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Experimental evidence for delayed stormwater runoff from building roofs covered with suspended vine canopies

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ABSTRACT

Rainfall interception by the leaf canopies of natural forests are typically 25% of annual rainfall. Promoting canopy interception in the urban environment (e.g., roofs and parking lots) with vine canopies grown on suspended trellises could delay and reduce urban stormwater runoff and suppress peak flows. Our aim was to experimentally determine the delay in runoff from a vining canopy, elevated on a trellis above a sloped, asphalt shingle roof. A rainfall simulator generated a 9 mm/h (8.5 inch in 24 h) rain event for a 15-minute period (2.25 mm) for roofs covered with and without vine canopies. Eleven (11) canopies, each consisting of a single species and various amounts of leaf material [measured as leaf area index (LAI), percent cover, and canopy thickness] and no canopy (i.e., bare roof) were tested. The vine canopies intercepted 12 to 20% of rainfall with higher interception associated with thicker and denser amounts of leaf material (LAI, percent cover and canopy thickness (R^2: 0.82, 0.64, 0.48, respectively). Vining canopies show potential as a best management practice (BMP) for mitigating urban stormwater problems. Further work is needed to evaluate how much vine canopies reduce total and peak storm runoff.

Key words: BMP, stormwater management, green infrastructure, green building, green roof, vine canopy, interception

INTRODUCTION

A main goal of urban stormwater management is to restore stormflows to pre-development conditions to reduce surface erosion and stream degradation. In general stormwater best management practices (BMPs) focus on reducing peak flows and increasing base flows by detaining and retaining surface runoff. Modern-day ecologically-based BMP's include technologies that focus on retaining water in earthen basins [e.g., rain gardens (Yang et al., 2013), bioretention cells (Winston et al., 2016), constructed wetlands (Tuttolomondo et al., 2020)], and in the engineered soils of rooftops (e.g., extensive green roofs) (Bengtsson et al., 2005; Huang et al., 2020; Mentens et al., 2006; Moran et al., 2005). Practices also include using rain barrels (Qin 2020), urban tree canopies (Roy et al., 2012; Van Stan et al., 2015), and the soil pits of urban street trees (Szota et al., 2019) to detain rainfall. Retarding overland flow with vegetated filter strips and bioswales is also promoted by regulations and guidelines (Gavric et al., 2019; Qin 2020; Winston et al., 2016).

Rainfall interception, defined as the amount of gross precipitation that a vegetated canopy intercepts and evaporates before it reaches the ground (Van Dijk et al., 2015), is generally an underappreciated component of the ecosystem water balance. Its underappreciation is odd considering that it can represent from 20 to 50% of gross precipitation in a forest (Chang 2002; Huff et al., 1978; Liu 1997; van Dijk et al., 2015; Wang et al., 2007; Wang et al., 2008). Coniferous forests generally have higher values than broadleaved forests (Hormann et al., 1996). In a forest canopy each unit of leaf area, as typically measured by leaf area index (LAI), which is the ratio of the total leaf area in a canopy per a unit of ground (or roof) surface, can be expected to hold at least 0.31 mm of water, but maybe as much as 0.8 mm (Table 1).

As the first process in the chain from rainfall to runoff, interception influences all hydrological processes including: evaporation, infiltration, groundwater recharge, surface runoff, flood generation and moisture recycling (Tsiko et al., 2012). Evaporation from a wet canopy adds an appreciable amount to the evaporative cooling capacity of an ecosystem, which means increased interception can reduce the urban heat island effect. As interception increases there is less water flowing to the ground to generate surface runoff, which means that increased interception by foliage in urban areas will not only delay urban stormwater runoff, but will also reduce total flow.

As a percentage of rainfall, interception is highly dependent on rainfall intensity with the highest rates occurring during light rain events (Loustau et al., 1992). In addition, interception is affected by evaporation rates, saturation vapor pressure deficit, wind speeds during storms, and the structure of the canopy (Loustau et al., 1992; Van Stan et al., 2015).

Rain water intercepted by foliage becomes canopy storage (Gash et al., 1980). Water that bypasses the canopy is net precipitation. Water that falls from the canopy is throughfall and water that runs down the plant to the ground is stemflow. Water that resides as canopy storage will either become throughfall or canopy evaporation.

Canopy storage, the amount of water captured in the canopy at any one time, has been shown to range from 0.5 to 4.3 mm for various types of forests around the world (Table 1). In forests it varies seasonally, which is primarily associated with LAI, but it is also affected by other canopy elements like bark texture, branch density and abundance of epiphytes (Link et al., 2004).

Table 1. Water storage in forest canopies and their LAI.

Forest Type	Location	Steady State Storage, mm	LAI	Storage/LAI, mm	Source
Cashew trees	India	0.8	1.0-1.2	0.64-0.8	Rao, 1987
Mature rainforests	Colombian Amazon	1.33	5.4	0.25	Marin et al., 2000
Norway spruces, Scots pine	Sweden	1.69	4.5	0.38	Lankreijer et al., 1999
Deciduous	Japan	1.12	2.77	0.42	Deguchi et al., 2005
Deciduous	Japan	0.59	4.24	0.14	Deguchi et al., 2005
Tabonco	Puerto Rico	1.15	5.9	0.19	Schellekens et al., 1999
Temperate conifers	Pacific Northwest, US	2.7-4.3	8.6	0.31-0.5	Link et al., 2004
Temperate conifers	N. America	2.4	9-13	0.18-0.27	Klaassen et al., 1998
Temperate conifers	Europe	1.1	8.55	0.15	Rutter et al., 1975
Temperate conifers	Europe	0.50-0.55	3	0.17-0.18	Loustau et al., 1992
Hardwoods	Georgia, US	1.4	---	---	Bryant et al., 2005
Mixed	Georgia, US	1.58	---	---	Bryant et al., 2005
Pines	Georgia, US	1.97	---	---	Bryant et al., 2005
Pines, oaks	Georgia, US	1.7	---	---	Bryant et al., 2005
Wetland trees	Georgia, US	0.98	---	---	Bryant et al., 2005
Average				0.31	
Standard Deviation				0.17	

One novel way to increase plant interception of rainfall in urban environments is to introduce artificial structures that support the growth of vining plants in the horizontal plane so as to act as vegetated canopies (Schumann 2007). This increased interception will create canopy storage which will lead to less runoff and more evaporative cooling. Less urban runoff is known to protect the integrity and quality of receiving waters like streams, lakes, rivers, and estuaries (Regier et al. 2020). More evaporative cooling will lower the temperature of urban areas, thus helping mitigate the urban heat island effect (Clapp et al., 2014).

We developed the 'green cloak' (Figure 1), which has an artificial structure with a horizontal trellis that supports a live vegetated canopy consisting of vining plants. We previously proposed that the green cloak be used to cover impervious urban surfaces, like roofs, parking lots, and playgrounds, to provide ecosystem services (Schumann 2007; Tilley et al., 2014). We proposed that the green cloak has the potential for providing some of the same ecosystem services that urban trees do, including carbon sequestration, air purification, pollinator habitat, stormwater mitigation, increased property values, noise suppression, summertime cooling, positive human biophilic responses, and aesthetics.

The aim of this investigation was to experimentally determine how much a green cloak could detain runoff from a roof. We also sought to determine how much effect LAI, canopy thickness, and percent cover of the green cloak had on runoff detention. Green cloaks were established with multiple vine species and used to cover a sloped roof. Each cloak-roof combination was then exposed to a simulated rainfall event and runoff was measured.

Figure 1. Green cloak situated over the roof of the scaled-building with 20 cm gap.

MATERIALS AND METHODS

Description of Experimental System

The experimental system was designed to determine how much a green cloak could reduce runoff from a typically sloped roof. The experimental unit consisted of a scaled building covered with one of eleven (11) green cloaks or not covered (i.e. bare). Each green cloak had a unique amount of leaf material as measured by leaf area indices and a unique vine species. Since there was only one scaled building, the green cloaks were switched out to make an experimental unit. Each unit was subjected to the same artificial rain intensity, which was created with a professionally designed rainfall simulator.

The scaled-building (1.75 m x 1.5 m x 1 m) was constructed from wooden 2 in. by 4 in. (5.1 cm by 10.2 cm) framing and 0.75 in. (1.9 cm) plywood for the floor, walls, and roof (Figure 1). The roof with a slope of 38° was covered with standard black asphalt shingles (GAF Materials Corporation, Wayne, NJ).

Green cloaks consisted of a frame, wire trellis and plants grown in potted organic soils. The frame was constructed from 0.75 in. (1.9 cm) diameter polyvinylchloride (PVC) tubing (Charlotte Pipe and Foundry Company, Charlotte, NC). The trellis was constructed by connecting 16-guage wire to the PVC frame to make a 6 inch square grid (15.2 cm) (Figure 2).

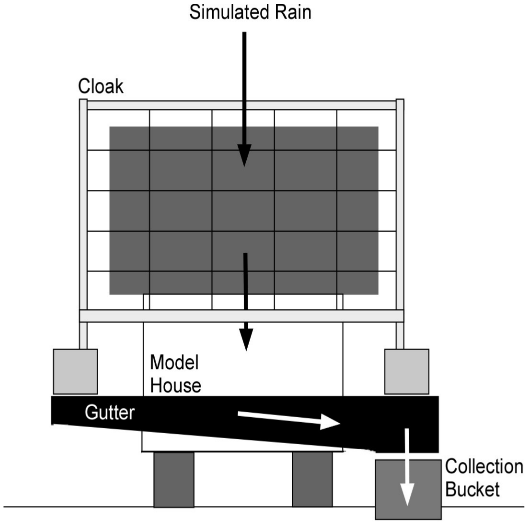


Figure 2. Schematic side view of the experimental setup for measuring roof runoff with and without green cloaks.

Each green cloak received one of nine vine species:

- black-eyed Susan vine (*Thunbergia alata*),
- Chinese trumpet creeper (*Campsis grandiflora*),

- cross vine (*Bignonia capreolata*),
- kudzu (*Pueraria lobata*),
- Japanese honeysuckle (*Lonicera japonica*),
- moonflower (*Ipomoea alba*),
- morning glory (*Ipomoea tricolor*),
- porcelain berry (*Ampelopsis brevipedunculata*), and
- Virginia creeper (*Parthenocissus quinquefolia*).

Species were selected on their known ability to thrive in the local climate. Use of some non-native and invasive species (i.e., kudzu, porcelain berry, Japanese honeysuckle, and Chinese trumpet) is not to be construed as endorsement of their use. Our goal was to find vines that could easily cover the green cloak.

Vines were planted in 2-gallon (nominally 8 liter) pots with organic potting soil (Sun Gro Horticulture, Bellevue, WA) and grown in the UMD Research Greenhouse from October to mid-May (225 days) under supplemental light and regulated climatic conditions that were representative of July in the mid-Atlantic region of the US. After May 15th, the potted plants were transferred outside where they grew for an additional 125 days. After their 350 days of growth the plants were subjected to the simulated rainfall for runoff experiment, which was conducted in mid-September. Green cloaks were sized to cover the entire roof area and have a 20 cm gap between the bottom of the vegetation and the asphalt shingles of the roof surface (Figure 1).

Canopy Water Balance

We employed a simplified version of the canopy water balance that we derived from Link et al. (2004), which was originally based on the earliest models developed by Rutter (1971) and Gash et al. (1980). The basic idea was that the canopy interception could be determined by knowing the gross precipitation, which was controlled by the rain simulator, the roof interception because the roughness of the asphalt shingles retains some water, and the roof runoff, which we measured. The canopy interception was the gross precipitation less the roof interception and the roof runoff.

More precisely, we derived a set of equations to find canopy interception from gross precipitation, roof interception and roof runoff. In general, gross precipitation P_g during a storm event is partitioned into canopy interception I_c, canopy evaporation E_c, and canopy throughfall Tc so that

$$P_g = I_c + E_c + T_c \qquad \text{(eq. 1)}$$

Where units are typically mm of depth. E_c is often ignored over short durations because it is very small, leaving:

$$P_g = I_c + T_c \qquad \text{(eq. 2)}$$

In our experimental setup we had the vine canopy above the roof so we needed a water balance for the roof. When there was no canopy, the water balance for the roof during the event was:

$P_g = I_r + E_r + R_r$ (eq. 3)

Where I_r was roof interception (i.e., the roof stores a small amount of water), E_r was roof evaporation, and R_r was roof runoff. Like we ignored E_c above in Eq. 1 to derive Eq. 2, we also assumed that E_r was zero in Eq. 3, leaving:

$P_g = I_r + R_r$ (eq. 4)

When the vine canopy was above the roof the input to the roof was T_c not P_g. Solving Eq. 2 for T_c we got:

$T_c = P_g – I_c$ (eq. 5)

We substituted T_c from Eq. 5 for P_g in Eq. 4 for the roof's water balance with canopy

$T_c = I_r + R_r$ (eq. 6)

And finally substituted T_c in Eq. 6 into Eq. 2 to get the combine water balance for the canopy-roof system:

$P_g = I_c + I_r + R_r$ (eq. 7)

When the canopy was absent I_c was zero in Eq. 7 so it reverted to Eq. 4.

Solving for I_r in Eq. 4 gave:

$I_r = P_g – R_r$ (eq. 8)

In our experiment we measured P_g and R_r and used Eq. 8 to find I_r. We assumed I_r to be the same for each test of a canopy.

Solving for I_c in Eq. 7 and using the estimated value of I_r means we can estimate I_c by measuring P_g and R_r for each test of a canopy:

$I_c = P_g – I_r – R_r$ (eq. 9)

Data Collection

The green cloaks were exposed to a 9 mm/h rain event for 15 minutes so P_g was 2.25 mm. If this rate were applied continuously for 24 hours it would be equivalent to 8.5 inches, which would be a major storm event. A rainfall simulator that was designed, built and calibrated by engineers in the Project Develop Center of the University of Maryland's Department of Biological Resources Engineering was used to create the rain event (Figure 3). This 3rd generation design for the simulator had six overlapping nozzles with the ability to produce a rainfall intensity between 1 - 150 mm/h over one square meter. Nozzle pressure was 138 kPa (20 psi). Nozzles were designed to produce expected rain drop size at terminal velocity. Rain intensity was calibrated by collecting water at multiple points within the 1 m^2 for 10 minutes. The coefficient of uniformity of the spatial distribution of the rainfall was 85%.

A runoff capturing system built to collect runoff from the roof included gutters, hidden from receiving direct rainfall, that discharged to 1-gallon buckets (Figure 3). Gutters were sloped and positioned so that runoff would collect in opposing corners of the scaled building.

All of the testing was completed on September 18, 2006. Prior to the experiment the rainfall rate of the simulator P_g was calibrated by capturing rainfall in a graduated 1-gallon bucket that was situated on the ground directly beneath the simulator. The graduated bucket had levels marked and calibrated to a known volume prior to data collection. Measurements were taken every minute for 30 minutes.

Each of the eleven green cloaks were placed over the scaled-building one at a time. The simulated rain event P_g was applied and roof runoff (R_r) was collected every minute for a total of fifteen minutes. The control experiment was run without a cloak (i.e., bare roof). Prior to the start of each test run, buckets and gutters were voided, and leaf debris was removed from the gutters and roof. Since the same scaled building was used for each run, the roof retained some wetness. Roof runoff was determined by measuring the water level in the graduated buckets every minute for the duration of the 15-minute experiment.

The area of the roof (33,912 cm^2) was measured with a meter stick. Depth (mm) of runoff was found by dividing the volume of runoff captured in the bucket by the roof area.

LAI, canopy thickness, percent canopy cover, and percent senesced cover measurements were made for each cloak immediately before runoff experiments were conducted. LAI was measured using the point-intercept method (Jonasson 1988), which consists of inserting a meter stick perpendicular to the plane of the canopy at equally spaced locations across the roof and counting the number of times a leaf or stem touches the meter stick. A total of six subsample measurements were made on each cloak. The LAI was calculated as the mean number of times the meter stick was touched.

Canopy thickness was the upward distance from the trellis to the most extended element of the canopy measured along a line orthogonal to the plane of the trellis. The thickness measurement was made at four random points in the canopy—twice on each side of the building.

Percent cover measured the amount of roof surface area that was covered by live plant material of the green cloak. Percent cover represents the amount of coverage in 2-dimensions of length and width, while LAI captures the 3-dimensional property of a canopy because it includes the height dimension. Percent cover was estimated for each side of the green cloak by having the researchers visually estimate how much vegetation covered each 6 inch (15 cm) grid of the trellis.

09/18/2006

(a) (b)

Figure 3 Experimental setup with (a) rainfall simulator poised above model house and (b) canopy placed over model house and (b).

The percent senesced cover was measured similarly to percent cover, except only senesced leaves—those that had started to yellow or were brown—were included.

Data Analysis

We found the mean of each plant coverage characteristic (i.e., LAI, canopy thickness, percent cover, and percent senesced cover) for each green cloak to explore relationships with canopy interception I_c.

Canopy interception (I_c) as a percentage of rainfall (P_g) was estimated (I_c/P_g) so it could be compared to studies of forest canopy interception. The percentage of a rainfall event that became runoff was estimated as Rr/Pg to ascertain the overall effect of the canopy system on roof runoff during a short storm event.

We conducted simple least squares regression to determine whether LAI, canopy thickness, percent leaf cover, and percent senescent leaf cover were correlated to canopy interception.

RESULTS AND DISCUSSION

Description of Experimental System

By the date of the experiment the green cloaks were about 350 days old, having spent the first 225 days growing in the university's research greenhouse and the latter 125 days growing outside in the Spring and Summer of Maryland.

The amount of vegetation varied across the 11 green cloaks with a few exhibiting fairly dense canopies and a few that were sparse (Table 2). LAI ranged from 0.67 to 3.67. It was highest for the Japanese honeysuckle and Virginia creeper, while lowest for morning glory, kudzu, black eyed Susan vine, and moonflower. By comparison the LAI of vines (*Campsis radicans, Hydrangea arborescens, Lonicera japonica, Parthenocissus quinquefolia, Rubus argutus, Toxicus radicans, Smilax rotundifolia, Vitis* spp.) growing wildly on dilapidated barns in rural southern Maryland (USA) for at least 7 years ranged from 1.5 to 5.

Table 2. Vegetation characteristics of each green cloak in LAI.

Canopy	LAI	Canopy Thickness, m	Leaf Cover %	Senesced Leaf Cover %
Japanese Honeysuckle	3.67	26.3	100	1
Virginia Creeper 1	3.17	31.5	90	2
Virginia Creeper 2	2.50	30.8	95	25
Chinese Trumpet Creeper	2.33	21.8	85	2
Kudzu 2	1.67	28.8	70	70
Cross Vine	1.17	14.5	55	1
Porcelainberry	1.33	16.8	65	3
Moonflower	0.83	17.5	60	10
Black Eyed Susan Vine	0.83	12.3	55	2
Kudzu 1	0.83	20.8	75	40
Morning Glory	0.67	18.0	50	10

Vines (*Akebia quinate*, *Bignonia capreolata*, *Campsis radicans*, *Celasturs scandens*, *Gelsemium sempervirens*, *Lonicera sempervirens*, *Parthenocissus quinquefolia*, *Parthenocissus tricuspidata*, *Trachelospermum jasminoides*, *Vitis* spp., *Wisteria frutescens*) growing on engineered green facades in central Maryland (USA) for 2 years had LAIs that ranged between 2.5 and 3.5 with a mean of 3.0 during their first year, but increased to a mean of 4.0 and a range of 2.0 to 7.0 the second year (Tilley et al., 2012; Tilley et al., 2014). Thus, the younger, horizontally grown green cloaks tended to have slightly smaller LAIs compared to the older, vertically grown vine canopies. Evidence from the green façade study indicates that the green cloaks are likely to develop higher LAI in their second year of growth. Also, the most prolific cloaks had LAIs that were comparable to natural, mixed hardwood forests of eastern North America, which range from 2.7 to 8.2 (Bolstad et al., 2001). A longer-term investigation is needed to determine the ultimate amount of leaf material that can develop in a suspended vine canopy.

The canopy thickness ranged from 12.3 to 31.5 cm (Table 2). Both of the Virginia creeper cloaks had the thickest canopies, while black eyed Susan vine and cross vine had the thinnest canopies. By comparison the canopy thickness of vines growing wildly on dilapidated barns in rural southern Maryland (USA) for at least 7 years ranged from 38 to 132 cm, while vines growing on engineered green facades in central Maryland (USA) for 2 years ranged from 30.2 to 95.6 cm (Tilley et al., 2014). Thus, the younger, horizontally grown green cloaks had thinner canopies than the two older, vertically grown vine canopies. The comparison indicates that the green cloaks will likely develop thicker canopies in subsequent years of growth.

Percent cover ranged from 50-100% (Table 2). Japanese honeysuckle had the most at 100 percent cover, while both Virginia creepers had percent cover greater than 90% (Table 2). Morning glory had the least percent cover at 50%.

Runoff rate from the roof started at 0 mm/h and steadily increased to 2.3 mm/h at minute 15 (Figure 4). With the rainfall rate held at a constant 9 mm/h, this meant that after 15 minutes of rainfall the roof runoff was 26% of rainfall intensity (Table 3). When any of the green cloaks covered the roof, regardless of LAI, the roof runoff was less than without a cloak (Figure 4). When a green cloak covered a roof, the runoff increased more slowly than it did with the bare roof and remained suppressed below the bare roof at minute 15. Due to the brevity of each test (i.e., 15 minutes) it is not known when roof runoff would have peaked, whether it had or did not have a green cloak. In a related modeling analysis, the authors use the results presented here to calibrate a runoff model to answer such questions (Schumann 2007; Tilley and Schumann, in preparation).

The Japanese honeysuckle and the fuller Virginia creeper cloaks intercepted 20% of rainfall (Table 3). This falls on the lower end of the range reported for forest canopies (20-50%--Chang 2003; Liu 1997; van Dijk et al., 2015; Wang et al., 2007; Wang et al., 2008). Even the most sparsely vegetated cloaks (kudzu and black-eyed Susan) intercepted 12% of rainfall. The vegetation of the green cloak simulates the canopy of small urban trees, which are known to provide interception and to delay and suppress peak storm runoff in urban areas (Qin 2020).

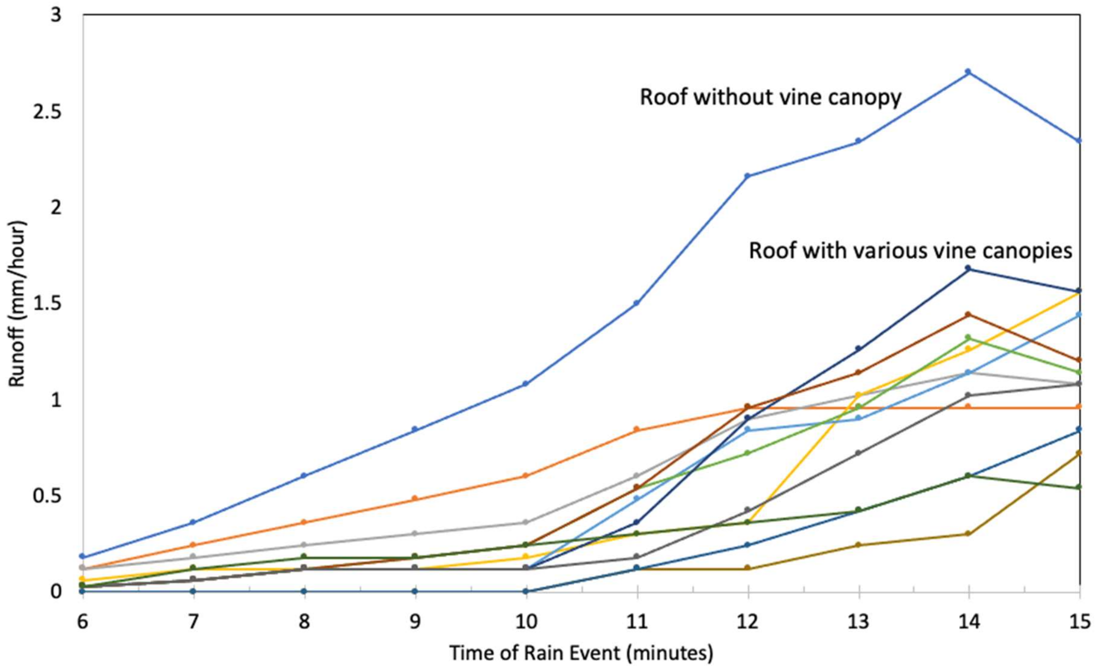
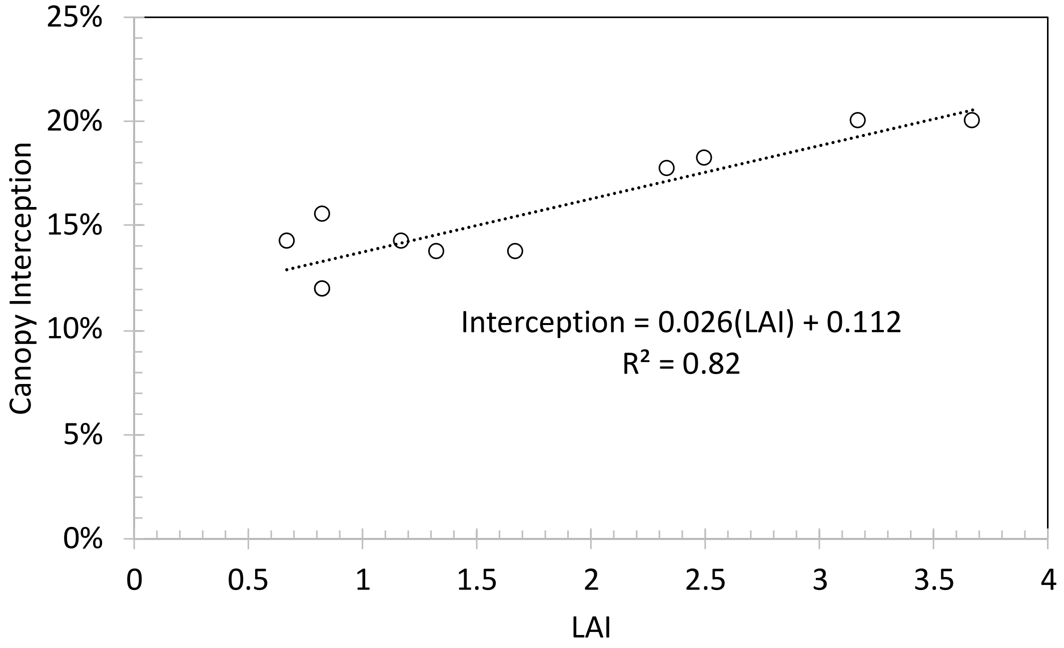


Figure 4. Runoff from roof with and without vine canopies. Simulated rainfall intensity was a continuous 9 mm/h. Since runoff was small during the first 5 minutes, measurements started at minute 6.

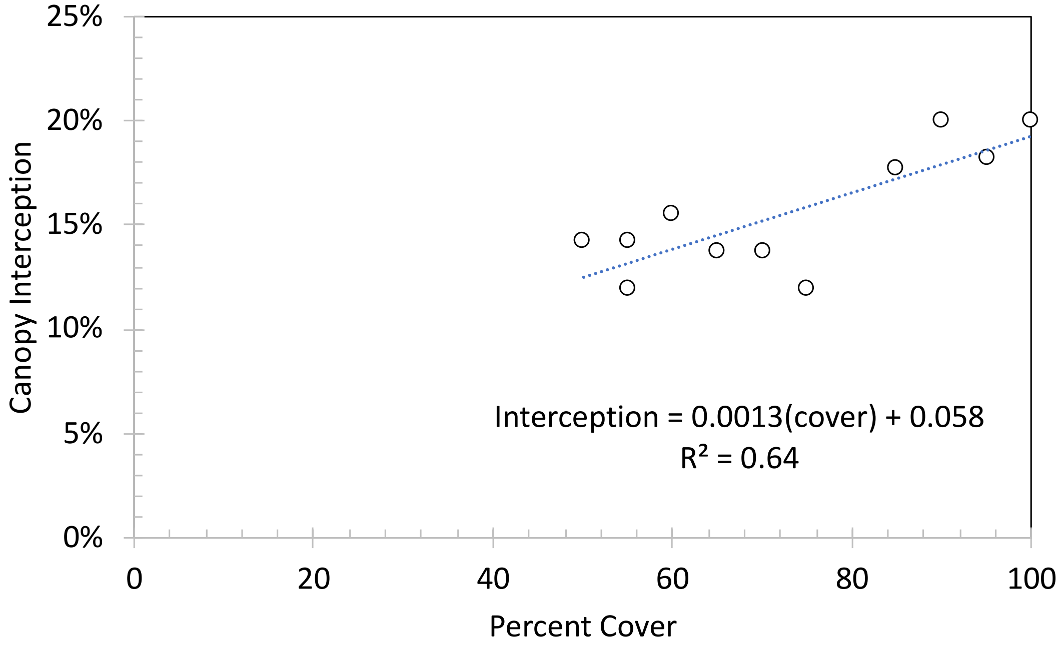
The more vegetation on a cloak, whether measured by LAI, percent cover, or canopy thickness, the greater the interception (Figure 5). Each unit increase in LAI increased interception by 2.6% (R^2=0.82, Figure 5a). Each 1% increase in percent cover and each 1 cm increase in canopy thickness increased interception by 0.13% and 0.3%, respectively (Figure 5b and 5c). Of the three vegetation metrics, LAI was the most predictive with an R^2 of 0.82. The amount of senesced vegetation was not predictive of runoff (data not shown). Notably, vine canopies with LAI > 3.0 were found to intercept 20% of rainfall, which mimics the hydrological properties of an urban tree.

If the LAI and canopy thickness of the green cloak can reach the higher values seen in nature on dilapidated barns or on engineered green facades (Tilley et al., 2014), then it is likely that interception could be higher and thus, runoff lower than we observed.

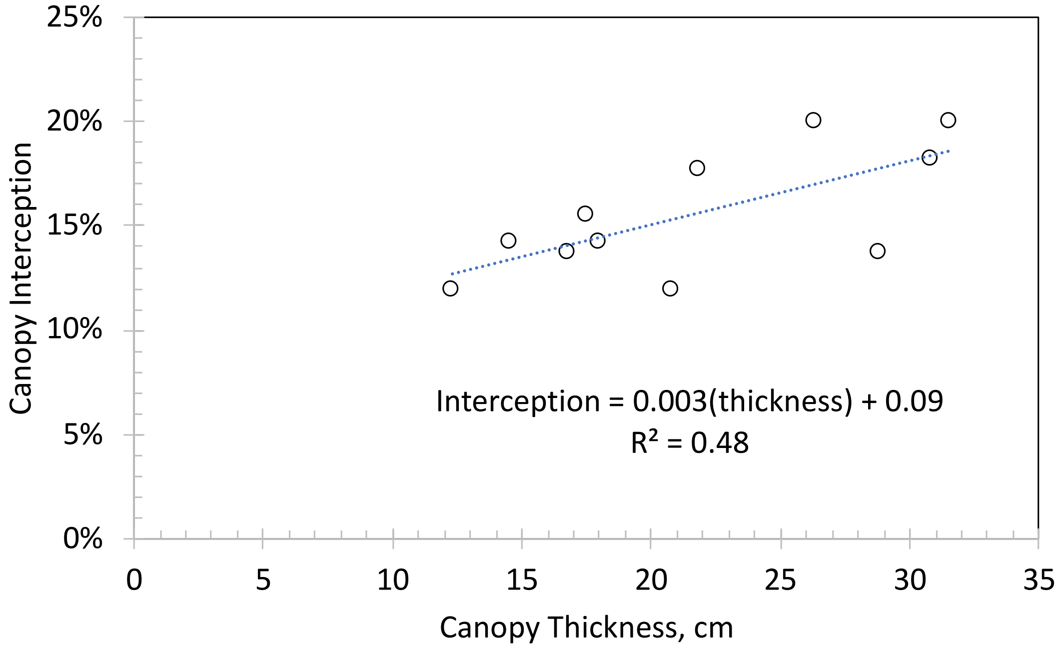
At the end of the 15-minute experiment only 26% of rainfall had become runoff when the roof was uncovered, but that was reduced to 6.2% for the 2 most fully vegetated cloaks (Table 3), indicating that a well-vegetated vine canopy can delay roof runoff by a substantial amount.


25%
20%
15%
10%
5%
0%
Canopy Interception
0
0.5
1
1.5
2
2.5
3
3.5
4
LAI
Interception = 0.026(LAI) + 0.112
R² = 0.82

(a)


25%
20%
15%
10%
5%
0%
Canopy Interception
0
20
40
60
80
100
Percent Cover
Interception = 0.0013(cover) + 0.058
R² = 0.64

(b)



(c)

Figure 5. Canopy interception of the vine canopies (i.e., green cloaks) related to a) LAI, b) percent cover, and c) canopy thickness.

Designed vine canopies, like plant-covered pergolas, the green cloak or the living umbrella (Tilley et al., 2015), can be added to the living architect's repertoire of green infrastructure tools. These tools can be used to mitigate issues surrounding urban stormwater and to provide additional ecosystem service benefits. These living technologies can likely offer ecosystem services similar to urban street trees. The beneficial value of these services can be extensive. For example, in Lisbon, Portugal, Soares et al. (2011) found that on average an urban street tree provided annual ecosystem service benefits as follows: energy $6.16; CO2 $0.33; air quality $5.40; stormwater $47.80; and property value $144.70. These five benefits totaled $204.45 per tree. They estimated the total costs to be $45.64 per tree, indicating that the net annual benefit was $159 per tree. Future investigations should apply values like these to suspended vine canopies like the green cloak, plant-covered pergolas, and living umbrellas.

The vine canopy was shown to intercept an appreciable amount of rainfall (20%) during the summer, which was on par with natural forests. However, due to the brevity of the experimental runs, delay and suppression of the peak flow was not readily apparent. Neither were we able to ascertain how interception would differ in the autumn or winter, when deciduous species are leafless. These are important properties to understand because the "first-flush" of a rain storm is known to carry the highest concentrations and most load of pollutants (Peter et al., 2020). Any stormwater BMP that delays the time to peak flow and suppresses it will lower the impact of stormwater runoff. Thus, an interesting question to explore for future research with vine canopies is their effect on the storm hydrograph with particular interest on how much they can delay the time to peak discharge and by how much they can suppress the peak flow. The time series data presented in this paper can provide a strong basis for calibrating a runoff model to ascertain these types of questions (Schumann 2007).

Table 3. Water balance components for canopy-roof system during 9 mm/h rain event (mm, Pg-gross precipitation, Rr-roof runoff, Ir-roof interception, Ic-canopy interception)

	P_g	R_r	I_r	I_c	I_c / P_g	R_r / P_g
Roof	2.25	0.59	1.66	--	--	26.2%
Species						
Virginia Creeper 1	2.25	0.14	1.66	0.45	20%	6.2%
Japanese Honeysuckle	2.25	0.14	1.66	0.45	20%	6.2%
Virginia Creeper 2	2.25	0.18	1.66	0.41	18%	8.0%
Chinese Trumpet Creeper	2.25	0.19	1.66	0.40	18%	8.4%
Moonflower	2.25	0.24	1.66	0.35	16%	10.7%
Cross Vine	2.25	0.27	1.66	0.32	14%	12.0%
Morning Glory	2.25	0.27	1.66	0.32	14%	12.0%
Kudzu 2	2.25	0.28	1.66	0.31	14%	12.4%
Porcelainberry	2.25	0.28	1.66	0.31	14%	12.4%
Black Eyed Susan Vine	2.25	0.32	1.66	0.27	12%	14.2%
Kudzu 1	2.25	0.32	1.66	0.27	12%	14.2%

The mechanism that allowed the green cloak to reduce runoff was the vegetation's ability to store rainfall on its leaves and stems temporarily before it evaporated or fell through the canopy to the roof surface. We found that runoff reduction by the green cloak was strongly affected by the amount of leaf surface area. Percentage of roof area covered by vegetation, canopy thickness, and LAI were strong explanatory variables of runoff reduction (Table 3, Figure 5). The three cloaks with the greatest interception had the most canopy leaf cover, canopy thicknesses, and LAI. To make full-use of the runoff reduction benefit of the green cloak, leaf growth should be a priority. However, a small amount of leaf material went a long way in reducing runoff. There was approximately a 50% reduction in runoff when LAI was only 1.0 (Figure 5), indicating that a young, poorly developed vine canopy can provide an appreciable amount of runoff reduction. From an implementation perspective this is promising because it indicates that a young vine canopy offers stormwater management benefits soon after installation. This is in contrast to a street tree which would likely take several years to provide the same size canopy as a vine-based canopy.

Identification of vine species best suited to provide hydrological benefit was not the aim of this study. However, some anecdotal observations are worth noting to inform future research on vine canopies. First, we included several non-native invasive species (i.e., kudzu, porcelain berry, Japanese honeysuckle and Chinese trumpet creeper) to see whether they could provide some hydrological benefit. Inclusion does not imply endorsement of their use in living architecture designs. Notably, kudzu had the highest proportion of senesced leaves and was the most difficult to culture in the greenhouse.

The variety of leaf morphologies, sizes and textures as well as canopy density of the vines likely plays a role in water holding capacity and interception rates. Anecdotal evidence indicated that the four vine species with the greatest runoff reduction had dense canopies with relatively small leaves or leaflets (~3 cm width). Kudzu and other canopy species with lower values of runoff reduction tended to have larger leaves and less dense canopies. The mechanical strength of small leaves may be higher than large leaves due to their higher stem-to-leaf ratio. A stem for a small leaf does not need to support as much weight as a large leaf and thus could presumably hold more water.

Research should be conducted on individual vine species to ascertain their specific hydrological properties. In addition, some species may be more desirable due to aesthetics, reflectance value, energetic values, water use, nativity, and climbing mechanisms (i.e., twining, aerial roots or tendrils).

Lastly, the vine canopy may overcome some of the limitations of installing extensive green roofs on existing buildings due to their lighter weight and the ability to focus their weight loads onto smaller areas of the roof structure (e.g., beams, posts, and walls). Since the stock of existing buildings (which is greater than 110 million in US) vastly exceeds the annual addition of new buildings (~0.5 to 1.5 million per year), it is imperative that ecological solutions be found for existing buildings if storm water produced by buildings is to be managed in an environmentally friendly way. The vine canopy may also greatly reduce the need for energy-intensive, engineered growing media such as high-temperature expanded shale. Additionally, the vine canopy could be used above non-roof impervious surfaces such as streets, highways, parking lots, playgrounds, and sidewalks to promote hydrological and ecological benefits like pollinator habitat, positive biophilic responses for humans, and scenic beauty. One challenge will be to ensure healthy soil conditions and sufficient soil volumes that can promote and sustain ground-based vegetation. However, technological advances in containerized growing systems offers some models that could be adapted.

In conclusion, we demonstrated that the vine canopies of the green cloak had the capability to intercept up to 20% of rainfall and delay storm runoff from buildings with sloped roofs during the growing season when plants had leaves. Since many, but not all, of the vine species tested are deciduous, interception during the cool season would likely be less. The vine canopies' ability to intercept rainfall was in the range of natural forests, suggesting that horizontal vine canopies in urban areas can provide ecosystem services similar to urban street trees. The spreading growth form of vines implies that vine canopies could be implemented in many novel ways in the hardscaped urban environment to transform it into a more lush oasis. The vine canopy shows potential as a significant stormwater management tool for use in place of or in conjunction with existing stormwater best management practices.

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