Journal of Environmental Management 281 (2021) 111882

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Effects of shading and composition on green roof media temperature and moisture

Michael A. Bollman [a,*], Grace E. DeSantis [b], Ronald S. Waschmann [a], Paul M. Mayer [a]

[a] U.S. Environmental Protection Agency, Center for Public Health and Environmental Assessment, Pacific Ecological Systems Division, 200 SW 35th St., Corvallis, OR, 97333, USA

[b] U.S. Environmental Protection Agency, Greater Research Opportunities Undergraduate Fellowship, 200 SW 35th St., Corvallis, OR, 97333, USA

ARTICLE INFO

Keywords:
Green infrastructure
Extensive green roof
Cool roof
Plant growing media
Building energy
Native plants

ABSTRACT

Three of the primary functions of green roofs in urban areas are to delay rainwater runoff, moderate building temperatures, and ameliorate the urban heat island (UHI) effect. A major impediment to the survival of plants on an unirrigated extensive green roof (EGR) is the harsh rooftop environment, including high temperatures and limited water during dry periods. Factors that influence EGR thermal and hydrologic performance include the albedo (reflectivity) of the roof and the composition of the green roof substrate (growing media). In this study we used white, reflective shading structures and three different media formulations to evaluate EGR thermal and hydrologic performance in the Pacific Northwest, USA. Shading significantly reduced daytime mean and maximum EGR media temperatures and significantly increased nighttime mean and minimum temperatures, which may provide energy benefits to buildings. Mean media moisture was greater in shaded trays than in exposed (unshaded) trays but differences were not statistically significant. Warmer nighttime media temperatures and lack of dew formation in shaded trays may have partially compensated for greater daytime evaporation from exposed trays. Media composition did not significantly influence media temperature or moisture. Results of this study suggest that adding shade structures to green roofs will combine thermal, hydrologic, and ecological benefits, and help achieve temperature and light regimes that allow for greater plant diversity on EGRs.

1. Introduction

Green infrastructure has been defined as "the network of green spaces and water systems that delivers multiple environmental, social and economic values and services to urban communities" (Pitman et al., 2015). Within this broad definition, green roofs are one of the most frequently installed structures because roofs in urban areas typically afford the greatest amount of under-utilized space (Carter and Jackson, 2007). The benefits of green roofs in urban areas include: (1) reducing and delaying rainwater runoff, (2) reducing the urban heat island (UHI) effect, (3) reducing building heating and cooling energy requirements, and (4) providing ecological and aesthetic benefits (Nawaz et al., 2015; Oberndorfer et al., 2007). Green roof designs can be categorized as intensive green roofs (IGRs) or extensive green roofs (EGRs). IGRs typically have deeper substrates with edible crops or landscaped gardens that in temperate climates require frequent summer irrigation and relatively high maintenance, whereas EGRs typically have shallow substrates, have minimal irrigation and maintenance requirements, and use a narrow set of plant species that are suited to the water stress created by this drier environment (Berndtsson, 2010; Oberndorfer et al., 2007). In this paper we address design considerations for EGRs.

Due to load limitations of many roofs, EGRs are typically designed with light, shallow (e.g., 10 cm deep) substrates of some water absorbent material that will detain rainwater runoff, but that are also permeable enough for water to pass through them during heavy rains. EGR media mixtures typically consist primarily of inorganic constituents, and should contain no more than about 20% organic matter (e.g., peat moss or compost) to reduce fire risk, minimize media shrinkage through decomposition, and avoid leaching of excess nutrients (e.g., nitrogen and phosphorus) into the runoff (Fassman and Simcock, 2012; Sailor and Hagos, 2011). Commonly used inorganic EGR media constituents vary among different geographic regions, largely due to the cost and availability of materials (Sailor and Hagos, 2011). For example, crushed brick has been widely used in Europe (Molineux et al., 2009), lightweight aggregates are commonly used in the eastern US (Ampim et al., 2010; Griffin et al., 2017), and volcanic materials (e.g., pumice and red cinder)

* Corresponding author.
E-mail address: bollman.mike@epa.gov (M.A. Bollman).

https://doi.org/10.1016/j.jenvman.2020.111882
Received 2 September 2020; Received in revised form 15 December 2020; Accepted 19 December 2020
Available online 6 January 2021
0301-4797/Published by Elsevier Ltd.

are more often used in the western US (BES, 2013; Sailor et al., 2008). An important consideration for green roof media composition in the Pacific Northwest is the ability of the media to retain water over time, which may be critical to plant survival during the seasonal drought that typically occurs from July through September (July and August average rainfall near Corvallis OR, USA are only about 10 and 13 mm, respectively). While native plant EGRs in the region may require summer irrigation for plant survival (Schroll et al., 2011), the additional water use during the summer months will contribute to the demands on already scarce water resources and should be minimized. Limiting media heating by incorporating reflective shading structures into green roof designs may reduce water loss over time, reducing irrigation requirements.

The thermal benefits of green roofs include reducing building and urban warming in hot weather and retaining building heat in cold weather. Urban areas have been shown to generate an urban heat island (UHI) effect, due in part to the lack of vegetation present (Bounoua et al., 2015). Urban heating is likely to have adverse human health effects (Larsen, 2015; Patz et al., 2005), and correspondingly, one of the reasons for promoting green infrastructure is to reduce the UHI effect. Studies have suggested that heat waves will become more numerous and severe in the near future (Meehl and Tebaldi, 2004), which is likely to exacerbate the UHI effect. EGR thermal performance is strongly influenced by substrate (growing media) and vegetation composition (Jim, 2012; MacIvor and Lundholm, 2011; MacIvor et al., 2011; Sailor and Hagos, 2011; Sailor et al., 2008; Theodosiou, 2003). Thermal performance is also strongly influenced by moisture, with greater evaporative cooling occurring when media moisture is higher and vegetation is actively transpiring, and greater thermal conductivity and heat capacity occurring in media with higher moisture content (Sailor et al., 2008, 2012; Sailor and Hagos, 2011; Theodosiou, 2003). In cold weather, traditional insulation materials or non-vegetated green roof media may have a similar ability to retain building heat than green roofs, with the presence of any live or dead vegetation having variable effects, depending on insulation materials, green roof media, vegetation composition, and climatic conditions (Getter et al., 2011; Lundholm et al., 2014; Squier and Davidson, 2016). Although cooling building interiors has been identified as a benefit of green roofs, several studies have shown that increasing roof albedo (e.g., painting roofs white to reflect light and thus reduce heating) may often be a more effective way to cool buildings (Georgescua et al., 2014; Mackey et al., 2012; Sailor et al., 2012). Nonetheless, given that other benefits of green roofs (e.g., reducing rainwater runoff, increasing urban ecological diversity, and aesthetics) validate their construction, green roof designs should maximize desirable temperature amelioration to the extent practical. Increasing the albedo of green roofs by incorporating reflective shading into green roof designs should reduce the heat load of the roof while retaining the functionality of a plant community, effectively combining the benefits of both cool roofs and green roofs.

The typical EGR environment is inhospitable to most plants due to shallow soils, lack of irrigation, and direct exposure to sunlight and wind, which cause dramatic fluctuations in temperature and moisture regimes. Accordingly, hardy, drought-tolerant species (e.g., *Sedum* spp.), often not native to the area, are commonly planted (Emilsson, 2008; Nagase and Dunnett, 2010; Thuring and Dunnett, 2014). These same environmental stresses may also lead to dominance of volunteer ruderal ("weedy") species over planted native species (Brown and Lundholm, 2015). Using diverse, regionally adapted native plant communities may be the optimal approach for ensuring an EGR will succeed over time (Dvorak and Volder, 2010). Native plants are preferable for EGR plant communities because: 1) native plants are likely to be best adapted to the climatic conditions of the area, 2) non-native plants may escape from green roofs and compete with native plants in natural settings, and 3) native plants provide more appropriate food sources and habitat for native birds and insects (MacIvor and Lundholm, 2011). Biodiversity is declining in many ecoregions in North America, and the isolated conditions of EGRs make them ideal locations for reintroduction of native species, but little is known about native plant performance on green roofs in North America (Dvorak and Volder, 2010). Because the Pacific Northwest has very dry summers and wet winters (soils are often at or near field capacity for extended periods of time), identifying native plant communities that will survive and provide the desired functions of an EGR can be challenging (Schroll et al., 2011). Incorporating shading structures into EGR designs may help to meet that challenge by reducing solar radiation and moderating temperature extremes, potentially providing appropriate conditions for additional native plant species, particularly those which typically grow in cooler, more shaded habitats. Except for portions of the Willamette Valley and a few other interior valleys, the natural vegetation of the Pacific Northwest west of the Cascade Mountains is predominantly forest, which supports diverse communities of shade-adapted native plant species (Franklin and Dyrness, 1973).

The objective of this study was to evaluate the effects of artificial reflective shading on moisture and temperature regimes of several media formulations during summer in the Pacific Northwest. The purpose was to determine if artificial shading could supplement the thermoregulation and moisture retention benefits of EGRs. Media formulations used in the evaluation were from an earlier growth chamber study that indicated optimal hydrologic performance could be obtained using mixtures of peat moss, perlite, and pumice (Bollman et al., 2019). Shading was provided by simple shading structures consisting of an acrylic panel mounted on an aluminum frame. Design objectives for the shading structures were that they would be durable, lightweight, and modular so they could be easily removed and stored during winter. This study was conducted using EGR media without growing plants present. Thermal and moisture dynamics in the presence of growing plants would likely vary substantially from those observed here.

2. Materials and methods

The effects of reflective shading on temperature and moisture patterns of green roof media mixtures were evaluated using modular

Fig. 1. Exposed (foreground) and shaded (background) experimental green roof modules (tubs) deployed on a rooftop in Corvallis, OR, USA.

shading structures and a tub and tray system (Fig. 1). This study was conducted on a building rooftop at the US EPA Pacific Ecological Systems Division research laboratory in Corvallis, OR, USA (latitude = 44.5657°, longitude = −123.2914°). The study was initiated on August 10, 2016 and terminated on September 15, 2016.

A common EGR design is to use modular trays containing media and plants. For this study we used heavy-duty (45 kg weight capacity) 53 cm × 38 cm HDPE horticultural (nursery) trays (Kadon Corp., Dayton, OH) lined with a geotextile fabric ("weed cloth"). Three 24" (61 cm) x 48" (122 cm) polycarbonate tubs, each containing three nursery trays filled to a depth of approximately 9 cm with growing media, were placed on the roof under aluminum-frame shading structures fitted with 24" (61 cm) x 48" (122 cm) white reflective acrylic panel shades so trays were shaded but open to the air (Fig. 1). Shade panels were tilted at an approximate 30° angle and designed so rainwater would drain into the tubs holding the trays, where it could be absorbed by the growing media. Shade panels were oriented with the tilt toward the south because at this latitude the sun is south of vertical most of the day. Acrylic panels are available in several standard thicknesses, and with several levels of translucency. We selected Type 2447 acrylic panels in a thickness of 1/8" (3.2 mm), rated to provide about 54% light transmission. Type 2447 is most commonly used for skylights, light tables, etc., and is a reasonable choice for green roof shading that will reflect a substantial amount of light while allowing enough light transmission for plant growth. Three similar exposed (unshaded) tubs were likewise installed for a total of 18 trays (9 shaded, 9 exposed).

The six tubs (1–6) were placed in a single west-to-east row on the roof of the building at a height of approximately 3 m above the ground. The rooftop covering was a smooth, white, flexible material. Tubs 1, 2, and 3 were exposed while tubs 4, 5, and 6 had shades. Each tub contained three different media, with one replicate tray of each media placed in each of the 3 shaded and exposed tubs (Fig. 2). To evaluate the potential effect of tray position, the three replicates of each media were placed in each of the three available positions within the tubs in each of the shaded vs. exposed treatments. The same tray position was used for both the shaded and exposed sets of tubs. The three media formulations used in this study were "Mix #9" (20% peat moss, 80% perlite), "Mix K" (20% peat moss, 50% perlite, 30% pumice) and "Mix N" (20% peat moss, 20% perlite, 60% pumice). Media mixtures were homogeneous in trays rather than layered as in some EGR substrate designs. Sixteen-liter batches of each media mixture were prepared, mixed by hand, moistened with 1.5 L of water, mixed again, then placed into the nursery trays. Trays of media were wetted to saturation, allowed to drain for 24 h, then placed in the tubs. The initial moisture holding capacity (%, V/V) for the different media used in this study were 24.9% for Mix #9, 29.5% for Mix K, and 25.9% for Mix N.

Two aluminum bars, centered over the trays, were attached to ring stands at 25 cm above the top edge of the nursery trays to hold environmental attribute monitoring sensors. Photosynthetically active radiation (PAR), measured as photosynthetic photon flux density (μmol m^{-2} s^{-1}), was monitored using LI-190 Quantum Sensors (LI-COR Inc., Lincoln, NE). PAR sensors were placed in pairs at each measurement location, with one sensor oriented upwards and the other oriented downwards. PAR sensor pairs were placed under the center of each of the shade structures, while a single pair of PAR sensors was placed over the centermost exposed tray. Soil temperature and moisture in the trays were monitored from field capacity through drying using Decagon 5TM probes (Decagon Devices, Inc., Pullman, WA). A soil moisture/temperature probe was inserted into the media in the center of each tray at an approximate 35° angle until only the coated wire was visible. A Campbell CR10X datalogger (Campbell Scientific, Inc., Logan, UT), placed to the north of the tubs, was used to collect PAR, media temperature (°C), and media moisture readings (%, V/V) at 1-min intervals, and record an average of these readings every 15 min. Air temperature (°C) and relative humidity (RH, %) were monitored at approximately 10 cm above the surface of the trays using shielded HOBO dataloggers (HOBO U-23-001 Pro v2 Temp/RH, Onset Computer Corporation, Bourne, MA) set to collect data at 15-min intervals. In addition, 1-min totals of ambient precipitation were measured at an on-site weather station located approximately 100 m from the green roof installation using a TE5251 tipping-bucket rain gauge (Texas Electronics, Dallas, TX). However, no measurable precipitation fell during the study period.

SAS/STAT software Version 9.4 of the SAS system for Windows was used to analyze the data. Analysis of variance (ANOVA) was completed using the method of least squares to fit a general linear model (GLM procedure) to determine significant differences ($a = 0.01$) among positions and mixtures, and between shaded vs. exposed locations. In evaluating interactions between independent variables (position, mixture, shade), a significance level of 10% ($a = 0.1$) was used to be conservative. For temperature data analyses, readings were averaged for each 24-hr period, and for day vs night, determined using the light sensor data. Day was defined as when exposed PAR was 10 μmol m^{-2} s^{-1} or greater. Temperature variables analyzed were 24-hr mean, daytime mean and maximum, and nighttime mean and minimum. Moisture retention was evaluated as the percentage of the initial moisture content remaining. Mean daily water loss was also calculated in seven-day increments. In addition, a repeated measures ANOVA using daily means was used to explore within-subject effects (how variables changed from day-to-day) over the course of the study period. The study was terminated after 35 days when media moisture levels approached zero.

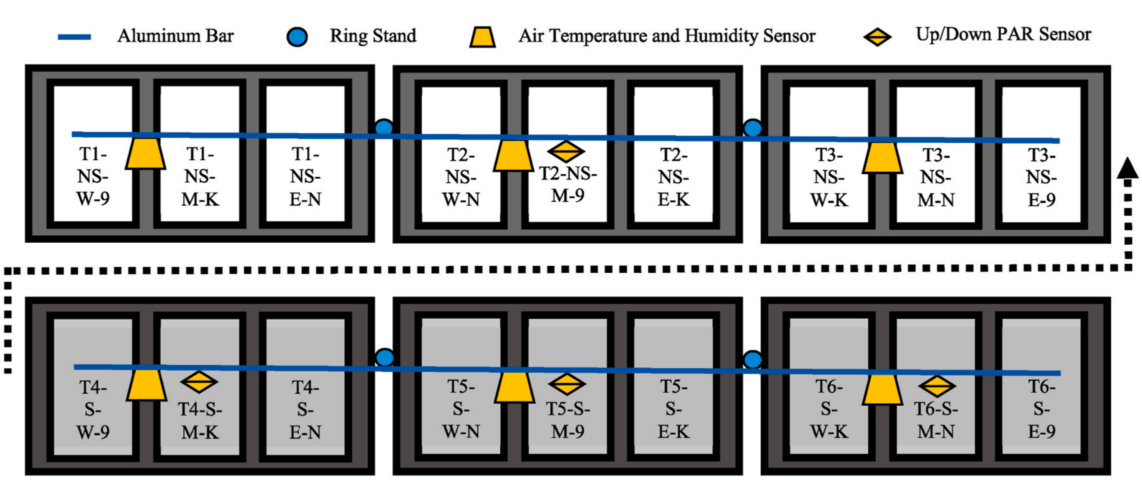

Fig. 2. Tub and tray experimental design; T = tub, NS = no shade, S = shade, W = west tray, M = middle tray, E = east tray, 9 = Mix #9, K = Mix K, N = Mix N. The dotted arrow indicates the tubs were arranged in a single row on the building rooftop.

3. Results and discussion

3.1. Media composition

There were no significant interactions ($p > 0.1$) for mix*position for any of the analyzed temperature or moisture variables and no significant differences ($p > 0.01$) in temperature or moisture among the three positions within a tub, so data for the different positions were pooled to evaluate the effects of media composition. There were also no significant interactions ($p > 0.1$) between shade*mix for any of the analyzed temperature or moisture variables and no significant differences ($p > 0.01$) in temperature or moisture among the three media mixtures tested here. One possible contributing factor for the finding of no significant differences in moisture retention among mixtures is that variability in moisture retention values among the replicate trays, particularly for Mix #9, was high (see Appendix A, Supplemental Data). One of the replicate shaded trays for Mix #9 was the most westerly shaded tray and was depleted of water more quickly than all the other shaded trays and all but two of the exposed trays, possibly because the afternoon sun was not blocked by the shade panel (Fig. 1). This tray also had a mean daytime maximum temperature greater than all the other shaded trays and similar to the exposed trays. Due to this anomaly, statistical analyses were also completed with this tray considered to be an exposed tray, but as before there were no significant differences ($p > 0.01$) in temperature or moisture among the three media mixtures.

The lack of a significant effect of media composition on either temperature or moisture in this study strengthens the conclusion from our earlier study that pumice may be a preferable alternative to perlite in EGR media mixtures (Bollman et al., 2019). Perlite is a mined mineral that expands with high-temperature heating (>850 °C). When expanded, perlite absorbs large amounts of water relative to its weight and therefore expanded perlite is a desirable EGR media constituent. However, because perlite is processed with high-temperature heating, it has greater embodied energy (i.e., energy required for production) than pumice, which is unprocessed. Green roofs with lower embodied energy, fewer maintenance requirements, and longer functional lifespans will be the most environmentally beneficial, all else being equal (Carter and Keeler, 2008; Getter et al., 2009; Kosareo and Ries, 2007; Saiz et al., 2006). Because there were no differences in thermal or hydrologic performance between mixtures ranging from 80% perlite/0% pumice to 20% perlite/60% pumice, mixtures using more pumice and less perlite will have similar performance for these attributes but will be more environmentally beneficial because they have lower embodied energy.

3.2. Temperature and shading

Shading effects were initially evaluated independently for each tray position (east, middle, west) for daytime maximum temperature because shade*position interaction was significant at the $a = 0.1$ level ($p = 0.0567$, $F = 6.40$, $df = 2$). There were no significant interactions ($p > 0.1$) for shade*position for any of the other temperature variables, and no significant differences ($p > 0.01$) among the three tray positions for any of the other temperature variables. Daytime maximum temperatures were significantly higher in the exposed trays than in the shaded trays for the east and middle tray positions ($p = 0.0018/0.0019$, $F = 54.05/53.44$, $df = 1$), but not significantly higher at the $a = 0.01$ level for the west position ($p = 0.0420$, $F = 8.70$, $df = 1$). Also, whereas there were no significant differences ($p > 0.01$) in daytime maximum temperature among any of the tray positions in the exposed trays, in the shaded trays the east and middle positions were not significantly different from one another but were both significantly lower than the west position. The three west-position shaded trays all had higher daytime maximum temperatures than any of the east- and middle-position shaded trays, and as noted above the most westerly shaded tray had a mean daytime maximum temperature equal or greater than two of the exposed trays. The repeated measures ANOVA showed that these differences for the west-position shaded trays were most pronounced on sunny days. The lack of a shading effect for daytime maximum temperature for the west-position trays is likely because the daytime maximum temperatures occurred during the afternoon when the sun was angled to the west and the west-position trays were partially exposed to the sun (see Fig. 1). When the most westerly shaded tray was considered as an exposed tray for statistical analyses there was no longer any significant shade*position interaction ($p > 0.1$) for daytime maximum temperature, and no significant differences ($p > 0.01$) among the three tray positions for any of the temperature variables within the shaded or exposed groups. Despite the shade*position interaction for daytime maximum temperature, data for the different positions were pooled for overall analysis of shading effects. Whether or not the most westerly shaded tray was considered as an exposed tray, there were no significant interactions ($p > 0.1$) between shade*mix for any of the analyzed temperature or moisture variables, and no significant differences ($p > 0.01$) in temperature or moisture among the three media mixtures, so data for the different media were also pooled to evaluate the effects of shading.

The shade structures moderated EGR media temperatures, significantly reducing daytime high temperatures and significantly increasing nighttime low temperatures (Table 1, Fig. 3).

The repeated measures ANOVA of daily data showed that daytime temperatures were only significantly lower under the shade structures during sunny weather and were not significantly lower on cloudy days (e.g., Fig. 3, Day 27). The presence of the shades not only reduced media heating during the day but also reduced heat loss from the media during the night. Because the nighttime temperatures in the exposed trays were lower than for the shaded trays even though the daytime temperatures in the exposed trays were higher, the exposed trays must have dissipated heat more rapidly than the shaded trays. Longwave radiation emission cools the earth's surface at night, and maximum emission occurs under clear skies when humidity is low because the dark sky has an effective temperature approaching absolute zero and low humidity minimizes interception and return of radiation by water vapor (Lu et al., 2016). Cloudy skies reflect and absorb longwave radiation and re-emit some radiation back to the surface, which reduces cooling of the earth.

Similarly, thermal radiation from media in the exposed trays was unobstructed into the clear summer night sky, whereas some of the thermal radiation from the media in the covered trays may have been reflected and absorbed and re-emitted from the shade panels back to the media. Although mean daytime air temperatures over the media in the exposed trays were significantly higher than for the covered trays (Table 2), the difference was small, and neither nighttime air temperatures nor 24-h air temperatures were significantly different at the $a = 0.01$ level. These lesser differences for air temperature relative to media temperature indicate that radiational heat transfer to and from the media was greater than convective heat transfer via the air.

Although the positive effect that shade structures might have on the UHI effect by reflecting solar energy and thus reducing daytime media temperatures appears to be partially counteracted by reduced heat dissipation from the media during the night, the effect of daytime heat reduction was greater than nighttime heat retention, and over a 24-h period the mean media temperature was significantly lower in the

Table 1
Mean and (standard error) of media temperature. All of the temperature variables were significantly different** at the $a = 0.01$ level (ANOVA, $df = 1$) between exposed ($n = 9$) and shaded ($n = 9$) treatments.

Media Temperature (°C)				
	Exposed	**Shaded**	***F***	***p***
Day Mean**	25.9 (0.24)	22.9 (0.21)	56.68	0.0017
Day Maximum**	35.1 (0.34)	29.5 (0.91)	103.40	0.0005
Night Mean**	17.5 (0.08)	18.5 (0.13)	78.77	0.0009
Night Minimum**	13.0 (0.07)	14.4 (0.12)	108.92	0.0005
24-Hour Mean**	22.1 (0.15)	20.9 (0.09)	34.45	0.0042

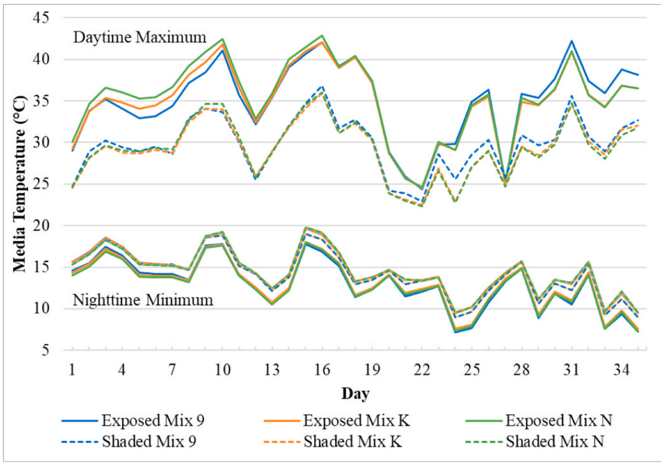

Fig. 3. Mean daytime maximum media temperatures and nighttime minimum media temperatures for each day over a 35-day period for different extensive green roof media mixtures in exposed vs. shaded trays ($n = 3$). Error bars are omitted from the figure to improve visual clarity.

Table 2
Mean and (standard error) of air temperature, relative humidity, and vapor pressure deficit (VPD) over trays ($n = 3$). Photosynthetically active radiation (PAR) was evaluated with two sensors over shaded trays but only one sensor over exposed trays. Only daytime air temperature and VPD were significantly different** at the $a = 0.01$ level (ANOVA, $df = 1$) between exposed and shaded treatments. Significant differences could not be calculated for PAR due to a lack of replicate exposed sensors.

Air Temperature (°C)	**Exposed**	**Shaded**	***F***	***p***
Day**	23.3 (0.02)	23.0 (0.04)	32.22	0.0048
Night	15.8 (0.01)	15.9 (0.04)	2.16	0.2156
24-h	20.0 (0.02)	19.9 (0.04)	9.75	0.0354
Relative Humidity (%)	**Exposed**	**Shaded**	***F***	***p***
Day	51.6 (0.29)	52.5 (0.21)	6.72	0.0606
Night	72.7 (0.35)	72.8 (0.16)	0.09	0.7775
24-h	60.8 (0.31)	61.4 (0.19)	2.34	0.2010
VPD (kPa)	**Exposed**	**Shaded**	***F***	***p***
Day**	−1.713 (0.0082)	−1.658 (0.0064)	29.31	0.0056
Night	−0.609 (0.0061)	−0.612 (0.0033)	0.17	0.6975
24-h	−1.232 (0.0073)	−1.202 (0.0049)	11.11	0.0290
PAR (μmol s^{-1} m^{-2})	**Exposed**	**Shaded**	***F***	***p***
Day	919 NA	533 (13.7)	NA	NA

shaded trays than in the exposed trays, suggesting that incorporating shade structures into EGR designs may indeed reduce the UHI effect.

Shade structures may provide a substantial energy benefit under conditions where buildings require cooling during the daytime because heat reflected by the shade panel is not absorbed by the media where it could add to the building heat load. Other considerations regarding the potential effects of EGR shade structures on building energy budgets involve the timing (both daily and seasonal) of the temperature effects of shading, and the climatic conditions where the EGR is located. In situations where cooling is required during the day and heating is required during the night, the moderation of daytime highs and nighttime lows provided by the shade structures would both be beneficial. The modular design of the shade structures used in this study allows for removal in winter which could potentially increase media heating during the day and reduce building heating requirements. Conversely, shade structures may trap warmer air near the roof and insulate buildings during winter. Shade structures could also be designed so the reflective panels could be rotated to a vertical position for increased flexibility in optimizing their thermal benefits, whether daily, seasonally, or in response to environmental conditions at any given time. The current study was conducted during the hottest part of the year when there was no precipitation, and any effect shade structures might have on thermal performance under different climatic conditions should be directly assessed under those conditions. In addition, a cost-benefit analysis of shading structures in terms of energy savings vs. installation costs could inform decisions on a specific deployment. Such an analysis would depend on a number of variables, including the climate where the EGR was located, the costs of materials and labor for the particular structures used, and site-specific energy costs.

3.3. Moisture and shading

There were no significant differences ($p > 0.01$) in the mean media moisture retention at any of the time intervals evaluated (7, 14, 21, and 28 days) between the shaded and exposed trays (Table 3, Fig. 4).

We also evaluated mean daily water loss in 7-day increments (1–7 days, 8–14 days, etc.), and there were no significant differences ($p > 0.01$) between the shaded and exposed trays. The most westerly shaded tray was depleted of water more quickly than any of the other shaded trays and had a mean daytime maximum temperature similar to two of the exposed trays, so statistical analyses were also completed with this tray considered to be an exposed tray, but as before there were no significant differences ($p > 0.01$) in moisture retention between the shaded and exposed trays. The repeated measures ANOVA showed that this lack of significant differences in moisture retention between the shaded and exposed trays was consistent throughout the course of the study. Although not statistically significant, the mean moisture retention in the shaded trays was higher than in the exposed trays, and the differences were of a similar magnitude to the differences in temperatures, which were significantly different. One contributing factor to these differences in moisture retention not being significant is that variability in moisture retention among the trays within treatment groups was high, with greater standard errors than for temperature (Table 1).

We expected lower daytime temperatures in the shaded trays would have reduced evaporative moisture loss, but we did not observe this effect. Although the higher nighttime temperatures in the shaded trays may have increased evaporation during the night that partially compensated for the daytime reduction, the increase in nighttime minimums was not as great as the decrease in daytime maximums. Also, over a 24-h period, the mean temperature was significantly lower in the shaded trays than in the exposed trays, suggesting that there should have been a net conservation of moisture in the shaded trays due to reduced

Table 3
Mean and (standard error) of media moisture content (percent of media volume) and moisture retention (percent of initial media moisture content). Moisture retention was not significantly different at the $a = 0.01$ level (ANOVA, $df = 1$) between exposed ($n = 9$) and shaded ($n = 9$) treatments at any time point.

	Media Moisture Content		**Media Moisture Retention**			
	% of Media Volume		**% of Initial (Day 0) Moisture Content**			
	Exposed	**Shaded**	**Exposed**	**Shaded**	***F***	***p***
Day 0	26.0 (1.37)	27.5 (1.35)	100	100	NA	NA
Day 7	8.1 (0.34)	9.1 (0.82)	31.3 (1.25)	33.1 (1.78)	1.16	0.3423
Day 14	4.2 (0.43)	5.3 (0.62)	16.2 (1.41)	19.0 (1.57)	1.57	0.2782
Day 21	1.3 (0.35)	2.7 (0.56)	5.0 (1.30)	9.5 (1.74)	2.82	0.1683
Day 28	0.7 (0.25)	1.7 (0.48)	2.6 (0.94)	6.0 (1.48)	2.60	0.1823

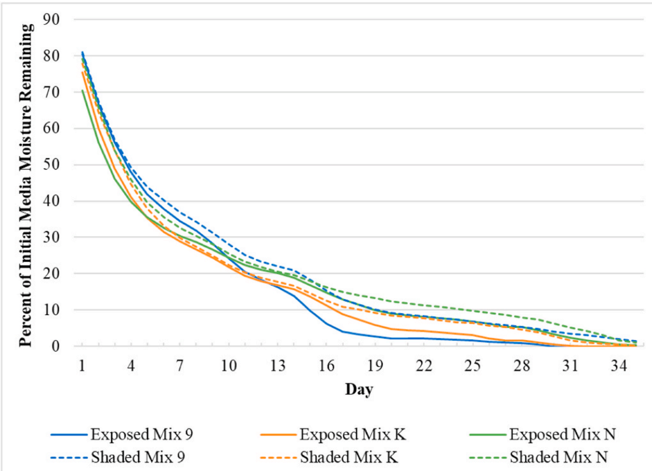

Fig. 4. Moisture retention over 35 days for different extensive green roof media mixtures in exposed vs. shaded trays. Values are daily mean ($n = 3$) percent of initial (Day 0) media moisture content. Error bars are omitted from the figure to improve visual clarity.

evaporative moisture loss. However, a variable that may be more important than temperature in regulating evaporative loss from the trays of media is vapor pressure deficit (VPD), which is the difference between the amount of water in the air and how much water the air can hold (Brady, 1974; Kramer, 1983). VPD is a function of temperature and humidity, but in contrast to temperature or humidity, VPD has an essentially linear relationship with evaporative capacity. As with air temperature, daytime VPD over the media in the exposed trays was significantly greater than for the shaded trays (Table 2), but neither nighttime VPD nor 24-h VPD were significantly different at the $a = 0.01$ level. Humidity over the trays was not significantly different ($p > 0.01$) between exposed and shaded trays during the day, night, or over the entire 24-h period. Although the significantly greater VPD during the day would suggest increased evaporation and thus lower expected cumulative moisture levels for the exposed trays by the end of the study, the lack of a significant difference in VPD over the entire 24-h period suggests that overall evaporation was not significantly greater for the exposed trays, which supports the finding of no significant differences in moisture retention between the shaded and exposed trays. Horizontal advection due to wind likely also played a role in evaporation from the trays. However, because humidity was not significantly different above exposed vs. shaded trays and because trays in both treatments were open on all sides, the effects of horizontal advection on media moisture should have been similar between the two treatments.

One possible contributing factor for why there were no significant differences in moisture retention between the shaded and exposed trays even though daytime VPD was greater for the exposed trays is that the shade panels prevented development of conditions favorable for dew formation on the media, which could have partially compensated for the decrease in evaporative moisture loss from the shaded trays during the day. Dew can contribute to water budgets, and evaporation is limited during dew formation because VPD is essentially zero (Heusinger and Weber, 2015; Jacobs et al., 2006; Richards and Oke, 2002; Sherrard and Jacobs, 2012). The dewpoint is the temperature at which the air is saturated with water and condensation occurs, and like VPD is dependent on both temperature and humidity. Whereas fog is condensation that forms in the atmosphere when the air temperature equals the dewpoint, dew is condensation that forms on surfaces when surface temperatures are equal to or below the dewpoint. Dew can form on the ground or other surfaces when the air temperature is above the dewpoint because radiational cooling at night cools those surfaces more than the air is cooled, much like when condensation forms on a cold drink glass on a warm day. Clear skies provide optimal conditions for dew formation due to enhanced radiational cooling, and, as discussed above, the presence of the shade structures in our study limited media cooling. Mean nighttime media temperature was significantly warmer under the shades than when exposed, although the air temperatures were not significantly different. Media temperature in every shaded tray was always above the dewpoint during the study, whereas media temperature in at least one of the exposed trays was equal to or below the dewpoint on 10 out of 35 mornings. Conditions favorable for dew formation typically occurred shortly after dawn (when cumulative radiational cooling was greatest) when air temperatures were warming more quickly than media temperatures, driving the dewpoint above media temperatures. This suggests that morning dew formation on the media in the exposed trays may have partially compensated for increased evaporative moisture loss later in the day. As suggested above for thermal dynamics, optimal moisture dynamics might be achieved by designing shade structures so reflective panels could be rotated a vertical position at night to increase media radiational cooling, allowing dew formation to contribute to media moisture retention.

3.4. Implications of shading for native plants on EGRs

Species diversity is often an objective in green roof construction. In addition, a larger suite of available plant species may help in assembling an optimal plant community for a specific green roof installation. The moderation of high daytime media and air temperatures provided by the shade structures in our study may allow the inclusion of additional desirable native species into EGR plant communities, particularly those adapted to cooler, more shaded conditions (e.g., mosses, ferns) which may not be as heat-tolerant as the non-native plants (e.g., *Sedum* spp.) typically used on green roofs. Mosses, for example, are ideal for EGRs because they are tolerant of desiccation yet quickly respond to the addition of moisture (Proctor et al., 2007), and have been shown to be valuable additions to EGR plant communities by moderating temperature fluctuations and increasing stormwater retention (Anderson et al., 2010). A wide variety of arboreal epiphytic mosses grow in the Pacific Northwest due to the broad range of forest types present. Because most epiphytes typically grow on tree trunks and branches under the shade of the tree canopy, they should be well-adapted to growing under shade structures.

Light is a critical factor for plant growth, and optimal plant growth is usually achieved with moderate light intensities. Under very low light conditions plant growth is reduced due to insufficient ATP production causing reduced carbon fixation and carbohydrate biosynthesis, whereas under excessively high light conditions photosynthesis is inhibited and reactive oxygen species are formed that can damage tissues (Demmig-Adams and Adams III, 2006; Keren et al., 1997). PAR intensities in greenhouses designed for optimal growth of both sun- and shade-adapted plant species are typically around 350–400 μmol m^{-2} s^{-1}. Mean daily PAR over the shaded tubs in our study was 533 μmol m^{-2} s^{-1}, approximately 58% of the PAR intensity over the exposed tubs (919 μmol m^{-2} s^{-1}). Optimal PAR levels for shade-tolerant plants can be at levels of 50% or less of full natural light intensity. Shade-tolerant plants often do not tolerate full sun because adaptations that allow them to tolerate low light intensities are frequently incompatible with high light intensities (Valladares and Niinemets, 2008). Because forested ecosystems with a wide variety of shade-adapted understory plant are common in the Pacific Northwest and in other forested regions worldwide (e.g., tropical rainforests), the reduced light intensity under the shade structures used in our study would allow for the inclusion of many additional native vascular and non-vascular plant species on EGRs in forested regions.

Ameliorating green roof temperature extremes by using shade structures that will reduce building energy use while increasing the palette of native plant species available for use on EGRs could provide substantial functional and ecological benefits for many EGR installations. The acrylic shade panels we used are available in several standard thicknesses and with several levels of translucency, so shade structures could be modified to provide optimal light for a variety of plant communities on the sun-to-shade tolerance spectrum. Also, during cooler weather in spring and fall shade structures may keep media temperatures above the minimum threshold for plant growth for a longer time, effectively extending the day length or growing season. In addition, other shade structure materials (e.g., white wooden slats or white fabric) or designs could provide similar shading benefits to those observed here while potentially providing additional benefits as well. For example, solar panels that reduce temperatures and light intensity beneath them could also generate electricity. EGR designs integrating photovoltaic (PV) solar panels and green roofs have shown that plant growth can be enhanced with optimally-spaced arrays of PV panels (Jahanfar et al., 2019; Schindler et al., 2018), and that under certain conditions PV energy output can be increased by the presence of the green roof plants (Lamnatou and Chemisana, 2015).

4. Conclusions

Incorporating reflective shade structures into green roof designs combines the temperature-moderating benefits of cool roofs with the hydrologic and ecological benefits of green roofs. Results of this study demonstrated that shading structures were successful in reducing daytime green roof media temperatures and elevating nighttime media temperatures relative to exposed media trays, while reducing light intensity (PAR) by approximately 40%. These results suggest that significant building energy savings may be realized under certain conditions, particularly where climate or seasonal conditions would require daytime building cooling and nighttime heating, by moderation of day-night temperature extremes. Shade structures may also help to mitigate certain impacts of the urban heat island (UHI) phenomenon by moderating daytime peak temperatures.

Shade structures did not significantly reduce moisture loss over time from the media, which may have been partially due to morning dew formation in the exposed trays which did not occur in the shaded trays, and which may have provided some compensation for greater evaporative moisture loss from the exposed trays during the hottest part of the day. In addition, variability in moisture data in this study may have obscured differences, and further study is recommended to clarify the potential effects of shade structures on media moisture regimes.

Using shade structures on EGRs is likely to increase the diversity of native plant species available for use on EGRs, and additional studies should be conducted to evaluate the effects of shading on the growth of different species and determine optimal light and temperature conditions for various native species.

Results of this study suggest that adding shade structures could be a design option for green roofs for some climatic conditions or plant communities to help achieve desired temperature and light regimes.

Credit author statement

Michael A. Bollman conceived and designed the study, performed the analysis, and wrote the manuscript. Grace E. DeSantis set up and conducted the experiment and managed the data. Ronald S. Waschmann set up instrumentation and collected environmental monitoring data. Paul M. Mayer provided technical guidance, project management, and administrative oversight, and reviewed and edited the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The views expressed in this article are those of the author(s) and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Any mention of trade names, products, or services does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. The EPA does not endorse any commercial products, services, or enterprises. DeSantis was supported by an EPA Greater Research Opportunity Fellowship. John Lambrinos provided constructive comments on manuscript preparation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111882.

References

Ampim, P.A.Y., Sloan, J.J., Cabrera, R.I., Harp, D.A., Jaber, F.H., 2010. Green roof growing substrates: types, ingredients, composition and properties. J. Environ. Hortic. 28, 244–252.
Anderson, M., Lambrinos, J., Schroll, E., 2010. The potential value of mosses for stormwater management in urban environments. Urban Ecosyst. 13, 319–332.
Berndtsson, J.C., 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecol. Eng. 36, 351–360.
BES, 2013. BES Red Cinder Ecoroof Design Guidelines, p. 23. Portland, OR.
Bollman, M.A., DeSantis, G.E., DuChanois, R.M., Etten-Bohm, M., Olszyk, D.M., Lambrinos, J.G., Mayer, P.M., 2019. A framework for optimizing hydrologic performance of green roof media. Ecol. Eng. https://doi.org/10.1016/j.ecoleng.2019.105589.
Bounoua, L., Zhang, P., Mostovoy, G., Thome, K., Masek, J., Imhoff, M., Shepherd, M., Quattrochi, D., Santanello, J., Silva, J., Wolfe, R., ToureAlly, M., 2015. Impact of urbanization on US surface climate. Environ. Res. Lett. 10 https://doi.org/10.1088/1748-9326/10/8/084010.
Brady, N.C., 1974. The Nature and Properties of Soil, eighth ed. Macmillan Publishing Co., Inc., New York, NY.
Brown, C., Lundholm, J., 2015. Microclimate and substrate depth influence green roof plant community dynamics. Landsc. Urban Plann. 143, 134–142.
Carter, T., Jackson, C.R., 2007. Vegetated roofs for stormwater management at multiple spatial scales. Landsc. Urban Plann. 80, 84–94.
Carter, T., Keeler, A., 2008. Life-cycle cost–benefit analysis of extensive vegetated roof systems. J. Environ. Manag. 87, 350–363.
Demmig-Adams, B., Adams III, W.W., 2006. Photoprotection in an ecological context: the remarkable complexity of thermal energy dissipation. New Phytol. 172, 11–21.
Dvorak, B., Volder, A., 2010. Green roof vegetation for North American ecoregions: a literature review. Landsc. Urban Plann. 96, 197–213.
Emilsson, T., 2008. Vegetation development on extensive vegetated green roofs: influence of substrate composition, establishment method and species mix. Ecol. Eng. 33, 265–277.
Fassman, E., Simcock, R., 2012. Moisture measurements as performance criteria for extensive living roof substrates. J. Environ. Eng. 138, 841–851.
Franklin, J.F., Dyrness, C.T., 1973. Natural Vegetation of Oregon and Washington. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.
Georgescua, M., Morefield, P.E., Bierwagen, B.G., Weaver, C.P., 2014. Urban adaptation can roll back warming of emerging megapolitan regions. In: Proceedings of the National Academy of Sciences of the United States of America, vol. 111, pp. 2909–2914.
Getter, K.L., Rowe, D.B., Andresen, J.A., Wichman, I.S., 2011. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy Build. 43, 3548–3557.
Getter, K.L., Rowe, D.B., Robertson, G.P., Cregg, B.M., Andresen, J.A., 2009. Carbon sequestration potential of extensive green roofs. Environ. Sci. Technol. 43, 7564–7570.
Griffin, W.N., Cohan, S.M., Lea-Cox, J.D., Ristvey, A.G., 2017. Green roof substrate composition affects *Phedimus Kamtschaticus* growth and substrate water content under controlled environmental conditions. Hortscience 52, 320–325.
Heusinger, J., Weber, S., 2015. Comparative microclimate and dewfall measurements at an urban green roof versus bitumen roof. Build. Environ. 92, 713–723.
Jacobs, A.F.G., Heusinkveld, B.G., Wichink Kruit, R.J., Berkowicz, S.M., 2006. Contribution of dew to the water budget of a grassland area in The Netherlands. Water Resour. Res. 42 https://doi.org/10.1029/2005WR004055.
Jahanfar, A., Drake, J., Sleep, B., Margolis, L., 2019. Evaluating the shading effect of photovoltaic panels on green roof discharge reduction and plant growth. J. Hydrol. 568, 919–928.
Jim, C.Y., 2012. Effect of vegetation biomass structure on thermal performance of tropical green roof. Landsc. Ecol. Eng. 8, 173–187.
Keren, N., Berg, A., van Kan, P.J.M., Levanon, H., Ohad, I., 1997. Mechanism of photosystem II photoinactivation and D1 protein degradation at low light: the role of back electron flow. Proc. Natl. Acad. Sci. Unit. States Am. 94, 1579–1584.

Kosareo, L., Ries, R., 2007. Comparative environmental life cycle assessment of green roofs. Build. Environ. 42, 2606–2613.
Kramer, P.J., 1983. Water Relations of Plants. Academic Press, New York, NY.
Lamnatou, C., Chemisana, D., 2015. A critical analysis of factors affecting photovoltaic-green roof performance. Renew. Sustain. Energy Rev. 43, 264–280.
Larsen, L., 2015. Urban climate and adaptation strategies. Front. Ecol. Environ. 13, 486–492.
Lu, X., Xu, P., Wang, H., Yang, T., Hou, J., 2016. Cooling potential and applications prospects of passive radiative cooling in buildings: the current state-of-the-art. Renew. Sustain. Energy Rev. 65, 1079–1097.
Lundholm, J.T., Weddle, B.M., MacIvor, J.S., 2014. Snow depth and vegetation type affect green roof thermal performance in winter. Energy Build. 84, 299–307.
MacIvor, J.S., Lundholm, J., 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecol. Eng. 37, 407–417.
MacIvor, J.S., Ranalli, M.A., Lundholm, J.T., 2011. Performance of dryland and wetland plant species on extensive green roofs. Ann. Bot. 107, 671–679.
Mackey, C.W., Lee, X., Smith, R.B., 2012. Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. Build. Environ. 49, 348–358.
Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305, 994–997.
Molineux, C.J., Fentiman, C.H., Gange, A.C., 2009. Characterising alternative recycled waste materials for use as green roof growing media in the U.K. Ecol. Eng. 35, 1507–1513.
Nagase, A., Dunnett, N., 2010. Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity. Landsc. Urban Plann. 97, 318–327.
Nawaz, R., McDonald, A., Postoyko, S., 2015. Hydrological performance of a full-scale extensive green roof located in a temperate climate. Ecol. Eng. 82, 66–80.
Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. Bioscience 57, 823–833.
Patz, J.A., Campbell-Lendrum, D., Holloway, T., Foley, J.A., 2005. Impact of regional climate change on human health. Nature 438, 310–317.
Pitman, S.D., Daniels, C.B., Ely, M.E., 2015. Green infrastructure as life support: urban nature and climate change. Trans. Roy. Soc. S. Aust. 139, 97–112.
Proctor, M.C.F., Oliver, M.J., Wood, A.J., Alpert, P., Stark, L.R., Cleavitt, N.L., Mishler, B. D., 2007. Desiccation-tolerance in bryophytes: a review. Bryol. 110, 595–621.
Richards, K., Oke, T.R., 2002. Validation and results of a scale model of dew deposition in urban environments. Int. J. Climatol. 22, 1915–1933.
Sailor, D.J., Elley, T.B., Gibson, M., 2012. Exploring the building energy impacts of green roof design decisions – a modeling study of buildings in four distinct climates. J. Build. Phys. 35, 372–391.
Sailor, D.J., Hagos, M., 2011. An updated and expanded set of thermal property data for green roof growing media. Energy Build. 43, 2298–2303.
Sailor, D.J., Hutchinson, D., Bokovoy, L., 2008. Thermal property measurements for ecoroof soils common in the western. U.S. Energy and Buildings 40, 1246–1251.
Saiz, S., Kennedy, C., Bass, B., Pressnail, K., 2006. Comparative life cycle assessment of standard and green roofs. Environ. Sci. Technol. 40, 4312–4316.
Schindler, B.Y., Blaustein, L., Lotan, R., Shalom, H., Kadas, G.J., Seifan, M., 2018. Green roof and photovoltaic panel integration: effects on plant and arthropod diversity and electricity production. J. Environ. Manag. 225, 288–299.
Schroll, E., Lambrinos, J., Righetti, T., Sandrock, D., 2011. The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. Ecol. Eng. 37, 595–600.
Sherrard, J.A., Jacobs, J.M., 2012. Vegetated roof water-balance model: experimental and model results. J. Hydrol. Eng. 17, 858–868.
Squier, M., Davidson, C.I., 2016. Heat flux and seasonal thermal performance of an extensive green roof. Build. Environ. 107, 235–244.
Theodosiou, T.G., 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy Build. 35, 909–917.
Thuring, C.E., Dunnett, N., 2014. Vegetation composition of old extensive green roofs (from 1980s Germany). Ecological Processes 3, 1–11.
Valladares, F., Niinemets, Ü., 2008. Shade tolerance, a key plant feature of complex nature and consequences. Annu. Rev. Ecol. Evol. Syst. 39, 237–257.