing tidal energy and slowing storm surge.

The city of Baltimore, MD, which falls on the dividing line between the Coastal Plain and Piedmont ecoregions, is drained by the tidal Patapsco River into the Chesapeake Bay (Fig. 1). The Bay, one of the world's largest tidal estuaries, lost tidal wetlands at rates estimated between 52–300 ha/year prior to the establishment of the Clean Water Act in 1972 (Perry et al. 2001). In Baltimore, portions of the extant waterfront were bulkheaded as early as the mid-1800s (Wicks et al 2011). The loss of the city's wetlands compounds a decades-long struggle with water quality indicated by the Harbor's inclusion in the Clean Water Act's Impaired Waters list (Wicks et al. 2011). A 2013 Harbor Health report issued by the city's Waterfront Partnership, Blue Water Baltimore, and Ecocheck gave the Inner Harbor's waters an overall failing grade on measures of levels of multiple contaminants including dissolved oxygen, water clarity, total nitrogen, total phosphorus, and bacteria, and trash (Waterfront Partnership 2014).

Spurred by these indicators, Baltimore's Inner Harbor is now the subject of an extensive, long-term clean-up effort spearheaded by the Waterfront Partnership through its Healthy Harbor initiative. The Partnership's goals include a swimmable and fishable Inner Harbor by 2020, and green infrastructure is explicitly recognized as one path to this goal (Waterfront Partnership 2013). Among other projects, the initiative has supported the development of artificial “floating wetland” islands (Streb 2013).

Figure 1. Map of Baltimore, MD, and Inner Harbor (indicated). The Chesapeake Bay extends to the image’s right. Photograph courtesy Google Maps.

A green wall designed for urban waterfronts such as Baltimore’s has the unique potential to promote ecological restoration in heavily degraded habitat, as well as generating some of the benefits documented by other green wall designs. This waterfront infrastructure is increasing globally along with urbanization and sea level rise (Browne and Chapman 2011), presenting ever-growing area for modification. As the removal of seawalls, river retaining walls, and bulkheads is not usually feasible (Francis and Hoggart 2008), an ecological engineering informed approach that does not compromise the structural integrity of the walls and that draws on local water sources and local ecology, while drawing inspiration from locally appropriate ecosystems, should have the best chance of success.

At the same time, green wall design for urban waterfronts presents a number of unique challenges. Because of the vertical face of retaining walls and bulkheads, the intertidal zone can be measured in centimeters instead of meters (Fig. 2; Chapman

2006). Tidal marshes display distinct zonation patterns driven by factors including flooding and salinity tolerance and competition (Flowers 1973, Pennings et al. 2005). This urban compression of the area directly exposed to tidal flux means that in a waterfront green wall, a very narrow zone will experience tidal flux, while lower and higher areas of the wall will be consistently submerged and exposed, respectively.

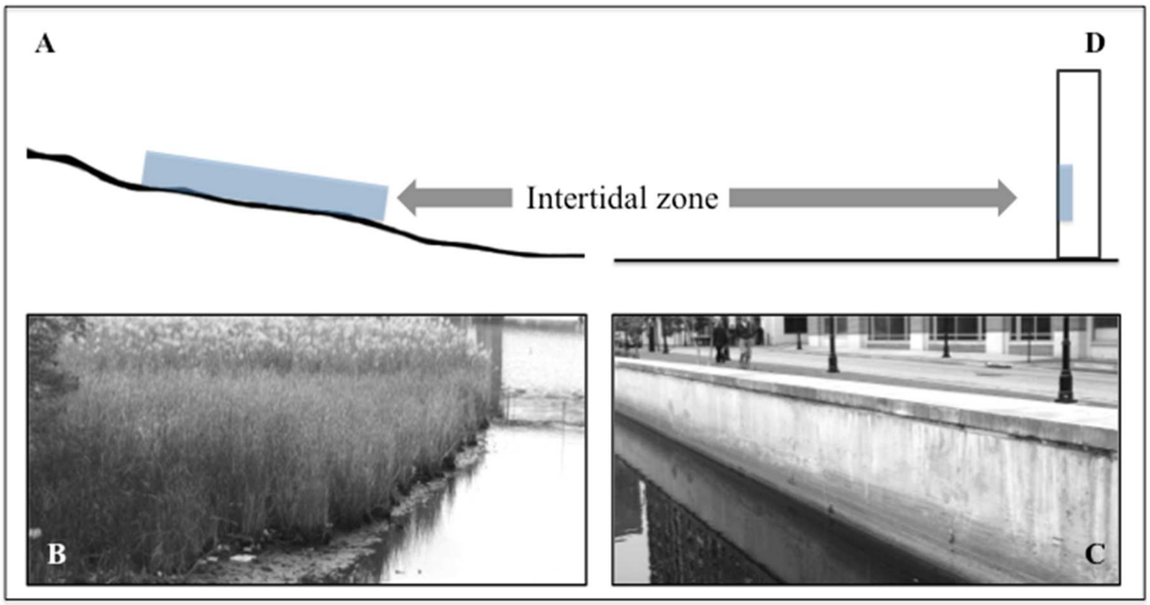


Figure 2. Natural shorelines like this Baltimore marsh (A) present a more gradual slope (B) than heavily engineered, often vertically oriented urban waterfronts such as these bulkheads in Baltimore (C), dramatically compressing urban intertidal habitat (D). Concept adapted from Dyson and Yocom (2015). Photographs: Lela Stanley.

In Baltimore, significant quantities of trash clog the Harbor (Wicks et al. 2011) and are cleaned by trash skimmers that join other municipal and private boat traffic throughout the waterway. Both the presence of trash and the passage of boats need to be considered in designing green walls that will maintain a shallow profile to not impede traffic and, ideally, will not accumulate trash. Some challenges are general to green wall design. These include the difficulties of efficiently conveying water to plants; the tendency of taller plants to topple over, as well as patchiness created by uneven plant growth; the difficulty of holding plants and growing medium in position. Wind velocity and turbulence, irrigation, and securing plants and medium in position are also factors to consider (Dunnett and Kingsbury 2008). Francis (2010) notes that walls can have unstable and more extreme (relative to their surroundings) microclimates, dynamics that depend highly on wall orientation and may vary even along a vertical gradient within a given wall. Finally, river walls, and waterfront walls in general, are naturally exposed to a flow of water, which can pose a structural threat while also depositing nutrient-rich detritus (Francis and Hoggart 2009).

The objective of this thesis project was to design, build, and operate a green wall for Baltimore Inner Harbor bulkheads that was informed by native tidal marshes in its structure (zonation), and to evaluate the degree to which such a green wall model performed like local marshes in terms of supporting native tidal marsh vegetation and exhibiting hydrologic and soil conditions typical of wetlands.

Design, Methods, and Materials

Green bulkhead panels were installed in the Baltimore Inner Harbor on 4 July 2014 and operated until 15 December 2014.

Study area

Baltimore Harbor lies at the confluence of the Jones Falls and Gwynns Falls Creeks and the Patapsco River, a tidal tributary of the Chesapeake Bay. The Harbor is mesohaline (>5–18 ppt) and experiences a daily tidal flux of approximately 30 cm (Wicks et al. 2006).

Bulkhead space was provided by the Living Classrooms Foundation's Fells Point Campus. The Living Classrooms site is located at 801 S. Caroline St, Baltimore, MD (39.281666, -76.598762), at the southeastern corner of the Inner Harbor and adjacent to a heavily used public marina. A lot directly to the south was under construction for the duration of the panels' installation period (Fig. 3).

Figure 3. Location of bulkhead space (indicated by arrow) provided by the Living Classrooms Foundation. Photograph courtesy Google Maps.

<u>Climate and weather conditions</u>

Monthly precipitation and temperature records were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center (Maryland Science Center station: ~1.3 km west of the Living Classrooms site). The installation period was characterized by typical Mid-Atlantic summer temperatures, with high temperatures peaking at 36º C in July and lows reaching -6º C in November (Table 1).

Table 1. National Oceanic and Atmospheric Administration National Climatic Data Center temperature and precipitation totals for July–December 2014. Data gathered at the Maryland Science Center, Baltimore, MD station.

Month	Monthly average temp (ºC)		Maximum high (ºC)	Maximum low (ºC)	Precipitation (total cm)
	High	Low			
July	30.3	21.3	36	16	8.7
August	28.3	20.3	34	17	16.1
September	25.9	18.3	35	12	7.1
October	19.7	12.2	25	6	9.4
November	11.3	3.5	22	-6	8.6
December	8.1	2.2	22	-2	8.5

Panel design and installation

Design requirements for the green bulkhead system included the following:

- Shallow horizontal profile
- Overall size no larger than bulkhead space provided by Living Classrooms
- Capable of supporting wetland plants at different heights above Harbor (“zones”)
- Relatively lightweight and ideally modular
- Capable of slowing and retaining water flow through the panel

Green bulkhead panels (N=3, 180 cm high x 60 cm wide) were constructed from lightweight, durable, inexpensive, and easily sourced materials. A full materials list is provided in Appendix 1. The body of each panel consisted of a section of Poly-Flo Biological Filtration Media attached to a backing of sturdy plastic mesh that provided structural support. Six 60-cm lengths of 10 cm (4”) diameter corrugated drainage pipe were affixed using beaded cables to the front of each panel at ~2° angles, alternating right and left. One end of each length was sealed. This allowed water poured into the top level to drain down through its entire length and into the next lower level, and so on (Fig. 4). The center of each level was 30 cm above the next, to allow vertical room for plant growth, and all levels combined spanned a total of 180 cm from the top of the bulkhead to just above the harbor floor. Sections (6.4 cm by 51 cm) were cut from each irrigation pipe length to provide space for planting. Each level was filled with approximately 2000 ml soil (to ~5 cm depth) and planted with one species of wetland plant, as described below. The final weight of each panel including six planted levels of soil was ~19.5 kg.

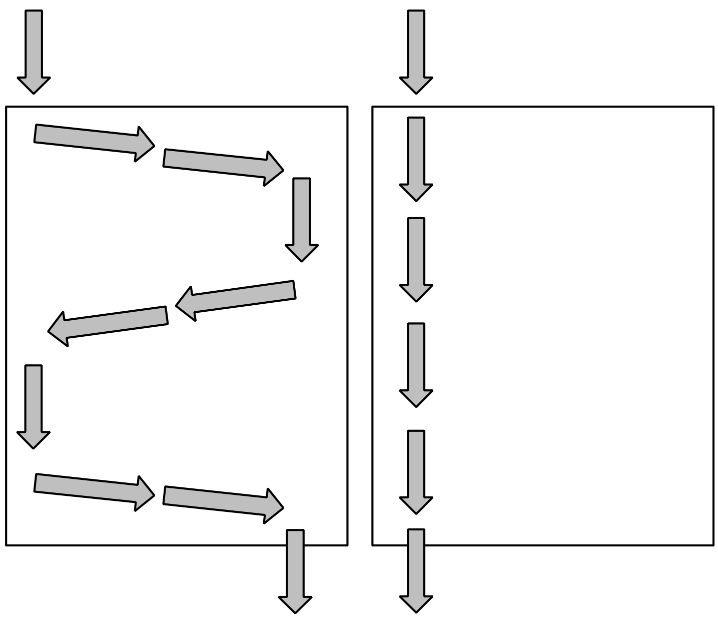


Figure 4. Water is channeled along a more sinuous vertical path through constructed green bulkhead models (L) than simply draining vertically through the panel (R).

Green bulkhead panels were hung on a sheltered, south-facing wall of the Living Classrooms campus (Fig. 5). At low tide the panels were fully exposed; high tides routinely submerged the bottom (6^{th}) and often the 5^{th} levels, and occasionally reached as high as the 4^{th} level.

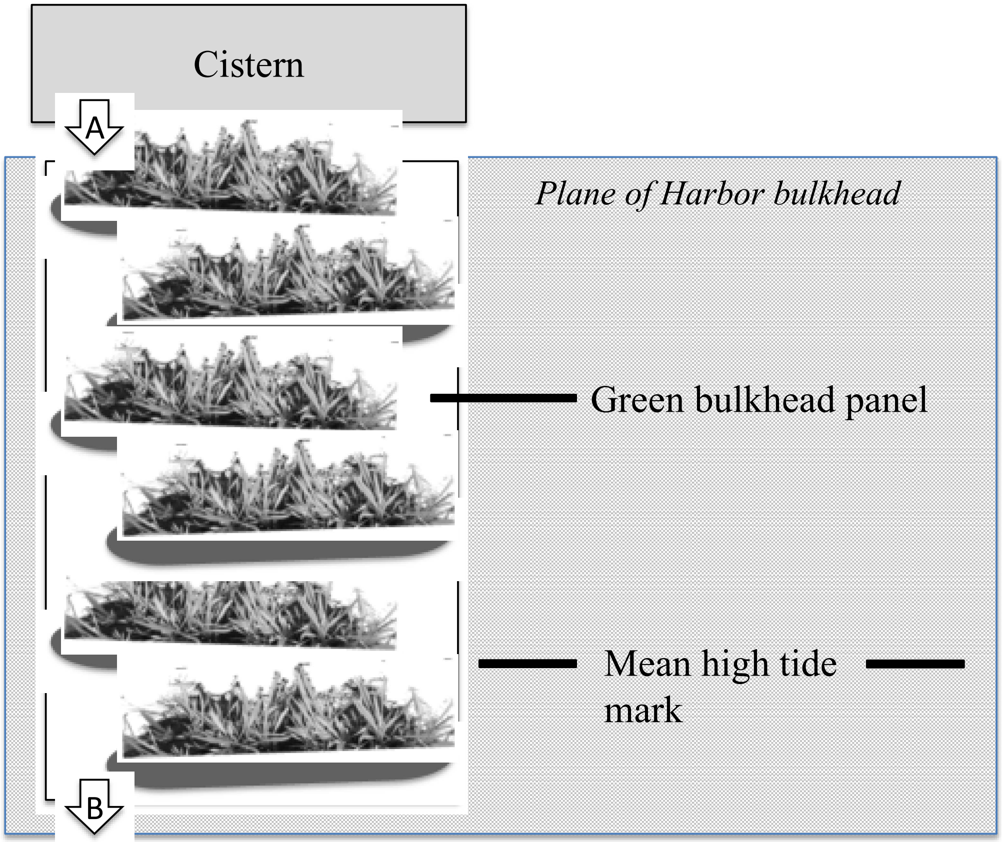


Figure 5. Schematic of green bulkhead positioning in Baltimore Harbor. Water enters the green bulkhead at point A, flows in succession through each gently inclined horizontal level, and exits into the Harbor at point B.

Irrigation and water measurements

Irrigation

A white 114 L water cistern was installed on the harbor wall directly above the experimental panels, and connected via a bulkhead fitting to a low-pressure hose timer (Toro 54736 Drip Hose End Timer), adjustable hose splitter, and a length of clear 5/8" (1.59 cm) outside diameter hose running to the intake point of each panel (Fig. 6). White and clear materials were selected where possible to reduce cistern water temperature during the summer months.

Each panel was provided with ~8 L water/day. Exact irrigation amounts and timing varied depending on the extent of algal growth in the timer filter and resulting flow rates.

The cistern was refilled manually on a biweekly basis. Water was strained through 1-mm mesh to remove particulate matter before being poured into the cistern, which was cleaned monthly to remove algal build-up. A removable filter in the timer provided another barrier against algae and other debris. This filter was cleaned as needed, roughly every two weeks, to remove algal growth. Bivalve biofouling of the connection between the tank and timer was noted on one occasion (Appendix 2); no routine antibiofouling measures were necessary. In September, the cistern was replaced with a larger (209 L) model to reduce maintenance time.

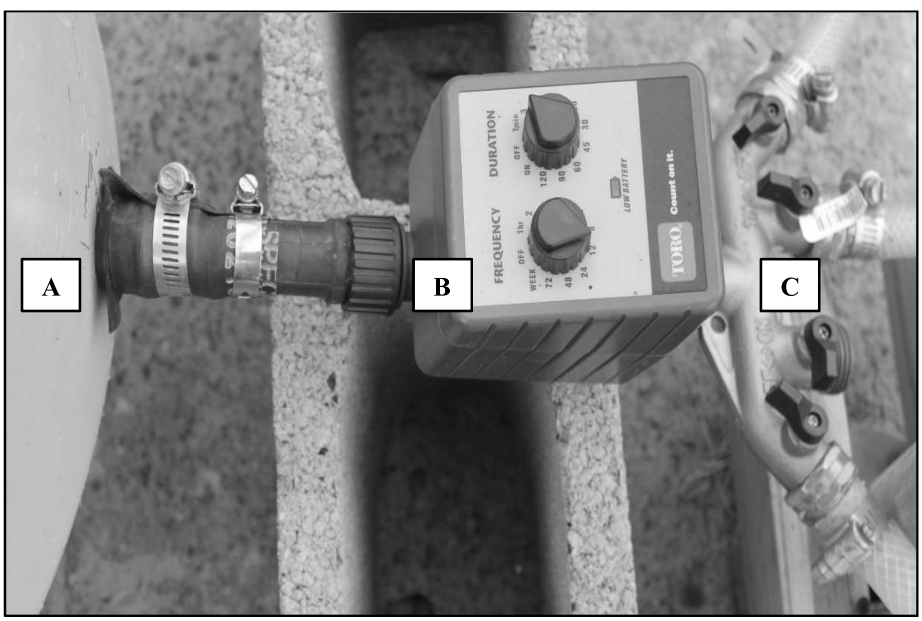


Figure 6. Green bulkhead panel irrigation system: 209 L cistern (A) connected to zero-pressure irrigation timer (B), hose splitter (C), and three hoses running to bulkhead panels (out of frame).

Water flows and retention time

The capacity of individual green bulkhead panels to slow and retain water passing through the systems was assessed in 15 trials (1 trial = 1 test of a single panel). For each trial, 4 L water was poured into a panel's intake point over the course of 6 minutes (~667 ml/minute) and allowed to flow through the panel. Water drained from level 5 at 2, 5, 19, and 60 minutes after cessation of pouring was captured and measured. Level 6 quantities were not assessed because in practice panel level 6 was so frequently submerged at high tide. The total amount of water lost from the system via leaking from individual levels or splashing out of the system was also quantified. For trials conducted while the panels were installed in the Harbor, the amount lost to splashing was estimated; in subsequent indoor trials all water quantities were captured and measured. At the 60 minute mark, the difference between 4 L and the total amount of water draining or leaked mark was considered retained in the system.

<u>Vegetation measurements</u>

Plant selection and zonation

Salt-tolerant native wetland plants were sourced as 2" (5.1 cm) plugs from American Native Plants (Perry Hall, MD). Each panel level was planted with one species, mimicking zonation patterns of Chesapeake brackish marshes (Flowers 1973, Perry et al. 2001). In vertically descending order, the plant species selected were *Solidago sempervirens* (seaside goldenrod), *Distichlis patens* (seashore saltgrass), *Spartina patens* (salt-marsh hay), *Hibiscus moscheutos* (swamp rose-mallow), *Juncus gerardii* (black needle rush), and *Spartina alternifolia* (salt-marsh cordgrass) (Fig. 7). *Juncus roemerianus* was unavailable from the vendor at the time plants were selected.

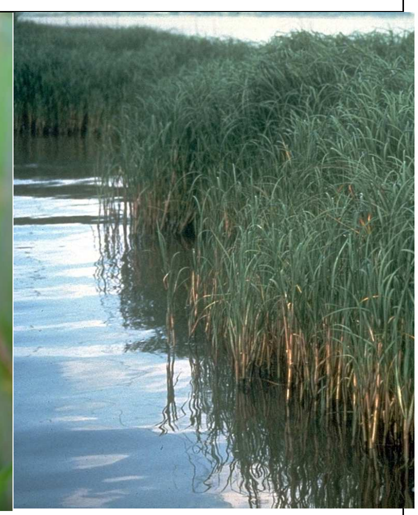
		
Solidago sempervirens (seaside goldenrod) FACW; perennial; 60–240 cm. Photograph: José Luís Ávila Silveira/Pedro Noronha e Costa, Public domain via Wikimedia Commons	*Distichlis spicata* (seashore saltgrass) OBL; perennial; 30–90 cm. Photograph: Matt Lavin via Wikimedia Commons	*Spartina patens* (saltmarsh hay) OBL; perennial; 30–90 cm. Photograph: By V. Howard, UCGS; Public domain via Wikimedia Commons
		
Hibiscus moscheutos (swamp rose-mallow) OBL; perennial; 90–240 cm. Photograph: Mokkie via Wikimedia Commons	*Juncus gerardii* (black needle rush) OBL; perennial; 30–90 cm. Photograph: Kristian Peters via Wikimedia Commons	*Spartina alterniflora* (salt-marsh cordgrass) OBL; perennial; 90–180 cm, sometimes 60–240 cm. Photograph: MPH, Public domain via Wikimedia Commons

Figure 7. Native salt-tolerant wetland species selected for green bulkhead panels. OBL: obligate wetland species in Maryland. FACW: Facultative wetland species in Maryland. Height ranges are listed.

Plant height

Plant height was measured six times between 16 July–15 November, on average every three weeks. Each plant was measured from its base to the highest photosynthetic tissue on any stem.

Flowering

All species were examined for flower production during height measurements.

Leaf water content

To obtain a species-specific indicator of relative water status, leaf water content was measured once monthly from Aug–Nov. All plant species were sampled with the exception of *H. moscheutos,* which produced so few leaves it was judged their removal would adversely affect individual survival. Individual leaves were selected at random. On two sampling dates, all plants were sampled except for those out of reach due to tide conditions; on the remaining two sampling dates, alternating plants were sampled. This approach was chosen to reduce cumulative stress on any given plant. The top five cm of a selected leaf was clipped and immediately double-bagged in plastic. Leaf fresh weights were taken within five hours of clipping. Clippings were dried for 24 hours at 70 C° and then re-weighed to obtain percent water content. Water content is expressed as a percentage of fresh weight.

Biomass

At the end of the experiment, all above-ground biomass was harvested and oven-dried for 24+ hours at 70 C° to obtain dry weights. Total dry weights were summed by species and expressed as dry g/m^2 (each individual panel level area equaled 0.03 m^2).

Soil measurements

Soil sourcing

Wetland soil was collected on 30 June from Church Creek, Homewood Farm Park (Edgewater, MD). This site is approximately 1500 m from Maryland Department of Natural Resources long-term fixed monitoring station WT8.1 - South River (mesohaline site). Soil was homogenized before being used to fill panel levels; samples of unused homogenized soil were stored at ~5° C throughout the course of the panels' installation period.

Soil moisture

Soil moisture readings were taken on a frequent, ad hoc basis using a copper/aluminum probe that registered fully saturated soil as a value of 10 on a 1-10 scale. Readings were taken at two points along the length of each level, at 14 and 28 cm from the point where water entered that level. After the experimental period, the probe was calibrated to calculate gravimentric (g/g) soil water content using irrigation water and soil taken from the panels (Fig. 8).

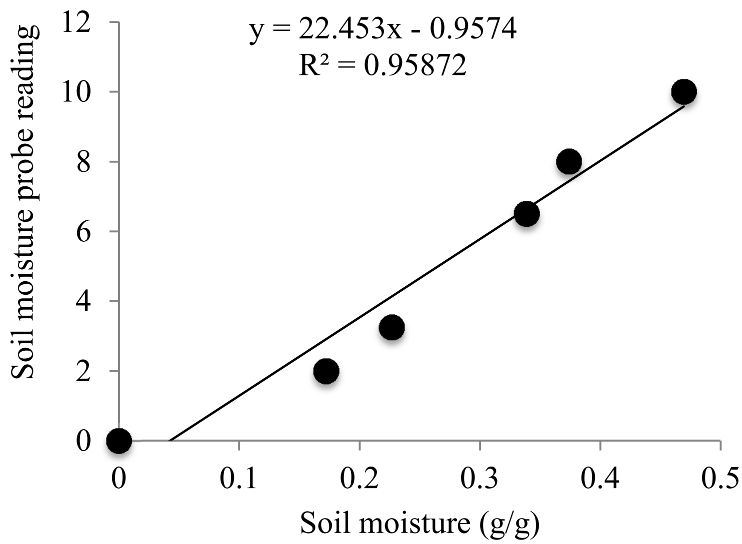


Figure 8. Calibration results of soil moisture probe.

Soil organic matter

On 31 Dec 2014–1 Jan 2015, soil subsamples were taken from three points along levels 1, 3, 5, and 6 of each panel, for a total of 36 panel subsamples. Six subsamples were also taken from original soil used to plant the panels, which had been stored at ~5° C since 4 July 2014. Subsamples were analyzed for organic matter content (% as loss on ignition, 16 hours at 400ºC).

Reducing conditions

IRIS (indicator of reduction in soils) tubes were cut to 10-cm lengths and placed as deeply as possible in the soil at panel levels 5 and 6, following Rabenhorst (2008) (Fig. 9). Seven IRIS tubes were installed at level 5 and nine tubes were installed at level 6. Tubes remained in the panels from 15 November–20 December. Paint removal from tubes was calculated using the grid method described by Rabenhorst (2012).

Figure 9. IRIS (indication of reduction in soils) tubes installed in green bulkhead panels.

<u>Arthropod counts</u>

Arthropod presence in the panels (at soil surface and in foliage) was assessed 12 times between August–November 2014 by directly searching all above-ground habitat (Ausden and Drake 2006). Each level of each panel was inspected for the presence of spiders (*Araneae)*, ants (*Formicidae)*, or other invertebrate species. These categories were selected based on the relative scarcity and lack of diversity of invertebrates noted in preliminary assessments. Each level took >120 s to search. Searches were made on an opportunistic basis during regular panel maintenance visits, which depended on high tide timing; therefore, timing of arthropod searches varied accordingly.

Reference site measurements

One objective of this study was to evaluate the extent to which green bulkhead panels functioned like native marshes. Data was therefore collected from two reference sites in Baltimore Harbor for purposes of comparison with the panels.

Reference site #1 was located at the Living Classrooms campus, on the north side of the property (39.282116, -76.597501). On 29 September 2014, six *Hibiscus* sp. and ten *Solidago* sp. individuals were randomly selected. Height and soil moisture at the base of the plant were collected; leaf cuttings were taken to determine water content as described above.

Reference site #2 was located near the Gwynns Fall South trailhead (39.273770, -76.624589). Ten *Juncus* sp. and ten *Hibiscus* sp. individuals were randomly selected and measured as above on 12 October 2014. Flowering rates were also noted for *Hibiscus* sp; because *Juncus* flowers earlier in the season, the flowering success of this genus was not described.

Results

Irrigation: water flow/retention

Trials of water flow through individual green bulkhead panels demonstrated that panels were capable of slowing and retaining a significant amount of water, although there was considerable variability between trials (Table 2). On average, in twelve trials, 28% of the 4000 ml used to irrigate panels flowed through five levels of the panels, following the intended path of flow, while 35% was retained in the panels for at least 60 minutes.

Table 2. Mean percent of 4000 ml water used to irrigate green bulkhead panels that drained fully through 5 levels of panel, was lost as leakage, or was retained in the panel for at least 60 min. N = number of individual trials.

	Mean (%)	SD (%)	N
Total drained through 5 levels	28	15	12
Total lost (leakage)	38	15	12
Total retained	34	19	12

Trials revealed considerable variation in the rates of flow through panels. In one instance, where panel soil had been allowed to dry for several days, all irrigation water either leaked from a point within the panel or was absorbed by panel soil, resulting in a total of 0 ml draining from the lowermost level (Fig. 10)

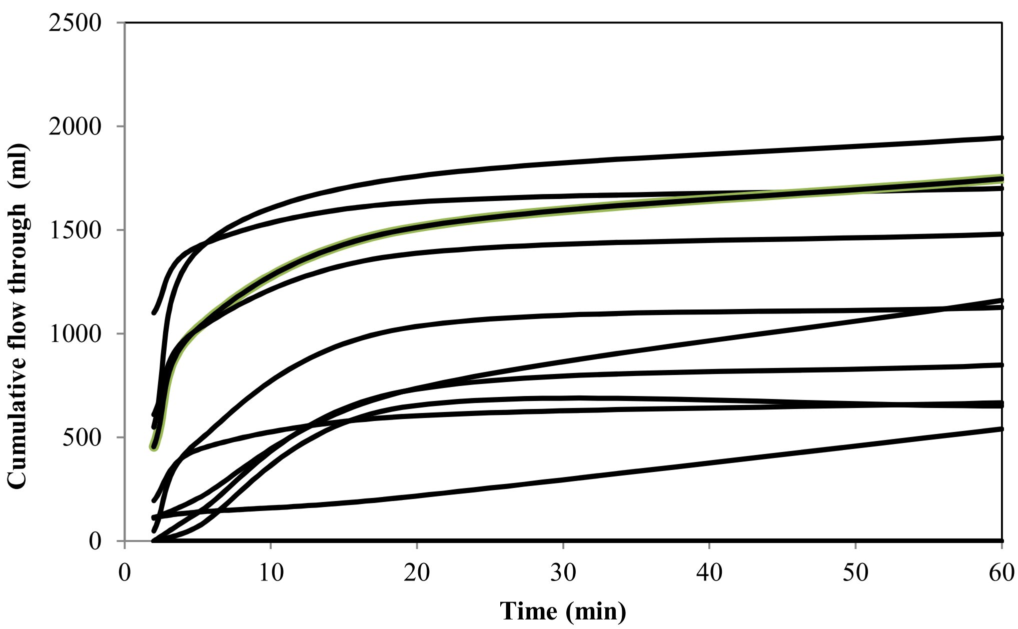


Figure 10. Cumulative amount of water (ml) filtering through five levels of green bulkhead panels within 60 minutes. Each line represents a single trial. N=12.

Considerable quantities of water were lost to leaks within the system (Table 2) either by flowing backward from the point in each level where water entered it from the previous level, or due to splashing off soil or leaf surfaces (pers. obs.).

Plant measurements

Height

With the exception of *Spartina alterniflora*, mean heights of all species decreased over the course of the installation period. *Solidago* (Fig. 11), *Distichlis* (Fig. 12), and *Spartina patens* (Fig. 13) exhibited an overall pattern of stunted growth followed by a slow decline in height over the course of the installation period. Main stems of *Hibiscus* (Fig. 14) and *Juncus* (Fig. 15) both experienced near-complete dieback by November, although *Juncus* continued to put out shoots (pers. obs.). In contrast, *Spartina alterniflora* heights initially decreased and then more than recovered, to reach roughly twice their mean starting point (mean height in November = 45.4 cm ± 5.0 cm, compared to mean height of 27.1 cm ± 2.6 cm in mid-July) (Fig. 16). No species' mean height exceeded 67 cm (the maximum mean height recorded for *S. patens* mid-growing season). *Solidago*, *Distichlis*, *Spartina patens*, *Juncus*, and *S. alterniflora* all maintained active photosynthetic tissue into November (Fig. 17).

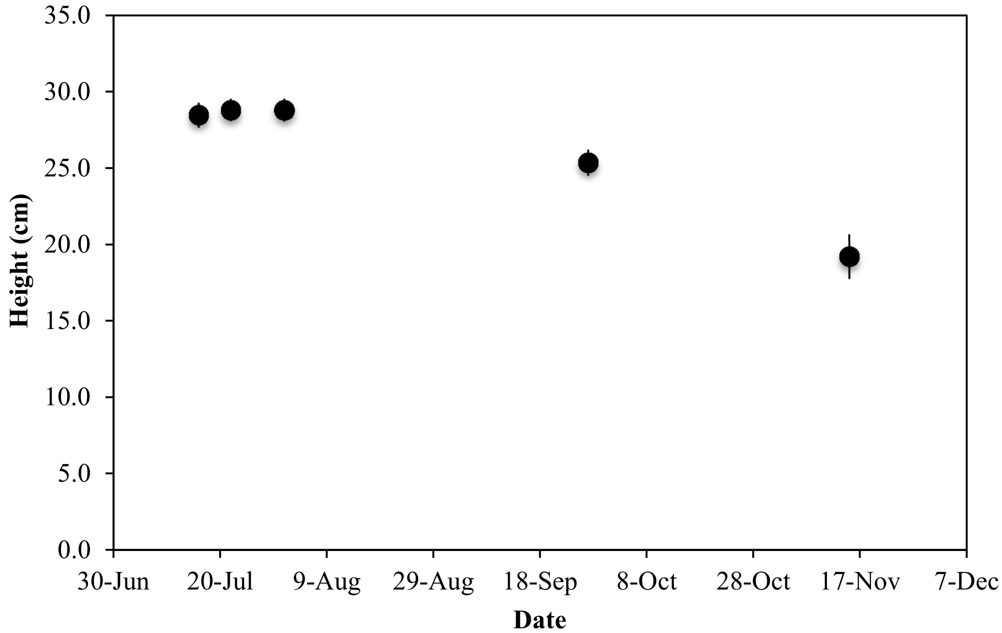


Figure 11. Mean heights (cm) of *Solidago sempervirens* planted in green bulkhead panels. Error bars are ± 1 SEM; N=18.

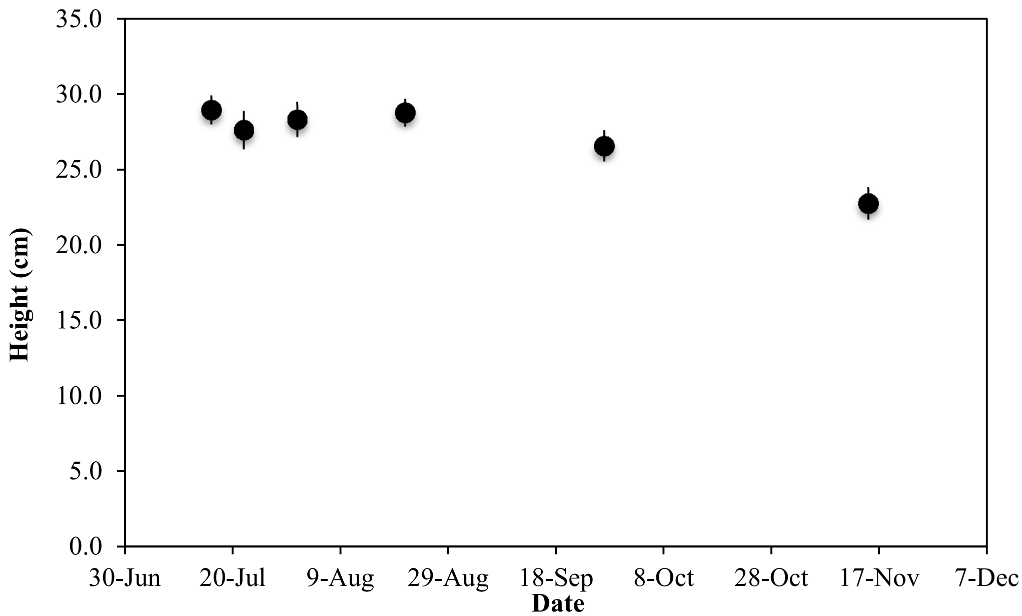


Figure 12. Mean heights (cm) of *Distichlis spicata* growing in green bulkhead panels from July–November 2014. Error bars are ± 1 SEM; N=18.

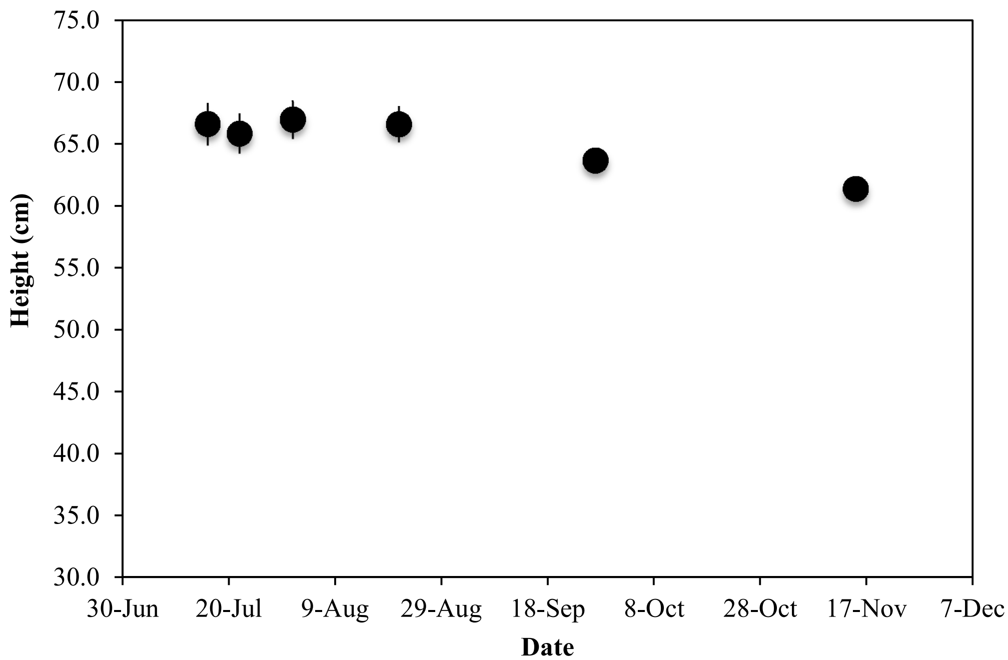


Figure 13. Mean heights (cm) of *Spartina patens* growing in green bulkhead panels from July–November 2014. Error bars are ±1 SEM; N=17.

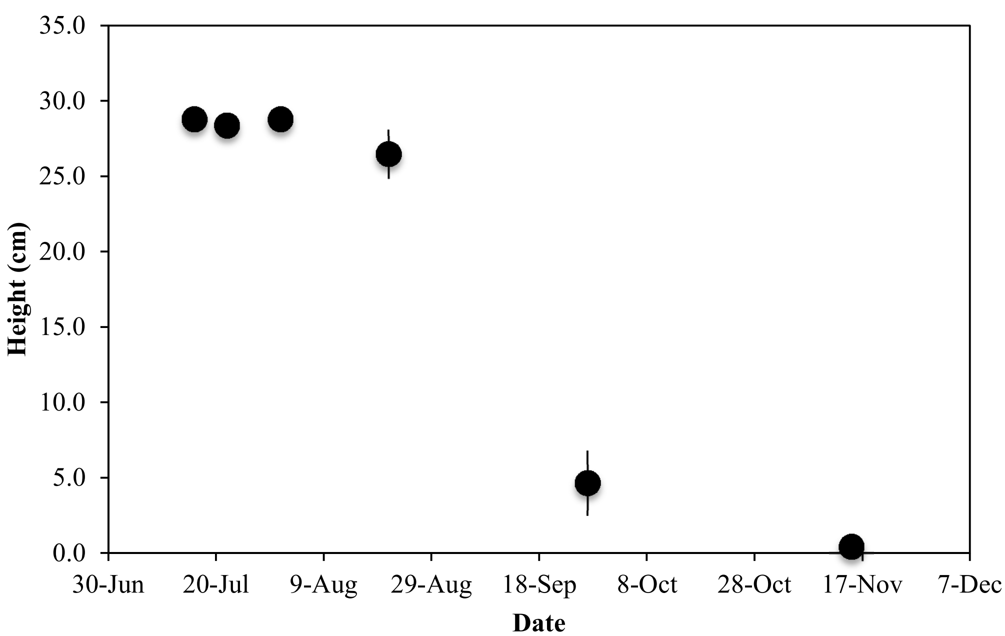


Figure 14. Mean heights (cm) of *Hibiscus moscheutos* growing in green bulkhead panels from July–November 2014. Error bars are ±1 SEM; N=15.

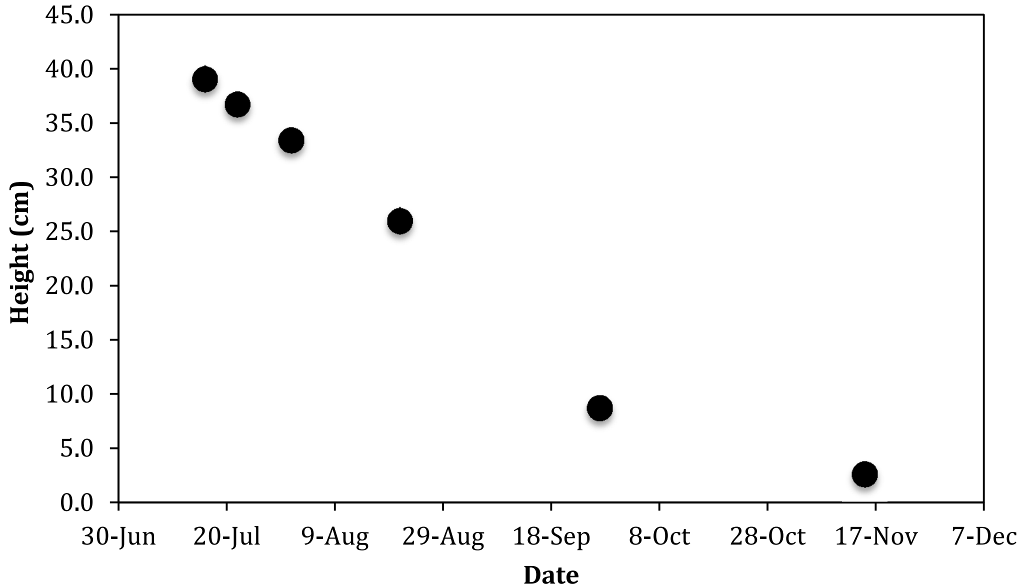


Figure 15. Mean heights of *Juncus gerardii* growing in green bulkhead panels from July–November 2014. Error bars are ± 1 SEM; N=21.

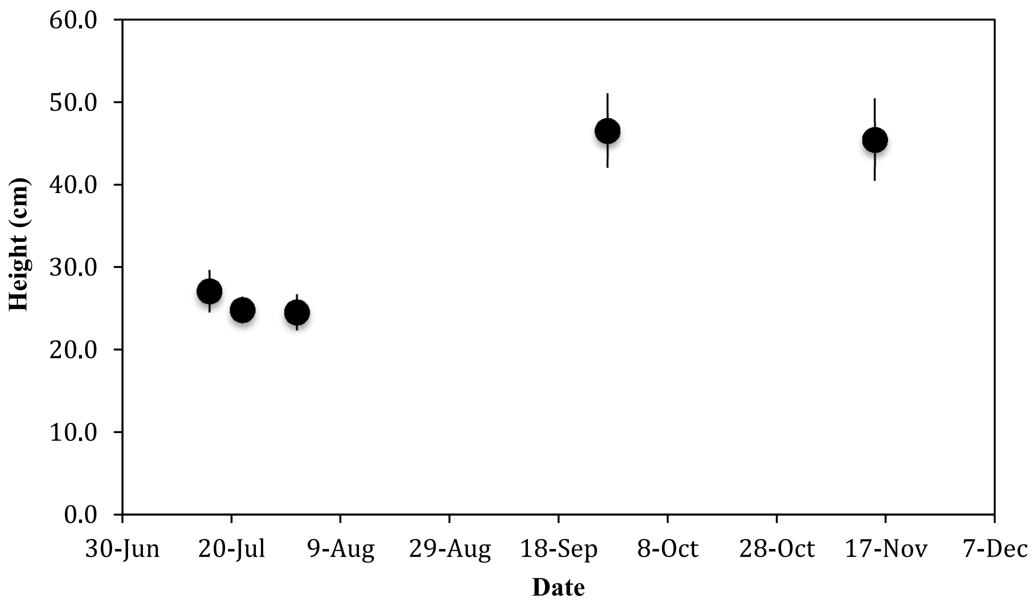


Figure 16. Mean heights of *Spartina alterniflora* growing in green bulkhead panels from July–November 2014. Error bars are ±1 SEM; N=18.

Figure 17. Green bulkhead panels in Baltimore Harbor, MD (15 November 2014).

Reference plant heights

Green bulkhead *Solidago* and *Hibiscus* measured on 9/27/14 were on average 25.3 ± 0.8 cm (*Solidago*) and 4.6 ± 2.2 cm (*Hibiscus*) high. Congeners growing in a reference marsh site and measured two days later averaged 119.5 cm ± 11.4 cm (*Solidago)* and 112.0 cm ± 6.7 cm (*Hibiscus)* high, respectively (Fig. 18).

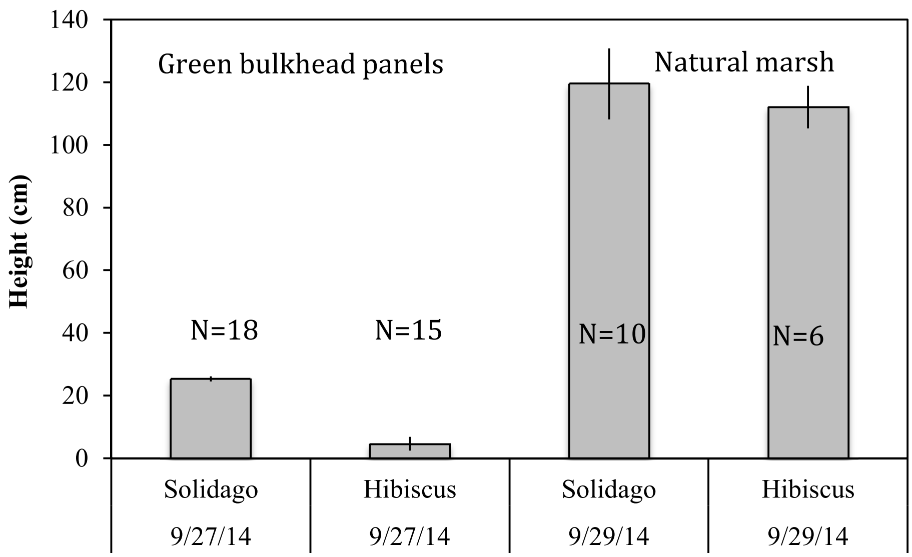


Figure 18. Mean heights of green bulkhead plants (measured on 9/27/14) and congeners from a natural marsh (measured on 9/29/14). Error bars are ± 1 SEM.

Leaf water content

Species-specific percent leaf water content expressed as average values over time either decreased slightly or did not change over the course of the panel installation period (Fig. 19).

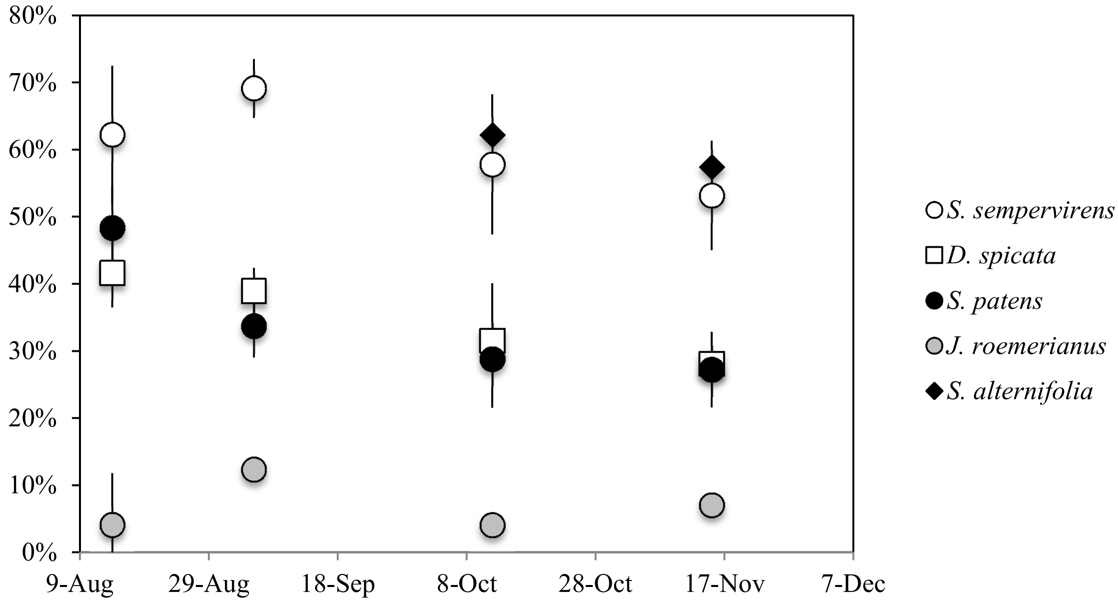


Figure 19. Leaf water content in six wetland plant species growing in green bulkhead panels in Baltimore Harbor. Means ± 1 SEM are shown.

Leaf water content was not directly comparable between reference natural marsh plants and green bulkhead panel plants because measurements were taken on different days and/or species. In one exception, *Juncus* sp. were both measured on 12 October. Natural marsh plants had far higher leaf water content (36% ± 7% compared to 5% ± 1% in green bulkhead plants) (Fig. 20).

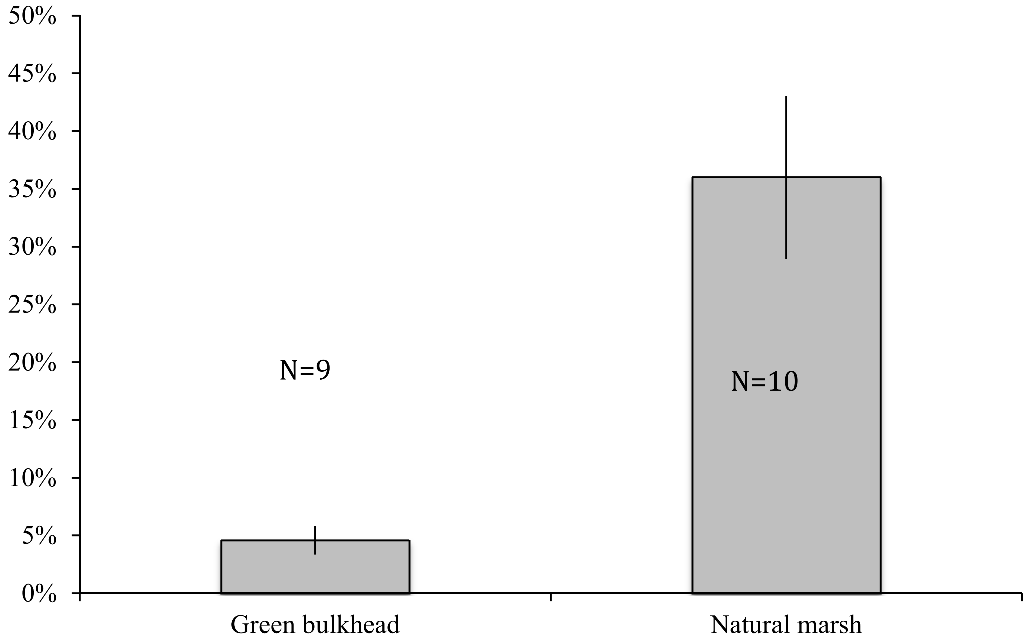


Figure 20. Mean leaf water content (± 1 SE) in *Juncus* growing in green bulkhead panels and naturally occurring marsh in Baltimore Harbor.

Flowering success

Juncus gerardii flowers in April–May; the plugs used to plant panels had already flowered when the panels were built. Two green bulkhead panel *Spartina patens* individuals flowered and set seed over the course of the installation period. No other green bulkhead species successfully flowered during the installation period. In contrast, 100% of the ten *Hibiscus* sp. individuals surveyed on 10/12 were in flower.

Above-ground biomass

When adjusted to values of dry g/m^2, biomass production ranged from 47.5 (*Hibiscus*) to 833.6 (*Spartina patens*) (Table 3).

Table 3. Above-ground dry biomass of species in green bulkhead panels harvested in January 2015.

Species	Total dry g collected	Dry g/m^2 (adjusted)	Literature values (dry g/m^2)
Solidago sempervirens	18.0	185.9	*
Distichlis spicata	15.1	156.0	991[a]
Spartina patens	80.7	833.6	807-1200[b]
Hibiscus moscheutos	4.6	47.5	1212–1224[c]
Juncus gerardii	10.2	105.4	244–524[b]
Spartina alterniflora	20.7	213.8	750–2600[d]

Literature values reported in:
[a] Hopkinson et al. (1980)
[b] Linthurst and Reimold (1978)
[c] Cahoon and Stevenson (1986)
[d] Kirby and Gosselink (1976)

Soil measurements

Moisture

Panel soil moisture was consistently high (Fig. 21) and pooling water was frequently observed in panel levels (Fig. 22) after irrigation. A one-time, temporary drop in moisture was noted in all three panels when the timer flow rate was mistakenly increased and the cistern ran out of water for 1-2 d in August.

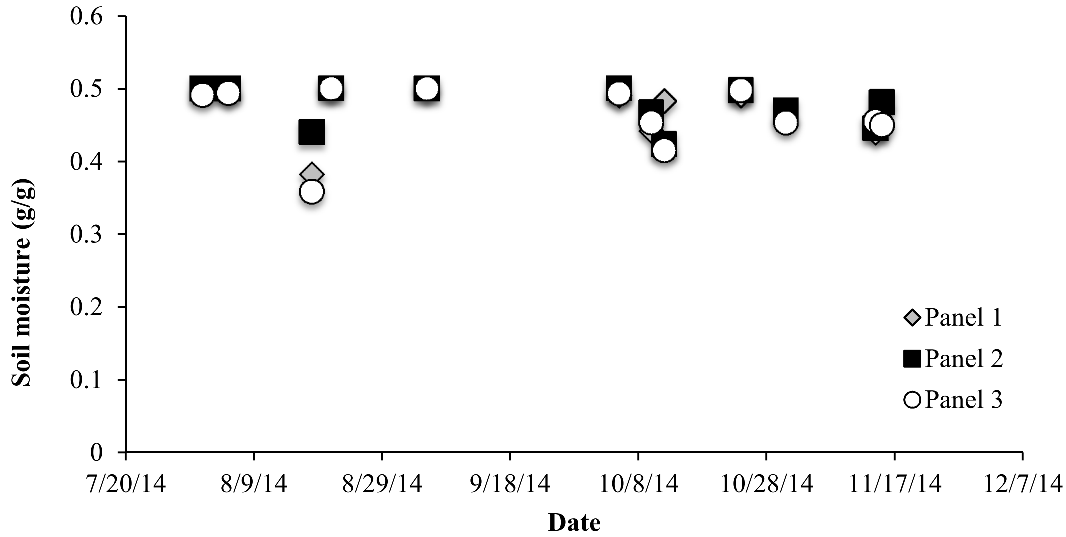


Figure 21. Soil moisture values for green bulkhead panels, July–November 2014. Each point is the mean of 8-12 readings per panel.

Figure 22. Pooling water in a green bulkhead panel after an irrigation cycle. Photograph: Lela Stanley.

The amount of water retained by panels decreased linearly with increasing mean panel soil moisture ($p=0.025$; Fig. 23).

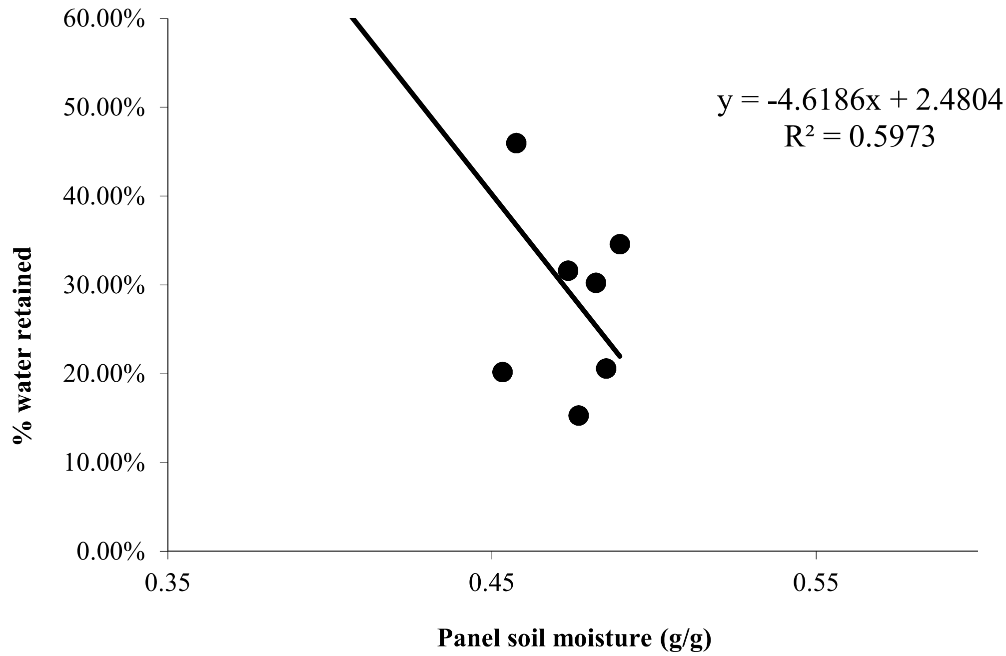


Figure 23. Water retention by green bulkhead panels as a function of mean panel soil moisture in individual trials (N=8).

Soil organic matter content

Soil subsamples taken from four levels of each panel were higher (two-sample t-tests; $p<0.05$) in soil organic matter than subsamples collected from the original soil used to plant green bulkhead panels (Fig. 24), with the exception of subsamples from level 1. SOM values ranged from 2.76 ± 0.19% in original soil used to 5.19 ± 0.71% in the soil in level 6, but did not vary significantly as a function of level ($p=0.293$; Fig. 25).

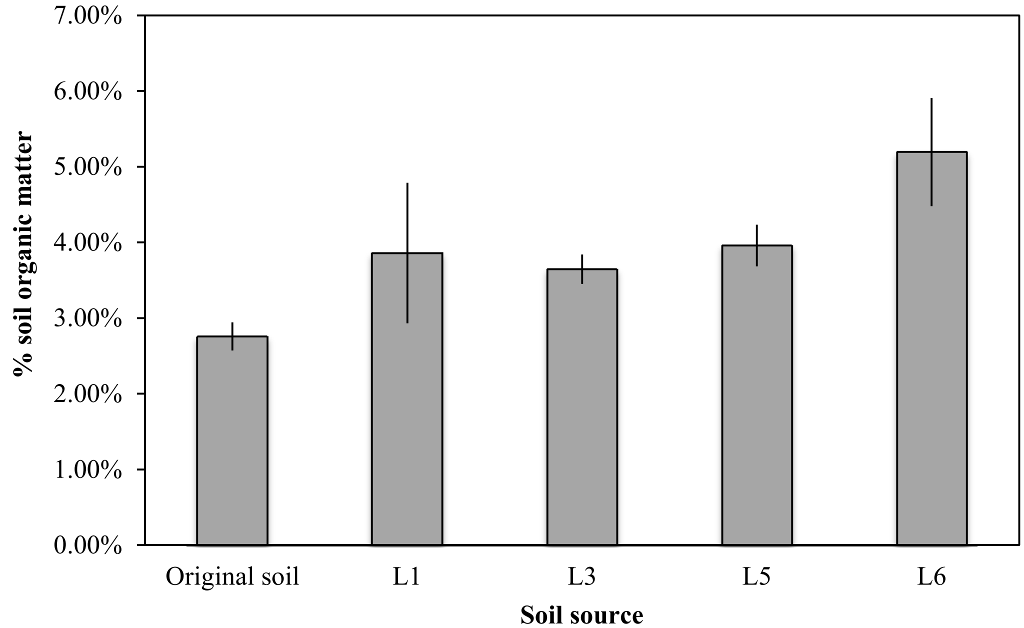


Figure 24. Mean organic matter content of soil harvested from green bulkhead panel levels (L1–L6; N=9 per level) and soil used to plant panels (N=6). Error bars are ± 1 SEM.

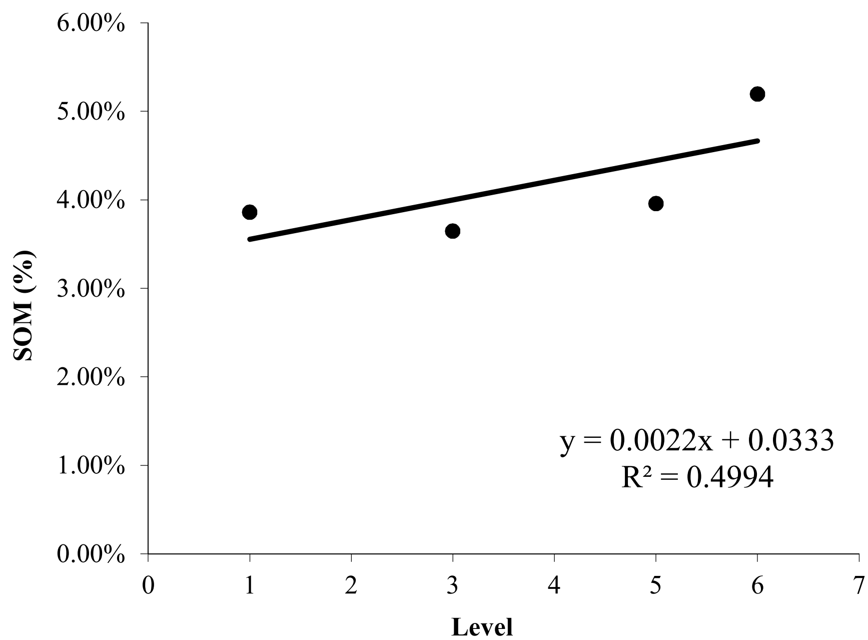


Figure 25. Soil organic matter as a function of green bulkhead panel level.

Reducing conditions

The 14 IRIS tubes installed in green bulkhead panels levels 5 and 6 demonstrated considerable variation in the amount of Fe oxide paint removed, ranging from 0–68% in level 5 and from 0–75% in level 6 (Table 4). The average amount of Fe oxide paint removed did not differ significantly between levels. Reducing conditions were present in multiple locations but most noticeably in level 6, where 6 of 7 tubes demonstrated >20% paint removal (Fig. 26).

Table 4. Percentage of Fe oxide paint removed from IRIS (indicator of reduction in soils) tubes installed at two elevations in green bulkhead panels in Baltimore Harbor, MD between 15 November – 20 December 2014. Average paint removal between levels was not significantly different (two-sample t-test; df=4; p=0.1748). N=number of panels.

Elevation above Harbor mean low water mark (cm)	Mean removal (%)	Standard deviation	Range	N
60	38.3	25.0	0-68	3
30	15.3	25.6	0–75	3

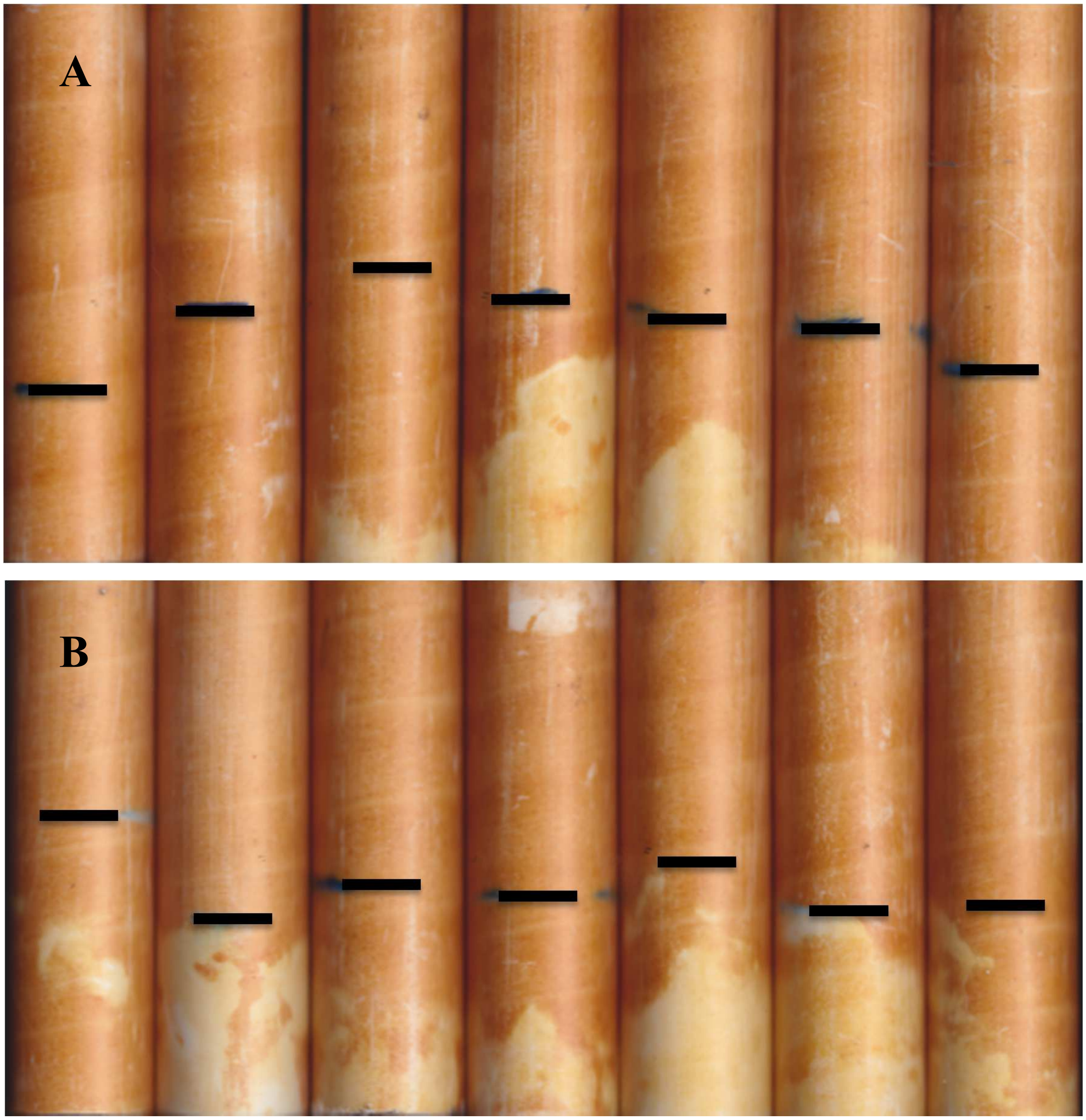


Figure 26. Fe oxide paint removal from IRIS (indication of reduction in soils) tubes installed in level 5 (A) and 6 (B) of green bulkhead panels in Baltimore Harbor, MD from 15 November–20 December 2014. Black bars represent soil height at individual tube locations.

Arthropod presence

Surveys of the green bulkhead panels revealed few arthropods. Twelve surveys over four months revealed a total of 12 spiders, 3 ants, and 4 unidentified insects (Table 5).

Table 5. Total invertebrates observed by level within green bulkhead panels, 5 August–15 November 2014.

	Arthropod group		
Level planting	Ants	Spiders	Other
Solidago sempervirens	0	0	0
Distichlis spicata	0	1	1
Spartina patens	0	3	1
Hibiscus moscheutos	3	5	0
Juncus gerardii	0	3	2
Spartina alterniflora	0	0	0
Total	3	12	4

Discussion

The green bulkhead system described in this thesis is a novel approach to green wall construction that attempts to recreate some guiding conditions of wetland ecosystems. In the Baltimore context, that wetland template is a tidal mesohaline marsh. This iteration of the green bulkhead model demonstrated significant overlap with features of both native tidal marshes and traditional green walls (Fig. 27). Green bulkhead panels successfully supported some native macrophytes throughout the 2014 growing season (Fig. 28), demonstrated the possibility of reducing conditions, and absorbed and retained water flowing through the system.

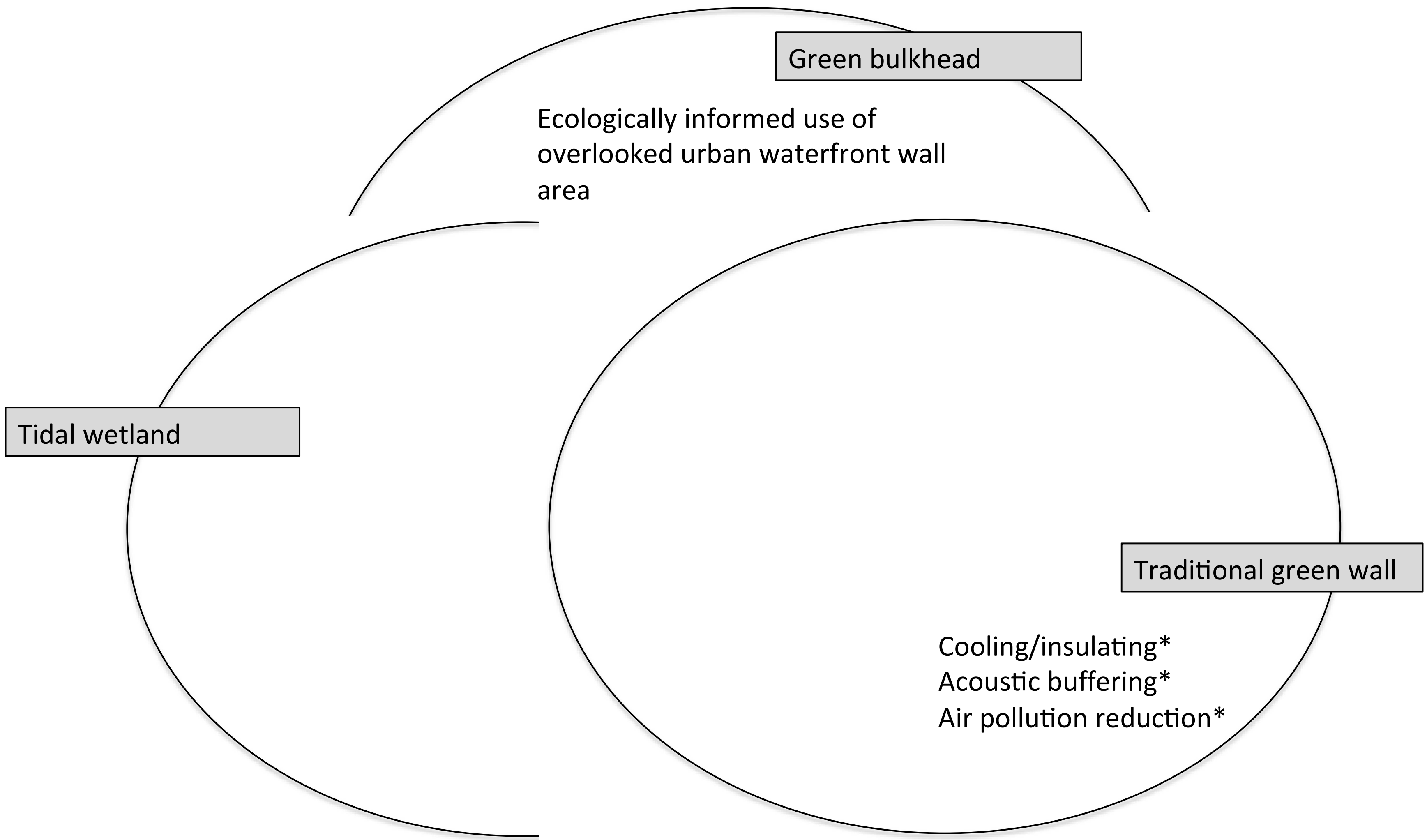


Figure 27. Venn diagram of characteristics of and ecosystem services provided by salt marshes, green bulkheads, and traditional green walls. * indicates this property was not evaluated in the green bulkhead panel system.

=

Figure 28. Green bulkhead panels on July 4 (L) and October 30, 2014 (R).

Water measurements

Flow

The design of this version of green bulkheads relied entirely on gravity to move water through the panels. Water was allowed to fall freely from the upper level into the lower one. This design choice was made to minimize complexity and materials used, and to allow gravity alone to direct water flows. Although successful in this regard, from an engineering perspective, the transition between levels was flawed. Windy conditions sometimes resulted in falling water being blown away from the wall. Allowing water to fall freely sometimes resulted in splashing and the loss of water into the Harbor. This issue could be addressed in the next design iteration of green bulkheads. Using small rain chains, for instance, would cut back on water losses while not adding significant weight or cost to panel design.

Residence time

Water turnover rates and residence times in wetlands are key elements of ecosystem function. These dynamics, influenced by factors including total inflow rate and wetland volume, in turn affect plant community composition and primary productivity, nutrient cycling, and the accumulation of organic matter (Mitsch and Gosselink 1993). In normal tidal marshes, residence time is measured in days. In contrast, the green bulkhead panels, limited by their size and steep gradient, experienced very fast flow-through (short residence times) of a percentage of irrigation water. However, not all irrigation water flowed immediately out of the panels. Even panels with moist to saturated soils retained measurable quantities of water after the 60-minute mark. On average, this figure was 35% of the 4000 ml used to irrigate panels. Factors influencing flow rate through the panels include, notably, the incline of each level and the rapid drop in elevation between levels.

Green bulkhead panels provided a total of 2.5–3 linear meters of planted soil through which water could flow, depending on whether the lowermost level was submerged. Increasing this length by increasing either the length of individual levels or by including more levels per panel would improve the residence time, thus providing longer opportunities for nutrient cycling and SOM build-up.

Vegetation parameters

In general, green bulkhead panel plants remained stunted and never approached the values observed in reference sites or in literature. While all non-*Hibiscus* species continued to put out new shoots into November (pers. obs.), overall, plants in the green bulkhead panels slowly died back over the course of the installation period with the exception of *Spartina alterniflora*. *Hibiscus* individuals fared especially poorly, demonstrating virtually complete dieback by the end of the study period. Interestingly, floating wetlands installed in the Harbor by the Waterfront Partnership and National Aquarium reported similar results with *H. moscheutos* in 2010 (Table 6).

Table 6. Comparison of plant performance in green bulkhead panels and floating wetlands installed by the National Aquarium and Baltimore's Waterfront Partnership. Assessments of floating island vegetation are provided in MDE (2011).

Species	**Green bulkhead panel**	**National Aquarium floating wetland**	**Waterfront Partnership floating wetland**
Hibiscus moscheutos	Complete dieback	Complete dieback/early senescence	Not thriving
Solidago sempervirens	Stunted growth No flowering	Extremely robust growth and flowering	Not planted
Spartina patens	Fair performance Stunted growth Limited flowering and seed production	Not planted	Fair growth Some flowering and seed production
Spartina alterniflora	Fair growth No flowering/seed production	Thriving Limited flowering/seed production	Thriving Extensive flowering/seed production
Volunteers	None	None	*Polygonum pensylvanicum*

Because each plant species was restricted to a single level within the green bulkhead panels, therefore circumventing competition between species and preventing a direct comparison between levels, it is not possible to determine why *Spartina alterniflora* rebounded and grew where other species failed. Generally, the panels presented difficult growing conditions for all species, most strikingly in the limited amount of space available for root expansion. Positioned at the lowest level within panels, *S. alterniflora* was inundated twice daily, and soils in its level demonstrated significantly higher levels of organic matter - potentially a result of that inundation and subsequent deposition of detritus. At the same time, its positioning exposed *S. alterniflora* to waterfowl herbivory, and the same detritus deposition tended to cover leaves with a heavy layer of muck, potentially reducing photosynthetic capacity.

Solidago in green bulkhead panels experienced high rates of fungal (rust) infection (Fig. 29) (pers. obs.). Rust can be caused by overly moist conditions, including watering from above (Moorman 2015). The irrigation design of the green bulkhead panels may have contributed to this infection, which in turn likely contributed to the poor growth rates observed in *Solidago*. No other pathogens were identified in green bulkhead panel plants.

Plants were installed in the green wall panels in early July, relatively late in the growing season. Earlier planting times might have allowed individuals to better acclimate to panel growing conditions.

Baltimore Harbor water has been consistently found to be high in total nitrogen and phosphorus; e.g. 2009 Inner Harbor concentrations ranged from ~1.0–3.0 mg l^{-1} (N) and 0.06–0.20 mg l^{-1} (P) (Wicks 2011). Given these concentrations in the water used to irrigate green wall panels, nutrient scarcity was likely not a contributing factor to plant growth.

Figure 29. Rust infection in *Solidago sempervirens.* Photograph: Lela Stanley.

Leaf water content

Leaf water content is no longer widely used as an indicator of plant water stress because of the high variability between species leaf water contents (Jones 2007). However, on a per-genus basis it may serve to illustrate the different conditions experienced by particular green bulkhead plants, e.g. *Juncus*, versus congeners growing in natural marshes. Although green bulkhead plants were saturated on a regular basis, their root systems may have been too constricted to benefit.

Soil parameters

Panel irrigation schedules, soil moisture and reducing conditions measurements, and the frequent visible surface pooling of water in green bulkhead panel levels all support the conclusion that panel soils were frequently flooded. Due to equipment limitations, however, irrigation schedules could not follow a diurnal tidal schedule, and so only levels that were directly inundated at high tide (containing *Juncus gerardii* and *Spartina alterniflora*) were flooded on a natural tidal schedule.

Organic matter

Soil organic matter content in wetlands is critical to overall ecosystem functioning, including plant establishment and growth, cation exchange, water retention, and N fixation (Zedler and Callaway 2001). Although the green bulkhead panels are not a form of ecological restoration per se and were not intended to exactly mimic conditions of local wetlands, their SOM content still provides a useful indicator of function.

Soil organic matter content in green bulkhead panels was low compared to literature values for brackish tidal wetlands. Morrissey et al. (2014) report SOM values of 16.4% ±7% for a brackish Chesapeake wetland. Their numbers, like those in this thesis, were calculated via loss on ignition. Although low, SOM values from green bulkhead panel soil were still higher on average than subsamples collected from stored original soil used to plant panels. This suggests that some accumulation of SOM is due to Baltimore harbor conditions. In Baltimore, water quality is compromised not only by nutrient concentrations, which are consistently unacceptably high (Wicks et al. 2011), but also by a profusion of garbage flowing through the Gwynns Falls and Jones Falls Creek outfalls (Fig. 30). Lower levels of the green bulkhead were submerged by tidal flux on a regular basis and experienced visible deposition of a remarkable diversity of organic matter and detritus including leaves, plastic trash, and woody debris. Frequent flooding also saturated the soil at those levels. Both of these dynamics may have contributed to the slightly higher build-up of soil organic matter in lower panel levels.

Figure 30. Trash and woody debris are left behind after heavy rains in October 2014. Green bulkhead panels are obscured by the ramp to the right. Photograph: Lela Stanley.

Reducing conditions

IRIS (indication of reduction in soils) tubes signal the presence of reducing conditions by the amount of Fe oxide paint removed from a tube during its installation in suspected hydric soils (Rabenhorst 2008). IRIS tube use typically calls for 60-cm tubes to be installed in soils for ~4 weeks. Upon removal, the top ~15 cm of a tube is inspected for paint removal. If 20% of the paint has been removed, reducing conditions are expected to be present 90% of the time (Rabenhorst 2008).

The very shallow soils of the green bulkhead panels precluded typical installation. Soil in each level was ~5 cm deep. However, reducing conditions were still present at several tube locations throughout the panels, notably in level 6. The fact that paint removal took place during an especially cold 5-week period of the year (15 November–20 December) when microbial activity is lower suggests that reducing conditions would be even more extensive in warmer weather. Since levels 5 and 6 experienced tidal inundation as well as regular irrigation, more extensive use of tubes, or Eh electrode measurements of reducing conditions at each level, would provide information on whether regular irrigation alone is sufficient to produce reducing conditions throughout panels.

Arthropod presence

Surprisingly few arthropods were observed using the green bulkhead panels. No surveys of unused (non-greened) bulkheads were made for comparison. However, even conservatively assuming that no arthropods would colonize unmodified bulkheads, the low diversity and richness of observed invertebrates observed in green bulkhead panels is striking. Extrapolated to total counts/m^2 over the observation period, green bulkhead panels supported fewer than 100 individuals/m^2. In contrast, Angrandi et al. (2001) report total macroinvertebrate densities in brackish *Spartina alterniflora* and *Phragmites australis* marshes in New Jersey on the order of 82,000–97,000/m^2. Several elements of the panel design and performance may explain this.

Surveys were strictly observational, relying on direct searches of above-ground habitat to find individuals; no destructive methods such as traps or vacuum collections were used. This likely contributed to severely underestimating the total arthropod population.

However, it may be more useful to compare these green bulkhead panel arthropod numbers with those of other green walls In her survey of arthropod use of urban green walls, Matt (2012) found on the order of 6-10 (least square means) individuals per $0.56m^2$ quadrat in summer (June-August) months. These numbers, though collected using vacuum sampling, are significantly closer to green wall panel arthropod totals and suggest this comparison may be more appropriate.

Finally, vegetation cover within panels was generally patchy and may not have provided sufficient cover for arthropod species. These results suggest that the green bulkhead panels, at least in isolation, do not afford choice arthropod habitat. Increasing the number of panels (reducing bulkhead habitat patchiness) and increasing the foliage cover within each panel would partially address this issue.

<u>Panel design and durability</u>

Design process

Each choice made in the design process limits and directs subsequent choices and the ultimate product of the process. For instance, numerous internet searches, personal communication with garden stores, and queries on Internet gardening fora yielded a single available model of timer that could function with the very low water pressure of the green bulkhead cistern. That timer, which was used for green bulkhead panel irrigation, had a limited number of predefined, inflexible settings for watering duration and frequency. This influenced the watering schedule for green bulkhead panels and ruled out the possibility of watering them only at high tide, for instance.

Panel design considerations included the following limitations. The total amount of bulkhead space could be no larger than the space provided by Living Classrooms (a ~2m X 3 m area). Panels needed to be lightweight enough to be handled and installed by an individual researcher, but at the same time sturdy enough to hold multiple levels of planted and frequently saturated soil. Water retention time and minimalist design were prioritized. Finally, the working budget was conservative, which limited material selection and prioritized use of materials on hand.

In these regards, the panel design succeeded. However, sacrifices were made in other areas. The result was not aesthetically pleasing (pers. obs.), although it drew considerable interest from marina users, who frequently stopped to ask how the panels worked.

Model durability

The green bulkhead panel model proved physically durable. Over its 24-week installation period, no components of the model failed or needed replacement, with the exception of the timer. This failed in mid-September, after only two months, and was replaced with an identical model. Heavy summer rains did not compromise panel structural integrity, nor did tides rising as high as level 4 (Fig. 31) wash any plants out of the panels. The two other attempts at developing green bulkhead-like systems, reviewed in Dyson and Yocom (2015), failed at this point in deployment, although both of those examples were on river walls where tidal forces may have been stronger. The panels' installation in a sheltered section of the harbor likely contributed to their success in this regard.

Figure 31. Heavy rainfall and high tide submerged green bulkhead panels as high as level 4 (L), stranding a hapless fish (R) and washing debris into the panels. No other adverse effects of high tide levels were observed. Photographs: Lela Stanley.

Algal growth in the irrigation hoses was so light that no cleaning was required throughout the entire growing season. However, algae frequently clogged the timer's filter, requiring maintenance to allow the irrigation system to function. A single instance of bivalve biofouling was also recorded, wherein several larval molluscs had [adhered] and grown to ~1cm inside the hose connecting the water tank to the timer (Appendix 2).

Accessibility and maintenance

At 10,800 cm^2 and ~19.5 kg when planted, individual panels were unwieldy to move and adjust as a unit. The ability to easily remove individual planted levels made it possible for a single researcher to install panels.

The bulkhead location provided by Living Classrooms was in a shallow area, where low tides routinely left the entire green bulkhead panels exposed. This made it possible to access all but one individual level either from above or below the installation, at low tide. (Panel 1/Level 2 was not accessible from either direction and as such could not be included in arthropod surveys.) Most bulkhead areas in the Inner Harbor are not as easily accessed. For green bulkheads to be deployed on a large scale, either maintenance would need to take place from the water (e.g. via municipal vessel) or bulkhead panel would need to be light enough to be readily removed from the top of the bulkhead. The former scenario is more practical, but raises new issues of boat traffic and operating time.

Major issues and delays encountered with green bulkhead panel design, assembly and operation were primarily the result of operator inexperience.

Study problems and sources of error

Space and budget constraints precluded creating more than one set of bulkhead panels. Any subsequent trials of this model should deploy several replicate sets throughout the Harbor in order to directly test similarities with natural marsh conditions. At the same time, extensive reference marsh plant and soil sampling was not done for this thesis. Having a robust set of such measurements to better contextualize and evaluate the performance of the green bulkhead panels is an invaluable

Time and financial considerations likewise precluded water quality testing on the 2014-2015 green bulkhead model. Particularly given the emphasis of Baltimore Harbor decision-makers on improving water quality, subsequent green bulkhead design testing would be well advised to incorporate testing improvements. Any significant reduction in these parameters would increase the value of green bulkhead design.

Recommendations for future designs

Although the panels were originally inspired by Chesapeake Bay marsh zonation, because of the intertidal compression experienced in the Harbor, actual zonation is very different than that in native marshes (see e.g. Chapman 2006). In salt marshes, factors influencing zonation range from salinity and inundation tolerance to extant mycorrhizal fungi (Daleo et al. 2008). It would be informative for urban waterfront ecological design as a discipline to understand what the comparable factors in city harbors and riparian systems are. To test this, replicate panels could be pre-planted with the same mixture of species at each level and deployed at several locations around the Harbor under, for example, different light conditions (south- vs. north-facing), protection from debris, etc.

Design constraints imposed by various elements (e.g. timer settings) made it impossible to irrigate green bulkhead panels on a truly tidal schedule. This moved them conceptually one step further from the original marsh ecosystem template. Devising a way to use actual tidal flux to water walls – whether by constraining them to a single planted level within the natural narrow urban intertidal, or by mechanical means.

Sustainability

It may be tempting to assume that green walls are an inherently more sustainable option than leaving walls bare. This is not necessarily the case. Feng and Hewage (2014) considered the environmental costs of producing, maintaining, and disposing of three green wall modalities (trellis, planter box, and felt layer) balanced against their air pollution removal and cooling benefits. They found that materials selection can have a profound effect on the overall sustainability of a green wall system: e.g. that a felt layer system containing PVC foam would not subsist long enough to balance out the costs of its production. Significantly more thorough quantification of green bulkhead benefits would be necessary in order to assess their overall environmental cost/benefit ratio. For instance, panels were not evaluated for their cooling properties. In fact, because panels were made of primarily black materials, it is possible that they actually raised the temperature of the bulkheads more than they cooled it (via shading and evapotranspiration). Ambient air temperatures inside the panels were almost certainly higher than their surroundings as a result of these dark materials. This may have influenced plant survivorship and performance by increasing heat stress during the summer months, and/or by warming the panel microclimate in cooler fall months, thereby potentially lengthening the growing season.

Societal benefit

It is interesting to speculate on the non-ecological effects of deploying green bulkheads at a large scale throughout the Harbor. Research on the psychological benefits of green walls specifically is sparse, but numerous studies have indicated a positive link between green spaces and mood, and between the perception of biodiversity and psychological well-being (Fuller et al. 2007). Barton and Pretty (2010)'s review showed that exercise near green spaces, including water, improved mood and self-esteem, while Taylor et al. (2002) found that views of nature replenished directed attention and improved self-discipline in girls living in urban neighborhoods. These results tantalizingly suggest that greening large, currently blank areas like urban waterfront walls (Fig. 32) could have benefits to communities that extend beyond the ecological ones already enumerated here. The green bulkhead model offers a way to integrate such urban waterfront greening with extant architectural choices, as well as a paradigm for future urban landscape design.

Conclusions

Baltimore's Inner Harbor bulkheads can be ecologically engineered to support green walls that provide some of the functions of native marsh ecosystems, including slowing and retaining water used to irrigate them and growing some species of native macrophytes, particularly *Spartina alterniflora*. This design of green bulkheading does not compromise bulkhead/retaining wall function, is modular and easily removable, and maintains a shallow horizontal profile so as not to interfere with boat traffic.

Urban waterfront walls are an abundant spatial resource that have to date been overlooked in the development of green wall technologies. Using this space to promote the restoration of some ecological function is an example of a reconciliation ecology approach to urban development relevant to any city with a river, harbor, or coastline. As sea levels rise, cities are increasingly challenged to rethink and redesign their coastal and waterfront infrastructure (Airoldi et al. 2005). Green bulkheads offer an opportunity to do so in a way that restores ecological function to the urban landscape.

Figure 32. Bulkheads in Baltimore's Inner Harbor without (above) and with (below) rendition of green bulkhead modifications. Illustration and photograph: Lela Stanley.

Chapter 3: Design and Performance of a Grassland-Inspired Green Wall

Introduction

Green façades and living walls, here collectively termed green walls, are a rapidly growing field at the intersection of ecology, horticulture, architecture, and urban design. Depending on their structure, irrigation design, and plants used, green walls can provide a range of benefits from building envelope shading and cooling and graywater recycling to food provision and arthropod habitat (Dunnett and Kingsbury 2008, Loh 2008, Köhler 2008, Matt 2012).

Compared to the closely related field of green roof development, research into the functions and performance of green walls, including the viability of native Mid-Atlantic species for green walls, is sparse. Furthermore, few studies have examined the potential to recreate elements of naturally occurring ecosystems using green walls. Francis and Lorimer (2011) propose this approach as a form of reconciliation ecology: using otherwise overlooked "edges" of anthropogenically dominated landscapes to foster the development of ecosystems, which may resemble natural analogues to a greater or lesser degree.

Like green roofs, green wall environments on building exteriors offer harsh growing conditions. Thin substrate levels and increased wind speeds and temperatures, driving increased evapotranspiration compared to ground level, are all identified issues (Dunnett and Kingsbury 2008). Green wall growing conditions are further complicated compared to green roofs by the pull of gravity on plants, substrate, and water. Some of these dynamics, especially the movement of water, are mitigated to a degree by green wall design elements (see Manso and Castro-Gomes 2015), but green walls are still a broadly challenging place in which to grow.

These challenges presented by green walls can be compared to physiological stressors in natural ecosystems. Cliffs are often postulated as the closest natural analog to green walls (Lundholm and Richardson 2010). Another possible template is the serpentine grasslands of North America. Well known for the endemic, rare, and unusual assemblages of species they support above serpentinite deposits (Latham 1993), serpentine areas present generally high-light conditions and dry, nutrient-limited soils (Latham 1993).

This convergence of natural and designed systems presents an interesting dynamic. Once planted with species tolerant of moisture-limited, thin soils, how would green wall panel plant communities self-organize? We hypothesized that species characteristic of serpentine grasslands should be able to survive in thinly soiled, low-moisture green walls, but that they would demonstrate better performance with regular irrigation than rainfall alone. We further hypothesized that volunteer species composition would vary between different watering regimes and between planted and unplanted levels within a green wall panel.

Materials and Methods

Green wall panels were installed and operated from July 18, 2014–October 31, 2014 on the University of Maryland College Park, MD campus.

Study species selection and sourcing

A list of common plant species found in Eastern serpentine barrens grasslands was compiled based on Latham (1993), Tyndall (1993) and Tyndall and Farr (1994). This list was then narrowed down to include only plants currently (in June 2014) available in 2” (5.1 cm) plug sizes at local Mid-Atlantic native plant nurseries. Two species (*Schizachyrium scoparium*, little bluestem, and *Sorghastrum nutans*, Indiangrass (Fig. 33), both C4 grasses, were selected from the final list of 5 available species. Plants were ordered as 2” (5.1 cm) plugs from Mid-Atlantic Natives (New Freedom, PA).

Schizachyrium scoparium (little bluestem) Photograph: Chhe/Wikimedia Commons/Public Domain	*Sorghastrum nutans* (Indiangrass) Photo: Matt Lavin/Wikimedia Commons/Public Domain

Figure 33. Grass species chosen for grassland–inspired green wall panels.

Green wall panel construction

Six panels were constructed using wooden pallets (100 cm wide X 122 cm high) as frames, and waterproofed with 1-mm plastic slip covering. Each panel held four wooden levels set at angles of ~2º from the horizontal, tilted alternately right and left to allow water to drain from one level into the next. These levels supported lengths of corrugated 4” (10.2 cm) diameter drainage pipe, with a 6.4-wide cm cut made to allow plant growth. Rows were screwed directly into panel backing for additional support, and could be removed easily for maintenance. Each row was filled with 2000 ml soil, or to approximately 5 cm depth, which was collected in June 2014 from a nearby floodplain meadow on the University of Maryland campus.

Panels were aligned at 20” intervals and secured along the east-facing wall of the University of Maryland Animal Science building wing 5 (College Park, MD) (Fig. 34).

Figure 34. Green wall panels installed at the University of Maryland (College Park, MD).

Green wall terminology and classification systems are still in a state of flux (e.g. Francis and Lorimer 2011, Manso and Castro-Gomes 2015), but practitioners separate these approaches to modifying building walls into several categories based on their physical characteristics. Using the classification system proposed by Manso and Castro-Gomes (2015), this design is a type of modular tray living wall.

Planting design

Wall panel levels L1-L4 were planted as follows: L1 was planted with two individuals each of *Sorghastrum nutans* and *Schizachyrium scoparium*, alternating between species; L2 contained five *S. nutans* individuals; L3 contained five *S. scoparium* individuals; and L4 was left unplanted (Fig. 35).

L1: *Sorghastrum nutans* and *Schizachyrium scoparium* alternating

L2: *Sorghastrum nutans*

L3: *Schizachyrium scoparium*

L4: Unplanted

Figure 35. Planting diagram of green wall panels.

Watering

Wall panels 1, 3, and 5 were designated as watered walls, while walls 2, 4, and 6 were left unwatered. Over the course of the experiment, watered panels received a total of 120 L water each (4 L every ~3 d) from irrigation, in addition to rainfall. Unwatered panels received only rainfall.

Panels were watered in four-liter increments, an amount that allowed each level to be fully saturated. When watering panels, all water was poured into the beginning of the top level and allowed to drain through each level in succession.

Rainfall was measured with a gauge installed on Panel 2. A total of 10.4 cm was collected over the course of the experiment (July 23–October 31).

Vegetation measurements

Height

Stem heights (base of stem to tallest visible photosynthetic tissue on a plant) of *Sorghastrum nutans* and *Schizachyrium scoparium* were measured once monthly from July–October. Rapid and complete dieback of plants in unwatered walls meant that these measurements were only taken in July for this subset of plants.

Leaf water content

Leaf water content of grasses was measured in July, September, and October. Leaves were selected at random from each *S. nutans* and *S. scoparium* individual. The top five cm was clipped and immediately weighed. Clippings were dried for 24 hours at 70 C° and then re-weighed; leaf moisture is expressed as a percentage of original fresh weight.

Flowering success

Flowering was noted in *S. nutans* and *S. scoparium* individuals at the same time height measurements were made. Flowering success in volunteer species was not assessed systematically but was noted on an ad hoc basis.

Volunteer species surveys

All volunteer plants growing in watered panels were counted on three dates (8 August, 9 September, 30 October). Unwatered panels had no volunteer species on the first two survey dates and were thus excluded from surveying.

Climate

Precipitation data was sourced from the National Oceanic and Atmospheric Administration's National Climatic Data Center (NOAA-NCDC) (College Park, MD station) to provide a comparison with rain gauge measurements. Temperature data for the experimental period was sourced from NOAA-NCDC (Beltsville, MD station, ~6 km from site). This data was unavailable for the College Park station.

Temperature and precipitation amounts during the experimental period were typical for the Mid-Atlantic region (Table 7).

Table 7. National Oceanic and Atmospheric Administration National Climatic Data Center temperature[1] and precipitation[2] data for July–October 2014.

	Monthly average temp (ºC)				
Month	High	Low	Maximum high (ºC)	Maximum low (ºC)	Precipitation (total cm)
July	29.4	18.9	35.0	13.9	8.3
August	27.6	17.1	31.7	11.7	8.2
September	25.8	15.3	32.8	6.1	6.4
October	20.2	9.6	26.7	1.7	5.9
				Total	28.8

[1]Beltsville, MD station
[2]College Park, MD station

Results

Plant height

Plants of both species in unwatered panels demonstrated a rapid and complete dieback. *Sorghastrum* nutans unwatered plant height fell from 19.8 ±1.2 cm to 0 by the second measurement period (Fig. 36). This pattern was consistent among all planted levels.

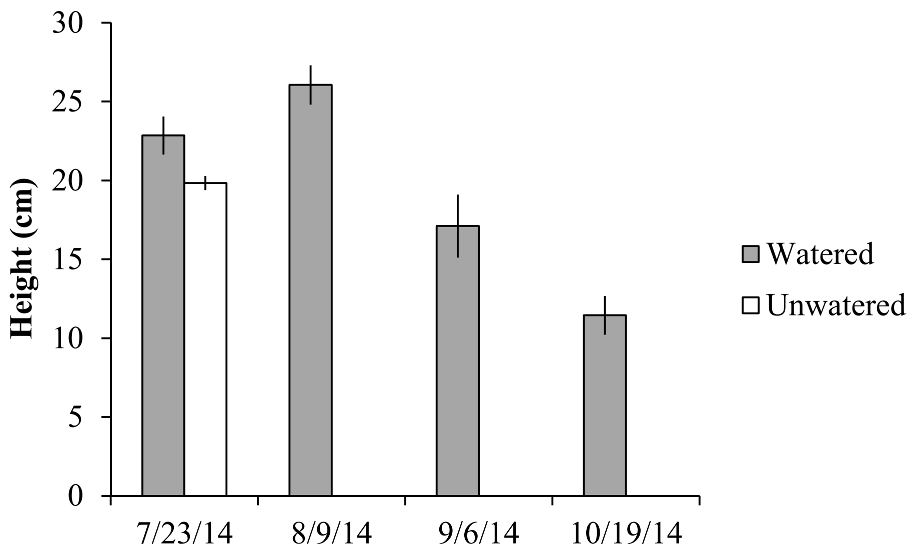


Figure 36. Heights (in cm) of all *Sorghastrum nutans* growing in watered and unwatered green walls. N=3. Differences are not statistically significant on the July measurement (two-sample t-test; p=0.0785). After the July measurement, all unwatered plants had died completely back. No initial measurement data was taken; July data represents plant height after ~1 week at experimental conditions. Means ± 1 SEM are shown.

Schizachyrium scoparium demonstrated a similar pattern of unwatered plants dying immediately; in this species, watered plants exhibited an insignificant decline in height from August–October (Fig. 37).

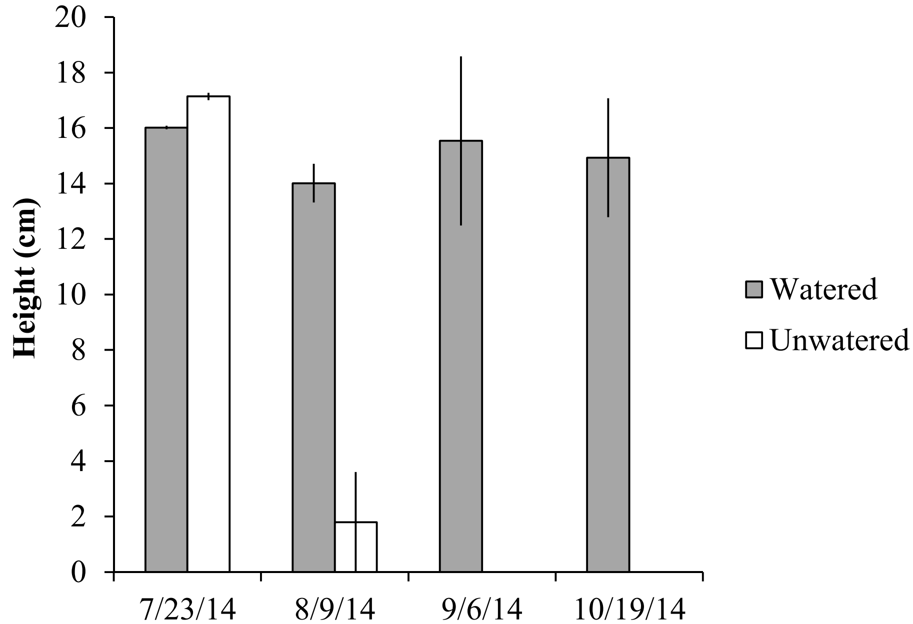


Figure 37. Heights (in cm) of *Schizachyrium scoparium* growing in watered and unwatered green walls. N=3. Differences are significant in July (two-sample t-test, df=4, p=0.0015). A single plant was still alive in August in unwatered walls; after this point all unwatered plants had completely died back. No initial measurement data was taken; July data represents plant height after ~1 week at experimental conditions. Means ± 1 SEM are shown.

Watered panel plants also died back over the course of the growing season, but at different rates and to different degrees depending on species and level. Comparing species performance by row shows that level 1 plants of both species died back faster than plants of the same species in a lower row, though differences were not always significant (Fig. 38, Fig. 39).

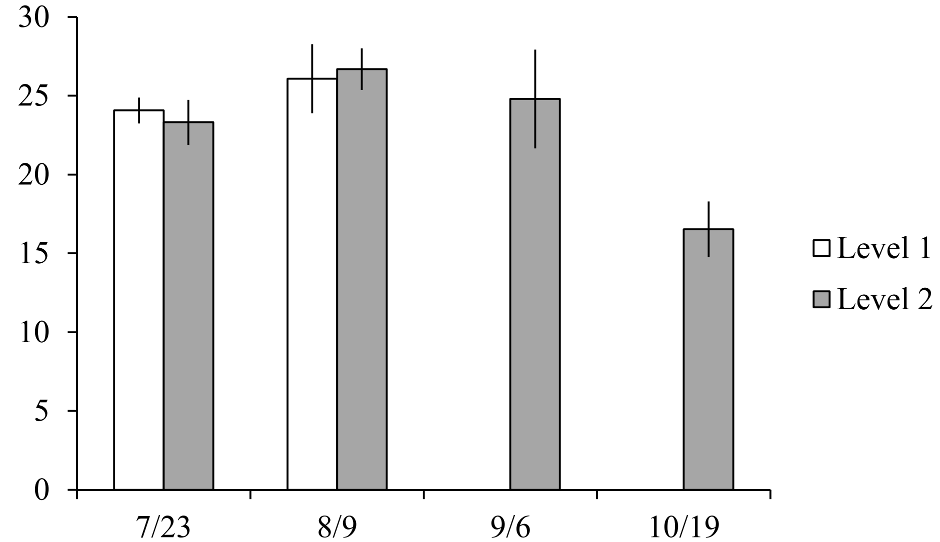


Figure 38. Heights of *Sorghastrum nutans* growing in levels 1 and 2 of green wall panels in autumn 2014. Values for level 1 plants in September and October = 0. N=3. Differences are not significantly different in July (two-sample t-test, df=4, p= 0.6758) or August (p=0.8225); by the September measurement all Level 1 plants were dead.

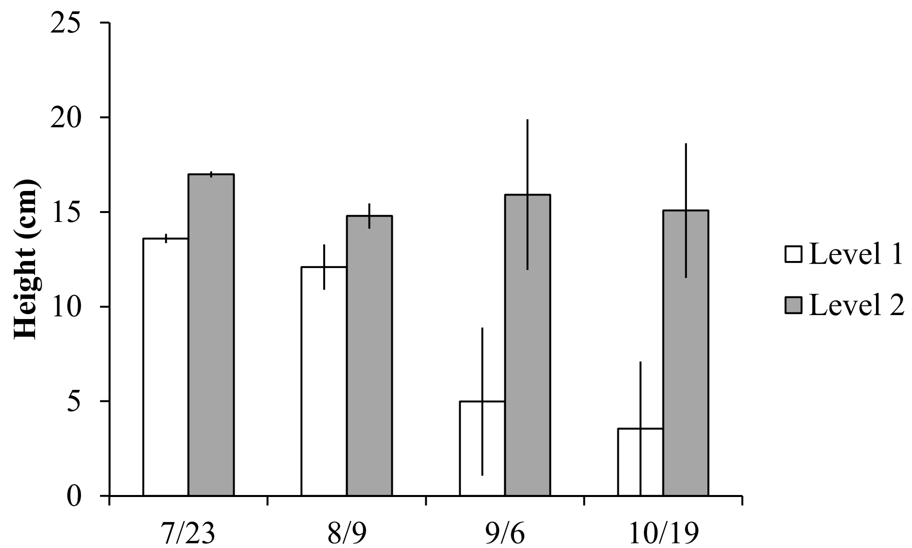


Figure 39. Heights of *Schizachyrium scoparium* growing in levels 1 and 3 of green wall panels in autumn 2014. N=3. Differences were significant on the July measurement dates (two-sample t-test, df=4, p=0.0004) but not the August, September, or October measurements (p=0.1195, p=0.1220, p=0.0838).

Leaf water content

Unwatered wall plants of both species demonstrated the same pattern of rapid reduction in leaf water content as their height dieback (data not shown).

When compared by growing level, leaf water content of *Sorghastrum nutans* fell in both levels over the course of the experimental period (Fig. 40).

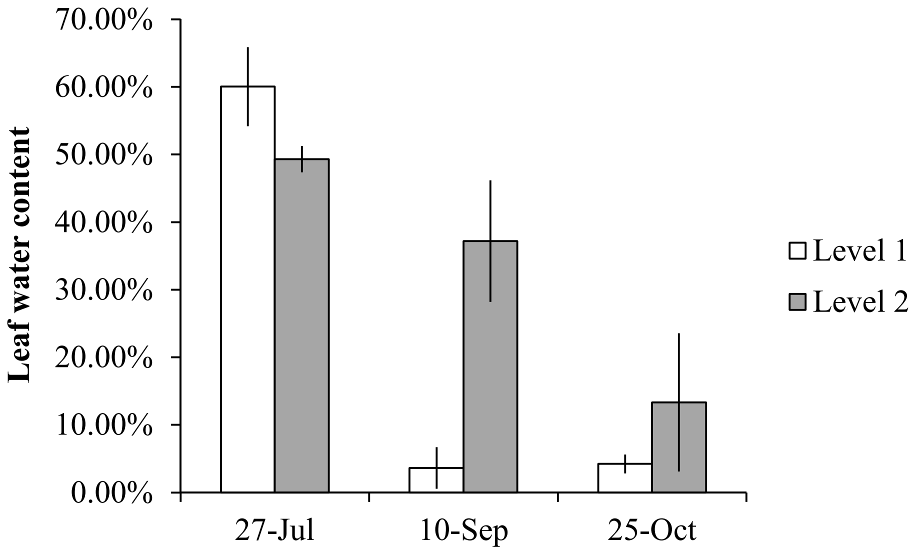


Figure 40. Mean leaf water content (as % fresh weight) of *Sorghastrum nutans* growing in watered green wall levels 1 (L1: full sun) and 2 (L2: part shade). Error bars are ± 1 SEM. N=3. Differences are significant on the September date only (two-sample t-test, df=4, p=0.0242).

Leaf water content of *S. scoparium* did not follow the same pattern; while LWC of plants in level 1 fell from 23% ±8% to 4% ±1% over the experimental period, plants in the partially shaded level 3 displayed the same LWC at the end of the period as at the beginning (Fig. 41).

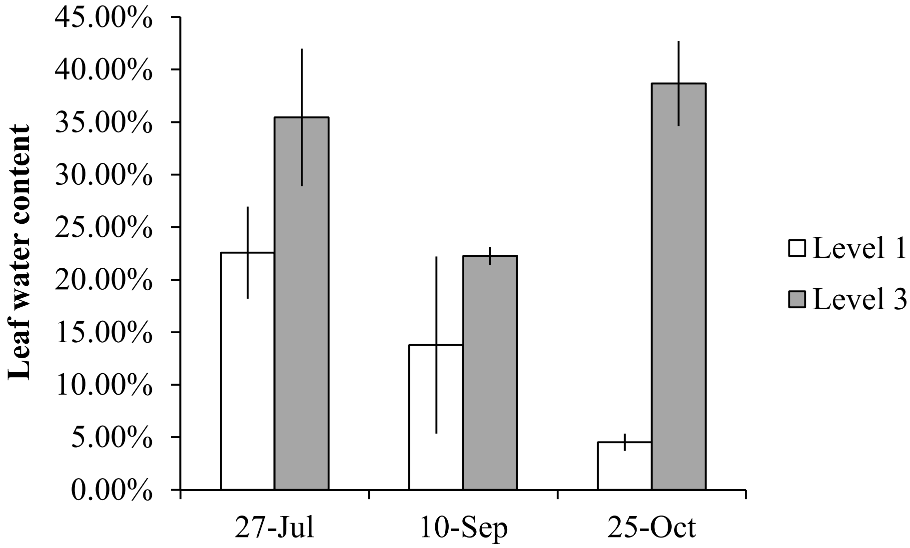


Figure 41. Mean leaf water content (as % fresh weight) of *Schizachyrium scoparium* growing in watered green wall levels 1 (L1: full sun) and 3 (L3: part shade). Error bars are ± 1 SEM. N=3. Differences are not significant on the July date (two-sample t-test, df=4, p=0.1774) or September (p=0.3719) but are significant in October (p=0.0011).

Flowering success

A total of two *S. scoparium* individuals flowered over the course of the experimental period. No *S. nutans* individuals flowered.

On the 9/8 survey date, 100% of one volunteer species (*Mollugo verticillata)* was flowering.

Volunteer counts

A total of 2,275 volunteer plants were counted over three survey dates spanning August 9–October 31, 2014 (Fig. 42). Volunteers were keyed to genus and species where possible and assigned to categories based on taxonomy. All grass species were combined into one category (*Poaceae)*. Unidentifiable individuals, many at the cotyledon stage, were combined into a single category. All groups with fewer than 10 individuals counted over the course of the season were included in this unidentified category.

Some individual volunteers were visible in unwatered panels on 30 October but were extremely dessicated and unidentifiable, and were not counted.

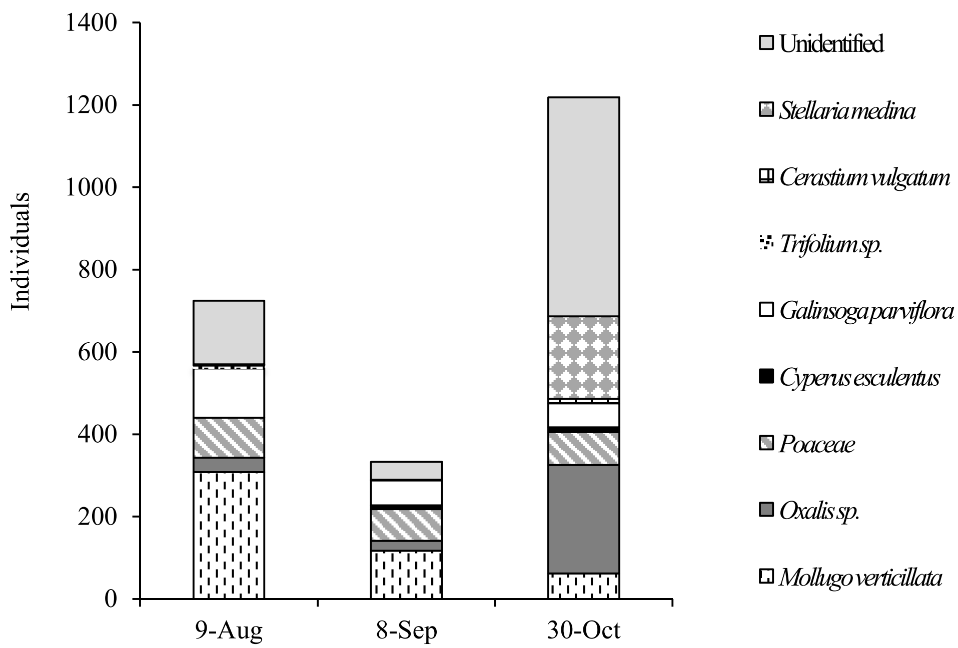


Figure 42. Volunteer plants germinating in grassland green wall panels on three survey dates in 2014. Total numbers of volunteers are shown by category. Plants were keyed to genus and species level where possible; all volunteer grasses were lumped into *Poaceae*. 'Unidentified' category includes individuals too small to identify (cotyledon stage) and groups containing a combined total of ten or fewer individuals. N = 3 panels.

<u>*Discussion*</u>

Over the course of the experimental period, planted native grasses *Sorghastrum nutans* and *Schizachyrium scoparium* generally died back as a prolific number of weeds germinated in green wall levels. Although chosen for their ability to survive in stressful environments, these species may have simply been overstressed by the design and irrigation of this green wall. Substrate depth was extremely shallow, at ~5 cm, and did not include any content engineered to enhance moisture retention.

Because of the modular planter design of this green wall, comparisons to green roof studies may be helpful to understand its stressors and the plant community dynamics exhibited in walls over time. Substrates on extensive green roofs may be as shallow as 4 cm without supplemental irrigation (Getter and Rowe 2008), but plants succeeding in these conditions tend to exhibit low growth forms and high groundcover density. Given the shallow design of this green wall and the root depths normally observed by these species in prairie environments (Nippert et al. 2012) it seems likely that the limited substrate depth and space available for developing root structures was a significant limiting factor in the establishment of these plugs and subsequent plant performance (but see Schedlbauer and Pistoia 2013).

Native grass performance in the green walls was indicated by generally falling maximum heights and species-specific leaf water contents, and an almost complete failure to flower. During the course of the experimental period, a total of 28.8 cm precipitation was recorded at a nearby (Beltsville) weather station; however, less than 11 cm was collected by the rain gauge installed on one wall replicate. Even allowing for local precipitation variation and the possibility that some water evaporated from rain gauges before it could be measured, this discrepancy suggests a very significant rain shadow effect created by the building against which green wall panels were secured. Rain shadows are an issue in green wall success or failure (Dunnett and

Kingsbury 2008) and the effects here suggests that a more frequent irrigation schedule was needed to supplement low natural rainfall. Additionally, including soil amendments such as perlite to retain additional soil moisture would be a simple, low-cost approach to increasing the water available to plants. Getter and Rowe (2008) used a water-retaining membrane in tests of sedum growth on an extensive green roof; this could be applied to a modular green wall system as well.

Temperatures of the green wall panels were not compared to local ambient air temperatures. Because black materials were used to waterproof the panels and support the plantings, however, temperatures within the panel were almost certainly higher, with the possible exception of sporadically shaded areas within panels. These relatively higher temperatures can reasonably be assumed to have increased heat stress on already water-stressed grasses. Additionally, the panels were oriented along an east-facing wall. Compared to a theoretical north-facing site, which was not available for this study, this orientation increased the hours of direct sunlight the panels received, and therefore also contributed to increasing plant water stress.

Grasses were planted in mid-July as 2" (5.1 cm) plugs sourced from a local wholesale supplier using unspecified ecotypes. This approach may have additionally impeded their rooting success and subsequent growth. Planting levels with grass seed might allow germinating individuals to acclimate to the extremely challenging conditions presented by wall panels. Alternately, sourcing ecotypes of these species from analog grassland ecosystems might also improve overall performance with these levels of irrigation (see e.g. Smith et al. 2009). Starting plugs at the beginning of the growing season would also allow plants to establish in green wall levels before high mid-summer temperatures and related heat stress peaked.

Competition from volunteer species may have also played a role. Volunteer species representing at least seven families and possibly many more, due to a large number of unidentified individuals, were found in green wall panels. Volunteer species identified to genus were all weeds commonly found in Maryland (Table 8). No weeds were ever removed, indicating that the fluctuations in weed populations were due entirely to natural (biotic and abiotic) conditions. Weeds may have entered the panels in the seed bank in the soil used to plant panels, or have been transported via wind or animal dispersal. Although volunteer plant measurements were not taken (with the exception of simple counts) on a systematic basis, the 100% flowering rate observed in one species compared with virtually 0% in planted grass species suggests that at minimum *Mollugo verticillata* developed a self-sustaining population within wall panels.

Table 8. Characteristics of volunteer plant taxa germinating in grassland green wall panels (July–October 2014) in College Park, MD.

Family	**Genus/species**	**Life cycle**	**Distribution notes**
Asteraceae	*Galinsoga parviflora*	Summer annual	Global distribution
Caryophyllaceae	*Cerastium vulgatum*	Perennial	Found in most of U.S.
Caryophyllaceae	*Stellaria medina*	Winter annual	Global distribution
Cyperaceae	*Cyperus esculenta*	Perennial	Widespread in N. Am.
Fabaceae	*Trifolium sp.*	Perennial	Widespread in N. Am.
Molluginaceae	*Mollugo verticillata*	Annual	Common in eastern N. Am.
Oxalidaceae	*Oxalis sp.*	Perennial	Global distribution

While the robust weed germination rates in walls may be unwelcome from an aesthetic standpoint, from a functional perspective it simply alters some of the benefits offered by plant communities, such as providing resources for invertebrates (Nagase et al. 2013).

As in green roof systems (MacIvor et al. 2013), plant survival and coverage within green walls is key not only to societal uptake but to many of the benefits provided by green walls including albedo change, the potential for evaporative cooling, and the self-sustaining nature of plant communities. The failure of native grasses to establish in this green wall contrasted with the germination rate of numerous aggressive volunteer species suggests that this moisture-limited and shallow wall may be too challenging an environment for the cultivation of even these hardy native C4 grasses.

Conclusions

Native grass species *Schizachyrium scoparium* and *Sorghastrum nutans*, although capable of survival in difficult environments including serpentine barren savannas, did not thrive in moisture-limited, modular, planter-style green walls with shallow natural soil substrates. As these grasses died back, a profusion of weeds germinated in the wall models. These volunteers numbered in the hundreds (an order of magnitude higher than planted grasses) and included species from eight identified families and hundreds of unidentified individuals. Weed community composition and total population varied over the course of the growing season. Limited moisture and very shallow soil depths likely contributed to the failure of the grass species to thrive, compounded by competition from vigorous weed species.

Appendices

Appendix 1. Green bulkhead panel materials and cost list.

Table A1. Green bulkhead panel parts list. Panel component cost and number of units needed for assembly of three panels and irrigation system are presented.

Component	Units	Unit cost	Total cost ($)
Solidago sempervirens (2” [5.1 cm] plug)	18	0.85	15.30
Distichlis spicata (2” [5.1 cm] plug)	18	0.75	13.50
Spartina patens (2” [5.1 cm] plug)	18	0.75	13.50
Hibiscus moscheutos (2” [5.1 cm] plug)	15	0.85	12.75
Juncus gerardii (2” [5.1 cm] plug)	21	0.75	15.75
Spartina alterniflora (2” [5.1 cm] plug)	18	0.75	13.50
55 gal. (209 L) plastic drum	1	65.00	65.00*
180 cm x 60 cm Poly-Flo Biological Filtration Media	3	3.21	9.63*
180m x 60 cm heavy-duty plastic mesh	3	1.44	4.32*
60-cm length, 10.16 cm (4”)-diameter corrugated plastic drainage pipe	18	1.24	22.32
45 cm (18”) plastic bead ties, set of 10	8	6.49	51.92
30 cm of 5/8" (1.59 cm) outside dimension hosing	8	1.99	15.84*
4-way adjustable hose faucet connection	1	14.99	14.99
Toro 54736 Drip Hose End Timer	1	30.00	30.00
Bulkhead fitting	1	1.99	1.99
Rubber gasket	1	1.19	1.19
9/16”–1 ¼” (1.43–3.18 cm) hose clamps	2	1.99	3.98
Polypropylene rope (1' / 30 cm)	15	0.49	7.35*
Landscaping fabric		†	†
		†	†
Total cost			**312.83**

* = materials used for construction in this thesis were donated or on hand. † = negligible cost.

Appendix 2. Biofouling of green bulkhead panels.

Figure A1. Bivalve growth in green bulkhead panel irrigation system.

References

Airoldi, L., M. Abbiati, M.W. Beck, S. J. Hawkins, P. R. Jonsson, D. Martin, P. S. Moscella, A. Sundelof, R. C. Thompson, and P. Aberg. 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coastal Engineering 52:1073–1087.

Angrandi, T. R., Hagan, S. M., and K. W. Able. 2001. Vegetation type and the intertidal macroinvertebrate fauna of a brackish marsh: Phragmites vs. *Spartina.* Wetlands 21:75–92.

Ausden, M. and M. Drake. 2006. Invertebrates. *In* Ecological Census Techniques: A Handbook, ed. William J. Sutherland. Cambridge University Press. 214–249.

Azkorra. Z., G. Pérez, J. Coma, L. F. Cabeza, S. Bures, J. E. Álvaro, A. Erokoreka, and M. Urrestarazu. 2015. Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics 89:46–56.

Barton, J. and J. Pretty. 2010. What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. Environmental Science and Technology 44:3947–3955.

Browne, M. A. and M. G. Chapman. 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. Environmental Science and Technology 45:8204–8207.

Cahoon, D. R. and J. C. Stevenson. 1986. Production, predation, and decomposition in a low-salinity *Hibiscus* marsh. Ecology 67:1341–1350.

Cameron, R. W. F., J. E. Taylor, and M. R. Emmett. 2014. What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. Building and Environment 73:198–207.

Carter, T. and C. Butler. 2008. Ecological impacts of replacing traditional roofs with green roofs in two urban areas. Cities and the Environment 1:1–17.

Chapman, M. G. and A. J. Underwood. 2011. Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. Journal of Experimental Marine Biology and Ecology 400:302–313.

Chiquet, C., J. W. Dover, and P. Mitchell. 2013. Birds and the urban environment: the value of green walls. Urban Ecosystems 16:453–462.

Dunnett, N. and N. Kingsbury. 2008. Planting green roofs and living walls. London/Portland, OR: Timber Press.

Dyson, K. and K. Yocom. 2015. Ecological design for urban waterfronts. Urban Ecosystems 18:189–208.

Everard, M. and H. L. Moggridge. 2012. Rediscovering the value of urban rivers. Urban Ecosystems 15:293–314.

Feng, H. and K. Hewage. 2014. Lifecycle assessment of living walls: air purification and energy performance. Journal of Cleaner Production 69:91–99.

Flowers, M.G. 1973. Vegetational zonation in two successional brackish marshes of the Chesapeake Bay. Chesapeake Science 14:197–200.

Francis, R. A. 2010. Wall ecology: A frontier for urban biodiversity and ecological engineering. Progress in Physical Geography 35:43–63.

Francis, R. A. and S. P. G. Hoggart. 2008. Waste not, want not: The need to utilize existing artificial structures for habitat improvement along urban rivers. Restoration Ecology 16:373–381.

Francis, R. A. and S. P. G. Hoggart. 2009. Urban river wall habitat and vegetation: observations from the River Thames through central London. Urban Ecosystems 12:465–485.

Francis, R. A. and J. Lorimer. 2011. Urban reconciliation ecology: The potential of living roofs and walls. Journal of Environmental Management 92:1429–1437.

Fuller, R. A., K. N. Irvine, P. Devine–Wright, P. H. Warren, and K. J. Gaston. 2007. Psychological benefits of greenspace increase with biodiversity. Biology Letters 3:390–394.

Getter, K. L. and D. B. Rowe. 2008. Media depth influences *Sedum* green roof establishment. Urban Ecosystems 11:361–372.

Groffman, P. M., D. J. Bain, L. E. Ban, K. T. Belt, G. S. Brush, J. M. Grove, R. V. Pouyat, I. C. Yesilonis, and W. C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1:315–321.

Hopkinson, C. S., J. G. Gosselink, and R. T. Parrondo. 1980. Production of coastal Louisiana marsh plants calculated from phenometric techniques. Ecology 61:1091–1098.

Hunter, A. M., N. S. G. Williams, J. P. Ravner, L. Aye, D. Hes, S. J. Livesley. 2014. Quantifying the thermal performance of green façades: a critical review. Ecological Engineering 63:102–113.

Joshi, S. V. and S. Ghosh. 2014. On the air cleansing efficiency of an extended green wall: a CFD analysis of mechanistic details of transport processes. Journal of Theoretical Biology 361:101–110.

Kirby, C. J. and J. Gosselink. 1976. Primary production in a Louisiana Gulf Coast *Spartina alterniflora* marsh. Ecology 57:10521059.

Köhler, M. 2008. Green facades – a view back and some visions. Urban Ecology 11:423–436.

Kowarik, I. 2011. Novel urban ecosystems, biodiversity, and conservation. Environmental Pollution 159:1974–1983.

Latham, R.E. (1993) The serpentine barrens of temperate eastern North America: critical issues in the management of rare species and communities. Bartonia 57 61-74.

Liu, Z., C. He, Y. Zhou, and J. Wu. 2014. How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. Landscape Ecology 29:763–771.

Linthurst, R. A. and R. J. Reimold. 1978. An evaluation of methods for evaluating the net aerial primary productivity of estuarine angiosperms. Journal of Applied Ecology 15:919–931.

Loh, S. 2008. Living walls – a way to green the built environment. BEDP Environment Design Guide, 1(TEC 26), pp. 1-7.

Lundholm, J. T. and P. J. Richardson. 2010. Habitat analogues for reconciliation ecology in urban and industrial environments. Journal of Applied Ecology 47:966–975.

MacIvor, J. S., L. Margolis, C. L. Puncher, and B. J. C. Matthews. 2013. Decoupling factors affecting plant diversity and cover on extensive green roofs. Journal of Environmental Management 130:297–305.

Manso, M. and J. Castro-Gomes. 2015. Green wall systems: a review of their characteristics. Renewable and Sustainable Energy Reviews 41:863–871.

Matt, S. 2012. Green façades provide habitat for arthropods on buildings in the Washington, D.C. area. MS thesis. University of Maryland MS, College Park, MD.

Maryland Department of the Environment. *Initial Assessment of the Habitat Value, Local Water Quality Impacts and Nutrient Uptake Potential of Floating Wetlands in the Inner Harbor.* 2011. Baltimore, MD: Maryland Department of the Environment.

Millennium Ecosystem Assessment, 2005. Ecosystems and human well–being: wetlands and water synthesis. World Resources Institute, Washington, DC.

Mitsch, W.J., and J. G. Gosselink. 1993. Wetlands, 2nd ed. John Wiley, New York.

Moorman, G. 2015. Goldenrod (Solidago) diseases. Penn State Extension fact sheet. The Pennsylvania State University.

Morris, J. T. and B. Haskin. 1990. A five-year record of aerial primary productivity and stand characteristics of *Spartina alterniflora*. Ecology 71:2209–2217.

Morrissey, E. M., J. L. Gillespie, J. C. Morina, and R. B. Franklin. 2014. Salinity affects microbial activity and soil organic matter content in tidal wetlands. Global Change Biology 20:1351–1362.

Nagase, A., N. Dunnett, and M.-S. Choi. 2013. Investigation of weed phenology in an extensive semi-establishing green roof. Ecological Engineering 58:156–164.

Nippert, J. B., R. A. Wieme, T. W. Ocheltree, and J. M. C. Raine. 2012. Root characteristics of C4 grasses limit reliance on deep soil water in tallgrass prairie. Plant Soil 355:385-394.

Odum, W. E. 1988. Comparative ecology of tidal freshwater and salt marshes. Annual Review of Ecology and Systematics 19:147–196.

Ottelé, M. 2011. The green building envelope: vertical greening. Doctoral thesis. Delft University of Technology, Delft, Netherlands.

Pennings, S. C., M.–B. Grant, and M. D. Bertness. 2005. Plant zonation in low–latitude salt marshes: disentangling the roles of flooding, salinity, and competition. Journal of Ecology 93:159–167.

Perini, K., M. Ottelé, A. L. A. Fraaij, E. M. Hass, and R. Raiteri. 2011. Vertical greening systems and the effect on air flow and temperature on the building envelope. Building and Environment 46:2287–2294.

Perkol–Finkel, S., F. Ferrario, V. Nicotera, and L. Airoldi. 2012. Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. Journal of Applied Ecology 49:1457–1466.

Perry, J. E., T. A. Barnard, Jr., J. G. Bradshaw, C. T. Friedrichs, K. J. Havens, P. A. Mason, W. I. Priest, III, and G. M. Silberhorn. 2001. Creating tidal salt marshes in the Chesapeake Bay. Journal of Coastal Research 27:170–191.

Pickett, S. T. A., Cadenasso, M. L., Grove, J. M., Nilon, C. H., Pouyat, R. V., Zipperer, W. C., and Costanza, R. 2001. Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan systems. Annual review of Ecology and Systematics 32:127–157.

Rabenhorst, M. 2008. Protocol for using and interpreting IRIS tubes. Soil Survey Horizons 49:74–77.

Rabenhorst, M. 2012. A simple and reliable approach for quantifying IRIS tube data. Soil Science Society of America Journal 76:307–308.

Roe, J. J., Thompson, C. W., Aspinall, P. A., Brewer, M. J., Duff, E. I., Miller D., Mitchell, R., and Clow, A. 2010. Green space and stress: evidence from cortisol measures in deprived urban communities. International Journal of Environmental Research and Public Health 10: 4086–4103.

Rosenzweig, M.L. 2003. Win–win ecology: How the earth's species can survive in the midst of human enterprise. Oxford University Press, Oxford.

Schedlbauer, J. L., and V. L. Pistoia. 2013. Water relations of an encroaching vine and two dominant C4 grasses in the serpentine barrens of southeastern Pennsylvania. Journal of the Torrey Botanical Society 140:493–505.

Seto, K. C., M. Fragkias, B. Güneralp, and M. K. Reilly. 2011. A meta–analysis of global urban land expansion. PLos ONE 6:e23777.

Smith, B. M., A., Diaz, R. Daniels, L. Winder, and J. M. Holland. 2009. Reference and ecotype traits in *Lotus corniculatus* L., with reference to restoration ecology. Restoration Ecology 17:12–23.

Streb, C. 2013. Building floating wetlands to restore urban waterfronts and community partnerships. National Wetlands Newsletter March–April 2013:24–27.

Taylor, A. F., F. E. Kuo and W. C. Sullivan. 2002. Views of nature and self–discipline: Evidence from inner–city children. Journal of Environmental Psychology 22:49–63.

Tyndall, R.W. (1994) Conifer clearing and prescribed burning effects to herbaceous layer vegetation on a Maryland serpentine "barren." Castanea 59 255-273.

Tyndall, R.W. and P. M. Farr (1990) Vegetation and flora of the Pilot serpentine area in Maryland. Castanea 55 259-265.

Waterfront Partnership of Baltimore, Inc. 2014. Baltimore's annual Healthy Harbor report card: 2013.

Waterfront Partnership of Baltimore, Inc. 2013. Baltimore Inner Harbor 2.0.

Wicks, E. C., R. H. Kelsey, and S. L. Powell. 2011. State of Baltimore Harbor's ecological and human health. IAN Press, Cambridge, Maryland.

Zedler, J. B. and J. C. Callaway. 2003. Tidal wetland functioning. Journal of Coastal Research Special Issue 27:38–64.