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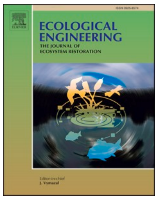

Vegetated roofs for managing stormwater quantity in cold climate

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ABSTRACT

Vegetated roofs, i.e. green roofs, were continuously measured for runoff to quantify their capacity to manage stormwater in a field experiment in southern Finland, with distinct seasonality and varying weather conditions. Attention was paid to heavy storms to study the potential in mitigating urban flooding. In addition, the impact of biochar amendment (10% *v*/v) on rainfall retention was studied. Meadow vegetation was established on crushed brick based substrate either by introducing plants as seedlings and seeds or by using pre-grown readymade mats. Annual retention varied from 40% to 70%. The highest retention, ca. 80%, was found in summer even though it was the rainiest season. Wintertime retention was 30–40%. The coarse substrate enabled infiltration even when frozen and, thus, the roofs operated also in winter. Heavy storms occurred mainly in summer, the season with the highest hydrologic performance of the roofs, resulting in >80% peak attenuation and slow release of runoff. In individual rain events, runoff from meadow roofs was largely a function of rainfall depth. However, retention was weakly explained by the amount of rainfall or by other variables, such as rainfall intensity or antecedent dry period, indicating the difficulty in capturing the complex phenomena behind variable weather conditions. Biochar improved retention only slightly, at maximum by ca. 10%. The empirical evidence of this study highlights vegetated roofs as a feasible technology to be applied in urban runoff management even in cold climate.

1. Introduction

The spread of impervious surfaces with urban development and the intensification of extreme precipitation due to global warming (Pfleiderer et al., 2019) contribute to excessive surface runoff that will be increasingly difficult for conventional stormwater systems to handle. To meet such challenges, new urban runoff measures are needed, such as ecosystem-based approaches using green infrastructure (Larsen et al., 2016). Excessive runoff resulting in urban flooding is most pronounced in densely built downtown areas, where limited available space and high land value hinder the implementation of ecological structures. As roofs may account for half of the impermeable urban area (Stovin et al., 2012), it is not surprising that the utilisation of this mostly unused space has received attention (Li and Babcock Jr., 2014). Such ecosystem based, or nature-based, solution can reduce stormwater and detain runoff, i.e. attenuate peak flow. Rainfall entering vegetated roofs, also traditionally known as green roofs, is partly stored in the substrate and taken up by plants, partly returned back to the atmosphere via evapotranspiration and partly discharged as runoff. The fraction of rainfall that is not released as runoff is defined as retention, which is affected by complex interactions among the components of vegetated roofs and their physical environment. Retention has turned out to be difficult to predict especially for individual rainfall events (Stovin et al., 2012). Thus, better empirical evidence on their performance across different spatial/temporal scales under different climatic conditions has been called for (Nagase and Dunnett, 2012; Carson et al., 2013; Nawaz et al., 2015; Johannessen et al., 2018). Most studies on vegetated roofs have been done in temperate climates, but the limited knowledge on their performance in urban landscapes with distinct seasonality (Teemusk and Mander, 2007; Berghage et al., 2009; Schroll et al., 2011; Kuoppamäki et al., 2016; Johannessen et al., 2018) is one of the central barriers to the adoption of such technologies in cold climate (Driscoll et al., 2015).

Local climate with varying distribution, size and intensity of rainfall events, seasonal evapotranspiration rates and the length of antecedent dry weather periods influence the capacity of vegetated roofs to retain water (Bengtsson et al., 2005; Stovin, 2010; Elliott et al., 2016). In cold and wet climates, precipitation volume and patterns vary between different locations, resulting in highly variable retention capabilities (Johannessen et al., 2018). Modelling suggests the highest retention in areas with low annual precipitation, warm summers and either mild or cold winters (Johannessen et al., 2017). Studies performed in areas with high seasonality include the caveat that the observed seasonal trends may be masked by variable storm event size distribution and the length

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of antecedent dry weather periods within each studied season (Stovin et al., 2012; Carson et al., 2013; Elliott et al., 2016). Thus, multiple years of seasonal observations are needed.

Besides climate, varying design configurations of vegetated roofs make it difficult to predict runoff reduction (Li and Babcock Jr., 2014). A thin (3–8 cm) substrate naturally has less capacity to store water than a thicker (10–20 cm) substrate (Bengtsson et al., 2005; Morgan et al., 2013; Soulis et al., 2017). 10 cm has been shown to provide better stormwater retention than shallower substrates (5 cm), whilst the same retention as deeper (15–20 cm) substrates, but to weigh less and cost less in materials (Morgan et al., 2013). Retention can be improved by amending substrates with additives, such as biochar (Farrell et al., 2016; Kuoppamäki et al., 2016). The same effect can be achieved with organic matter (OM). Active water uptake and transpiration by vegetation improves retention via moisture loss from substrates but is mainly restricted to growing season (Teemusk and Mander, 2007; Dunnett et al., 2008). Species of *Sedum* are typically used in vegetated roofs due to their drought tolerance and ability to survive on thin substrates. In terms of stormwater reduction, however, they are not the best choice due to their conservative water use, resulting in even lower retention as compared to bare substrates (Nagase and Dunnett, 2012; Soulis et al., 2017). Under wet and cold conditions, *Sedum* roofs may be hard to justify as a reliable solution (Johannessen et al., 2017). Nagase and Dunnett (2012) recommended studying species-rich meadow roofs with herbaceous plants and grasses for water management rather than only *Sedum*.

The aim of this study was to quantify the capacity of meadow roofs to retain rainfall and detain runoff in a field experiment in southern Finland, with varying weather conditions for four years, during all four seasons. Vegetation was introduced on crushed brick based substrate either by adding seeds and seedlings or by installing pre-grown mats. One additional mat treatments was amended with biochar (10% *v*/v). Annual, seasonal and event-based hydrologic performance of these three designs was studied by continuously measuring runoff and substrate moisture and temperature. It was hypothesised that the retention and detention of runoff is better in summer than in the other seasons, is enhanced by dense vegetation cover in the pre-grown mats, biochar amendment and, in due course, by increased OM content. Dense vegetation was expected to improve retention especially in summer, when plants are active. Among weather parameters, rainfall depth, the amount of antecedent precipitation and the length of the antecedent dry period were assumed to primarily affect runoff depth and retention capacity during individual rainfall events. Special attention was paid to the performance of roofs during heavy storms to study their potential in mitigating urban flooding.

2. Material and methods

2.1. Experimental setup

In early July 2013, a vegetated roof platform experiment was established at a field research station (60° 55′ 37.33″ N, 25° 35′ 35.85″ E) in the City of Lahti, southern Finland, where the 1981–2010 average yearly temperature is +4.4 °C and precipitation 639 mm (FMI, 2020a). The experiment had two levels of vegetation establishment method: either by planting with seeds and plug plants (hereafter referred to as "plantings") or as pre-grown mats (hereafter "mats"). Both treatments had three replicates. A second factor was biochar, which was absent in the three mats and present (10% *v*/v) in one mat as a 1 cm layer (hereafter "mat+bc") (SI Fig. A1). The impacts of establishment method, biochar amendment and weather (see 2.4.) were studied as independent factors against runoff retention as dependent factor.

The seven studied platforms, being part of a bigger experiment (Kuoppamäki and Lehvävirta, 2016), were each 1 m × 2 m in size, made of plywood and adjusted to a slope of 4° (approximately 1:14 or 7%) at a height of 1.5 m from the ground (SI Fig. A2). The floors and 15 cm high edges of the platforms were covered with a roofing membrane of HD polyethylene. A 25 mm thick egg carton-like drainage layer made of molded polystyrene (Nophadrain; Veg Tech, 2014) was installed on the bottom and above it a 7 mm thick water holding fabric (VT-filt; Veg Tech, 2014). The substrate consisted of crushed, recycled brick (85%), compost (5%), peat (5%) and crushed bark (5%; all percentages by fresh volume). The bulk density of this crushed brick mixture was 1.3 g/cm and the dry weight was 1190 g/L. Particle size distribution was as follows: 13.8% < 0.25 mm, 12.8% 0.25–0.50 mm, 17.2% 0.5–1.0 mm, 18.8% 1–2 mm, 20.9% 2–4 mm and 16.5% 4–10 mm. The biochar, made of birch (*Betula* spp.) via pyrolysis in a continuous retort at 380–420 °C for a holding time of 2 h, had a BET specific surface area of 7 m^2/g and bulk density of 0.39 g/cm. The pre-grown mats were produced by VegTech in Sweden and consisted of dense vegetation of mosses, *Sedums*, herbs and grasses grown on a 4-cm thick substrate (Veg Tech, 2014), which was supported by a plastic net that was attached to a 1 mm fabric perforated with 1 mm holes at 5 mm intervals. Plant species are listed in Kuoppamäki and Lehvävirta (2016). The total thickness of all meadow roofs was set to 10 cm (SI Fig. S1).

2.2. Measurements and sampling

Discharge from meadow roofs, hereafter referred to as runoff, was measured at 10 min intervals with Decagon ECRN-100 rain gauge tipping buckets (resolution 0.2 mm). An additional ECRN-100 rain gauge continuously monitored rainfall. Runoff was collected through three holes in the front rim of each experimental platform via a gutter to a tipping bucket and then through a funnel into a 25 l container (SI Fig. A2). Containers were occasionally used to control the reliability of rain gauge readings. Substrate moisture (as volumetric water content, VWC) and temperature were continuously measured at 10 min intervals since April 2014 using Decagon 5TE sensors placed at 1, 5 and 9 cm depths in the centre of one randomly selected replicate per treatment. Decagon Em50 data loggers stored the data.

The Vaisala WXT520 Micro Weather Station next to the platforms collected data on rainfall, relative air humidity and wind velocity at 10 min resolution. Rainfall measured by Vaisala and the Finnish Meteorological Institute's (FMI, 2020a) local weather station, which is situated 5 km from the experimental site, was used for comparison and validation to detect possible temporary technical problems. Data obtained from FMI were used for wintertime precipitation, since snowfall cannot be measured reliably by either unheated tipping buckets or by the Vaisala station. The same source also provided long-term precipitation data for the area.

Organic matter (OM) content of substrate was monitored once a year by taking two core samples of 5 cm diameter from the surface to the bottom in each roof and pooled into one composite sample. Plant shoots and roots were removed as well as the plastic and fabric material of mats. Each sample was sieved through 2 mm and mixed to get a composite sample from each roof, except in 2016 when the mat and crushed brick substrates were analysed separately for OM, since measurements on moisture and temperature gave a reason for it. 20 g subsamples were dried at 70 °C for 24 h, transferred to pre-weighed crucibles, weighed, burned in a furnace at 550 °C for 4 h and re-weighed.

Vegetation was inventoried and substrate depth measured once a year. No changes were observed in the depth of substrates. Plantings had ca. 10% vegetation cover in the first year, 50% in the second year and 95% thereafter. Seedlings died in the first winter so vegetation in plantings was established only with seeds. Vascular plants were abundant in mats throughout the study and increased in plantings two years after establishment (Fig. 1). The initially high moss cover in mats decreased over time but increased in plantings. Biochar affected vascular plants negatively and mosses positively (Fig. 1).

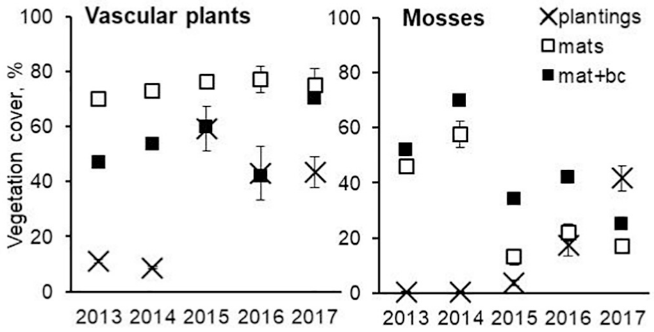


Fig. 1. The average (±SE) cover of vascular plants and mosses on the meadow roofs during the study years.

2.3. *Data analyses*

Data collected from 1st December 2013 until 30th November 2017 were analysed for event-by-event, cumulative seasonal and cumulative annual runoff and retention. Events were separated by a continuous dry period of at least 6 h (Hathaway et al., 2008; Speak et al., 2013; Nawaz et al., 2015; Gong et al., 2021). Retention was defined as the percentage share of rainfall not released as runoff from meadow roofs and detention as the percentage of peak hourly runoff in relation to peak hourly rainfall depth. When rain gauges measuring runoff had apparent blockages, evidenced as zero readings despite rainfall and subsequent runoff from the other roofs, means of the other replicates of the same treatment were used to calculate cumulative runoff for the platform.

In order to enable comparisons on the seasonal performance of vegetated roofs between years, seasons were defined as 3-month periods: winter = December–February, spring = March–May, summer = June–August and autumn = September–November (FMI, 2020b). Melting events were not included in the analysis of individual events. When analysing storm events, criteria of FMI (2020c) were used: rainfall exceeding 2.5 mm in 5 min, 5.5 mm in 30 min, 7 mm in an hour, 10 mm in 4 h, 15 mm in 12 h or 20 mm in 24 h were defined as heavy storms. As the major interest here was in events that might cause urban flooding, only storms exceeding 5.5 mm rainfall in 30 min were selected for further analyses.

Statistical analyses were run with IBM SPSS Statistics Version 21 for Windows. The impacts of vegetation (mats vs. planted) on accumulated runoff and the capability of meadow roofs to retain rainfall were examined both annually and seasonally by using an ANOVA repeated measures procedure. If the assumptions for parametric tests were not met, log transformation was used to stabilise heterogeneous variances or to normalise the distribution (nevertheless, non-transformed values appear in the figures). t-test or, if data were not normally distributed even after log transformation, independent samples Mann-Whitney U test were used to compare substrate moisture and temperature between treatments. A stepwise multiple linear regression analysis was run to study how well weather parameters explain the hydrologic behaviour of the meadow roofs. The independent parameters tested in this analysis were rainfall depth, rainfall intensity as the maximum hourly precipitation for the event (mm/h), antecedent dry weather period (ADWP; days) and mean air temperature (°C), relative air humidity (%) and wind velocity (m/s) during events and during the 30 days before each event. Runoff volumes from vegetated roofs and their retention were the dependent factors. Eigenvalues of the obtained models were examined to study possible strong multicollinearity between these predictive factors and if the value was close to zero, the model was not accepted.

3. Results

3.1. *Annual and seasonal runoff retention and the development of vegetation*

Despite the 100% vegetation cover of the mats treatment, these roofs retained less rainfall annually (40–60%) than the less densely vegetated plantings (50–70%) (repeated Anova; $F = 11.50$, $p = 0.027$) (Fig. 2). Runoff retention was improved by biochar by ca. 10% but only in the first two study years (Fig. 2) and the impact of biochar on retention was insignificant (t-test; $p > 0.05$). Yearly precipitation totals increased and the capacity of meadow roofs to retain rainfall declined during the experiment (repeated Anova; $F = 16.36$, $p < 0.001$) (Fig. 2).

Highest retention was measured in the summer, which was also the rainiest season (Fig. 3). Autumn and winter were characterised by reduced retention. Runoff reduction was lowest in spring and winter, the seasons with melting periods (SI II.). Only minor ponding was occasionally observed on frozen roofs, indicating that the coarse and porous substrate could infiltrate rainfall also in winter and early spring. Snow cover on roofs melted earlier than snow on the ground (SI Fig. A5). Plantings retained more rainfall than mats in spring and winter (repeated Anova $F = 8.21$, $p = 0.046$ and $F = 44.92$, $p = 0.003$, respectively) and marginally so in autumn (repeated Anova $F = 6.71$, $p = 0.061$). In summer, retention capacity did not differ between plantings and mats. Although mat+bc had slightly higher retention than mats in autumn and winter, biochar did not affect retention in any of the seasons (t-test; $p > 0.05$) (Fig. 3). Seasonal variation was considerable, since weather conditions differed between years.

3.2. *The hydrologic performance of meadow roofs in individual events*

The 4-year monitoring data included altogether 288 runoff events, of which 269 were not melting events. Of these 269 events, the majority (72%) had <10 mm rainfall and almost half (42%) < 5 mm. The average retention of plantings and mats was 83% and 76%, respectively.

Runoff from both plantings and mats was largely a function of rainfall (Fig. 4a), which was the best explanatory variable for the variation in runoff from meadow roofs (Table 1). However, retention was less well explained by the amount of rainfall and was also affected by, e.g. air temperature, either during the rain events or during the preceding 30 days (Table 1). The length of the antecedent dry weather period (ADWP) and rainfall intensity were among the weakest predictors of runoff and retention. The mostly efficient retention of events with <20 mm by both mats and plantings was in summer, observed as a dense cluster of measurements near 100% retention below 20 mm rainfall (Fig. 4d), while retention capability was more variable during the other

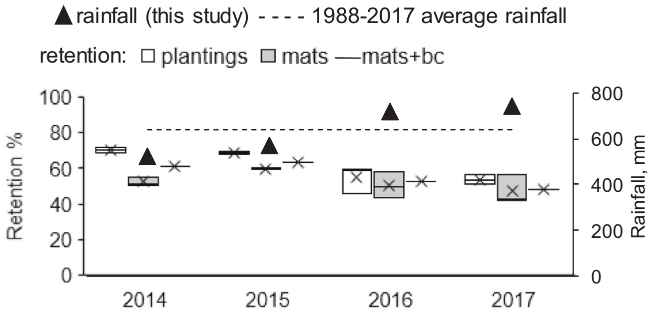
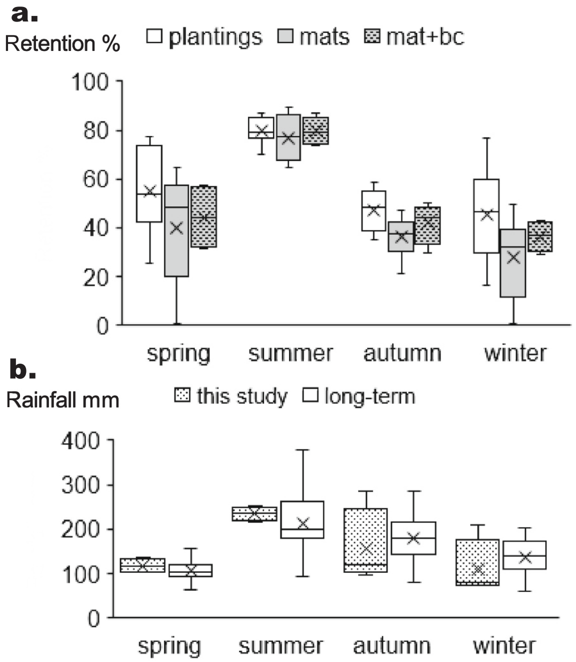


Fig. 2. Yearly retention of rainfall by meadow roofs (primary y-axis) established either with plantings ($N = 3$), mats ($N = 3$) or mat+bc ($N = 1$) and yearly rainfall depth (secondary y-axis) during the four study years. The figure also shows the long-term (1988–2017) mean precipitation (horizontal dotted line). Means are shown with a cross (x) and medians with a cross line. The top and bottom of each box are the 3rd and 1st quartiles, respectively.



	spring	summer	autumn	winter
Air temperature (°C)	5.1 ± 0.6	15.5 ± 0.4	5.5 ± 0.5	-3.1 ± 0.4
Relative humidity (%)	68.5 ± 0.8	72.7 ± 0.8	84.3 ± 1.1	83.9 ± 0.8

Fig. 3. Seasonal cumulative (a) retention of rainfall by meadow roofs established with plantings, mats and the one mat+bc and (b) rainfall during the four study years. The figure (b) also shows the long-term (1988–2017) seasonal precipitation. The top and bottom of each box are the 3rd and 1st quartiles, respectively. Means are shown with a cross (x) and medians with a cross line. Whiskers indicate maximum and minimum values. Air temperature and relative air humidity, measured by the local Vaisala weather station, are shown below the figure as averaged means (±SE) of each study year.

seasons (Fig. 4c, e, f).

All meadow roofs attenuated peak flow equally well and the highest attenuation values were found in summer and winter (Fig. 5). Most intense precipitation peaks were observed in summer, the season with the majority of heavy storms (see below).

3.3. *The hydrologic performance of meadow roofs in heavy storms*

The criteria of heavy storms were met in 33 rainfall events, which were studied for the potential of meadow roofs in mitigating urban flooding. 76% of the storms occurred during summer, 18% in autumn, 6% (only 2 events) in spring and none in winter. Eleven storms of various type, from short-term to longer-term events, were selected for deeper analysis. 90–99% of short-term downpours lasting <2 h were temporarily stored in the substrate irrespective of substrate moisture content at the start of precipitation, and runoff was delayed by several hours (SI Table A1) (Fig. 6a, b), indicating efficient detention. Storms were sometimes followed by minor showers so that gradual discharge from meadow roofs could last for several days (Fig. 6d).

Peak flow was efficiently attenuated in short-term storms (82–99%) and reasonably well in longer-term downpours (66–96%) (SI Table A1). Plantings usually generated less runoff and reached higher substrate moisture content as compared to mats after storm events (Fig. 6).

Peak attenuation ranged from 50% to 99% in 29 events where peak rainfall exceeded 20 mm/h (max 45 mm/h), which occurred mostly in summer (21 events). Two short-term summer storms in 2017 were most intense, with the highest measured rainfall of 5.5 mm in 10 min, corresponding to over 30 mm/h (SI Table A1). As peak runoff from meadow roofs varied from <1 mm to ca. 3 mm, they attenuated peak intensities by 90–98% in these storms. Even the lowest peak attenuation values were ca. 65%. Plantings often, but not in all cases, attenuated slightly better than mats (SI Table A1).

3.4. *Substrate properties as explaining the hydrologic behaviour of meadow roofs*

Daily temperature variation was higher in plantings than in mats (Mann-Whitney; $p < 0.001$) except in winter, when both treatments remained equally cold (Fig. 7). The high variation in plantings was due to higher maximum temperatures (as much as >40 °C) as compared to mats, especially in spring and summer (Mann-Whitney; $p < 0.001$) (SI Fig. A4). The mat substrate was wetter than the planting substrate at the start of rain events (Mann-Whitney; $p < 0.001$) except near the bottom, where moisture did not differ between the treatments. Biochar reduced moisture in the middle of the substrate (Mann-Whitney; $p < 0.05$) (Fig. 7).

Organic matter (OM) content in the crushed brick substrate of plantings was ca. 1.5%, while in mats it was 3–5 times higher (repeated Anova; $F = 719.85$, $p < 0.001$) due to the high OM content of pre-grown mats (Table A2). OM content in the brick substrate below mats was equal to that in plantings but biochar amendment in the mat+bc raised OM to 7.9%. No indication of an increasing amount of OM with time was observed (Table A2).

4. Discussion

4.1. *Annual and seasonal retention of rainfall*

The meadow roofs investigated here showed a 40–70% annual cumulative retention of rainfall, which is within the broad limits of 30% to 86% mentioned in Li and Babcock Jr. (2014). Given the cold climate here, such a substantial reduction in runoff is encouraging. Annual rainfall in southern Finland, on the other hand, is rather moderate. For instance in Oslo, Norway with a similarly humid continental cold climate but with 861 mm of rainfall annually, a *Sedum* roof with an 8 cm thick substrate was reported to retain only 26% of rainfall annually (Johannessen et al., 2018). On the other hand, that roof was facing north, was partly shaded and had little wind exposure, unlike the meadow roofs of this study that were facing west and located in a sunny and windy field. Thus, besides establishment method, local conditions and microclimate also play a major role in the hydrology of vegetated roofs, making generalisations difficult. In contrast to what I hypothesised, dense cover in the pre-grown mats did not improve retention as compared to plantings. Amending a mat roof with biochar enhanced retention only slightly and only during the first two study years. Previously, biochar has been shown to improve water retention in vegetated roofs in short-term experiments ranging from a couple of months (Farrell et al., 2016) to one year (Kuoppamäki et al., 2016). It may be that the capacity of biochar to hold water is reduced with time, or that the 10% volumetric amendment of biochar was too modest to contribute to runoff reduction especially during the latter two rainy years. On the other hand, only a single roof amended with biochar was continuously measured for runoff reduction, undermining generalisations on the role of biochar in runoff management.

As hypothesised, highest retention, ca. 80%, was measured in summer, even if it was the rainiest season, like it generally is in Finland (Pirinen et al., 2012). The good hydrologic performance of vegetated roofs in summer is in agreement with several previous studies (e.g. Bengtsson et al., 2005; Mentens et al., 2006; Schroll et al., 2011; Carson et al., 2013). High retention can be expected in summer, with high inter-event evapotranspiration (Mentens et al., 2006; Schroll et al., 2011; Johannessen et al., 2018). Autumn was the second rainiest season, when retention was only ca. 50%, with 10 °C lower air temperatures and > 10% higher humidity as compared to summer.

In spite of the least amount of rainfall, spring was characterised by low runoff reduction. This was due to snow and ice melting early in the season, while later in spring rainfall was efficiently retained. The

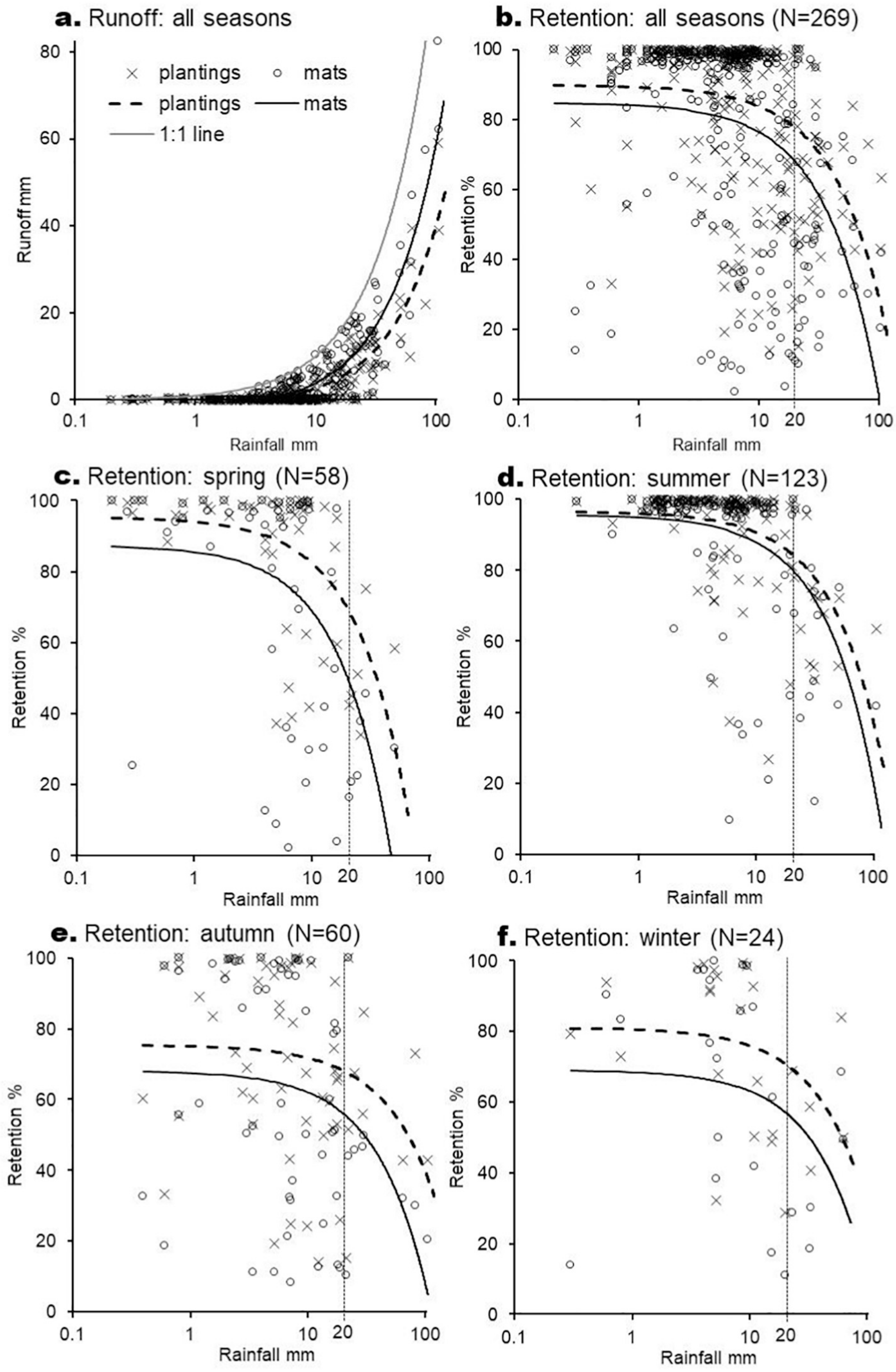


Fig. 4. (a) Runoff from meadow roofs in relation to rainfall depth and the retention of rainfall in (b)all seasons, (c) spring, (d) summer, (e) autumn and (f) winter in relation to rainfall depth. Note the log-scale of the x-axis showing rainfall depth. Dashed lines indicate 20 mm rainfall, above which retention decreased substantially.

occasionally negative runoff retention for individual events in winter was in agreement with previous findings (Berghage et al., 2009; Teemusk and Mander, 2007). Such events are sometimes excluded from rainfall and retention calculations (Hathaway et al., 2008). In this study, I attempted to estimate wintertime performance, since practitioners often doubt this, thereby being a barrier of adopting green infrastructure, given the limited number of studies (Driscoll et al., 2015). Several melting events in winter and early spring were documented in this study, mostly with negative retention due to the release of water stored in snow and ice. However, the cumulative wintertime retention was positive. In the future, vegetated roofs will be challenged by wet winter weather. Precipitation in Finland is predicted to increase by 30% (Ruosteenoja et al., 2016) and in Europe and the Northern Hemisphere a significant loss of snow mass is already evident (Pulliainen et al., 2020). Hydrologic performance of vegetated roofs is less efficient in cool and wet climate (Schroll et al., 2011). Nevertheless, under such conditions, they can perform better than many other stormwater technologies during warm weather, such as swales, wetlands, detention and retention ponds (Driscoll et al., 2015). Indeed, meadow roofs in this study infiltrated rainfall even when frozen, thanks to the coarse substrate. The highest moisture content was only ca. 20% so the amount of ice that can build up in the substrate is low, as was shown by Collins et al. (2017), who measured thermal insulation in the same experimental roofs used in this study. The fact that rooftop snow melted more quickly than snow on the

Table 1
Weather parameters that best predicted, in rank order, runoff from meadow roofs and the retention of rainfall in the two types of meadow roofs in different seasons as well as all seasons together, as modelled by stepwise multiple regression (df = 224, 32, 122, 58, 9, annually, in spring, summer, autumn and winter, respectively). All models were significant at $p < 0.001$. "30-d" refers to weather conditions during 30 days before rain events.

Treatment	Season	R^2	*F*	Best predictors of the model (ranked)
Runoff				
Plantings	all	0.77	772.49	rainfall depth
	spring	0.60	49.85	rainfall depth
	summer	0.82	578.15	rainfall depth
	autumn	0.78	206.91	rainfall depth
	winter	0.96	126.06	rainfall depth, air temperature
Mats	all	0.80	907.87	rainfall depth
	spring	0.77	53.99	rainfall depth
	summer	0.78	432.52	rainfall depth
	autumn	0.89	490.53	rainfall depth
	winter	0.84	49.02	rainfall depth
Retention				
Plantings	all	0.25	14.35	30-d air humidity, rainfall depth
	spring	0.45	35.12	rainfall depth
	summer	0.36	23.20	rainfall depth, 30-d rainfall depth
	autumn	0.43	14.22	30-d air temperature and humidity
	winter	0.60	38.31	air temperature
Mats	all	0.34	59.64	30-d air temperature, rainfall depth
	spring	0.73	29.70	rainfall depth, 30-d rainfall depth
	summer	0.39	40.59	30-d air temperature
	autumn	0.39	19.21	air temperature, rainfall depth
	winter	0.93	56.04	30-d air temperature, rainfall depth

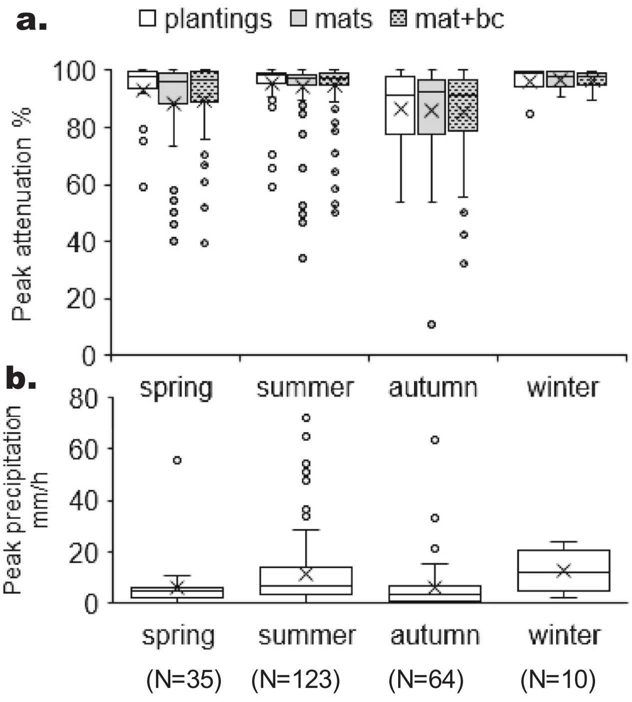


Fig. 5. (a) Peak attenuation by the meadow roofs and (b) peak precipitation in the four seasons during the four study years. Box plots as in Fig. 3.

ground and that snow cover on meadow roofs was thinner than that on the ground suggest that some of the accumulated snow was blown away from the roofs. The experimental site was windy, being situated in the middle of a field. As such, the study setup resembled true world windy conditions on building rooftops. On the other hand, this means that the retention potential in winter is somewhat overestimated, since precipitation that was used in the calculations, represented rainfall and snowfall accumulating on the ground.

4.2. *The impact of vegetation establishment method on retention*

The pre-grown mats with 100% plant cover did not show higher retention when compared to plantings with less dense vegetation, not even during the growing season. This was in contrast to my hypothesis and to observations made in previous studies showing the important role of plants (Teemusk and Mander, 2007; Schroll et al., 2011; Soulis et al., 2017). Mats maintained higher moisture than plantings, suggesting an important role of substrate in the hydrology of meadow roofs in this study. High daytime temperatures in plantings obviously contributed to high evapotranspiration as compared to mats that remained cooler. Dunnett et al. (2008) also noticed that bare substrates may release less runoff than vegetated ones because of quicker drying, as vegetation protects the substrate resulting in lower temperatures and less evaporation. Plant cover also protects substrates from wind scour (Morgan et al., 2013), which may reduce evaporation. The declining retention capacity of plantings over the course of this study, with an increasing plant cover, also support the significance of evaporation from the substrate. In addition, developing root systems may have created preferential flow paths that reduced storage capacity. Root channels can be even more decisive than evapotranspiration (Zhang et al., 2019). Carson et al. (2013) highlighted the importance of considering non-vegetated regions to reduce the impact of preferential flow paths that create hydraulic conductivity. On the other hand, retention is only one function of vegetated roofs that are generally supposed to be multifunctional (cf. Kotze et al., 2020), with biodiversity and amenity supported by plants being one of the important objectives.

One additional reason as to why mats maintained higher moisture and cooler temperatures than plantings may have been the 4-cm thick pre-grown mat rich in OM, associated with higher water holding capacity. Mats also had a dense cover of mosses, which are known to retain moisture and enhance cooling underneath them (Anderson et al., 2010). Furthermore, the fabric of mats, despite being thin and perforated, may have prevented moisture loss from the crushed brick substrate below mats. Mosses were favoured by biochar amendment, so perhaps they diminished the impact of biochar on retention also in mat+bc in due course.

The better retention and faster melting indicate that plantings could be a more beneficial design for vegetated roofs than mats in cold climate. Besides, vegetated roofs established with pre-grown mats are environmentally less sustainable than those established on site with local substrates and plants, since mats are often transported long distances, even from foreign countries with high energy consumption (Nurmi et al., 2016). Furthermore, imported mats may harbour non-native, unwanted species (Jauni et al., 2020).

4.3. *The impacts of weather on runoff and retention of individual events*

Apart from rare storms, vegetated roofs can be expected to be more effective in climates with rainfall patterns dominated by frequent small and moderate rain events than in areas with monsoon rains (Miller, 2008). This study was performed in a climate with almost half (42%) of the events of only <5 mm rainfall and the majority (72%) of <10 mm rainfall. These small and moderate events were generally well retained by meadow roofs, resulting in high cumulative runoff retention. Zhang et al. (2019) also found high retention due to the large number of small events.

Retention declined strongly when rainfall exceeded 20 mm. Variation in retention was, however, weakly explained by the amount of rainfall or other weather parameters, which did not improve model fit substantially. This difficulty in predicting the retention of rainfall by vegetated roofs is in agreement with Stovin et al. (2012), who argued that such processes are too complex to be captured by a regression modelling approach. Similarly, Speak et al. (2013) did not find a clear

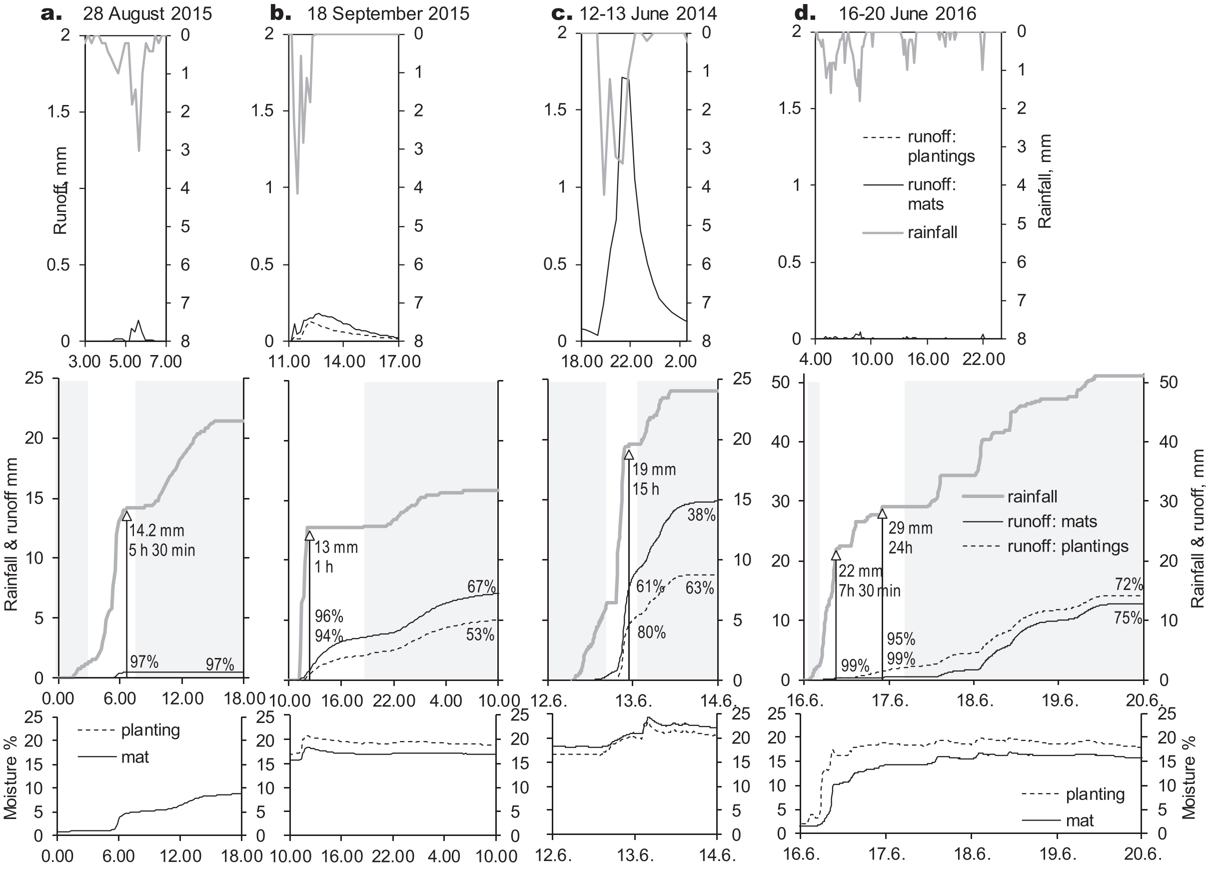


Fig. 6. Selected examples of heavy storm events of short duration with (a) low and (b) high initial substrate moisture content in meadow roofs and storms of longer duration with (c) high and (d) low initial substrate moisture content. Top panels: hyetographs showing runoff from meadow roofs (principal y-axis) and rainfall (secondary y-axis) at the time of peak rainfall (x-axis), middle panels: cumulative runoff from meadow roofs and cumulative rainfall, with unshaded areas indicating hyetographs of the top panels, bottom panels: volumetric moisture content in plantings and mats as means of the values measured through substrates.

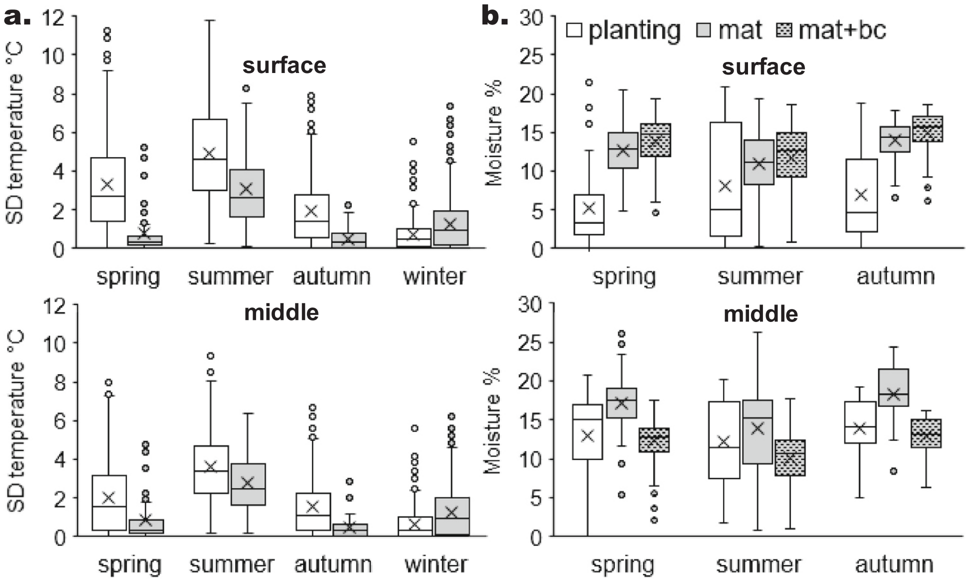


Fig. 7. (a) Standard deviation (SD) of daily temperatures and (b) volumetric moisture at the start of rainfall events measured near the surface (1 cm) and in the middle (5 cm) of substrates during the four study years. Temperatures of mat+bc are not shown, having not been affected by biochar. As substrate moisture cannot be measured at temperatures below zero, wintertime results were omitted. Box plots as in Fig. 3.

influence of explanatory variables on retention due to large variation in the data, which made predictive regression models unfeasible. Recently, Gong et al. (2021) reported rainfall depth as an important factor affecting retention of *Sedum* roofs but also dry periods and rainfall intensity. In my study, however, peak rainfall intensity was not associated with retention, and the antecedent dry weather period (ADWP) was among the weakest predictors of runoff depth and retention. Nawaz et al. (2015) also found a negligible influence of ADWP on retention, while Stovin (2010) identified it as a key factor in hydrological performance. Under variable climatic conditions, like in this study, runoff and retention may be weakly explained by ADWP, which does not take into consideration substrate moisture at the end of the previous rainfall event nor how moisture is affected by evapotranspiration, which, in turn, depends on, e.g. season, air temperature and wind speed (Hakimdavar et al., 2014; Elliott et al., 2016).

The retention capacity of a vegetated roof is finite, so even if it would be at maximum, the final retention will be modest in a heavy storm that exceeds the roof's capacity. Likewise, even if a rain event is very small, water may not be well retained if recently preceded by a heavy storm that has filled the field capacity. Thus, it is not surprising to face difficulties in predicting retention based on climate parameters. Depending on the length of the study period, observed seasonal trends might be masked by the influence of storm event size distribution and the length of ADWP (Stovin et al., 2012; Carson et al., 2013; Elliott et al., 2016). Variable weather conditions between years and seasons during this 4-year experiment highlight the importance of taking measurements over several consecutive years and all seasons to obtain a reliable view on the performance of green infrastructure like vegetated roofs in stormwater management. Nevertheless, even then retention capacity remains difficult to predict, but regression models can be improved when supplemented with more variables, such as information on the properties of the vegetated roof itself, essentially substrate water content (Longobardi et al., 2019). Even though the current study had data on substrate moisture, it was not used since it was only measured in one replicate of each treatment. Besides, our main focus was to determine how well weather parameters predict retention since resources are generally limited to measure a plethora of parameters. Obviously, more sophisticated simulations by using, for instance, Stormwater Management Model (SWMM) will yield better estimates than the simple approach used in our study. However, even such advanced models need to be accompanied with accurate estimates on potential evapotranspiration rates during inter-event periods and calibrated with the properties of vegetated roof, such as substrate porosity, field capacity, wilting point and saturated hydraulic conductivity (Krebs et al., 2015).

4.4. The performance of meadow roofs during heavy storms

In southern Finland, summer is the rainiest season and has the highest daily rainfall depths (Climate Guide, 2020a) and thunderstorms are concentrated during summertime (FMI, 2020d). Indeed, the majority (76%) of heavy storms during this study occurred in summer. They were efficiently detained, as at the time of the most intense rain, almost 100% of water was temporary stored in meadow roofs and then gradually released over an extended period of time. Similar performance has been documented in previous studies (Bengtsson et al., 2005; Hathaway et al., 2008; Stovin et al., 2012). Detention was also notable, with peak attenuation being almost exclusively above 80%. When managing stormwater, these metrics can be more relevant than the final retention, which, however, was also often high especially in short-term storms. These results suggest the potential of this type of stormwater technology in cold climate yet with rather warm, rainy summers. Thunderclouds associated with heavy showers typically develop following hot weather and are most frequent in inland areas of southern and central Finland (Saku et al., 2016). Thus, following heat periods with high evapotranspiration, vegetated roofs can be assumed to have high storage capacity to capture such storms. The so-called thunderstorm season in Finland spans from May to September (FMI, 2020d). In September 2015, for instance, 95% of a 13 mm rainfall event in one hour was stored in meadow roofs and finally, after 26 h of gradual runoff, 53–67% was retained. This storm was also reported by the Finnish Broadcasting Company (YLE, 2015) because it caused flooding in the local city centre (7 km north from the study area). Such storms are quite typical in Finland with a return period of 1.9 years and 52% probability (Climate Guide, 2020b) and according to findings of this study, could be managed by using meadow roofs like the ones used in this study. Larger, full-scale roofs can retain even more rainfall (cf. Hakimdavar et al., 2014). Given the projected intensification of rainfall extremes (Pfleiderer et al., 2019) and the apparently efficient detention and retention capacity of meadow roofs, implementing this type of nature-based solutions in densely built city centres would obviously help alleviating urban flooding and reduce the pressure on ground level stormwater technologies.

5. Conclusions

This 4-year long replicated field experiment provided empirical, scientifically sound evidence on the relatively high retention and detention capacity of meadow roofs in cold climate with moderately warm summers. Meadow roofs showed their potential in stormwater management annually and seasonally, including winter. They also operate during the cold season, from late autumn to early spring, as the coarse substrate enabled infiltration even when frozen. During individual events, retention declined strongly when rainfall depth exceeded 20 mm. Such events, however, were rare, since the prevailing weather was characterised by frequent but mostly minor showers, which were well retained. Heavy storms occurred almost exclusively in summer, the season with the best retention and detention capacity. Thus, the implementation of vegetated roofs would be worth considering in such a climate and especially in city centres susceptible to urban flooding, a major concern and an increasingly important issue with climate change. Amending a meadow mat roof with biochar only weakly improved hydrologic performance, with effectiveness declining with time. Future studies could determine whether higher amounts of biochar is worth applying to vegetated roofs. Meadow roofs established on site with plantings are dynamic ecosystems, with wide temperature variation, which contribute to high evapotranspiration, resulting in lower moisture at the start of rain events and, consequently, better rainfall retention as compared to mats. Although this difference declined with time, as roof ecosystems evolved, plantings are considered a better design than mats considering also other factors besides stormwater management.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2021.106388.

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