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Biochar-amended substrate improves nutrient retention in green roof plots

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ABSTRACT

Green roofs can act as pollutant sources due to the nutrients nitrogen (N) and phosphorus (P) leaching from the engineered soil-like substrate. Designing substrate to reduce this effect, while continuing to provide nutrients for plants, is essential to minimize this ecosystem disservice. Biochar is a water-retaining soil additive with the potential to increase stormwater retention and bind nutrients, thus could reduce loss of nutrients in runoff and simultaneously improve plant performance. Over two growing seasons, our study evaluated plant cover, nutrient retention and water retention in green roof experimental plots after the addition of biochar to the substrate. Replicated plots of green roof substrate amended with different amounts of biochar were established, both vegetated (*Sedum* mixture) and unvegetated. After initial establishment, plant cover was highest in the intermediate (5% w/w) biochar treatment, and lowest in the high (10% w/w) biochar treatment. Biochar addition did not significantly affect water retention, but improved runoff water quality by decreasing phosphorus, organic carbon and organic nitrogen export, all of which were high in runoff from the standard green roof substrate. Biochar was found to be a minor source of nitrate, but this effect was counteracted by plant presence, with plants greatly reducing N runoff losses. Overall, these results strengthen the case for biochar as a potentially useful amendment for green roofs.

1. Introduction

Green roof substrate is engineered soil typically comprised of a mixture of light-weight aggregate material such as heat-expanded shale or clay, and an organic component such as compost [1]. Substrate must perform the role of an artificial soil for plant growth and therefore must provide moisture, nutrients, and physical support to plants while remaining lightweight, chemically stable, aeratable, and able to drain freely [2]. The attempt to balance all of these characteristics is one of the key challenges when designing green roof substrate, affecting many of the ecosystem services provided by green roofs.

Green roofs may act as pollutant sources, often due to nutrients leaching from the organic component of the substrate. Extensive green roofs (those with substrate depth <10 cm) have commonly been found to be a source of total nitrogen (TN), dissolved organic carbon (DOC), and phosphate (PO_4^{3-}) in runoff [3–7]. Leaching of N, P, and C from green roofs has become a significant concern, and there is a need for research to develop mitigation actions [4,8]. Although NO_3^- can be retained [5,9,10] in some green roof substrates, other studies show green roofs to be a source of NO_3^- [3,8,11]. DOC in runoff can reach concentrations above 50 mg L^{-1}, giving runoff from many green roofs a brownish tint typical of humic-rich waters, and impacting the carbon balance of these systems [4,12]. Particularly concerning is the leaching of PO_4^{3-} to local waterways. Phosphorus is a limiting nutrient in many unmanaged freshwater environments, so additional contributions of P to local waterways could add to the eutrophication threat that already exists for P-limited aquatic ecosystems [4,8,13].

There is a need to find a delicate balance between reducing the leaching of these nutrients in the runoff while still providing sufficient nutrients for plant growth. Plant success is crucial, since increased vegetative growth is a major determinant of water retention and nutrient retention [2,14,15] as well as a host of other ecosystem functions and services in green roofs including aesthetics, habitat, cooling, and air quality improvement [15–17].

Understanding and fine-tuning substrate composition to aid in nutrient retention and stormwater runoff is important to optimize the performance of green roofs. Substrate characteristics directly influence some key ecosystem functions (water retention, insulation, etc.) and also constrain the development and productivity of the plant community [18, 19] which in turn influence nutrient and water cycling [4,20]. To this

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end, several research groups have explored the use of different substrate additives to improve runoff quality and quantity [14,21,22], but substrate composition has yet to be fully optimized [2].

Biochar, a lightweight carbon-rich residue produced from pyrolysis of biomass in a low-oxygen, high temperature environment, has been suggested as a green roof substrate amendment [23]. It has been used extensively as an agricultural amendment [24–26] due to its ability to enhance nutrient availability while also being stable relative to other soil amendments [27–29]. The pyrolysis process activates beneficial physical and chemical properties, which allows biochar to influence water and nutrient retention. Biochar influences nutrient leaching by increasing retention of water in the rooting zone, by directly binding or sorbing nutrients, or by interacting with other soil constituents [28,30]. The large surface area and porous structure of biochar makes it a water-absorbing soil amendment, increasing soil water holding capacity (WHC). This could be a great benefit to plants in green roofs, which commonly experience water stress due to frequent periods of drying out of the thin substrate layer [23]. Overall, the impact of these changes in the physical environment can influence plant growth and microbial communities, potentially enhancing the ecosystem functions of green roofs which include biochar [31]. Additionally, biochar is a lightweight material, so it will not overload green roofs, as weight is a major constraint on green roof substrates [32,33].

Previous studies have demonstrated the ability of biochar to reduce runoff water quantity in green roof substrate by increasing WHC [23, 32–35]. However, in terms of the impact on runoff water quality, there have been few published studies, most of which have been short term (a few months or less) and/or carried out in the lab. Results from published studies have also varied considerably. Beck et al. (2011) observed a decrease in nutrient leaching from green roof plots due to biochar presence following a short-term laboratory experiment with two sequential simulated rainfall events [23]. Similarly, in a one-month lab experiment with extensive green roof modules exposed to simulated rain events, the addition of biochar slowed TP leaching and improved interception of NH_4^+ and TN [34]. However, the patterns observed in the lab have not necessarily translated to similar results in the field. Kuoppamäki et al. (2016) carried out two controlled, replicated experiments, one in the laboratory for 6 weeks, and one in the field using platform-based green roof plots. In the laboratory experiment, one type of biochar reduced nutrient concentrations and load in runoff while another type had an opposite effect [35]. In the field experiment, biochar did not significantly reduce runoff nutrient concentrations during the first half year, but by 1 year had matured to successfully retain nutrients TN and TP [8]. Finally, in a short-term field experiment exposing green roof modules to nine simulated rainfall events, biochar-amended substrate was able to neutralize pH and reduce runoff TN, but failed to reduce the concentration of TP in runoff [36]. Based on the relatively few published studies and varied results found therein, there is a need for longer-term (a year or more) studies of green roof biochar amendments carried out in the field under natural climate conditions.

To evaluate the capacity of biochar as a substrate amendment to optimize green roof performance, our study examined biochar as a substrate additive in a one-year long field study. We analyzed the effect of biochar amendment on several important ecosystem functions: vegetative growth, nutrient retention, and stormwater retention. Four levels of biochar amendment in green roof substrate (0%, 2.5%, 5%, and 10% w/w) were evaluated with replicated plots. Each of the levels were tested with and without a green roof plant community (*Sedum* mixture) to examine the effect of biochar and plant presence, respectively, and to examine synergistic effects. We hypothesized that with increasing amounts of biochar added to green roof substrate, more nutrients and moisture will be made available to plants due to the retention capabilities of biochar, thereby increasing plant cover and reducing water and nutrient losses in runoff. A synergistic effect was expected in plots containing both biochar and plants due to increased plant growth and water uptake and increased substrate water holding capacity (WHC).

2. Material and methods

2.1. Experimental design

Forty-five experimental green roof plots were assembled in May 2016. Each plot contained two black high-density polyethylene (HDPE) 60 cm x 29 cm plastic trays (Ecoroofs, Berrien, MI). The top trays have drainage holes and contain basic green roof components: a geotextile filter layer (DeWitt Filter Fabric, Forestry Supplies, Jackson, MS), and a corrugated plastic drainage board (signoutfitters.com; Wyandotte, MI). The bottom trays are lined with waterproof plastic sheeting (6 mil standard clear greenhouse film; Greenhouse megastore; Danville, IL) to assist in the drainage of water from the plots.

Ten plots with each of the following were assembled: substrate without biochar (0%); substrate amended with 2.5% biochar by weight (w/w); substrate amended with 5% w/w biochar, and substrate amended with 10% w/w biochar. Five plots without substrate, considered empty, control plots ('EC'), were set up in addition to the 40 plots described above. The levels of biochar addition were chosen in order to represent a moderate range of values similar to those used in previous studies of biochar amendment to green roof plots, i.e. 7% w/w [23,35] and 2.5%−15% w/w [33]. The value of 10% w/w biochar in our study corresponds to a biochar addition of about 5 kg m^{-2}, a level up to which crops typically respond positively in agricultural settings [37].

The substrate used was a proprietary aggregate-based blend (Tremco Roofing Inc., Cincinnati, OH). The substrate material was analyzed at the Agricultural Analytical Services Laboratory (Pennsylvania State University, University Park, PA) using standard methods according to the Forschungsgesellschaft Landschaftsentiwicklung Landschaftsbau (FLL) guidelines for the planning, execution, and upkeep of green-roof sites, specifically for single course extensive systems [38]. The bulk density (dry weight basis) was 0.94 g cm^{-3}, and 1.21 g cm^{-3} at maximum water holding capacity (WHC). The WHC of 29% (w/w) was within the accepted FLL guidelines, while water permeability (saturated hydraulic conductivity) measured 0.03 cm s^{-1}, slightly below FLL standards [38]. In terms of chemical characteristics of the substrate, the pH ($CaCl_2$ extraction method) was 7.4, total organic matter content was 33 g L^{-1} (equivalent to 3.5% by weight), phosphorus (calcium acetate lactate (CAL) extraction method) was 218.5 mg L^{-1} as P_2O_5 (95 mg P L^{-1}) and nitrate and ammonium together ($CaCl_2$ extraction method) accounted for 13.0 mg L^{-1}. These values were within FLL standards except for phosphorus, which was slightly above the standard [38].

The biochar used in this study was sourced commercially from Charcoal House, LLC (Crawford, NE; https://www.buyactivatedcharcoal.com), and was created from a blend from mixed hardwoods derived from pyrolysis between 500 and 700 °C. The nutrient and water retaining capabilities of biochar vary based on feedstock type and preparation technique [25,39,40]. The particular type of biochar used in this study was selected based on its reported ability to sorb PO_4^{3-} ions [41], a desirable characteristic for green roof substrate, since P leaching is a major concern [4,42]. The biochar was sieved and particles in the size range 2.5 - 4.0 mm were used, with a dry bulk density of 0.31±0.03 g cm^{-3}. Additional biochar characteristics were provided by the manufacturer based on analysis at the International Biochar Initiative (IBI) Laboratory Tests for Certification Program, and are listed in Table 1.

All green roof plots were filled to exactly 7 cm depth with the respective substrate/biochar mixes, giving the same total volume for all plots, but a lower total mass for the biochar-containing plots, since biochar has a low bulk density. The dry mass per unit area ranged from approximately 60 kg m^{-2} for the substrate without biochar (0%) treatment, to approximately 50 kg m^{-2} for the high biochar (10%) treatment. Half of the ten plots of each substrate mix were then planted with vegetation, while half were left bare. The vegetated plots were

Table 1
Characteristics of biochar according to Charcoal House, LLC.

Parameter (units)	Value
Ash content (%)	1.2
pH value	8.49
EC (mmhos cm^{-1})	310
Organic C (%)	81.7
Total N (%)	0.32
Total P (mg kg^{-1})	24.0
Nitrate (mg kg^{-1})	41.0
Ammonia (mg kg^{-1})	8.0
Water holding capacity (%)	89

established with fresh cuttings of a mixture of *Sedum* species (Emory Knoll Farms, MD) at a density of 365 g m^{-2} wet weight (ca. 64 g m^{-2} dry weight). The following species were planted in each plot: *Sedum album, Sedum kamtschaticum, Sedum middendorfianum, Sedum spurium,* and *Sedum sexangulare. Sedum* species are especially successful, in terms of plant coverage and survival, in green roof installations in the American northeast and Midwest [43–46]. Prior to planting, *Sedum* species were sorted, and each cutting was measured and weighed to ensure uniform size within species [46]. Each vegetated plot was planted with: 15 cuttings of *Sedum middendorfianum,* 10 cuttings of *Sedum kamchaticum,* 50 cuttings of *Sedum album*; 50 cuttings of *Sedum spurium* and 20 cuttings of *Sedum sexangulare.* The cuttings were planted in rows and the species were mixed randomly throughout the plot (Fig. 1).

During plant establishment for 2 months, the plots were placed side by side in a greenhouse (University of Cincinnati, OH) and watered as needed. The plots were then moved outdoors to the University of Cincinnati Center for Field Studies (UCCFS, Hamilton, OH) in July 2016 in two raised south-facing rows with a 5% slope, with individual plot locations assigned randomly. Extra unused plots were placed on the end of each row to minimize edge effects. Over the course of the subsequent experimental period, the plots were exposed to natural climatic conditions, with supplemental irrigation water additionally used during particularly dry periods in July 2016 and August 2016. During irrigation, the same amount of water was delivered to each plot.

Fig. 1. Overhead view of one of the experimental plots. Left: initial establishment with fresh cuttings. Right: Growing season 2. Both photos taken of Plot #1; 10% biochar treatment.

2.2. Sample collection overview

Sampling was carried out from July 2016 – August 2017, just over 1 year. Runoff quantity was assessed for $n = 26$ discrete rain events, which included most but not all of the runoff-inducing events during this period. Once per month ($n = 12$), the runoff samples were collected and processed for water quality parameters and to calculate nutrient fluxes. Plant cover was assessed monthly using digital photographs. Details of each method follow.

2.3. Water collection and runoff/retention amount

A HOBO H400 weather station at the field site collected rainfall data every 15 min throughout the experimental period and was used to determine incoming precipitation amount in mm. Each plot was outfitted with a spigot, tygon tubing, and a 7.5 L polyethylene collection bucket to allow for the collection of water outflow. Collection buckets were emptied between events. Water runoff was determined, and retention estimated by weighing the collection buckets after runoff inducing events ($N = 26$) using CPW+35 bench scales (Adam equipment, CPWplus 35, Industrial scales; H&C Weighing Systems; Columbia, Maryland). This occurred approximately twice per month. Not every runoff inducing event was captured as our sampling regime did not allow us to easily quantify intermittent rain events, and for logistical reasons.

2.4. Runoff water quality analysis

Plot runoff and precipitation samples were collected monthly within 8 h after a runoff-inducing rain event, in polyethylene buckets which had been emptied and cleaned just before the event. Samples were then kept refrigerated in 500 mL HDPE bottles until subsampling, which took place within 48 h. Water samples were tested for pH (Orion Ross Ultra Combination pH; Thermo Fisher Scientific, Waltham, MA) and conductivity (Orion Conductivity Cell; Thermo Fisher Scientific, Waltham, MA). Samples were then filtered through a 0.45 μm mixed cellulose ester membrane filter (Millipore, Billerica, MA) and stored frozen until analysis. The nutrient concentrations were determined using colorimetric reactions. Samples were analyzed for: PO_4^{3-} using the ascorbic acid method [47] adapted for a microplate reader (Biotek® Synergy H1Hybrid Microplate reader; Biotek, Winooski, VT); NH_4^+using the phenol-hypochlorite reaction [48] adapted for a microplate reader; and NO_3^-using a vanadium chloride spectrophotometric method [49] adapted for a microplate reader [50]. Dissolved organic carbon (DOC) and total nitrogen (TN) were determined using a Shimadzu TOC-V_{CPH} analyzer equipped with TNM-1 total nitrogen analyzer (Shimadzu, Kyoto, Japan). Dissolved Organic Nitrogen (DON) concentration was calculated as TN − NH_4^+ − NO_3^-, in units of mg N L^{-1}.

2.5. Calculations

Runoff amount was calculated by normalizing the runoff amount (L) to plot area to give units of L m^{-2}. Nutrient fluxes were calculated by multiplying the water volume (L) by concentration (mg L^{-1}) and normalizing to plot area to give units of mg m^{-2}.

2.6. Vegetative cover

Pictures (JPEG) were taken monthly from a standard height and position directly above each plot and percent cover was analyzed using JMicroVision (JMicroVision 2.7, Geneva, Switzerland). Photos were converted to .tiff files using the conversion software built into the program. The Point Counting Method feature [51] was used to assess plant cover. A sampling grid of 250 points was used to assess the percentage of plant cover. Each photo was assessed three times for an average percent cover. If the standard deviation of the mean was 4% or greater, the photo was analyzed a fourth time, and the cover was averaged, including all four replicate assessments.

2.7. Statistical analyses

For statistical tests, repeated measurements were averaged to give a single value for each response variable for each plot. For instance, the values for nutrient fluxes (to estimate nutrient retention) were averaged over 12 runoff events before analysis. Similarly, water retention was determined by examining runoff water fluxes averaged over 26 runoff-inducing events for each plot. The treatments included each of the biochar levels (0%, 2.5%, 5%, and 10% by weight) crossed by vegetation presence/absence in replicates of five ($n = 40$). The value of $\alpha = 0.05$ was used as a threshold for significance for all statistical analyses. R 3.4.2 statistical software (R Core Team, Vienna, Austria) was used for all statistical analyses. Prior to analysis, data was found to be normally distributed according to Shapiro-Wilks Test for Normality. One-way ANOVA was used to assess the effect of biochar addition on vegetation responses. Two-way ANOVA was used to assess the influence of biochar, plant presence and their interaction on nutrient retention and water retention. Post-hoc comparisons using lsmeans [52] were performed for any test which was found to be significant.

3. Results

3.1. Water runoff vs. retention

There was no significant effect of biochar or plant presence on water runoff amount (Fig. 2). However, all treatments significantly retained precipitation compared to empty control plots, with the proportion of incoming rainfall leaving as runoff varying from 62 to 65% on average, i. e. water retention averaging 35–38%.

3.2. Water chemistry

Biochar significantly increased the pH of water runoff (Table 2; Fig. 3), while plant presence significantly reduced the conductivity compared to non-planted treatments (Table 2; Fig. 3). It was expected that pH would increase in the presence of biochar, due to biochar's high cation exchange capacity having a buffering effect; increased plant productivity could further increase pH as seen in other studies [36,53]. However, plant presence did not have a significant effect on the runoff pH. Plant presence did significantly decrease conductivity compared to substrate only treatments; however, all treatments leached some dissolved salts as indicated by the heightened conductivity.

In the absence of plants, total N leaching was lower in the high biochar treatment compared to substrate-only plots. In the presence of plants, total N fluxes were greatly reduced (Fig. 3). Nitrate fluxes were significantly increased by biochar. However, the presence of plants had a stronger effect, decreasing NO_3^- loads below incoming overall precipitation amount for the planted plots (Table 2; Fig. 3).

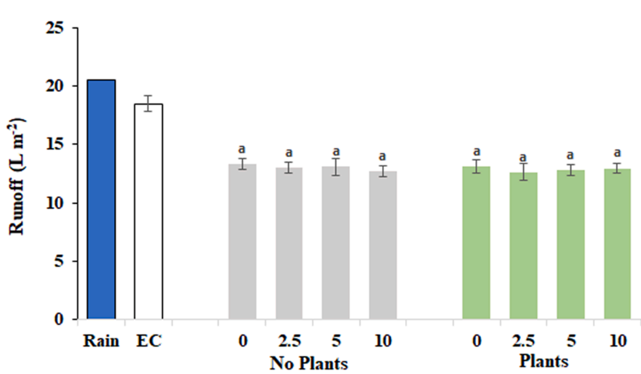

Fig. 2. The effect of biochar addition (0, 2.5, 5, 10%, w/w) and plant presence on mean event runoff amount (means ± SE of 5 replicate plots for each treatment) (biochar: $F_{3,35}$=1.03, p>0.05; plant: $F_{3,35}$= 0.76, p>0.05). Rain = amount of incoming precipitation; EC = runoff amount from empty control plots.

Table 2
Two-way ANOVA results for differences in runoff water chemistry from green roofs a function of biochar amount, plant presence, and their interaction.

Response	Treatment	F	d.f.	p-value	Sig.
pH	biochar	150.3	3,36	<0.0001	***
	plant	1.08	1,32	0.307	
	biochar x plant	2.60	3,32	0.070	
Conductivity	biochar	0.745	3,35	0.536	
	plant	42.5	1,38	<0.0001	***
	biochar x plant	0.716	3,32	0.550	
NO_3^-	biochar	6.728	3,32	0.001	**
	plant	209.4	1,32	<0.0001	***
	biochar x plant	3.33	3,32	0.03	*
NH_4^+	biochar	0.767	3,35	0.520	
	plant	1.478	1,35	0.232	
	biochar x plant	1.153	3,32	0.343	
PO_4^{3-}	biochar	35.59	3,36	<0.0001	***
	plant	3.744	1,35	0.06	
	biochar x plant	1.112	3,32	0.359	
DOC	biochar	15.63	3,32	<0.0001	***
	plant	4.234	1,32	0.048	*
	biochar x plant	7.536	3,32	<0.001	***
DON	biochar	44.65	3,32	<0.0001	***
	plant	153.2	1,32	<0.0001	***
	biochar x plant	10.40	3,32	<0.0001	***
DOC:DON	biochar	0.911	3,32	0.447	
	plant	35.77	1,32	<0.0001	***
	biochar x plant	6.51	3,32	<0.01	**

Sig. = Significance level (*** p<0.001; ** p<0.01; * p<0.05).

All green roof treatments were a source of DON (Table 2; Fig. 3). However, biochar decreased DON leaching in runoff when compared to substrate-only plots. In the presence of plants, DON flux was greatly reduced (Fig. 3). There was also an interaction effect: the effect of plant presence on DON runoff flux reduction was greatest for the 0% biochar treatment, and smaller for the biochar treatments, with the net result that in the presence of plants, the effect of biochar on DON flux was muted. Neither biochar nor plants significantly influenced the overall ammonium (N) flux, however all treatment plots which contained substrate reduced NH_4^+ flux compared to incoming rainwater (empty control plot) (Table 2; Fig. 3).

Phosphate runoff fluxes were significantly reduced by biochar. Although biochar addition reduced the overall PO_4^{3-} flux, all treatments which contained substrate were still a net source of PO_4^{3-}. (Table 2; Fig. 3). Between the 0% and 10% biochar treatments, there was an overall 40% decrease in the PO_4^{3-} flux.

Dissolved organic carbon (DOC) in runoff was significantly reduced by biochar when compared to the substrate only treatment (Table 2; Fig. 3). Substrate only plots released significantly more DOC in runoff than all other treatments, leaching 1.5x as much on average as the biochar amended plots, and about 1.2x as much as the planted treatment. There was also an interaction effect: the presence of plants had the effect of decreasing the DOC in runoff for the 0% biochar treatment, but increasing the DOC in runoff relative to the plant-free biochar-amended plots. The net result of this was a similar DOC flux for all planted treatments, regardless of biochar level (Fig. 3). The C:N of the dissolved organic matter as measured by the mass ratio of DOC to DON in runoff was not significantly affected by biochar, but was significantly higher in

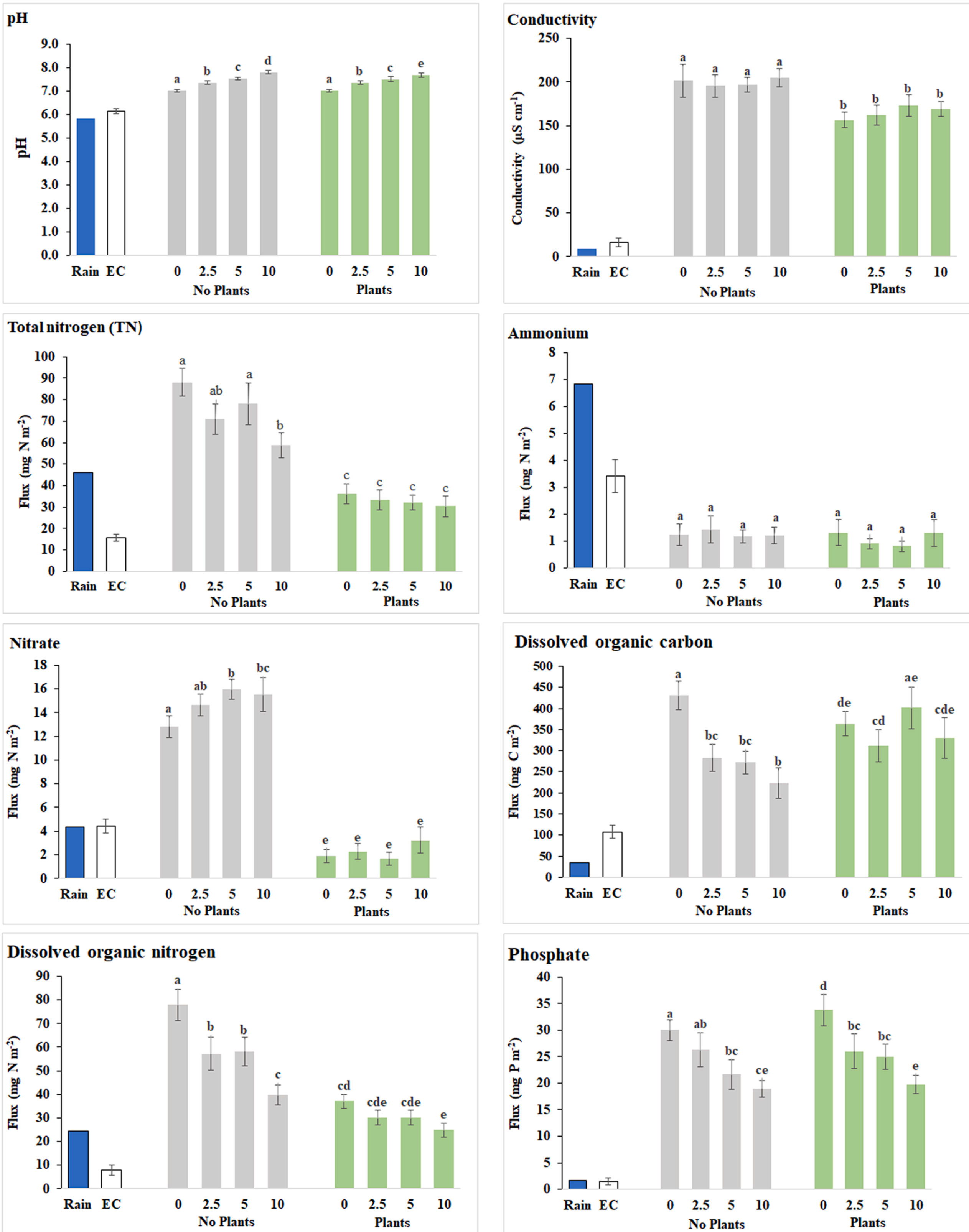

Fig. 3. The effect of biochar addition (0, 2.5, 5, 10%, w/w) and plant presence on average runoff water quality parameters (means ± SE of 5 replicate plots for each treatment). Within each panel, columns which do not share a letter are significantly different. Rain = value from incoming precipitation; EC = value from empty control plots.

the presence of plants. There was also an interaction effect with the presence of plants having a stronger effect on increasing the runoff DOC: DON for the highest (5%, 10%) biochar-amendment treatments (data not shown).

3.3. Plant cover

On average, the plant cover for the 5% biochar treatment remained higher than all other treatments throughout the experiment (Fig. 4). A statistical comparison was made among treatments during 3 distinct time periods (Table 3). During the first growing season (August 2016), plant cover was significantly higher in the 0% (control) and 5% biochar treatments than in the 2.5% and 10% treatments, but no biochar treatments were significantly higher than the 0% control (Table 3; Fig. 4). During the non-growing season (February 2017), cover for the 5% biochar treatment was higher than in all other treatments (Table 3; Fig. 4). During the second growing season (July 2017), the 5% biochar treatment had significantly higher cover than the 10% biochar treatment (Table 3; Fig. 4).

4. Discussion

4.1. Effects on nutrient retention

The ideal green roof substrate amendment would prevent water-soluble nutrients from leaching into runoff while ensuring these same nutrients remain available to plants. The results from this study show biochar addition is promising in this respect. Biochar amendment had a large effect on effluent water quality, with many different parameters impacted, the most significant of these being the reduction in PO_4^{3-} runoff fluxes. Runoff PO_4^{3-} concentrations remained lowest in the high biochar treatments throughout the experiment, averaging about 40% lower in the high biochar treatments relative to the biochar-free control. Beck et al. (2011) found similar results in a short-term laboratory experiment, with a 38–42% reduction in discharge of PO_4^{3-} in the presence of biochar in vegetated test plots during two simulated rainfall events [23]. Similarly, Kuoppamäki and Lehvävirta (2016) found a TP reduction of 28% in their yearlong study while using 7% by weight biochar amendment in green roof plots [8]. Green roofs commonly act as a source of PO_4^{3-} following installation [54] and for several subsequent years [1,4]. It appears that for many green roofs, the major source of P is the organic component of the substrate, especially of compost when it is

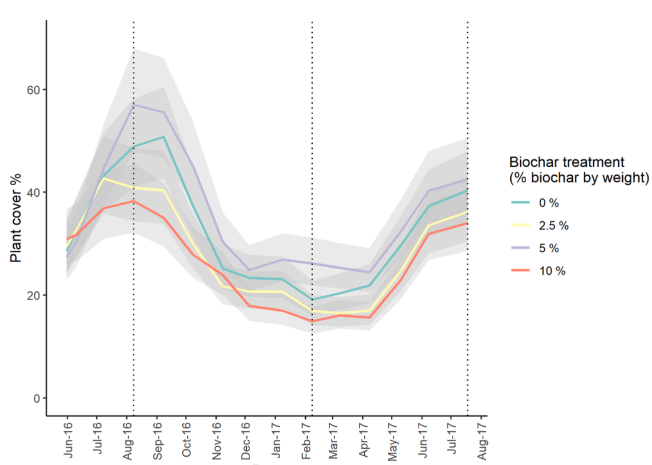

Fig. 4. Mean plant cover during monthly measurements in green roof plots as a function of % biochar in substrate. The gray shading corresponds to 95% confidence interval, and the vertical dotted lines correspond to the three occasions where a statistical comparison was made among treatments (Table 3). The 5% biochar treatment remained highest and the 10% treatment remained lowest throughout the experiment, after initial establishment.

Table 3
Mean (± SE; $n = 5$) percent plant cover in vegetated plots, as a function of biochar treatment during both growing seasons (August 2016; July 2017) and non-growing season (February 2017). Treatments indicated by the same letter in a given column are not significantly different (Tukey; $p>0.05$).

Biochar (% w/w)	Peak season cover, August 2016 (%)	Off-season Cover, February 2017 (%)	Peak season cover, July 2017 (%)
0	49.4 ± 3.48^{a}	19.6 ± 1.99^{ab}	40.9 ± 2.00^{ab}
2.5	41.4 ± 3.60^{b}	17.5 ± 2.34^{ab}	36.9 ± 3.01^{ab}
5	57.4 ± 2.50^{a}	26.4 ± 0.88^{a}	42.8 ± 1.73^{a}
10	39.5 ± 4.25^{b}	15.1 ± 1.32^{b}	34.3 ± 1.73^{b}

present [4]. If P levels exceed the binding and uptake capacities of the substrate and biota, then P will be leached from the system whenever runoff occurs [4]. The reduction of P in runoff from the biochar amended plots in our study, as well as several other recent studies [8,23,34] suggests that biochar has potential to bind P, helping reduce P runoff losses. Depending on the feedstock and preparation method, biochar can also provide a lower P source compared to substrate containing compost, which tends to be rich in P [4]. Thus, replacement of part of the organic matter in green roof substrate has the potential to reduce P leaching both by a decrease in P source, and an increase in P binding.

Plant presence did not have an effect on PO_4^{3-} loads in our study. Buffam et al. (2016) examined the seasonal patterns of PO_4^{3-} in green roof runoff and determined that plant P uptake was relatively small; they attributed inorganic P availability to other processes such as microbial mineralization [50]. Our study also found that plants play a minor role in P uptake relative to leaching losses, likely due to the typically high P availability in fresh green roof substrate relative to plant P demand [4].

Although biochar was a minor source of nitrate in unvegetated plots, biochar decreased organic N leaching, resulting in a net decrease in total N leaching losses. Furthermore, the effect of biochar increasing nitrate in runoff was not seen in the presence of plants, as the plants had a strong effect of reducing nitrate in runoff, presumably due to uptake and incorporation into plant biomass. Overall, the presence of plants caused a substantial decrease in runoff losses of TN, DON and particularly NO_3^-, an effect consistent with other green roof studies [4,55].

The effects of biochar on N leaching in our study diverged from those observed in previously published studies [23,34], perhaps attributable to variation in biochar type or plant communities among the different studies. For instance, Beck et al. (2011) found a decrease of nitrate and total N leaching from the 7% w/w biochar treatment when added to substrate-only or Ryegrass-planted plots, and little change in N leaching from biochar additions in *Sedum* planted trays [23]. Beck et al. used a blend of 70% agricultural char, derived from the processing of rice hulls, pecan shells, walnut shells, and coconut shells, and 30% manufactured waste char derived from pyrolysis of passenger car tires whereas the biochar in our study was derived from a mixture of hardwoods. In a laboratory study, one type of birch-derived biochar reduced nutrient concentrations and load in runoff while another type from different origins and pyrolysis conditions had an opposite effect [35]. A related field study using an amendment of birch biochar (7%) found that the addition of biochar reduced annual cumulative runoff of TN by 62% in their planted green roofs (plots originating with *Sedum* seeds and plug plants) and 28% on pre-grown green roof plots, suggesting a significant interaction between biochar and vegetation type on N retention [8].

In our study, we found interactions in the effects of biochar and plant presence on the quantity and quality of dissolved organic matter runoff losses. First, we found a mean 50% reduction of DOC (and DON) runoff loads from the high-biochar treatment in the absence of plants, similar to Beck et al. (2011) results, where a 67–72% reduction of total organic carbon due to biochar was observed following two simulated rain events [23]. Our results thus indicate that biochar addition does aid in binding organic carbon over the course of the yearlong field experiment. However the presence of plants confounded this effect, causing an increase in DOC leaching losses in plant-containing compared to biochar-only treatments; at the same time, plant presence caused a decrease in DON leaching losses, resulting in an increase in the mean C:N of the runoff dissolved organic matter. These results indicate shift in the character of soluble organic matter being exported from green roof plots as a function of the plant community. This plant-derived DOC could originate from root exudates, degrading plant material, or both [56].

4.2. Effects on water retention

Interestingly, there was no effect of biochar on average water retention vs. runoff in our study, even though the biochar has a higher water-holding capacity than the base green roof substrate. Our findings regarding the effect of biochar are consistent with the findings of one recent study which evaluated water retention of biochar-amended substrate in unvegetated modular plots using simulated rainfall events and found little effect [36]. However, our results are inconsistent with other studies which found a significant influence of biochar on WHC and/or water retention [23,33,35]. One reason for this lack of significant effect of biochar on water retention could be the amount of substrate used in our experimental approach. Since all plots had the same total volume of substrate mix, the plots with biochar had substantially lower total mass than the plots with substrate alone. For example, the high biochar plots weighed 15–20% less than the plots with standard green roof substrate, yet both were equally effective at reducing runoff. Thus, the biochar plots do indeed retain more water when expressed as runoff reduction per mass of substrate, although not when expressed per unit area or substrate volume.

Another possible explanation is the size of precipitation events, since our study measured water retention only after runoff-inducing rain events, which involves a sizeable amount of precipitation causing the substrate in all of the plots to exceed field capacity. Kuoppamäki et al. (2016) found that the water retention was improved by biochar with infrequent rain events, but less effective when precipitation was frequent [35]. Extensive green roofs in general can achieve a runoff retention rate of 75–100% in light and moderate rain events [57,58], while in our study the runoff ratio averaged 32–35%, corresponding to the relatively larger precipitation events in focus since we were primarily interested in monitoring total water and nutrient fluxes. Thus, we would have missed any differences among treatments which may have occurred during smaller events if they only induced runoff in some of the plots.

Neither was there any significant effect of plants on average water retention vs. runoff. The lack of a consistent impact of *Sedum* presence on runoff amount is a common theme in other studies of water balance in extensive green roofs, reviewed in Zheng et al. 2021 [59]. *Sedums* are commonly used on green roofs as due to their conservative water use strategies, enabling the plants to withstand periods of drought when shallow green roof substrates dry out [18,20,60]. However, *Sedums* also have relatively slow evapotranspiration rates and thus may not effectively dry out green roof substrates between rain events relative to what would occur from evaporation alone in the absence of plants [20,61].

4.3. Effects on vegetation cover

Although green roof vegetation cover was not significantly improved by biochar addition at any dose relative to the substrate-only control plots, there was a consistent trend with the 5% biochar treatment having the highest plant cover throughout the experiment. It is noteworthy that plant cover for the 10% biochar treatment was significantly lower than the 5% biochar treatment on every measurement occasion. This suggests that there may be an optimal intermediate biochar proportion for plant growth. It is possible that the 10% biochar addition caused the substrate to become too alkaline, which impacted plant growth (Fig. 2). At high pH levels, nutrients become insoluble and cannot be readily taken up by plants [53].

4.4. Future research needs

More long-term (multi-year) field studies of biochar amendment are needed to flesh out the impacts of biochar amendment on green roof structure and function. It is important to understand the enduring capabilities of biochar amendment, both to determine the effect of biochar on plant community resilience to infrequent disturbances such as drought [62], and to detect any long-term changes in the properties of the biochar-amended substrate. Gul et al. (2015) suggested that the retention capacity of biochar will decline as it “ages” in the soil environment due to weathering, loss of reactive surface due to irreversible binding with soil substances, decrease in its pH [63], and decrease in its bulk density [63,64]. However, Kuoppamäki and Lehvävirta (2016) found that although biochar performance varied throughout their green roof plot experiment, the strongest positive effect on nutrient retention occurred during their final sampling event (1 year into the experiment). This suggests that the use of aged biochar is worth investigating in future studies. Kuoppamäki and Lehvävirta (2016) speculate that this result might be due to the development of microbial biofilm on the large surface area and pore volume of biochar [8]. Gul et al. (2015) point to recent studies where soil microbial communities are responsive to biochar amendment because it increases microbial abundance and activity [26,65] by providing an environment with ample aeration, water and nutrients [65,66]. In turn, a diverse microbial community is implicated in efficient nutrient transfer to plants and greater nutrient retention in soil, which is beneficial in reducing nutrient loss from agricultural soil to the environment [63]. An exciting but as-yet little-explored frontier in green roof research is the study of belowground dynamics and interactions with the microbial community, which could provide insight into the mechanistic responses of biochar addition.

Finally, relevant to the generalization of our results, other recent studies have shown that biochar characteristics can play an important role in the resulting function – thus not all biochar preparations can be expected to have the same effect. For instance, enhancement of water retention depends on biochar feed-stock, soil type, and mixture rates [67]. And, the release of nitrogen from biochar is a complicated process that is affected by many factors, such as the type of biochar, the mode and amount of applied biochar, and the application time [68]. To optimize the use of biochar as a green roof substrate amendment, continued work is needed to test different types of biochar, and to characterize the effects of biochar feedstock and pyrolysis temperature, biochar particle size distribution, substrate material and mixture proportion, vegetation community, and their interactions.

5. Summary

In this yearlong field experiment, we found that extensive green roof substrate amended with biochar could support a thriving plant community (a *Sedum* mixture), while at the same time reducing phosphate and dissolved organic matter leaching in runoff. The plant community responded differently to different levels of biochar, with the highest plant cover observed for a 5% (w/w) biochar addition to substrate. This suggests that there may be an optimal, intermediate level of biochar for green roof substrate. The importance of the plant community on nutrient cycling was also evident, with plant presence dramatically reducing N leaching losses from green roofs plots. There were also interesting interactions observed in the effects of biochar and plant presence. Notably, in the absence of plants, biochar had a strong and clear impact on reducing dissolved organic carbon and nitrogen in runoff. The presence of plants masked this effect, likely by contributing new sources of soluble organic matter less easily bound by biochar. Overall, our results reinforce the idea that biochar can be a viable and useful amendment to green roof substrate.

5.1. NbS impacts and implications

Environmental: This study focuses on the mitigation of nutrient pollution which can occur in runoff from green roofs, a potential ecosystem dis-service which could pollute downstream waterways. The results show that the integration of biochar into green roof substrate can successfully bind phosphorus and thus reduce leaching of P in runoff.

Economic: The results of this study suggest that the integration of biochar in green roof substrate could be a cost-effective means to reduce nutrient losses while preserving plant productivity, thus reducing the need for costly fertilizer addition to green roofs, and reducing the need for remediation of downstream waterways.

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.

Data availability

Data will be made available on request.

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References

[1] M.E. Mitchell, et al., Elevated phosphorus: dynamics during four years of green roof development, Urban Ecosyst. 20 (5) (2017) 1121–1133, https://doi.org/10.1007/s11252-017-0664-3.
[2] T. Young, et al., Importance of different components of green roof substrate on plant growth and physiological performance, Urban Forestry Urban Green. 13 (3) (2014) 507–516, https://doi.org/10.1016/j.ufug.2014.04.007.
[3] J.C. Berndtsson, L. Bengtsson, K. Jinno, Runoff water quality from intensive and extensive vegetated roofs, Ecol. Eng. 35 (3) (2009) 369–380, https://doi.org/10.1016/j.ecoleng.2008.09.020.
[4] I. Buffam, M.E. Mitchell, Nutrient cycling in green roof ecosystems. Green Roof Ecosystems, Springer, New York, 2015, pp. 107–137, https://doi.org/10.1007/978-3-319-14983-7_5. Sutton R.Editor.
[5] A. Teemusk, U. Mander, The influence of green roofs on runoff water quality: a case study from Estonia, Water Resour. Manag. 25 (14) (2011) 3699–3713, https://doi.org/10.1007/s11269-011-9877-z.
[6] M.A. Monterusso, et al., Runoff Water Quantity and Quality from Green Roof Systems, Expanding Roles for Horticulture in Improving Human Well-Being and Life Quality, 2004, pp. 369–376.
[7] K. Vijayaraghavan, U.M. Joshi, Can green roof act as a sink for contaminants? A methodological study to evaluate runoff quality from green roofs, Environ. Pollut. 194 (2014) 121–129, https://doi.org/10.1016/j.envpol.2014.07.021.
[8] K. Kuoppamäki, S. Lehvavirta, Mitigating nutrient leaching from green roofs with biochar, Landsc Urban Plan 152 (2016) 39–48, https://doi.org/10.1016/j.landurbplan.2016.04.006.
[9] J.C. Berndtsson, Green roof performance towards management of runoff water quantity and quality: a review, Ecol. Eng. 36 (4) (2010) 351–360, https://doi.org/10.1016/j.ecoleng.2009.12.014.
[10] H.B. Wang, J. Qin, Y.H. Hu, Are green roofs a source or sink of runoff pollutants? Ecol. Eng. 107 (2017) 65–70, https://doi.org/10.1016/j.ecoleng.2017.06.035.
[11] D. Todorov, et al., Water quality function of an extensive vegetated roof, Sci. Total Environ. 625 (2018) 928–939, https://doi.org/10.1016/j.scitotenv.2017.12.085.
[12] J. Bousselot, et al., Green roof research in North America: a recent history and future strategies, J. Living Archit. 7 (2020) 27–64, https://doi.org/10.46534/jliv.2020.07.01.027.
[13] S.R. Carpenter, et al., Nonpoint pollution of surface waters with phosphorus and nitrogen, Ecol. Appl. 8 (3) (1998) 559–568, https://doi.org/10.1890/1051-0761(1998)008[0559:nposww]2.0.co;2.
[14] K. Vijayaraghavan, F.D. Raja, Design and development of green roof substrate to improve runoff water quality: plant growth experiments and adsorption, Water Res. 63 (2014) 94–101, https://doi.org/10.1016/j.watres.2014.06.012.
[15] D.B. Rowe, Green roofs as a means of pollution abatement, Environ. Pollut. 159 (8–9) (2011) 2100–2110, https://doi.org/10.1016/j.envpol.2010.10.029.
[16] E. Oberndorfer, et al., Green roofs as urban ecosystems: ecological structures, functions, and services, Bioscience 57 (10) (2007) 823–833, https://doi.org/10.1641/b571005.
[17] J. Lundholm, et al., Plant species and functional group combinations affect green roof ecosystem functions, PLoS One 5 (3) (2010) e9677, https://doi.org/10.1371/journal.pone.0009677, p. Article No.:.
[18] K.L. Getter, D.B. Rowe, Substrate depth influences sedum plant community on a green roof, HortScience 44 (2) (2009) 401–407.
[19] C. Friedrich, Low Impact development: Selecting the Proper Components For Green Roof Growing Media, A.S.o.C. Engineers, Reston, VA, USA, 2008, pp. 240–251. Editorp.
[20] Z. Zhang, et al., Influence of plant composition and water use strategies on green roof stormwater retention, Sci. Total Environ. 625 (2018) 775–781, https://doi.org/10.1016/j.scitotenv.2017.12.231.
[21] S. Ondono, F. Bastida, J.L. Moreno, Microbiological and biochemical properties of artificial substrates: a preliminary study of its application as Technosols or as a basis in Green Roof Systems, Ecol. Eng. 70 (2014) 189–199, https://doi.org/10.1016/j.ecoleng.2014.05.003.
[22] K. Vijayaraghavan, Green roofs: a critical review on the role of components, benefits, limitations and trends, Renew. Sustain. Energy Rev. 57 (2016) 740–752, https://doi.org/10.1016/j.rser.2015.12.119.
[23] D.A. Beck, G.R. Johnson, G.A. Spolek, Amending greenroof soil with biochar to affect runoff water quantity and quality, Environ. Pollut. 159 (8–9) (2011) 2111–2118, https://doi.org/10.1016/j.envpol.2011.01.022.
[24] H. Asai, et al., Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield, Field Crops Res. 111 (1–2) (2009) 81–84, https://doi.org/10.1016/j.fcr.2008.10.008.
[25] L.A. Biederman, W.S. Harpole, Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis, Glob. Change Biol. Bioenergy 5 (2) (2013) 202–214, https://doi.org/10.1111/gcbb.12037.
[26] J. Lehmann, et al., Biochar effects on soil biota - A review, Soil Biol. Biochem. 43 (9) (2011) 1812–1836, https://doi.org/10.1016/j.soilbio.2011.04.022.
[27] J. Lehmann, et al., Terra preta nova - where to from here?. Terra Preta Nova: A Tribute to Wim Sombroek Springer, Berlin, 2009, pp. 473–486. W. WoodsEditors.
[28] J. Major, et al., Biochar Effects On Nutrient leaching, in Biochar for Environmental management, science, and Technology, Earthscan, London, 2009, pp. 271–287. J. Lehmann and S. Joseph, Editorsp.
[29] N. Hagemann, et al., Organic coating on biochar explains its nutrient retention and stimulation of soil fertility, Nat. Commun. (2017) 8, https://doi.org/10.1038/s41467-017-01123-0.
[30] S. Huang, et al., Experimental study on the hydrological performance of green roofs in the application of novel biochar, Hydrol. Process. 34 (23) (2020) 4512–4525, https://doi.org/10.1002/hyp.13881.
[31] H.M. Chen, et al., Biochar increases plant growth and alters microbial communities via regulating the moisture and temperature of green roof substrates, Sci. Total Environ. 635 (2018) 333–342, https://doi.org/10.1016/j.scitotenv.2018.04.127.
[32] J. Werdin, et al., Biochar particle size and amendment rate are more important for water retention and weight of green roof substrates than differences in feedstock type, Ecol. Eng. (2021) 171, https://doi.org/10.1016/j.ecoleng.2021.106391.
[33] C.T.N. Cao, et al., Biochar makes green roof substrates lighter and improves water supply to plants, Ecol. Eng. 71 (2014) 368–374, https://doi.org/10.1016/j.ecoleng.2014.06.017.
[34] C. Xu, et al., Nutrient leaching in extensive green roof substrate layers with different configurations, Environ. Sci. Pollut. Res. 29 (23) (2022) 34278–34287, https://doi.org/10.1007/s11356-021-17969-3.
[35] K. Kuoppamäki, et al., Biochar amendment in the green roof substrate affects runoff quality and quantity, Ecol. Eng. 88 (2016) 1–9, https://doi.org/10.1016/j.ecoleng.2015.12.010.
[36] Q.Q. Zhang, et al., Analysis of the effect of green roof substrate amended with biochar on water quality and quantity of rainfall runoff, Environ. Monit. Assess. (5) (2019) 191, https://doi.org/10.1007/s10661-019-7466-4.
[37] J. Lehmann, J. Gaunt, M. Rondon, Bio-char sequestration in terrestrial ecosystems - a review, Mitig. Adap. Strat. Glob. Change 11 (2006) 403–427.
[38] FLL, Green Roof Guidelines: Guidelines for the Planning, Construction and Maintenance of Green Roofs, 6th ed., Landscape Development and Landscaping Research Society e. V, Bonn, 2018, 2018 edition.
[39] J. Lehmann, S. Joseph, Biochar For Environmental management: Science and Technology, Earthscan, Stirling, VA, 2009.
[40] S. Kuppusamy, et al., Agronomic and remedial benefits and risks of applying biochar to soil: current knowledge and future research directions, Environ. Int. 87 (2016) 1–12, https://doi.org/10.1016/j.envint.2015.10.018.
[41] D.V. Sarkhot, T.A. Ghezzehei, A.A. Berhe, Effectiveness of biochar for sorption of ammonium and phosphate from dairy effluent, J. Environ. Qual. 42 (5) (2013) 1545–1554, https://doi.org/10.2134/jeq2012.0482.

[42] Y. Li, R.W. Babcock, Green roofs against pollution and climate change. A review, Agron. Sustain. Dev. 34 (4) (2014) 695–705, https://doi.org/10.1007/s13593-014-0230-9.
[43] C. Butler, C.M. Orians, Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof, Ecol. Eng. 37 (11) (2011) 1796–1803, https://doi.org/10.1016/j.ecoleng.2011.06.025.
[44] B. Dvorak, A. Volder, Green roof vegetation for North American ecoregions: a literature review, Landsc Urban Plan 96 (4) (2010) 197–213, https://doi.org/10.1016/j.landurbplan.2010.04.009.
[45] O. Starry, et al., Photosynthesis and water use by two Sedum species in green roof substrate, Environ. Exp. Bot. 107 (2014) 105–112, https://doi.org/10.1016/j.envexpbot.2014.05.014.
[46] A.K. Durhman, D.B. Rowe, C.L. Rugh, Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa, HortScience 42 (3) (2007) 588–595.
[47] J. Murphy, J.P. Riley, A modified single solution method for determination of phosphate in natural waters, Anal. Chim. Acta 26 (1) (1962) 31. -&.
[48] M. Weatherburn, Phenol-hypochlorite reaction for determination of ammonia, Anal. Chem. 39 (8) (1967) 971, https://doi.org/10.1021/ac60252a045.
[49] T.A. Doane, W.R. Horwath, Spectrophotometric determination of nitrate with a single reagent, Anal. Lett. 36 (12) (2003) 2713–2722, https://doi.org/10.1081/al-120024647.
[50] I. Buffam, M.E. Mitchell, R.D. Durtsche, Environmental drivers of seasonal variation in green roof runoff water quality, Ecol. Eng. 91 (2016) 506–514, https://doi.org/10.1016/j.ecoleng.2016.02.044.
[51] M. Buckland-Nicks, A. Heim, J. Lundholm, Spatial environmental heterogeneity affects plant growth and thermal performance on a green roof, Sci. Total Environ. 553 (2016) 20–31, https://doi.org/10.1016/j.scitotenv.2016.02.063.
[52] R.V. Lenth, Least-squares means: the R package lsmeans, J. Stat. Softw. 69 (1) (2016) 1–33, https://doi.org/10.18637/jss.v069.i01.
[53] S. Beecham, M. Razzaghmanesh, Water quality and quantity investigation of green roofs in a dry climate, Water Res. 70 (2015) 370–384, https://doi.org/10.1016/j.watres.2014.12.015.
[54] J.C. Berndtsson, T. Emilsson, L. Bengtsson, The influence of extensive vegetated roofs on runoff water quality, Sci. Total Environ. 355 (1–3) (2006) 48–63, https://doi.org/10.1016/j.scitotenv.2005.02.035.
[55] C. Johnson, S. Schweinhart, I. Buffam, Plant species richness enhances nitrogen retention in green roof plots, Ecol. Appl. 26 (7) (2016) 2130–2144, https://doi.org/10.1890/15-1850.1.
[56] J. Franzaring, et al., Water retention, wash-out, substrate and surface temperatures of extensive green roof mesocosms-Results from a two year study in SW-Germany, Ecol. Eng. 94 (2016) 503–515, https://doi.org/10.1016/j.ecoleng.2016.06.021.
[57] D. Zhou, et al., Assessing the hydrological behaviour of large-scale potential green roofs retrofitting scenarios in Beijing, Urban Forestry Urban Green. 40 (2019) 105–113, https://doi.org/10.1016/j.ufug.2017.12.010.
[58] Y.L. Li, R.W. Babcock, Green roof hydrologic performance and modeling: a review, Water Sci. Technol. 69 (4) (2014) 727–738, https://doi.org/10.2166/wst.2013.770.
[59] X.Z. Zheng, et al., Green roofs for stormwater runoff retention: a global quantitative synthesis of the performance, Resour. Conserv. Recycl. (2021) 170, https://doi.org/10.1016/j.resconrec.2021.105577.
[60] N.D. VanWoert, et al., Watering regime and green roof substrate design affect Sedum plant growth, HortScience 40 (3) (2005) 659–664.
[61] C. Farrell, et al., High water users can be drought tolerant: using physiological traits for green roof plant selection, Plant Soil 372 (1–2) (2013) 177–193, https://doi.org/10.1007/s11104-013-1725-x.
[62] A.J. Bates, et al., Effects of varying organic matter content on the development of green roof vegetation: a six year experiment, Ecol. Eng. 82 (2015) 301–310, https://doi.org/10.1016/j.ecoleng.2015.04.102.
[63] S. Gul, et al., Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions, Agric. Ecosyst. Environ. 206 (2015) 46–59, https://doi.org/10.1016/j.agee.2015.03.015.
[64] F. Liang, et al., Crop yield and soil properties in the first 3 years after biochar application to a calcareous soil, J. Integr. Agric. 13 (3) (2014) 525–532, https://doi.org/10.1016/s2095-3119(13)60708-x.
[65] N. Ameloot, et al., Short-term CO2 and N2O emissions and microbial properties of biochar amended sandy loam soils, Soil Biol. Biochem. 57 (2013) 401–410, https://doi.org/10.1016/j.soilbio.2012.10.025.
[66] S.A. McCormack, et al., Biochar in bioenergy cropping systems: impacts on soil faunal communities and linked ecosystem processes, Glob. Change Biol. Bioenergy 5 (2) (2013) 81–95, https://doi.org/10.1111/gcbb.12046.
[67] B. Singh, B.P. Singh, A.L. Cowie, Characterisation and evaluation of biochars for their application as a soil amendment, Aust. J. Soil Res. 48 (6–7) (2010) 516–525, https://doi.org/10.1071/sr10058.
[68] S.N. Yuan, Z.X. Tan, Q.Y. Huang, Migration and transformation mechanism of nitrogen in the biomass-biochar-plant transport process, Renew. Sustain. Energy Rev. 85 (2018) 1–13, https://doi.org/10.1016/j.rser.2018.01.008.