FOOD PRODUCTION ON A LIVING WALL: PILOT STUDY

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ABSTRACT

Living walls and other vertical green infrastructure on building surfaces provide regulating, supporting, and cultural ecosystem services in the built environment. Green walls can also generate food as a provisioning ecosystem service. This article discusses a pilot study monitoring the productivity of a 7.5 m^2 outdoor living wall system planted with produce crops during the 2015 summer growing season in State College, Pennsylvania, USA. Irradiance, water usage, and soil moisture data were also collected to assess context and performance of the living wall system during the growing season.

KEYWORDS

living walls, green walls, urban agriculture, ecosystem services, Green Infrastructure (GI).

1. INTRODUCTION

Examples of green walls in the built environment date back to the famed, though possibly mythical, Hanging Gardens of Babylon, circa 600 BC. Better-documented examples of living walls include grape trellises in ancient Rome, privacy screens in medieval Europe, fruit walls in the 17th century Parisian suburbs, cooling facades constructed during early European settlement in Australia and New Zealand, and living wall infrastructure associated with the 20th century city garden movement in Britain and the United States (Hopkins and Goodwin 2011).

The term "green wall" encompasses a variety of vegetated wall systems, including green facades or living wall systems and vertical gardens. Green facades are comprised of a continuous or modular trellis that supports the growth of vining plants installed above, on, or below the trellis. Living wall systems are comprised of continuous screens or modular trays, vessels, planter tiles, or flexible bags that hold the growing medium and the plants (Manso and Castro-Gomes 2015). The green wall used in this study is a living wall system of modular vessels called planter boxes.

Green walls today are a form of Green Infrastructure (GI) that can contribute to the environment by providing four types of ecosystem services (Oberndorfer et al. 2007). Provisioning

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services manifest as material or energy outputs. Regulating services control ecosystem processes to generate benefits such as air quality and flood prevention. Supporting services provide quality habitat and species diversity to sustain ecosystems. Cultural services describe anthropogenic benefits such as tourism, recreation, mental health, spiritual connection, artistic expression, and the creation of a sense of place. Research has identified how green infrastructure provides ecosystem services such as wind and temperature moderation (Caprotti and Romanowicz 2013; Pérez et al. 2011), mitigation of the urban heat island effect (Cameron et al. 2014), carbon sequestration (Marchi et al. 2015; Lal and Augustin 2012; 2011), acoustic damping (Nilsson et al. 2014), air pollution reductions (Kessler 2013), stormwater filtration and retention (Kew et al. 2014), enhanced urban aesthetic and positive psychological response (Yang et al. 2011), increased habitat for urban pollinators and small wildlife (Dover 2015), and food production (Fisher 2013; Massingham 2011).

Green walls create a specific niche in the design of urban food production systems. They provide green space for areas where land is expensive, unavailable, or unsafe for growing edible plants. Expanding vertical food production to the scale of multi-story buildings will likely preclude their use in certain growing scenarios. This is due to the initial cost and physical challenges of using green walls to grow food. Design and research efforts are needed to make vertical food production technology cost-competitive and logistically practical. The value of urban food production can already be quantified economically as a provisioning service, providing motivation for further design research. There is potential to underestimate regulating, supporting, and cultural ecosystem services if they are not formally recognized as having economic value (Boyd 2007). The provisioning value of food production makes a stronger case for the use of green walls as an economical form of green infrastructure in urban environments.

1.1. Contemporary Vertical Food Production

Green walls used to produce food indoors and outdoors are featured in the work of designers and the green infrastructure industry. Examples include several case study designs by the firm Elmslie Osler Architect (Osler 2008), specifically how the firm collaborated with partners in Los Angeles to install a network of living walls to produce food in low-income neighborhoods. James Biber Architects worked with Bright Agrotech ZipGrow infrastructure to create American Food 2.0 (Expo Milano 2015), featuring an 860 m^2 vertical farm at the Expo Milano 2015. Kona Designs worked in Japan to construct an office tower that hosts 4,000 m^2 of growing space, including the building envelope (Meinhold 2013).

Architects Bohn and Viljoen, also researchers at the University of Brighton, have proposed Continuous Productive Urban Landscapes (CPULs) that feature vertical fields and gardens (e.g. Urban Nature; Growing Balconies). High-density, mixed-use green infrastructure can be designed for crop production and to enhance green space in a city such as London (Bohn and Viljoen 2010). The architects discuss how the "design, planning, landscape, horticultural and retail professions will need to relearn old skills and develop new ones, in particular, the practice of urban agriculture" (Bohn and Viljoen 2011).

Studies involving vertical food production in a controlled environment, such as a greenhouse or plant factory, often employ hydroponics and a variety of infrastructure, such as vertical columns, vertically-suspended grow bags, A-frames, stacked grow beds, etc. The soilless media is some combination of felt, foam, rockwool, perlite, vermiculite, gravel, growstones, Styrofoam, sand, or no substrate at all (e.g. aeroponics). The irrigation water is fertilized to provide the nutrient requirements of the plants. The range of design variables makes formal comparisons difficult among and between different systems (Touliatos et al. 2016; ZipGrow Production Estimates 2016; Gumble et al. 2016; Bergstrand et al. 2014). Logistical costs decrease the profitability of vertical food production. These costs are derived from paying for labor, heating greenhouses for year-round harvests in temperate climates, providing supplemental lighting, installing and maintaining the vertical infrastructure, and the limited lifespan of these systems.

Existing buildings retrofitted as plant factories are often able to make a profit from growing crops indoors as a result of favorable opportunities. These opportunities include a) partnering with tech companies to test reduced-price lighting prototypes; b) receiving corporate investment for urban development projects; c) sharing building utilities, costs, and advertising needs with other like-minded companies; d) being located in areas with a lack of fresh food due to difficult growing conditions; and e) benefiting from "extra fresh" shelf appeal compared to slightly less expensive imported foods (Egelhoff 2015). Once the upfront costs for renewable energy infrastructure are paid off, renewable energy generation may also help to offset electricity costs in the long run. Practitioners developing vertical green infrastructure for food production can contribute knowledge to this GI niche through follow-up documentation. Partnerships between researchers and practitioners can comprehensively capture both the design process and the ecosystem and user performance of designed systems once installed.

The living wall used in this study differs from greenhouse and plant factory vertical food production in that it contributes to the outdoor urban ecosystem. The outdoor living wall system requires no seasonal energy inputs for controlling ambient growing conditions such as light, temperature, and humidity, excluding irrigation inputs. Conversely, the profit and ecosystem benefits from outdoor green walls growing food in a temperate climate are limited by temperature and light constraints. Therefore, growing food outside on green walls is merely one component that can contribute to the network of urban agriculture and ecosystem services provided by GI.

2. MATERIALS AND METHODS

One of the key questions driving this study was to determine the productivity of a green wall growing fresh produce, depending on the type of green wall system used and the scale of operation. This pilot study is intended to represent how a hobbyist, micro-scale grower or a local-foods restaurateur could sustainably produce fresh food using a small-scale system. This pilot is inconclusive as a model for scaling food production up to skyscrapers or a food wall network in urban environments.

2.1. Infrastructure

The study utilized a 7.5 m^2, uniquely-fabricated living wall system initially designed to assess first flush capture and storm water retention capacity for a green wall compared to a green roof. The wall consisted of 64 planter boxes hung on a wooden lattice with metal hooks. The entire assembly was attached to a vertical concrete wall framing one side of an outdoor work yard that accommodates research and training activities in the School of Architecture and Landscape Architecture (Fig. 1). Each box had ten, 7.6 x 12.7 x 15.2 cm cells. The planter boxes were made

FIGURE 1. Living wall (highlighted) located on the College of Arts and Architecture Stuckeman Family Building at Penn State University in University Park, PA (Bing Maps 2016).

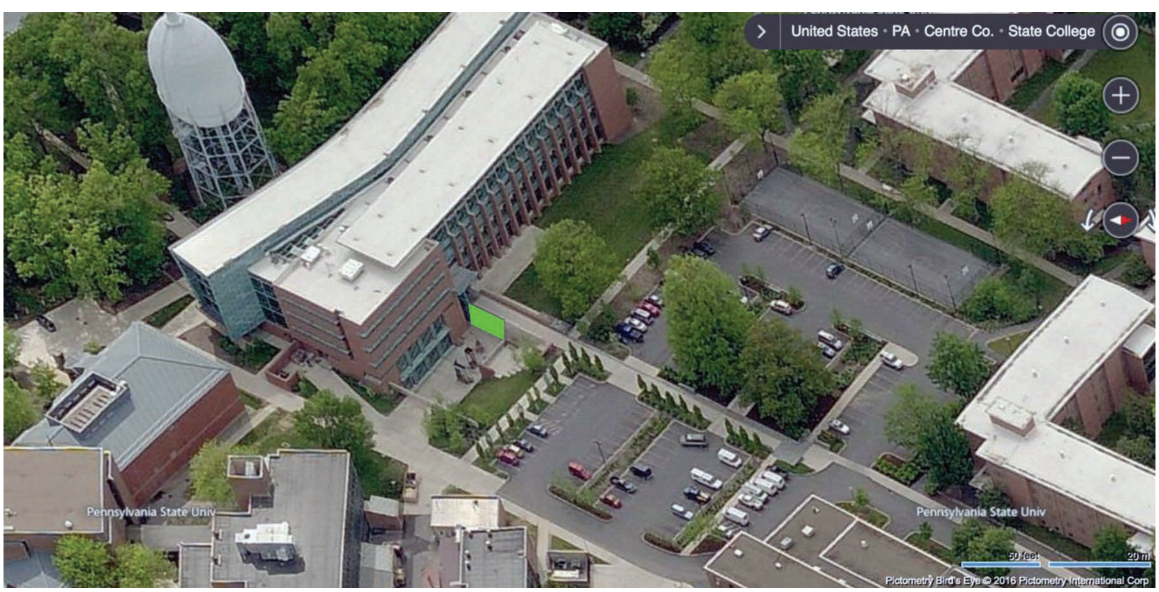
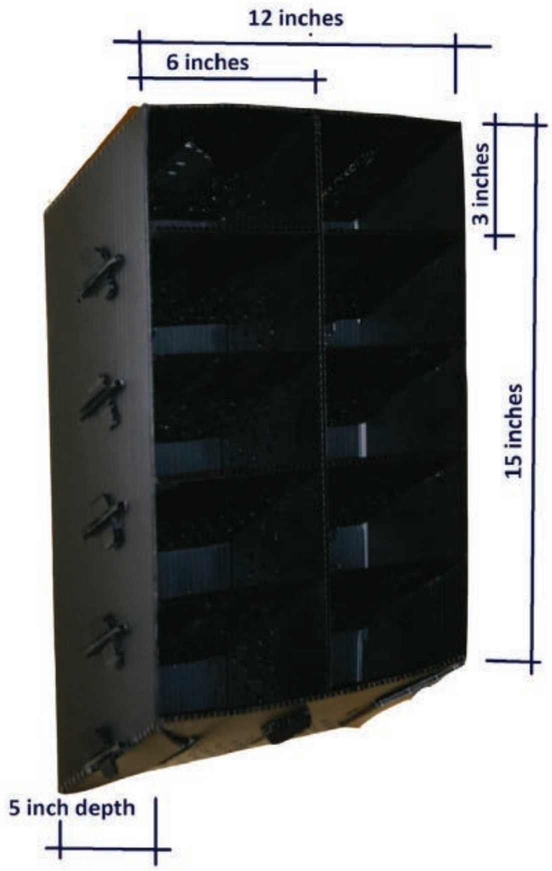


FIGURE 2. Individual Planter Box (Kew et al. 2014).



of black coroplast (Fig. 2), cut using a computer controlled router and then assembled on site. Readers should refer to Kew et al. (2014) for complete construction details of the living wall system. Modular living wall systems are available for sale to hobby gardeners who may not be equipped to fabricate their own system. Retail products such as the LiveWall ® Outdoor system (Outdoor Plant Walls by LiveWall 2017) feature modular grow boxes with drip irrigation similar to the system used in the study.

The soil used was a 50:50 mixture of native, screened topsoil and locally sourced compost from The Pennsylvania State University and State College Borough, respectively. These materials were intentionally selected for their local environmental footprint compared to other growing media, such as potting soil, peat, perlite, or rockwool.

2.2. Plants

Vegetable seed was sourced online from Johnny's Selected Seeds (Winslow, ME) and planted directly into the wall, or started in a greenhouse using a sterile potting mix. Greenhouse starts were then transplanted into the wall in late April/early May. A variety of crops were harvested once or twice every week from the end of May to the beginning of September. The crop selection reflected the variety found in a typical home vegetable garden, with an additional preference for shallow-rooted, continuous-harvest crops (Table 1). Most plants were continuously harvested with the exception of the mei qing choi (Brassica rapa var. chinensis) and the radishes, which once harvested in full were replaced with salad mix, Swiss chard, or collard greens. The Malabar spinach, an edible tropical vine, grew productively during the study. It was not harvested for its use in a separate study.

The south-east facing living wall was exposed to direct morning sunlight on average six hours per day, with shade establishing from left to right across the wall in early afternoon. The tomatoes were planted in the upper-right hand corner of the wall and the Malabar spinach on the same side to maximize length of sunlight exposure. The planter boxes in this study were placed according to the expected mature size of the crop, the growth habit of the crop, and the light levels on the wall (Fig. 3). This growing scenario is comparable to a city environment where buildings and the orientation of building faces would limit direct sunlight reaching the plants. Green wall placement and planting design should also be determined based on crop growth habit and management regime for ideal growing and harvesting conditions.

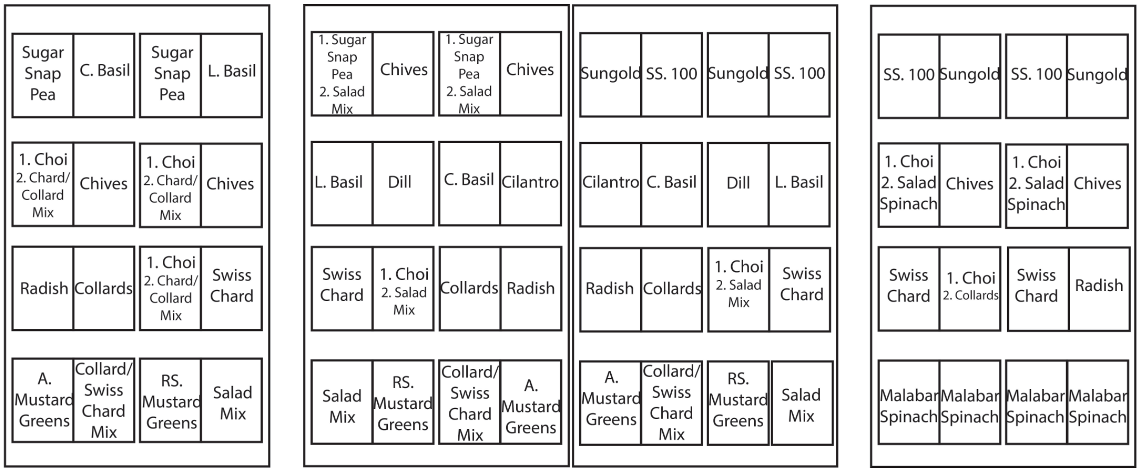
2.3. Harvests

In order to harvest once or twice per week, the researcher used a 12-foot step ladder. The weight of the fresh plant material (Fig. 4) was recorded in grams using a calibrated electronic scale immediately after harvest. Plant weights were summed cumulatively per month, and assessed

TABLE 1. List of Plants Grown in the Living Wall During the Pilot Study.

Plant	Type	Quantity	Harvest Type
Basil, Cinnamon	Transplant	30 plants in 30 cells	Continuous
Basil, Lemon	Transplant	30 plants in 30 cells	Continuous
Cherry tomato, Sun Gold	Transplant	32 plants in 16 cells doubled in size	Continuous
Cherry tomato, Supersweet 100	Transplant	32 plants in 16 cells doubled in size	Continuous
Chives, Staro	Transplant	60 plants in 60 cells	Continuous
Cilantro, Calypso	Direct Sow	5–10 cm spacing in 20 cells	Continuous
Collards, Flash	Transplant	70 plants in 30–60 cells	Continuous
Dill, Bouquet	Direct Sow	2 seeds per 3 cm spacing in 20 cells	Continuous
Mei Qing Choi	Transplant	80 plants in 80 cells	One-Time
Mustard greens, Ruby Streaks	Direct Sow	3 seeds per cell in 30 cells	Continuous
Mustard greens, Amara	Direct Sow	3 seeds per cell in 30 cells	Continuous
Radish, Crunchy Royale	Direct Sow	2 seeds per cell in 40 cells	One-Time
Salad mix, Ovation	Direct Sow	Microgreen spacing in 30–50 cells	Continuous
Spinach, Malabar	Direct Sow	2 seeds per cell in 40 cells	Not harvested
Spinach, Flamingo	Direct Sow	2 cm spacing in 20 cells	Continuous
Sugar snap pea	Direct Sow	2 seeds per cell in 20–40 cells	Continuous
Swiss Chard, Bright Lights	Transplant	80 plants in 80 cells	Continuous

FIGURE 3. Planting Pattern Elevation Diagram.



in value according to their comparable retail organic price. Varieties of the same crop were combined when weighed, e.g. the basil, cherry tomatoes, and mustard greens. The spinach was combined with the salad mix when weighed.

2.4. Pests and Pathogens

Synthetic fertilizer and some non-organic seed were used, though no conventional chemicals were sprayed to combat pests and pathogens. Hobby gardener remedies such as diluted mouthwash (active ingredients: eucalyptol (0.092%), menthol (0.042%, methyl salicylate (0.060%), thymol (0.064%); inactive ingredients: alcohol, sorbitol solution, etc.), vinegar, and baking soda were applied bi-monthly to help prevent or minimize mildew on the tomatoes, dill, and sugar snap peas (Lamp'l 2015). Such a strategy is accessible to amateur growers in an urban environment, but lacks scientific evidence whether it is practical as a formal control measure.

Other methods of accessible control included mechanical removal of pests (e.g. destroying cabbage moth eggs and larvae, and leaf miners by hand) and biological control (e.g. companion planting of herbs and marigolds to attract beneficial predatory insects) (Parker et al. 2013). The

FIGURE 4. Typical weekly harvest (left to right) of rainbow Swiss chard, radishes with greens, salad mix, collard greens, basil, mustard greens, cilantro, and cherry tomatoes, July 17, 2015.

FIGURE 5. Four Panels Comprise the Living Wall, July 29, 2015.

closely-spaced layout of planter boxes, above-average rainfall in June and July 2015, and partial shade conditions made for ideal pathogen growth and spread. It is estimated that chipmunks and birds also consumed and/or damaged more than 30% of the cherry tomatoes. Pest damage inevitably reduces harvests in any location where a green wall without netting or other pest barriers is accessible to small animals.

2.5. Irrigation

The irrigation system consisted of 1/3 hp sump pump-fed, 1.9 L/hr drip emitters spaced evenly so that each tier of planter boxes received irrigation from four drip emitters, two per cell. Each cell had several small drainage holes. A gutter system ran along each tier of planter boxes, collecting excess water and draining it to the cisterns below via rain chains and hose tubing. The cisterns consisted of two, 200-liter barrels, filled every two to three days with fresh water fertilized with 10-10-10 granular fertilizer at a rate of 100 g per month per barrel. One 200-liter cistern fed two out of four living wall panels (Fig. 5).

Natural precipitation was insufficient to keep the planter boxes watered due to their vertical orientation. Daily irrigation occurred in the morning and late afternoon to keep the small cells of soil from drying out from sun and wind exposure. The sump pumps each ran at most three times per day using electricity from a building outlet. This energy could be supplemented passively and remotely using small solar panel/battery pack assemblies wired to each pump. The typical irrigation regime pumped water for five minutes twice a day from both cisterns.

2.6. Monitoring

Secondary environmental conditions such as light levels, irrigation frequency, and soil moisture were monitored using pyranometers, water data loggers, and soil moisture sensors (Table 2). The data collected provide additional information to describe the context of the living wall pilot study and to make recommendations for future applications. Such data is unique to this pilot

TABLE 2. Types of Sensors Installed.

Equipment	Variable	Data Collection Method
2 Onset® Silicon Pyranometer Smart Sensor (Part # S-LIB-M003)	Light levels (W/m^2)	1. Direct/diffuse radiation 2. Reflected radiation
2 Onset® Soil Moisture Smart Sensors (S-SMx-M005)	Soil Moisture content (m^3/m^3)	Inserted into growing medium on left- and right-hand panels
2 HOBO® U20 Fresh Water Level Data Logger 13 feet—U20-001-04	Water Pressure in Irrigation cisterns (kPa)	Suspended in stormwater cistern

study, which limits direct extrapolation to other living or green wall systems. However, the data can contribute to an average range of observations made about the performance of outdoor living wall systems used for growing produce.

3. LIVING WALL PERFORMANCE

The living wall was partially shaded throughout the growing season. Average monthly rainfall in June was 6.9 cm above average, 6.6 cm above average in July, and 2.2 cm below average in August (Climate State College–Pennsylvania 2015). Irradiance measurements (Fig. 6) indicate that the wall experienced brief incidents of direct summer sun above 1000 W/m^2.

3.1. Irrigation

Over a two-week sampling period, water pressure and water temperature in the right-hand cistern were recorded to observe how the living wall processed the irrigation water over time. The processing rate varied based on weather, existing soil moisture, and the age and stage of growth of the plants (Wang et al. 2016). Between August and September 2015, it was observed that the soil moisture levels increased to saturated conditions (Fig. 8). The irrigation regime should be reduced in future, particularly as the average daily temperatures drop with shorter days and cooler nights.

FIGURE 6. Direct/Diffuse and Reflected Irradiance (W/m^2) Measured on the Living Wall.

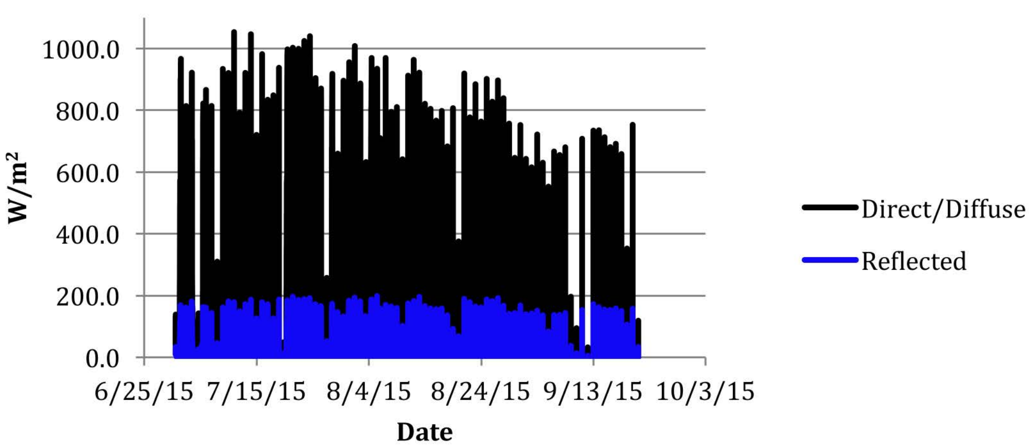
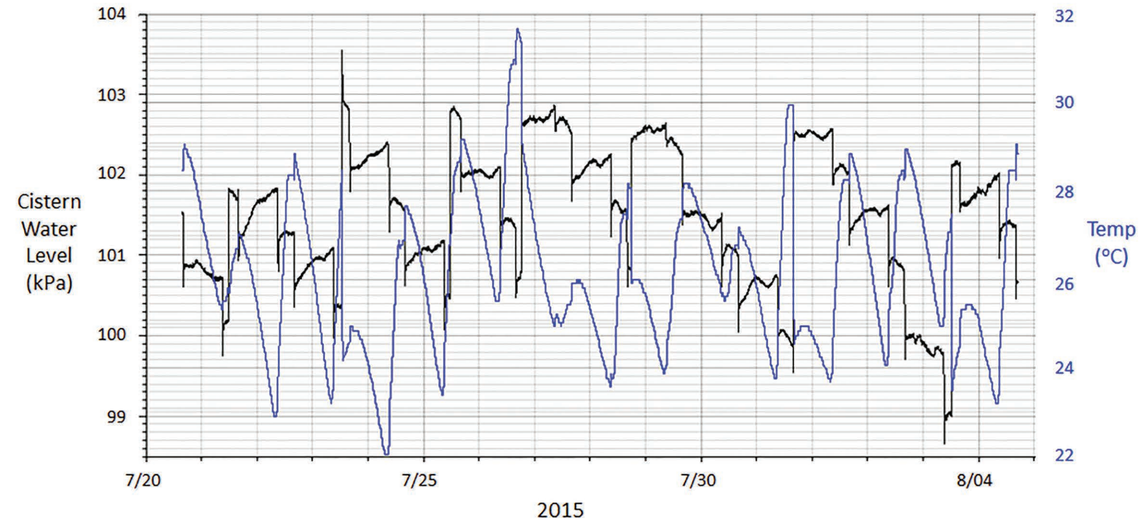


FIGURE 7. Water Pressure (kPa) and Temperature (°C) in Irrigation Cistern, July 20–August 4, 2015.



3.2. Growing Medium

A soil test conducted by the Penn State Agricultural Analytical Services Laboratory (University Park, PA) indicated that the growing medium had above optimum fertility levels in August (Fig. 9). Growing systems, such as hydroponic designs with closed loop irrigation, may experience an imbalance of nutrients over time in the form of salts (Resh 2013). This can lead to increased pH and burning of plant roots. The growing medium should be flushed regularly to restore the media to optimum pH and nutrient levels. Another approach is to separate irrigation and fertilization applications. It is further recommended that storm water used to irrigate food crops

FIGURE 8. Irradiance (W/m^2) and Soil Moisture (m^3/m^3), August 5–September 22, 2015.

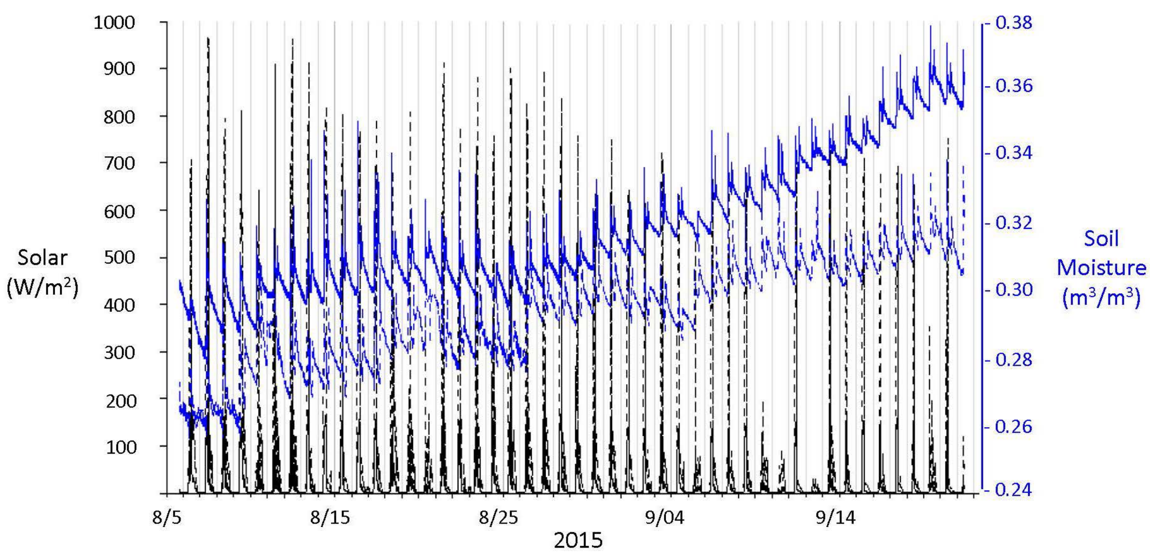


FIGURE 9. pH and Nutrient Levels of the Growing Medium, August 2015.

be ameliorated on site with a mechanical, chemical, or bio-filtration system in order to avoid the build-up of contaminants in the soil (Wuana and Okieimen 2011). Such a system could also process the water flushed through the living wall to remove salts and excess nutrients.

3.3. Crop Productivity

The biomass productivity of each living wall crop was summed cumulatively from late May to early September, generating a total weight in pounds that was valued according to average organic retail prices during the 2015 growing season (Specialty Crops 2015). The varied harvest rate and productivity of the crops grown indicates that some plants grew more prolifically than others (Table 3), as would be expected regardless of the vertical aspect of the garden. Growing a single crop per irrigated panel could optimize the management method.

TABLE 3. Productivity of the Living Wall.

Harvested Crop	Total Weight (kg)	Average Daily Weight (g)	Cumulative Harvest Rate (HR)	HR June (kg/m2)	HR July (kg/m2)	HR August (kg/m2)	Price ($/kg)	Value ($)
Basil	8.3	77.7	12.3	2	4.4	5.9	16.76	139.11
Chives	0.9	8.8	1.5	0.5	0.5	0.5	35.27	31.74
Cilantro	0.9	8.6	3.9	0.5	1.5	1.9	15.43	13.89
Collards	8.6	80.8	12.7	6.8	1.5	4.4	6.59	56.67
Dill	0.3	3.1	1.5	0.5	0.5	0.5	22.05	6.62
Mei Qing Choi	8.8	82.5	12.1	9.7	2.4	No harvests	7.72	67.93
Mustard Greens	2.5	23.5	4	0.5	1.5	2	6.59	16.48
Radishes (w/ greens)	3.9	36.5	8.3	2.4	5.4	0.5	7.72	30.11
Salad Mix	5	46.7	6.8	2.9	1.5	2.4	9.92	49.60
Sugar Snap Peas	0.4	3.3	0.0	n/a	n/a	n/a	11.02	4.41
Swiss Chard	9.8	91.8	10.2	3.4	2.9	3.9	5.49	53.81
Tomatoes (cherry)	6.4	60.1	7.4	0.5	4.9	2	8.80	56.32
Average	8.8	43.6	6.73	2.48	2.3	2	12.78	43.89
TOTAL	55.8	523.4						526.69

TABLE 4. Cumulative Values from Each Crop that Contribute to a Daily Vegetable Serving.

Crop (May 27–September 10)	Total (g)	Average Daily Grams (g)
Basil	8312.5	77.7
Chives	939.5	8.8
Cilantro	919.5	8.6
Collards	8640.5	80.8
Dill	336.5	3.1
Mei Qing Choi	8829	82.5
Mustard Greens	2512	23.5
Radishes (w/ greens)	3903.2	36.5
Salad Mix	5000	46.7
Sugar Snap Peas	356	3.3
Swiss Chard	9822.5	91.8
Tomatoes (cherry)	6430.5	60.1
TOTAL	56002	523.4

3.4. Dietary Value

The living wall used to grow produce for this study was considered for its value as a source of daily vegetables recommended for a healthy diet. According to the World Health Organization (Healthy Diet 2015), a healthy diet includes consumption of at least 400 g of fruits and vegetables per day. The harvest from the 7.5 m^2 green wall used in this study could provide 523 g of daily produce during the growing season (Table 4), enough for at least one adult per day. The plant palette and living wall design could be expanded to include more fruits, red and orange vegetables, and legumes to optimize the selection of vegetables depending on the target diet.

4. DISCUSSION OF FINDINGS

4.1. Comparing Yields

How does the yield from this living wall study compare with conventional horizontal production? The Rutgers Agricultural Experiment Station estimates that average production rates for mixed-stand, small-scale conventional agriculture is 2.44 kg/m^2 (Rabin et al. 2012). The five most productive crops from this study (in descending order: collard greens, basil, mei qing choi, Swiss chard, and radishes with greens) had harvest rates (HR) ranging from 3–5 times the average productivity rate of 2.44 kg/m^2. Yet other crops from this study underperformed compared with this average rate (chives, dill, and sugar snap peas). Cherry tomatoes, salad mix, mustard greens, and cilantro performed slightly above this average rate, with a harvest rate ranging from 1–3 times greater than 2.44 kg/m^2 (Table 5).

TABLE 5. Harvest Rates (HR).

Crop	HR (kg/m²)
Collards	12.7
Basil	12.3
Mei Qing Choi	12.1
Swiss Chard	10.2
Radishes (w/ greens)	8.3
Tomatoes (cherry)	7.4
Salad Mix	6.8
Pilot Study Average	6.73
Mustard Greens	4
Cilantro	3.9
Rabin et al. (2012)	2.44
Chives	1.5
Dill	1.5
Sugar Snap Peas	0

4.2. Determining the Value of Food Walls

This study suggests that food production can join other ecosystem services in contributing to the value created by green walls as a form of GI. Further study using this and other types of green wall infrastructure is necessary to quantify average productivity rates. In addition, quantifying the monetary value of other ecosystem services can help to justify the initial upfront cost of green wall infrastructure. It is estimated that the pilot study generated more than $500 worth of fresh produce during the growing season. Further research can determine how these savings plus other ecosystem service values contrast with the *disservices* and costs created by installation, maintenance, and disposal of the living wall system (Perini and Rosasco 2013). Refining design research of different green wall prototypes will determine the most cost-effective model and management regime for growing produce vertically outside.

Different metrics can highlight and promote the value of the food grown on a green wall. For example, this study compared the living wall crop yields in terms of recommended dietary quantities of daily vegetable servings. One could also determine the value of the produce using food prices within the niche market of "hyper-local" urban agricultural products (De Chabert-Rios and Deale 2016). A third metric could define value of the green wall infrastructure based on its percentage contribution to eradicating neighborhood food deserts and providing healthy physical activity, likely defraying costly medical and social services.

The observed productivity of crops given certain averages of solar exposure, temperature, soil moisture levels, and fertigation rates may also be useful for estimating the performance of this living wall system in different locations. Irradiance can be forecast in virtual models of the built environment based on geographic location and solar orientation, such as with AutoDesk's solar load analysis (Solar Load Analysis in BIM 2015). This feature could serve as one correlate to biomass productivity in the virtual modeling environment. Modeling tools contribute to the

FIGURE 10. Crops from top left clockwise: dill, sugar snap peas, cherry tomatoes, cilantro, collard greens, salad mix, rainbow Swiss chard, and mixed mustard greens, June 29, 2015.

growing field of urban ecology, as well as to urban planning and management of sustainable, food secure cities (Walloth et al. 2014; Arisona et al. 2012).

Green walls growing fresh produce play practical, educational, and ecological roles outside of the formal economy of food production. Green walls can serve as a tool for a hobby gardener, school garden curricula, or to create opportunities for health and wellness at a local community center. The role of the green wall would not be primarily as a source of food—it would contribute to community learning while still providing ecosystem services such as food production (Fig. 10). Living wall prototypes like the one used in this pilot study can diversify small-scale urban gardening activities throughout a community.

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