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More than sedum: Colonizing weedy species can provide equivalent green roof ecosystem services

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ABSTRACT

Green roofs are typically constructed for their provision of both environmental and associated economic benefits including increased habitat, thermal regulation, mitigation of air and noise pollution, and stormwater retention. The provision of these various ecosystem services is sharply influenced by plant species composition, with particular species and traits known to excel at specific services. For this reason, increased biodiversity can improve the overall provision of ecosystem services. However, one key contributor to green roof biodiversity, colonizing species, is understudied. In this study we examine the contribution of common colonizing species (lawn weeds) and one green roof species, to three important ecosystem services: stormwater retention, temperature reduction, and nitrogen retention. This experiment used replicated green roof modules to examine 13 different treatments: eight colonizing species in monoculture, one green roof species monoculture, two treatments with a mix of colonizing species, one treatment where vegetation was allowed to spontaneously colonize, and one substrate only control. Results from this study show that mixtures of colonizing species performed well for all three monitored ecosystem services, with a few of the monocultures, especially those with high biomass or canopy density, performing similarly. While it is unlikely that green roof installations would proceed equally well without adding vegetation, our results indicate that colonizing species can support a viable green roof ecosystem. This study shows that spontaneous growth and/or allowing new species to colonize may be a viable design alternative for green roofs, decreasing cost while maintaining the desired ecosystem services.

Introduction

Green roofs are typically constructed for their provision of both environmental and associated economic benefits including increased habitat, thermal regulation, mitigation of air and noise pollution, and stormwater retention [1–3]. The provision of these various ecosystem services is sharply influenced by plant species composition, with particular species and their corresponding traits known to excel at specific services [4]. For this reason, increased biodiversity can improve the provision of ecosystem services [5]. However, existing knowledge about the relationship between individual plant species or plant communities and the ecosystem services provided is focused on the “intended” plant communities, that is, those that were intentionally established. However, over time plant communities on green roofs tend to shift, with colonizing species expanding the initial vegetative profile [6–8].

Throughout this manuscript, we define colonizing species as those not intentionally introduced to the green roof by design. These unintended species can access rooftops through wind, and visiting fauna [9]. Green roof colonizers can increase roof biodiversity, prolong flower display, and fill vegetative gaps [10]. There are even examples where colonizing species come to dominate green roof communities. For instance, researchers examining 129 extensive green roofs in Belgium found that 77 % of the species present had spontaneously colonized [8]; research on green roofs across Sweden and Norway found that unintended species accounted for 69 % of the vegetation [7]; and in North America, researchers working with ten green roofs across New York City found colonizing species made up 87 % of species richness [6]. Thus, these common volunteer species may be equally or more important to green roof ecosystem services, in comparison to those initially established. However, very little is known about how colonizing species contribute to ecosystem services in comparison to intended vegetation [10]. Thus, research is needed to understand how colonizing species influence the benefits provided by the green roof system.

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Depending on their traits, colonizing plant species can play an important role in the provision of green roof ecosystem services, absorbing stormwater runoff and reducing substrate temperature alongside intentionally established vegetation. On roofs where purposefully established vegetation is found to be unsuitable (e.g. species less drought tolerant than expected), colonizing species can propagate and cover exposed substrate. Since green roof thermal regulation is influenced by shading and evapotranspiration [11], this increased plant cover may reduce substrate temperatures. Furthermore, research has found that taller and denser vegetation is associated with higher leaf area index, which can be a strong driver of roof cooling [12]. In terms of stormwater retention, species that are taller, have higher specific leaf area (SLA), lower leaf dry matter contents (LDMC), and a rapid growth rate tend to be more efficient [13–15]. These traits are associated with higher water usage, leading to more pore space in the substrate to capture water in subsequent rain events [16]. Since fast growth is a trait associated with colonizing species [10], their presence could assist in stormwater retention.

Another potentially important ecosystem service provided by green roofs is the uptake of reactive nitrogen which is a common pollutant in both air and water in urban environments. Reactive nitrogen is needed in moderate quantities for all ecosystems, but nitrogen levels exceeding plant demand commonly lead to nitrogen leaching losses in runoff, which can contribute to eutrophication in downstream waterways [17]. Excess nitrogen in green roofs can result from high nitrogen in the substrate from the original installation, from over-fertilization during later management interventions [18], or from atmospheric deposition which tends to be high in nitrogen in urban environments. In order to address issues associated with excess nitrogen the inclusion of species efficient at nutrient uptake, such as tall, fast-growing species [19,20], could assist. Biodiverse green roofs could further enhance nutrient capture due to plant species complementarity in resource use, maximising nitrogen uptake [21]. Since colonizing species can increase roof biodiversity, and tend to be fast growing, it is important to explore how they contribute to nitrogen retention.

The objective of this study was to understand how common colonizing species influence the ecosystem services provided by extensive green roofs. We examined three ecosystem services: stormwater retention, substrate temperature reduction, and nitrate retention. In addition to comparing different colonizing species and colonizing mixtures, we also explored how specific plant traits (the morphological, physiological, and phenological features that contribute to plant fitness (Grime, 2001)), influence these ecosystem services.

Methods

This study took place between June 2014 and September 2018 using experimental plots on the Atrium green roof at Saint Mary's University in Halifax, Nova Scotia (44°39′N, 63°35′W) (Fig. 1). This one-story green roof contains common lawn vegetation that is trimmed weekly during the growing season (May-August). The roof is surrounded on all sides by neighboring buildings, making for even wind exposure but uneven solar exposure. However, all modules are exposed to full sun during solar noon. As the sun sets, modules become shaded in a differing order. To address this, a block design was used, with block one receiving the most shade and block six the least. Halifax has a warm summer continental climate (Dfb on the Köppen-Geiger classification system [22]) with a mean annual temperature of 6.6 °C and total average precipitation of 1396.2 mm. During the growing season, the mean temperature is 15.8 °C with precipitation averaging 109.4 mm per month [23].

Fig. 1. Experimental green roof system during the 2016 growing season.

Treatments

This experiment contained five treatment types: monocultures, a mixture with clover, a mixture without clover, a spontaneous treatment, and a substrate only control. The purpose of the monoculture treatments was to see how individual species compared in terms of ecosystem services. The purpose of the two intentionally planted mixture treatments was to compare diverse species mixtures with the monocultures with respect to their influence on ecosystem services. Furthermore, we excluded clover from one of these mixed treatments to see if the presence of a nitrogen-fixing legume would impact plant performance. The purpose of the spontaneous treatment was twofold, we wanted to determine which species would colonize, and how these colonizing species influenced ecosystem services. Finally, the purpose of the substrate only control was to determine whether the vegetated treatments would outperform the control treatment in terms of ecosystem services.

Treatments were planted in free draining 36 × 36 × 12 cm modules each containing water retention fabric (Colbond, Enka, NC, USA) and 10 cm of green roof substrate (Sopraflor X, Soprema, Drummondville, QC, Canada). Except for one industry species, all intentionally planted species were chosen based on how frequently they were weeded from previous green roof experiments conducted at Saint Mary's University. These species are very common on lawns and disturbed urban habitats in the region. In June 2014, eight monoculture treatments (*Poa compressa, Cerastium fontanum, Ranunculus repens, Taraxacum officinale, Trifolium repens, Plantago major, Veronica serpyllifolia, Pilosella flagellaris*) and two mixed treatments were planted. One mixed treatment contained all the above-mentioned monoculture species ("mixed with clover") and the other mixed treatment contained all the above except *T. repens* ("mixed without clover"). Additionally, we created one spontaneous treatment in which naturally occurring seed (carried by wind, fauna, other) were allowed to establish on the bare substrate. In order to further understand this green roof system two additional treatments were added. In May 2015 a bare substrate treatment (control) was created and in May 2017 a monoculture treatment containing a common green roof species, *Sedum acre*, was created (Table 1). There were ten replicates for each treatment divided into six blocks. All intentionally planted treatments contained nine individuals per module with individuals in the mixed treatments arranged randomly. For these mixed treatments, additional individuals were added to the module to achieve nine individuals. The specific species that was added varied so that at least one module contained two individuals of the same species for each species. Since the focus of these treatments is how diversity influences ecosystem services, this design still allowed us to answer our key questions. Except for the spontaneous treatment, modules were weeded of vascular species throughout the study period. This experiment only received precipitation through natural events or during specific data collection periods.

Table 1
List of treatments and species used in this study.

Treatment	Species	Type	Date Established
Poa compressa	*Poa compressa*	Colonizing Species	June 2014
Cerastium fontanum	*Cerastium fontanum*	Colonizing Species	June 2014
Ranunculus repens	*Ranunculus repens*	Colonizing Species	June 2014
Taraxacum officinale	*Taraxacum officinale*	Colonizing Species	June 2014
Trifolium repens	*Trifolium repens*	Colonizing Species	June 2014
Plantago major	*Plantago major*	Colonizing Species	June 2014
Veronica serpyllifolia	*Veronica serpyllifolia*	Colonizing Species	June 2014
Pilosella flagellaris	*Pilosella flagellaris*	Colonizing Species	June 2014
Mixed with clover	All colonizing Species	Colonizing Species	June 2014
Mixed without clover	All colonizing Species except *Trifolium repens*	Colonizing Species	June 2014
Spontaneous	Colonizing species (See Appendix A)	Colonizing Species	June 2014
Control	No vegetation	–	May 2015
Sedum acre	*Sedum acre*	Green Roof Species	May 2017

Although the focus of this study is vascular species, we did observe small (height < 0.5 cm) acrocarpous mosses spontaneously colonizing the bare substrate. In general, the moss was seen as an additional random variable which was not measured, and was present to some degree in all plots, so likely adds some additional variability to the results but should not invalidate the observed significant differences among the vascular plant treatments. As these species cannot be easily removed without removing a layer of substrate, we chose not to remove them. Further, a personal observations and results from a small pilot study found that these small acrocarpous mosses perform similar to bare substrate (Appendix A).

Biomass and canopy density

Canopy density for each module was measured using the point interception method as a non-destructive measure of biomass [24] using a three-dimensional 12-point pin frame (Domenico Ranalli, Regina, SK, Canada). Throughout the experiment, canopy density was collected for all modules once a month during the growing season. At the end of the study, September 2018, above and below ground biomass were harvested, dried for two days at 60 °C and weighed.

Substrate temperature

Substrate temperature (°C) was recorded periodically during the two hottest months of the year, July, and August, using a Taylor 9878 Slim-Line Pocket Thermometer probe (Commercial Solutions Inc., Edmonton, AB, Canada). Substrate temperature was recorded on August 6, 2015, July 21, 2016, August 23, 2016, July 10, 2017, and July 4, 2018. Temperature was taken by inserting the probe into the base of the substrate at the center of the module during full sun within two hours of solar noon. From this data, for each date, we then calculated the variable temperature difference by subtracting the average temperature of the substrate only control from each vegetated treatment.

$$Temperature\ Difference = Vegetated\ Treatment - \ Average\ Control$$

In this way, data could be compared across all six collection periods regardless of weather conditions [25]. In our analysis, the raw temperature data was used to examine associations between temperature and plant traits, while the variable "temperature difference" was used to compare substrate temperature between treatments.

Nitrate and stormwater retention

Data for nitrate (NO_3^-) and stormwater analysis were collected during the last year of the study, summer 2018. To ensure an adequate amount of nutrients was available to detect vegetation effects on nutrient dynamics, 30 mL of fertilizer (Plant-Prod Smartcote 'Perennial & Rose' 12–12–12 with micronutrients-controlled release fertilizer) was applied mid July 2018 to seven out of ten replicates for each treatment.

Stormwater runoff was collected for nutrient analysis once prior to the addition of fertilizer, July 5, 2018 and on two dates following the addition of fertilizer, July 25 and August 21, 2018. Runoff collection involved applying 2 L of tap water (equivalent to 15.4 mm of water depth), point at which soil was over saturated, to each module and collecting the runoff for seven minutes in a containment bin. Seven minutes was chosen, as outflow by this point was essentially non-existent. Immediately after, 20 mL of runoff was placed in a VWR

Polyethylene scintillation vial, with a sample of tap water taken as a control. Vials were sealed and stored at −20 °C until analysis. Runoff nitrate was measured using a microplate adaptation [26] of the single-reagent vanadium chloride spectrophotometric method [27]. Analyses were carried out on unfiltered samples, which were preserved by freezing, then thawed immediately prior to analysis. The total amount of nitrate exported out of the green roof system (referred to as runoff nitrate, units of mg N) was calculated by multiplying the module stormwater runoff amount (L) by the module nutrient concentration (mg N/L).

Functional plant traits

Seven plant traits were examined in this study, plant height, specific leaf area (SLA), leaf dry matter content (LDMC), leaf thickness, canopy density and relative growth rate (RGR). (Collection methods: [28]). Plant height and SLA were chosen due to known associations with drought tolerance, stormwater retention, and temperature reduction. Research has found that taller plants with higher SLA tend to be more efficient at stormwater and temperature reduction while being less drought tolerant [29]. Leaf thickness was chosen due to known associations with drought tolerance [30,31], and to account for the presence of the succulent species used in this study. Specifically, due to their thick water dense leaves, previous research has found that succulents due not always follow the same patterns for SLA and LDMC as other vascular species [32]. LDMC was included due to known associations with nutrient and water conservation, with smaller LDMC usually associated with more nutrient and moisture availability [33,34]. Canopy density was included due to known associations with biomass and temperature reduction [24,35]. Finally, RGR was included due to known associations with water uptake. Species with a higher RGR tend to have greater water uptake [29]. RGR was calculated by using canopy density in the following formula [36]:

$$Relative\ Growth\ Rate = \frac{LN(Canopy\ Density\ Time\ 2) - LN(Canopy\ Density\ Time\ 1)}{\text{Number of Days}}$$

To calculate RGR for treatments with zero canopy density, values of zero were changed to 0.0001.

Average trait values for SLA, plant height, LDMC, and leaf thickness were gathered for all nine intentionally planted species (for data see: [37]) and all but two of the spontaneous species. These traits were collected from plants outside the experimental system as leaf collection involves damaging plant tissue which we wanted to avoid as it could impact plant health and in turn ecosystem services within the experimental plots. Since we solely use traits for interspecific comparison, general trends between species are still detectable (Kattge et al., 2011). For the two spontaneous species for which traits were not available, *Prunella vulgaris* and *Gnaphalium uliginosum*, trait averages across all species were used. This is a standard method commonly used in trait-based research to address missing data [38]. Furthermore, *P. vulgaris* was only observed in three modules between 2015 and 2017, and *G. uliginosum* was only observed in three modules in 2016 (therefore only temperature data was affected). Two traits, RGR and canopy density, were the calculated from the experimental modules, with data from the date closest to the response variable used in the analysis. For instance, temperature analysis from July 2016 used canopy data from July 2016 while Temperature analysis from July 2018 used canopy density data from July 2018. For the mixed modules, RGR and canopy density refers to the total RGR and canopy density across all species in the given module.

Trait collection for SLA, LDMC, leaf thickness, and plant height occurred between May and August 2018 from native populations naturally occurring around Saint Mary's University. For each species, traits were measured on ten healthy, adult individuals. The two spontaneous species for which traits were not available, *Prunella vulgaris* and *Gnaphalium uliginosum*, were removed from the analysis. Furthermore, *P. vulgaris* was only observed in three modules between 2015 and 2017, and *Gnaphalium uliginosum* was only observed in three modules in 2016 (therefore only temperature data was affected).

For treatments containing more than one species, two trait indexes were calculated, community weighted mean (CWM) and functional dispersion. Both of these indexes incorporate species abundance for which canopy density data was used. These variables were calculated using the FD package in R v 4.2.3 ([39]; R [40]) (Table 2). CWM was used to determine a trait average for traits gathered outside the experiment (SLA, LDMC, leaf thickness, and plant height) for each mixed module and was calculated using the following formula [41]:

$$Community\ Weighted\ Mean = \sum_{i=1}^{n} p_i \times trait_i$$

In this formula p_i is the relative contribution of species i to the community and $trait_i$ is the trait value of species i

Functional dispersion was used to determine how functionally diverse treatments were when SLA, LDMC, leaf thickness, and plant height were examined together. Here, a value of 0 represents monocultures with higher values representing greater trait diversity [42]:

$$Functional\ Dispersion = \frac{\sum a_j z_j}{\sum a_j}$$

In this formula, a_j is the abundance of species j and z_j is the distance of species j to the weighted centroid.

To reiterate, all monocultures of the same species shared the same value for plant height, SLA, LDMC, and leaf thickness. For all mixtures, plant height, SLA, LDMC, and leaf thickness were calculated using the abundance weighted CWM index. Functional diversity of all monocultures was set at 0 and the functional diversity of all mixtures was calculating using the abundance weighted functional dispersion index. Finally, RGR and canopy density were calculated, or gathered from, for each individual modal.

Statistical analysis

All statistical analyses were completed using R, version 4.2.3 (R [40]). Normality for each predictor variable was tested using the Shapiro-Wilks test. Variables that were unsuccessful in reaching a p-value of above 0.05 in the normality test were transformed as close as possible to normality. In cases where plotted residuals of untransformed data were closer to normality than the transformed data, then non-transformed data were used for analysis.

Mixed linear models were used to compare how stormwater retention, substrate temperature, runoff nitrate, and biomass varied by treatment. For these tests, treatment was the fixed effect with block included as a random variable. Tukey post-hoc tests were used to compare treatments. The R library nlme was used for these analysis [43].

Multiple linear regression was used to examine how functional plant traits (plant height, leaf thickness, SLA, LDMC, functional dispersion, RGR, canopy density) influenced ecosystem services (stormwater

Table 2
Average plant height (Height), specific leaf area (SLA), leaf dry matter content (LDMC), leaf thickness (Thick), functional dispersion (Diversity), relative growth rate (RGR) and canopy density for each treatment. Data is displayed as average ± standard error, with 10 replicates per treatment/species. Canopy density and RGR are from July 2018, before fertilizer was added. Legend: Monoculture treatments are listed for each species as the species name. An * indicates treatment is a mixture with community weighted mean used to calculate trait average for height, SLA, LDMC, and leaf thickness.

Treatment	Height (cm)	SLA (cm^2g^{-1})	LDMC	Thick (cm)	Diversity	RGR	Canopy Density
P. compressa	39.3 ±2.44	305.9 ±17.2	0.267 ±0.01	0.02 ±0.00	0	3.69 ±0.10	41.7 ±3.58
C. fontanum	13.4 ±1.21	364.5 ±31	0.137 ±0.01	0.03 ±0.00	0	0.17 ±1.08	4.3 ±1.32
R. repens	7.3 ±0.59	355.4 ±23.6	0.150 ±0.01	0.03 ±0.00	0	3.07 ±0.19	24.9 ±4.01
T. officinale	20.0 ±1.83	278.4 ±12.1	0.158 ±0.01	0.05 ±0.00	0	2.53 ±0.14	13.5 ±1.55
T. repens	8.5 ±0.43	342.7 ±21.3	0.186 ±0.02	0.02 ±0.00	0	−1.20 ±1.79	13.2 ±6.16
P. major	13.2 ±1.38	232.6 ±29.9	0.155 ±0.01	0.03 ±0.00	0	1.78 ±0.22	7.3 ±1.56
V. serpyllifolia	2.7 ±0.29	250.3 ±15.4	0.273 ±0.02	0.02 ±0.00	0	−3.44 ±1.58	1.1 ±0.43
P. flagellaris	13.7 ±1.36	211.9 ±19.5	0.177 ±0.01	0.03 ±0.00	0	3.01 ±0.08	21 ±1.84
S. acre	5.3 ±0.41	204.3 ±14.7	0.060 ±0.01	0.09 ±0.02	0	4.77 ±0.14	127.8 ±16.03
Mix W Clover*	32.5 ±1.39	289.8 ±4	0.240 ±0.00	0.02 ±0.00	0.72 ±0.08	4.01 ±0.06	56.1 ±3.2
Mix No Clover*	31.5 ±1.71	285.6 ±5.9	0.240 ±0.01	0.02 ±0.00	0.73 ±0.07	3.96 ±0.15	57.2 ±6.73
Spontaneous*	31.2 ±1.12	278.3 ±9.6	0.260 ±0.01	0.02 ±0.00	0.91 ±0.09	3.98 ±0.17	63.5 ±9.31

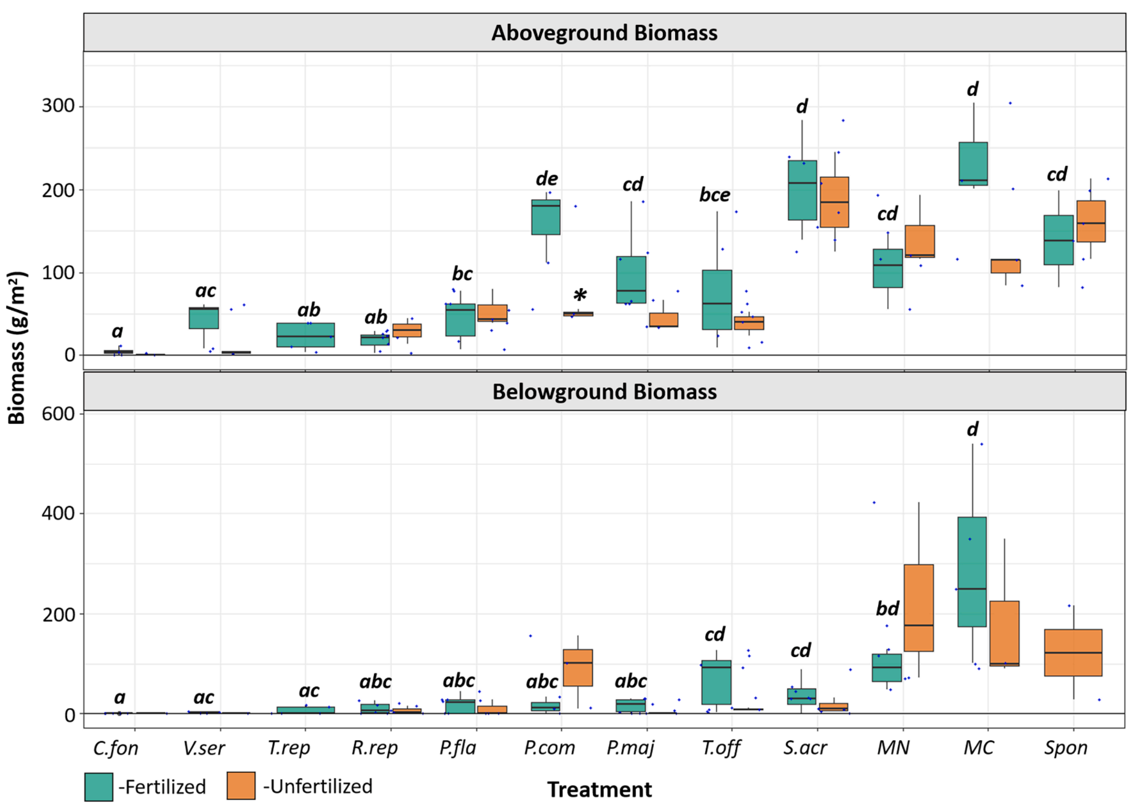

Fig. 2. Box plots depicting the above and belowground biomass g/m^2 harvested from each module containing living biomass at the end of the experiment (September 2018). Fertilized treatments were compared using Tukey post-hoc tests and those bars of the same type that share a letter are not significantly different ($p > 0.05$). For each treatment the unfertilized treatment was compared to the fertilized treatment, with an * indicating $p > 0.05$. Belowground biomass data is not available for the SPON treatment. Treatment Code: MC (mixed treatment with clover), MN (mixed treatment without clover), Spon (spontaneous treatment), monoculture treatments are listed for each species as the first letter of the genus name followed by the first three letters of the species name.

retention, substrate temperature, runoff nitrate). For these analyses the ecosystem service indicators were the response variables and the functional plant traits were the predictor variables. For stormwater and nitrate retention, only the seven modules designated for fertilization were included in the analysis. Additionally, for all three ecosystem services, only modules containing living vegetation were included. Nesting was incorporated into each model as random effects for block and date of data collection. In these models, date was incorporated as a factor with six dates used for temperature and three dates used for stormwater and nitrate retention. For each regression, Akaike information criterion was used to determine the best model to be used in each analysis. If a model had multiple delta scores below seven, then model averaging using the R library MuMIn was used [44].

Results

During the experiment, the spontaneous treatment became vegetated with 23 different species, many of which were the same species used in the other treatments. The five most dominant species in the spontaneous treatment, in order of dominance, were *P. compressa, Conyza canadensis, P. flagellaris, T. officinale*, and *Epilobium ciliatum* (Appendix B). By the end of the experiment, replicates from three of the monoculture treatments contained no vegetation: This included two replicates of *C. fontanum* (1 fertilized, 1 unfertilized), five replicates of *T. repens* (2 fertilized, 3 unfertilized), and five replicates of *V. serpyllifolia* (4 fertilized, 1 unfertilized).

When the harvested biomass from all fertilized treatments was compared to the unfertilized treatments, only the aboveground biomass of fertilized *P. compressa* was significantly greater than the unfertilized *P. compressa.* When the fertilized harvested biomass was compared by treatment, the mixed treatment with clover, the *S. acre* treatment, and the *P. compressa* treatment contained the greatest aboveground biomass; and the mixed treatment with clover, mixed treatment without clover, and the *T. officinale* treatment contained the greatest belowground biomass (Fig. 2). However, harvested biomass data from some fertilized treatments was lost before analysis could occur. This means only three replicates of the mixed treatments with clover, the mixed treatment without clover, the spontaneous treatment (aboveground only), and *P. compressa* could be analysed.

Substrate temperature difference

The majority of species had lower substrate temperature than the substrate only control. The treatment with the lowest average temperature was *S. acre* which was significantly cooler than three other treatments (*C. fontanum, T. repens, V. serpyllifolia*). The treatment with the warmest substrate, *V. serpyllifolia* was significantly warmer than all but two treatments (*C. fontanum, T. repens*) (Fig. 3). The mixed and spontaneous treatments had cooler than average temperatures, with the coolest being the mixed treatment with clover, which was significantly cooler than seven of the eight monocultures (Fig. 3).

Stormwater runoff

The treatments with the greatest stormwater runoff varied greatly between the three collection dates. On July 5, the average temperature was 24 °C, and it had been six days since the previous rain event (27.4 mm). For this date, the substrate only control had the lowest stormwater runoff with nine of the 12 other treatments releasing significantly more. On July 25, the average temperature was 24.3 °C, and it had been three days since the previous rain event (17.6 mm). For this date, the *V. serpyllifolia* treatment released the least amount of runoff with only the *T. repens* treatment releasing significantly more. Finally, on August 21, the average temperature was 18.7 °C, and it had been two days since the previous rain event (0.4 mm (day before this 11.8 mm fell)) (Historical Data, 2018). For this date, *P. major* released the least amount of runoff, with only *T. repens, S. acre* and the substrate only control releasing significantly more (Fig. 4).

Runoff nitrate

Before fertilizer was added, *T. repens* had the most nitrate in its runoff, with all but the control and *S. acre* treatment having significantly less. Two weeks after fertilizer was added, the control treatment had the greatest quantity of nitrate in its runoff, with all except *T. repens, V. serpyllifolia,* and *C. fontanum* containing significantly less. Five weeks after fertilizer was added, the control treatment had the greatest quantity of nitrate in its runoff, with all except *T. repens, V. serpyllifolia, C. fontanum,* and *R. repens* treatments having significantly less (Fig. 5).

Ecosystem services and plant traits

In this study, the treatments with the tallest species were the *P. compressa* treatment followed by the three mixed treatments. SLA was greatest in the *C. fontanum* treatment followed by *R. repens*, and *T. repens*. The trait LDMC was greatest in the *V. serpyllifolia* treatment, followed by *P. compressa* and the spontaneous treatment. The thickest leaves occurred in the *S. acre* treatment followed by the *T. officinale* treatment. RGR was highest in the S. acre treatment followed by the mixed treatment with clover, and the spontaneous treatment.

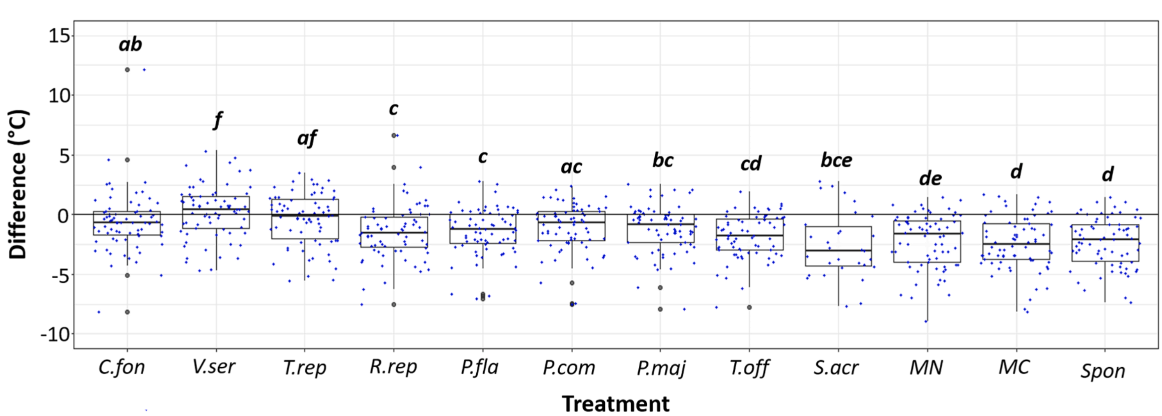

Fig. 3. Box and whisker plots depicting substrate temperature difference between the average temperature (°C) of the substrate only control and each vegetated treatment for each of the six sampling periods: August 2015, July 2016, and August 2016, July 2017, and July 2018. Treatments were compared using Tukey post-hoc tests and those bars that share a letter are not significantly different ($p > 0.05$). Treatment Code: MC (mixed treatment with clover), MN (mixed treatment without clover), Spon (spontaneous treatment). Monoculture treatments are listed for each species as the first letter of the genus name followed by the first three letters of the species name.

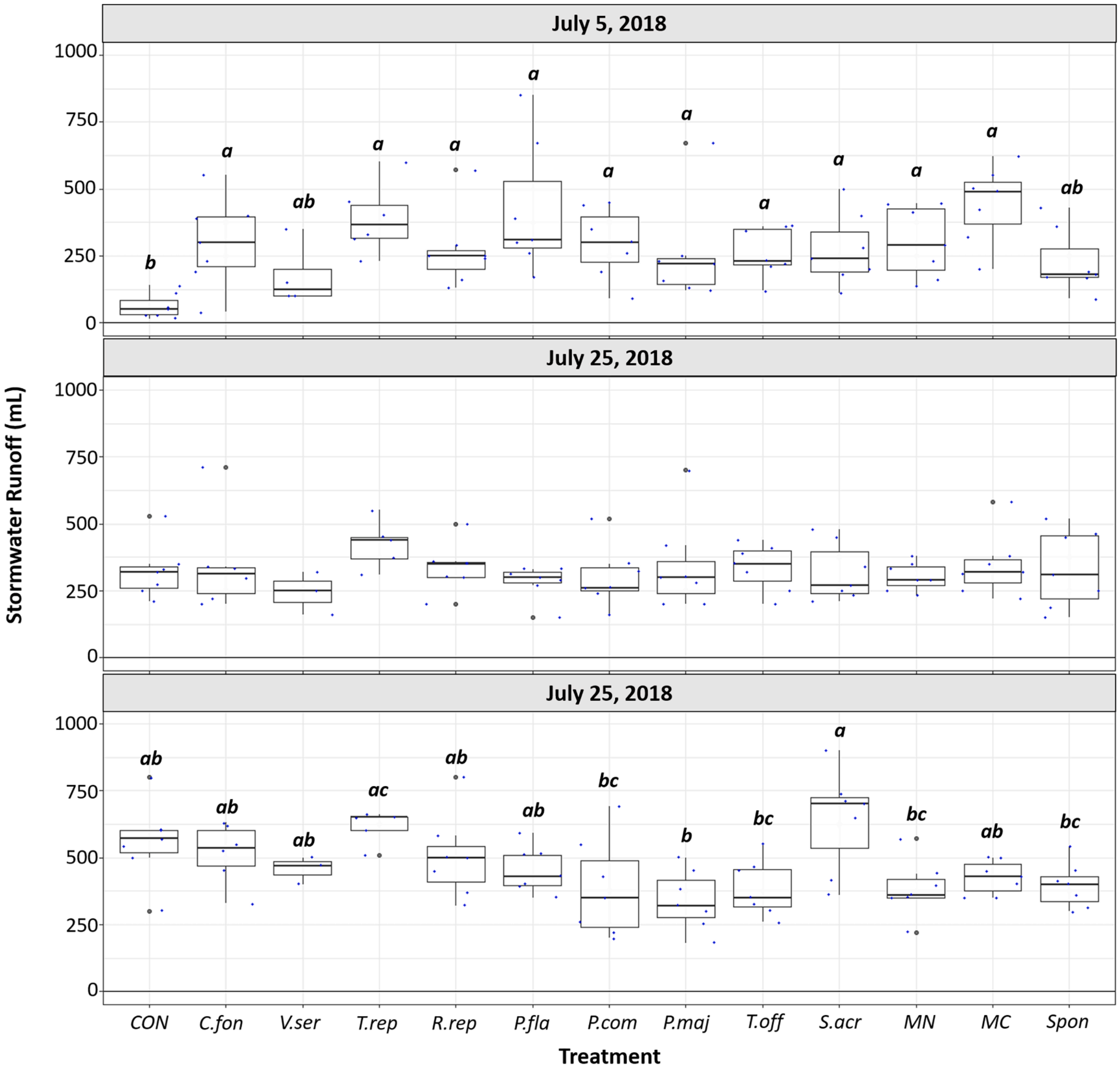

Fig. 4. Box and whisker plots depicting average stormwater runoff (mL) from each treatment during the three sampling periods, resulting from an addition of 2 L of water to each module. Treatments were compared using Tukey post-hoc tests and those bars that share a letter are not significantly different ($p > 0.05$). Treatment Code: CON (substrate only control), MC (mixed treatment with clover), MN (mixed treatment without clover), Spon (spontaneous treatment). Monoculture treatments are listed for each species as the first letter of the genus name followed by the first three letters of the species name.

Additionally, two treatments *T. repens* and *V. serpyllifolia* had a negative growth rate. Canopy density was highest in the *S. acre* treatment, followed by the spontaneous treatment, and mixed treatment without clover. For the three mixed treatments, functional dispersion was greatest in the spontaneous treatment followed by the mixed treatment without clover and the mixed treatment with clover (Table 2).

The treatments most effective at reducing substrate temperature (calculated from the raw temperature data) were characterized by vegetation with high RGR, low LDMC, and high functional dispersion. The treatments most efficient at reducing stormwater runoff were those with low SLA. Finally, the treatments most efficient at reducing nitrate runoff were those with thick leaves, tall stature, and low SLA (Fig. 6).

Discussion

In this study the majority of vegetated treatments provided greater temperature reduction, water retention, and nitrate retention relative to the substrate only control. This is in line with previous research demonstrating the benefits vegetation provides to the green roof system [45–47]. Many treatments performed equivalently to the commonly used green roof species *Sedum acre*, suggesting that lawn plant species can be used to create a functional green roof in Nova Scotia. Plant traits associated with high resource uptake rates were most effective at improving ecosystem services.

Substrate temperature

Treatments with greater functional diversity, higher relative growth rate (RGR), and lower leaf dry matter content (LDMC) were more efficient at cooling the green roof substrate. Since monoculture treatments had functional diversity values of zero, this result indicates that a mixed vegetative profile can play an important role in reducing substrate temperature. Indeed, the mixed treatments had significantly cooler substrate than 7 of the 9 monoculture treatments. Previous research has also observed reduced temperatures in more diverse mixtures. For example, treatments with diverse heights have been found to reduce temperatures as it can lead to the creation of air pockets, insulating substrate from solar radiation [48].

The findings for RGR may reflect two factors associated with substrate cooling, shade, and evapotranspiration. Plants with high RGR tend

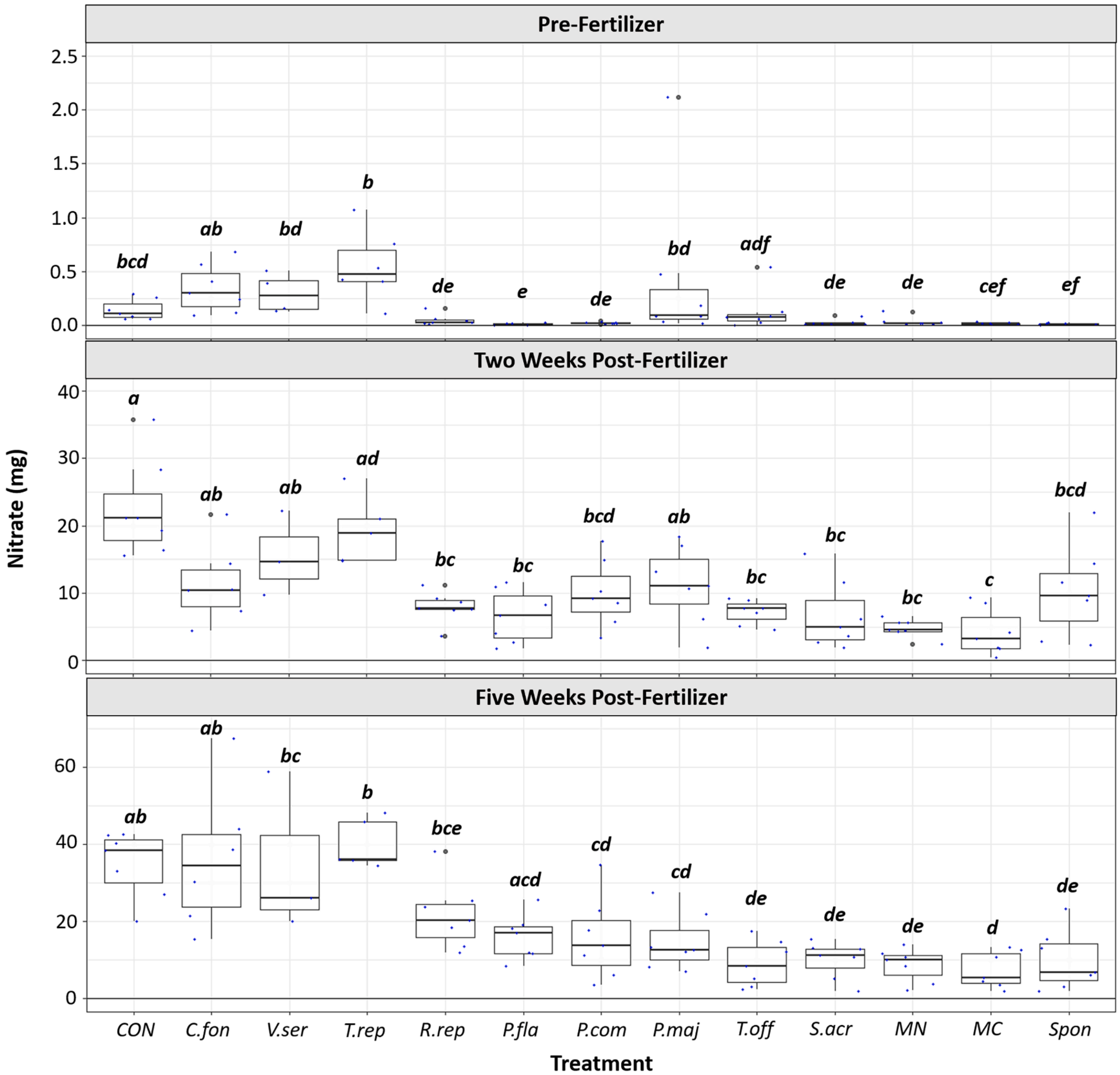

Fig. 5. Nitrate flux (mg N) in the runoff pre-fertilizer, two weeks post fertilizer, and five weeks post fertilizer, expressed as mass of nitrate-N in runoff resulting from an application of 2 L of water to each plot. Treatments were compared using Tukey post-hoc tests and those bars that share a letter are not significantly different ($p >$ 0.05). Treatment Code: CON (substrate only control), MC (mixed treatment with clover), MN (mixed treatment without clover), Spon (spontaneous treatment). Monoculture treatments are listed for each species as the first letter of the genus name followed by the first three letters of the species name.

to create biomass faster than plants with a low RGR. This means more biomass is present to shade the substrate and release moisture through evapotranspiration. However, since in our analysis canopy density was not associated with temperature reduction, more research is necessary to determine how RGR influences substrate temperature.

Plants with lower LDMC tend to belong to fast-growing, more competitive species [33,34]. One can reason then that the findings for LDMC are due to associations with RGR. However, in our study treatments with the highest RGR do not always have the lowest LDMC. For instance, the species with the lowest LDMC, *S. acre*, had an average RGR of 4.77 and the species with the second lowest LDMC, *C. fontanum*, had an RGR of 0.17. Additionally, the treatment with the coolest substrate, mixture with clover, which was significantly cooler than 8 of the 12 treatments, had the third highest average LDMC at 240. Therefore, it is possible that the results for LDMC are misleading, with more research necessary to how LDMC influences substrate temperature.

Stormwater retention

Stormwater retention differed greatly between the three collection dates, likely due to temporal variation in plant biomass and antecedent precipitation. The change in biomass can be attributed to the addition of fertilizer influencing plant growth. For precipitation, data was always collected during full sun, however the numbers of days since a previous rain event varied between six (July 5), three (July 25), and two days (August 21) [49]. High temperatures, and five days without water, may have forced some species to enter a water deficit phase featuring switches to CAM metabolism (in *Sedum*) or closed stomata [50,51]. In such cases, the short period of time in which water was added for data collection may not have been enough for species to change water uptake strategies and absorb water to their greatest potential.

Treatments with lower specific leaf area (SLA) were more efficient at stormwater retention. This association was unexpected as species with these traits tend to have lower water requirements and uptake [52,53]. For example, a glasshouse study by Chu and Farrell [29], found that across 14 green roof species, those with traits associated with fast growth, such as high SLA, had greater water use. One possible explanation for the trends observed in our study is that SLA may reflect differences in root morphology or other belowground characteristic. Personal observations made during the collection period noted more

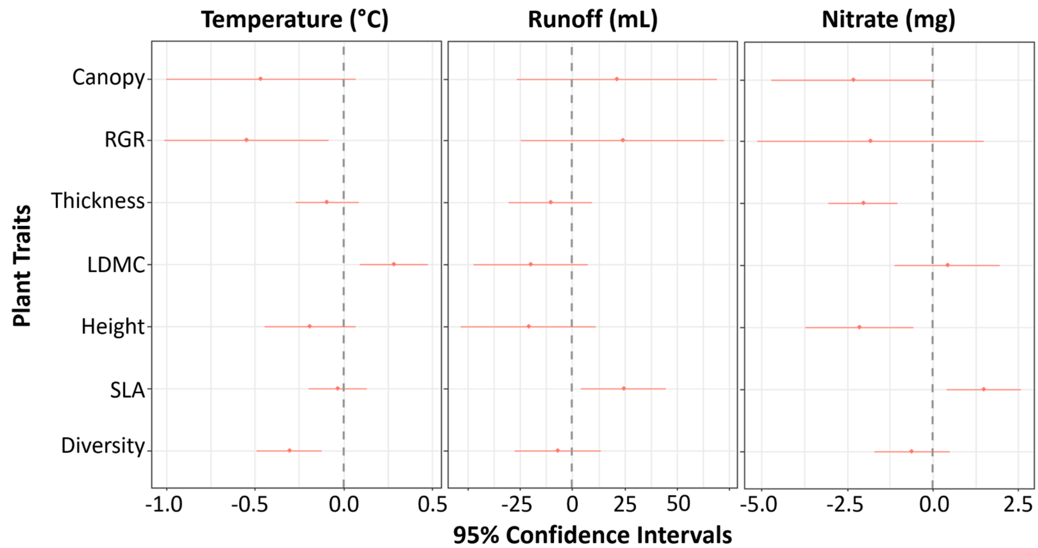

Fig. 6. Associations between functional plant traits (canopy density, relative growth rate (RGR), functional dispersion (diversity), plant height, specific leaf area (SLA), leaf dry matter content (LDMC), and leaf thickness) and substrate temperature (°C), Stormwater Runoff (mm), and nitrate runoff (mg). The lines indicate 95 % confidence intervals.

runoff then anticipated in modules with high belowground biomass, such as the mixed treatments, and *P. compressa*. More research is necessary to confirm if this is the case, but if correct this pattern could be due to dense root systems increasing porosity and stormwater infiltration, resulting in reduced retention due to preferential flow [54,55]. It is also possible that high root biomass could lead to cases where there is low porosity leading to runoff from the substrate surface. Root exudates can become hydrophobic when dry [56], so while dry soils are generally thought to be able to hold more water than wet soils [57], the opposite may occur under certain conditions.

Nitrate retention

After four years, only two treatments had significantly less nitrate runoff than the substrate only control, the spontaneous treatment, and the *P. flagellaris* monoculture. After fertilizer was added, for both the 2-week and 5-week collection date, more then half the treatments had significantly less runoff than the substrate only control. The clover monoculture (*T. repens*) exported the most nitrate via runoff. While this may in part be attributable to the nitrogen-fixation capabilities within the root-associated microbial symbionts of this species [58], it is more likely an effect of low biomass, as *T. repens* did not differ significantly from the control treatment in most cases, and unfertilized substrate nitrate levels were not higher in *T. repens* than controls. Low biomass (indicating low productivity) results in less nutrient retention (e.g., [17, 21]), and this is a likely explanation for the higher amounts of nitrate being exported by these treatments.

Treatments with thick leaves, low SLA, and tall stature contained the lowest nitrate in their runoff. Leaf thickness was associated with low nitrate in runoff likely due to the high productivity and nutrient requirements of *S. acre*, as opposed to any specific link between plant strategy and nitrate retention. It would be expected that traits associated with high growth rates, such as high SLA, would result in greater nitrate retention, as more nitrogen would be required for building biomass. High biomass is likely important for many green roof ecosystem services, including carbon sequestration [59] and nitrogen retention [17] because larger plants tend to require more resources. In our study, functional diversity was not significantly associated with reductions in nitrate discharge, likely because several monoculture treatments also had very low nitrate concentrations in the runoff. However, the species-rich mixed and spontaneous treatments did have lower levels of NO_3^- in the runoff compared to the average of the monocultures, consistent with the results of Johnson et al. [21] who found that species-rich treatments had greater nitrogen retention in green roof experimental plots.

Design implications

Spontaneously colonized green roof modules with a mixture of locally common lawn weeds performed equivalently to the *Sedum acre* treatment, a species commonly used in the green roof industry, and to high-maintenance (i.e., maintained by periodic weeding) species mixtures. Planting a green roof with a lawn mixture and then allowing for spontaneous colonization could result in a functional green roof that provides equivalent canopy coverage, biomass, and ecosystem services to other types of extensive green roof [10]. Since weedy species are readily available, and usually quick to establish, they could be utilized by consumers as a cheaper vegetative option [10]. However, the concept of using weedy species on green roofs requires testing in different climates and in different rooftop situations to determine how robust the vegetation might be in the face of more sun- and wind-exposed rooftops. Moreover, for roofs with spontaneous vegetation to be successful in the long run, the aesthetics of such roofs will have to be deemed acceptable, an aspect requiring further study.

Conclusion

Commonly, extensive green roofs are dominated by succulent plant species from the *Sedum* and *Phedimus* genera. These plants are drought-tolerant and can maintain substantial above-ground biomass even under stressful environmental conditions. Nevertheless, results from this study show that colonizing species did equally well in terms of stormwater water retention, substrate cooling, and nutrient retention. Mixtures performed well for all three monitored ecosystem services, though a few of the monocultures, especially those with high biomass or canopy density, performed equally well. While green roof plant communities are carefully designed at the outset, some spontaneous growth is expected to occur throughout the roof's lifespan. While it is unlikely that green roof installation would proceed with full success without adding vegetation, this result indicates that spontaneous vegetation can support a viable green roof ecosystem. This study shows that spontaneous growth and/or allowing new species to colonize may be a viable design alternative for green roofs, while maintaining the desired ecosystem services.

NBS impacts and implications

Environmental Concerns

- This paper demonstrates that common green roof colonizers can contribute to desired ecosystem services, specifically stormwater retention, reduced nitrate runoff, and reduced substrate temperature.

Social Concerns

- Green roofs provide numerous ecosystem services to residence while taking advantage of unused surface. However, more research, such as that provided by our study, is necessary to determine how green roofs can benefit their surrounding environment.

Economic Concerns

- Although green roofs can provide many ecosystem services, construction costs may prevent some consumers from building them. This study shows that spontaneous growth and/or allowing new species to colonize may be a viable design alternative for green roofs, decreasing cost while maintaining the desired ecosystem services.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2023.100101.

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