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Research Article

Vegetation cover and plant diversity on cold climate green roofs

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Abstract

Both vegetation abundance and community composition play important roles in functions of green roofs (e.g. stormwater retention, habitat provision, aesthetic appearance). However, green roofs' vegetation, and hence their functions, can change significantly over time. More understanding of these changes is required, particularly in cold climates. Therefore, this study investigated vascular plant covers and species compositions on 41 roof sections located in Sweden's subarctic and continental climate zones. For the roof sections with a known originally intended vascular plant composition ($n = 32$), on average 24 ± 9% of the intended species were detected in surveys, and unintended species accounted for 69 ± 3% of the species found. However, most colonizing species formed sparse cover on the roofs. Thus, they may make less contributions to green roofs' potential functionalities related to vegetation density (e.g. social perception, effectiveness in stormwater management and thermal performance) than the intended vegetation. The intended species dominated plant cover (93 ± 3%) and *Sedum acre* (58 ± 36% cover) was the most commonly detected species and as found in previous studies, substrate depth was positively related to both plant cover and species richness. Contrary to a hypothesis, the roofs' vascular plant cover was not related to species richness but was significantly and negatively correlated with moss cover. The results highlight the importance of substrate depth for both plant abundance and species diversity and show that even in a cold climate, colonizing unintended species can strongly contribute to green roofs' species richness.

Key words: green roof, vegetated roof, vegetation cover, plant diversity, subarctic climate, cold climate

Introduction

In urban areas, increasing amounts of impervious surfaces such as roofs, traffic areas and other structures have led to losses of ecosystem services including, *inter alia*, flooding control, clean water, clean air and a balanced microclimate (Elmqvist et al. 2015). These surfaces, often made from materials such as metal or asphalt, absorb heat from the sun (Lazzarin et al. 2005), increase noise levels by reflecting sounds (Van Renterghem and Botteldooren 2009) and are negatively correlated with urban plant diversity (Yan et al. 2019). They affect water cycles particularly strongly as they inhibit rainwater infiltration, thereby increasing surface runoff and risks of flooding while reducing groundwater recharge (Getter et al. 2007). Other problems related to impervious areas are increases in erosion and pollutant transport capacity, which affect receiving water ecosystems and bathing water quality (Wolman 1967).

Roofs constitute a significant amount of the hard surfaces in urban areas (Dunnett and Kingsbury 2004) and, unlike many ground-level hard surfaces such as roads and parking lots, they are seldom used for transport of people and goods. Thus, exploiting these unused spaces by installing green roofs to mitigate imperviousness problems, and thereby restoring some lost biodiversity and other ecosystem services, is clearly attractive (Oberndorfer et al. 2007).

Widely recognized ecosystem services provided by green roofs include retention and temporary storage of stormwater, which reduces runoff volumes and velocities (Bengtsson et al.

2005; VanWoert et al. 2005a; Getter et al. 2007; Czemiel Berndtsson 2010). The substrate type and depth are the main determinants of a green roof's stormwater retention capacity, but the vegetation also affect their retention and detention performance (VanWoert et al. 2005a; Stovin et al. 2015).

Although conventional roofs are occasionally colonized by vegetation (Jim and Chen 2011; Fornal-Pieniak 2012), they provide less habitat for vegetation than green roofs purposefully built to host diverse plant species. High plant diversity can help to maintain multiple ecosystem services, especially in ecosystems undergoing environmental change (Isbell et al. 2011). Organisms known to inhabit green roofs include mammals (Parkins and Clark 2015), birds (Baumann 2006), reptiles (Davies et al. 2010) arthropods (Madre et al. 2013) and fungi (John et al. 2014). Moreover, plant diversity on them is reportedly linked to the abundance and diversity of arthropods (Ebeling et al. 2018), and hence presumably insectivorous organisms. A feature that is highly dependent on vegetation cover is the aesthetic perception, which is often prioritized by architects and clients during green roofs' planning and implementation phases. Dense vegetation cover with no gaps of bare substrate appears to be the most important attribute for public acceptance (Vanstockem et al. 2018b).

Obtaining high vegetation cover can be challenging since a green roof is a harsh environment where temperatures, wind speeds and solar radiation are often more extreme than in most natural habitats in the surrounding area (VanWoert et al. 2005b). In combination with a limited amount of substrate for the plants, this makes green roof vegetation vulnerable to drought stress (VanWoert et al. 2005b). Thus, plants used on green roofs must be hardy enough to survive harsh conditions in the long term while providing ecosystem services, e.g. stormwater management (low water use during drought and high water use during and between rains) (Oberndorfer et al. 2007; Farrell et al. 2012).

Most modern green roof manufacturers have generally chosen succulent stonecrop species (*Sedums*), since they have high drought tolerance and survive well in thin substrates with little organic content (VanWoert et al. 2005b). More recently, there has been increasing interest in use of native plants adapted to local conditions (Monterusso et al. 2005; MacIvor and Lundholm 2011; Butler et al. 2012). However, the plant community (Catalano et al. 2016) and substrate properties (De-Ville et al. 2017) can change significantly over time. The substrate depth on usually shallow extensive green roofs can be a limiting factor for vegetation growth and cover (Getter and Rowe 2008). These shallow substrates generally provide limited water storage, which increases the frequency of drought stress (VanWoert et al. 2005b). Substrate composition also affect the vegetation performance and growth as it determines the plant water and nutrient availability (Young et al. 2014). In areas with sub-zero temperatures in winter, deeper substrates have also been shown to provide insulation for the vegetation, and thus more protection against root freezing injury (Boivin et al. 2001).

To date, green roof research and development efforts have been largely based on empirical data obtained from experience, experiments and observations of roofs in temperate regions (Rayner et al. 2016). However, as green roofs increase in popularity they are being installed in regions with different climates, where plants with different characteristics may be needed. For example, in hot and arid climates, resistance to prolonged drought will be crucial (Farrell et al. 2012), while plants used in cool temperate and subarctic climates must be adapted to short growth seasons, freeze–thaw cycles and long periods of snow cover (Boivin et al. 2001). Several studies have addressed features and functions of green roofs in Nordic countries. However, they have largely been performed in temperate parts of the region and focused on hydrological functions (Bengtsson et al. 2005), establishment methods (Emilsson and Rolf 2005) and leaching of nutrients (Emilsson et al. 2007; Kuoppamäki and Lehvävirta 2016). Gabrych et al. (2016) considered plant abundance on green roofs in southern Finland, which has a continental climate (Dfb) according to the Köppen Geiger classification system (Peel et al. 2007) and found that it was strongly influenced by substrate depth and roof age. In addition, species diversity and functional groups influence other ecosystem services provided by green roofs, such as stormwater retention and substrate cooling, in Halifax, Nova Scotia, Canada (Lundholm et al. 2010), which also has a Dfb climate. Further, it is often claimed that vegetated roofs can restore habitats lost due to exploitation and help conserve biodiversity (Williams et al. 2014). However, few ecological studies have rigorously evaluated these claims. In summary, several functions of green roofs are dependent on vegetation-related factors such as abundance, species composition and species diversity. However, since green roofs have largely been developed for, and mostly evaluated in, areas with temperate climates, little is currently known about interactive effects of these factors on green roofs installed in regions with a cold or subarctic climate.

To address the knowledge gap described above, the study presented here had two main aims. One was to evaluate the vegetation on green roofs in a cold climate, in terms of the presence/absence and cover of both originally intended and colonizing unintended species. The other was to explore relationships between biotic factors (vegetation diversity, composition and abundance) and abiotic factors (*roof age*, *substrate depth*, *slope*, *aspect* and *roof size*). We tested three hypotheses. First, due to the short growing seasons and long, cold winters, vegetation planted on green roofs in regions with a cold climate may have low survival rates. Second, species diversity may be positively related to the vegetation's resilience to extreme weather events and could affect plant coverage in cold climates. Third, substrate depth may be highly important for green roof vegetation in cold climates, to avoid both drought and freezing injuries, and thus positively correlated with vegetation survival and cover.

Methods

Study sites

Vegetation on existing green roofs in northern Sweden was surveyed during the summer and autumn of 2016 and summer of 2017 on 41 sections of roofs on 11 buildings in three geographical locations. The locations (Kiruna, Luleå, Umeå; Table 1) are spread across a north-south gradient in northern Sweden, which has a cold climate according to the Köppen Geiger climate classification (Peel et al. 2007). The northernmost site, Kiruna, has a subarctic climate (Köppen Dfc), while Luleå has a subarctic, bordering continental climate (Köppen Dfc) and Umeå has a continental climate (Köppen Dfb). The three sites receive similar yearly precipitation, but Kiruna receives more of its precipitation as snowfall and has more precipitation days than Luleå and Umeå (Table 1). The green roofs selected for the study were found through lists provided by local green roof manufacturers, municipalities and other contacts. They included extensive *Sedum*-based green roofs and roofs planted with *Sedum* and meadow flower mixes. Most known existing

Table 1: Locations and climatic data (for the reference period 1961-1990) taken from the Swedish meteorological and hydrological institute's database, and Köppen climate zones (Peel et al. 2007) of the towns where roofs were surveyed.

Location	Kiruna	Luleå	Umeå
Lat, Long	67.85, 20.32	65.58, 22.16	63.80, 20.29
Mean temp. °C (max, min daily mean)	−1.9 (24.9, −37.9)	1.6 (23.7, −31.1)	2.7 (23.1, −26.0)
Annual precipitation, mm (% snow)	500 (40)	506 (35)	591 (35)
Annual precipitation, days	180	162	137
Köppen climate zone	Dfc	Dfc	Dfb

green roofs in the region were covered in this study and 33 of the 41 surveyed sections had a known original intended plant list (entire lists not presented due to non-disclosure agreements with suppliers). The species found and not found in the plant lists provided by suppliers are respectively referred to as intended and unintended species.

Roof characteristics

All roof sections surveyed were extensive, with 3- to 10-cm deep substrate. Substrate type varied, but consisted mostly of scoria- or pumice-based lightweight green roof medium. Most of them (classified here as U1, U2 and K1 sections, Table 2) were parts of young green roofs, established 2 years before the survey, but there were also some substantially older roofs (9, 13 and 15 years old). All surveyed roofs were pitched, with 6°–38° slopes (Table 2). Most of the sections faced north or south (16 in both cases), but four and five faced east and west, respectively. The roof sections varied in size between 8 and 875 m^2.

Vegetation sampling

During the vegetation survey, the following variables were recorded. When referring to their use as modelling parameters (and for convenience here), these variables are *italicized*:

- *Species richness* (number of vascular plant species detected on a roof section)
- Cover of individual vascular plant species in quadrats (%)
- Total *vascular plant cover* (%)
- Total *moss cover* (%)
- *Substrate depth* (mm)
- *Age* (years)
- Slope (°)
- *Roof area* (m^2)
- *Roof width* (m)
- *Roof length* (m)
- *Aspect* (in cardinal direction: North, East, South or West)

Stratified random sampling was used to estimate the vegetation cover on the selected roof sections. For this, sampling quadrats (each consisting of a 1 × 1 m wooden frame) were evenly spread along transects on each roof section, avoiding edge zones such as ventilation shafts. The number of quadrats used on each section (3–54) was limited by the size of roof sections. The quadrats covered a minimum of 6% of the roof section surfaces and vegetation cover was estimated visually with grids in each quadrat. The buildings' owners or suppliers of the green roofs provided the *age* of the roof and the *substrate depth* was measured in each sampling quadrat as an average of three insertions using a 3-mm diameter metal rod. Total *vascular plant* and total *moss cover* were recorded separately as growing in separate layers, so their combined cover in a sampling quadrat could potentially exceed 100%. Vascular plant species were determined to species level when possible, using floras (Mossberg and Stenberg 2010; Krok et al. 2013), but in exceptional cases only to genus (e.g. *Taraxacum*). The percent cover of each detected vascular plant species was recorded in each sampling quadrat and mean values were calculated for each roof section. Species represented by small single specimens were assigned a minimum of 0.1% cover. All vascular plant species found outside the sampling quadrats were also recorded, during a further limited time spent searching for rare species on each roof section after scrutinizing the quadrats. The species found outside of quadrats were not assigned any percent cover values but were included in the list of species, and thus contributed to the recorded *species richness*, in each section.

Data analysis

To compare the species diversity of the roof sections, taking into account each species' relative abundance, the *Shannon diversity index* was calculated, in Excel, using the formula $H' = -\sum_{i=1}^{k} p_i \ln p_i$, where p_i is the percent cover of the ith species and k is the number of species. Partial Least Squares (PLS) analysis, implemented in SIMCA version 14 (Sartorius Stedim Data Analytics AB 2018) with unit variance scaling, was applied to explore relationships between *vascular plant cover*, *species richness* and other variables. The relationships indicated by PLS analysis were checked by Generalized Linear Models (GLMs) implemented in R, and differences between groups based on geographical location and *aspect* were analyzed with the Wilcoxon signed rank test implemented in R (R Core Team 2019).

Results

Species richness and presence of the originally intended vegetation

Most of the intended species originally planted on the roofs were not detected in the survey. However, there was still high *species richness* on several roofs. Figure 1 presents numbers of absent intended, present intended and unintended vascular plant species found on each section. A full list of all species found on each roof section is presented in Supplementary Appendix A.

On the roof sections with a known intended plant composition, 24 ± 1% of the intended species were detected during the survey and several unintended species were detected (Fig. 1). Unintended species accounted for most of the *species richness* on the sections (69% on average). Most of both the intended and unintended species found had low (<4%) individual cover (Table 3; for a full species list see Supplementary Appendix). Although many intended species were not detected in the survey, the total mean *species richness* was higher at the time of the survey than the intended richness due to colonizing unintended species.

Table 2: Vegetation survey sites and roofs. In the roof section codes, the first letter, first number, second number and second letter respectively indicate the town, designated number of the building complex area, designated roof section number and its aspect. The horizontal lines separate groups of roof sections on the same building (11 buildings in total).

Roof section	Location	Survey date	Substrate type	Original plant composition	Age (years)	Roof area (m^2)	Aspect	Slope (°)	Substrate depth (mm)*
K1-1-S	Kiruna	10/08/2016	Scoria-based	Sedum Moss	2	38	S	6	31
K1-2-S	Kiruna	10/08/2016	Scoria-based	Meadow	2	38	S	6	96
K1-1-N	Kiruna	11/08/2016	Scoria-based	Meadow	2	38	N	6	35
K1-2-N	Kiruna	11/08/2016	Scoria-based	Sedum Moss	2	38	N	6	92
K2-1-E	Kiruna	28/7/2017	Organic turf	N/A	9	126	E	20	36
K2-1-W	Kiruna	28/7/2017	Organic turf	N/A	9	118	W	20	42
K2-2-S	Kiruna	28/7/2017	Organic turf	N/A	13	102	S	20	44
K2-2-N	Kiruna	28/7/2017	Organic turf	N/A	13	102	N	20	48
K2-3-S	Kiruna	28/7/2017	Organic turf	N/A	13	102	S	20	49
K2-3-N	Kiruna	28/7/2017	Organic turf	N/A	13	102	N	20	51
K2-4-E	Kiruna	28/7/2017	Organic turf	N/A	13	102	E	20	52
K2-4-E	Kiruna	28/7/2017	Organic turf	N/A	13	102	W	20	53
L1-1-S	Luleå	18/8/2016	Scoria-based	Sedum Moss	4	251	S	10	27
L1-1-N	Luleå	18/8/2016	Scoria-based	Sedum Moss	4	552	N	10	26
L1-2-N	Luleå	9/9/2016	Scoria-based	Sedum Moss	4	107	N	5	30
L2-1-S	Luleå	9/9/2016	Scoria-based	Sedum Moss	3	8	S	12	22
L3-1-W	Luleå	7/10/2016	Organic	N/A	15	152	W	12	92
U1-1-S	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	142	S	8	92
U1-3-S	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	109	S	11	77
U1-5-S	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	149	S	12	55
U1-7-S	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	124	S	18	80
U1-9-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	352	S	20	58
U1-11-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	178	S	20	62
U1-13-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	232	S	25	69
U1-15-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	160	S	12	48
U1-17-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	206	S	17	59
U1-19-S	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	164	S	12	42
U1-2-N	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	88	N	15	50
U1-4-N	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	52	N	34	53
U1-6-N	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	79	N	15	65
U1-8-N	Umeå	14/9/2016	Crushed tile	Grass Sedum	2	76	N	16	66
U1-10-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	154	N	25	62
U1-12-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	154	N	38	63
U1-14-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	130	N	15	56
U1-16-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	134	N	25	63
U1-18-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	134	N	15	62
U1-20-N	Umeå	15/9/2016	Crushed tile	Grass Sedum	2	132	N	20	77
U2-1-E	Umeå	16/9/2016	Crushed tile	Grass Sedum	2	394	E	12	70
U2-4-E	Umeå	16/9/2016	Crushed tile	Grass Sedum	2	720	E	12	86
U2-2-W	Umeå	16/9/2016	Crushed tile	Grass Sedum	2	328	W	12	93
U2-3-W	Umeå	16/9/2016	Crushed tile	Grass Sedum	2	875	W	12	92

*Substrate depth refers to the measured plant-available substrate, excluding any additional underlying layers.

Two roof sections (K1-2-S and K1-2-N; Fig. 2, upper left corner) had thicker substrate (100 mm substrate + water holding mineral wool) than the other sections, and greater original *species richness*: 42 species of grasses, forbs and *Sedum* species representing typical Swedish dry meadow vegetation (Vegtech AB 2015) (left in Fig. 1). Section L3-1-W in Luleå (middle of Fig. 1) was the oldest roof surveyed (15 years) and had a relatively thick substrate (92 mm), unknown original species composition, relatively high *species richness* (25) and *moss cover* (82%), but low total *vascular plant cover* (29%).

Most commonly found vascular plant species

While 15 stonecrop (*Sedum* and *Phedimus*) species in total were originally planted on the roofs, only two were commonly recorded in the survey (Table 3). *Sedum acre* was the most abundant species (by cover), with an average cover of 58% and presence on 93% of the roofs. The only other stonecrop among the 10 most abundant species was *S. album*, which was detected on 66% of the roof sections, but only had a mean total cover of 3%. *Sedum* and *Phedimus* species other than *S. acre* and *S. album* were either no longer present or had very low total mean cover (>0.3%). Intentionally planted grasses such as *Poa alpina* (mean cover 6.6%), *Festuca ovina* (mean cover 2.2%) and Poa compressa (mean cover 0.2%) were among the most commonly found vascular plant species as well as three other grass species: *P. glauca*, *P. Pratensis* and *P. compressa*. Two unintended flowering plants, *Sonchus arvensis* and *Geranium columbinum*, only had a mean cover of 0.3% each, but were the eighth and ninth most abundant species on the surveyed roofs. Roofs K-1-2-S and K1-2-N had substantially higher numbers of intended species (42) than

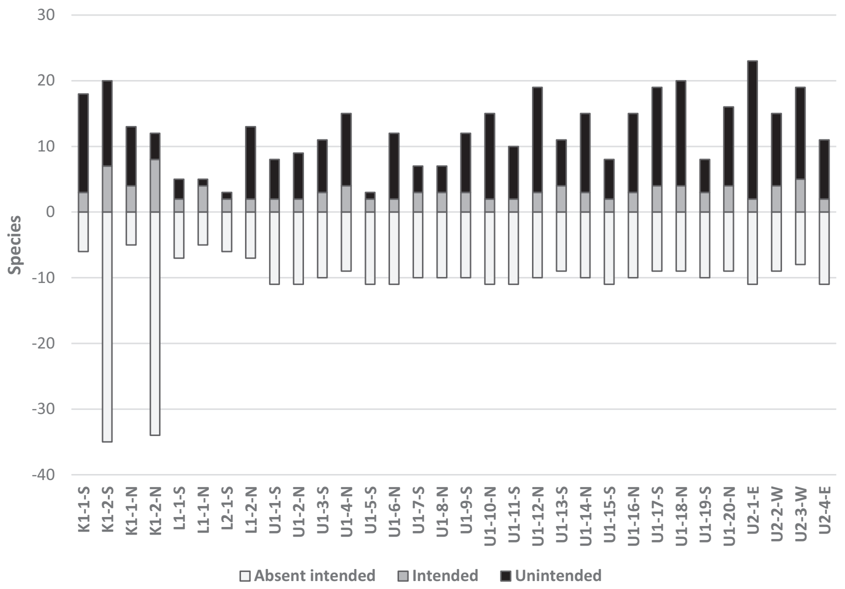

Figure 1: Bar chart showing species richness of each green roof section. Positive and negative bars, respectively, indicate the total number of species detected and number of intended species not detected during the surveys. Black bars show numbers of unintended species. Sections K2 and section L3 had an unknown intended original species composition and were excluded.

Table 3: The 10 most abundant vascular plant species (by cover) found on the roofs.

Species	Mean total cover (min, max)	Standard deviation	Coefficient of variation	No. roof sections where present (%)	Planted intentionally
Sedum acre	58.1 (0.0, 100.0)	36.4	0.6	38 (93)	yes
Poa alpine	6.6 (0.0, 60.5)	16.1	2.4	11 (27)	yes
Sedum album	3.0 (0.0, 36.0)	6.1	2.0	27 (66)	yes
Festuca ovina	2.2 (0.0, 23.7)	5.1	2.3	19 (46)	yes
Epilobium ciliatum	1.6 (0.0, 64.6)	10.1	6.3	5 (12)	no
Poa glauca	1.5 (0.0, 54.0)	8.5	5.7	2 (5)	n/a
Poa pratensis	0.4 (0.0, 8.8)	1.6	3.9	3 (7)	n/a
Sonchus arvensis	0.3 (0.0, 11.0)	1.7	4.2	4 (10)	no
Geranium columbinum	0.3 (0.0, 11.3)	1.8	6.4	1 (2)	no
Poa compressa	0.2 (0.0, 10.0)	1.6	6.4	1 (2)	yes

the others, but only seven and eight of those were detected in the survey.

Of the 10 most commonly found species, three were not planted intentionally on the roofs (*Epilobium ciliatum*, *Sonchus arvensis* and *Geranium columbinum*). Interestingly, the fifth most abundant species, *E. ciliatum*, was originally a non-native North American species. The species is common in southern Sweden but has not yet spread much to the northern parts (Mossberg and Stenberg 2010). The sum cover of all the other species (60) detected, but not included in Table 3, was only 2.3%, so most of the species that contributed to total *species richness* contributed little to total vegetation cover. In total, 93 vascular plant species were found in the survey (a full list is presented in the Supplementary Appendix). Of these, 25 were found outside the quadrats and did not contribute to the *vascular plant cover* recorded in this study.

Vegetation cover and species diversity

There was great variation in plant cover among the roof sections, as illustrated in Fig. 2. The U1 and U2 sections in Umeå and K2 sections in Kiruna had >70% *plant cover* (see Fig. 3 for examples). K1 roof sections located in Kiruna and both L1 and L3 sections in Luleå had relatively sparse *vascular plant cover* and high *moss cover*. Roof sections U1 and U2 roofs had relatively high mean *vascular plant cover* and low mean *moss cover*, but with one species dominating their plant cover (mean cover 83%). In contrast, section L1-1-S, a south-facing roof in Luleå with a thin substrate, had just 1% mean *vascular plant cover*, but substantial *moss cover* (37%) with *species richness* and *Shannon diversity index* values of 5 and 0.13, respectively.

Location and aspect

The median *vascular plant cover* at the three locations differed significantly, as shown in Fig. 4 (Wilcoxon rank sum test with pairwise comparisons, $P < 0.05$): the northernmost (Kiruna) sections had a mean cover of 63% while mid-latitude (Luleå) sections had only had 27% cover, on average, and the southernmost (Umeå) sections had the greatest mean *vascular plant cover* (89%). It should be noted that the 15-year-old section L3-1-W differs substantially from the other sections in Luleå (Fig. 4), but it is far older than the 3- and 4-year-old L1 and L2 Sedum roofs and has a thicker substrate (Table 1).

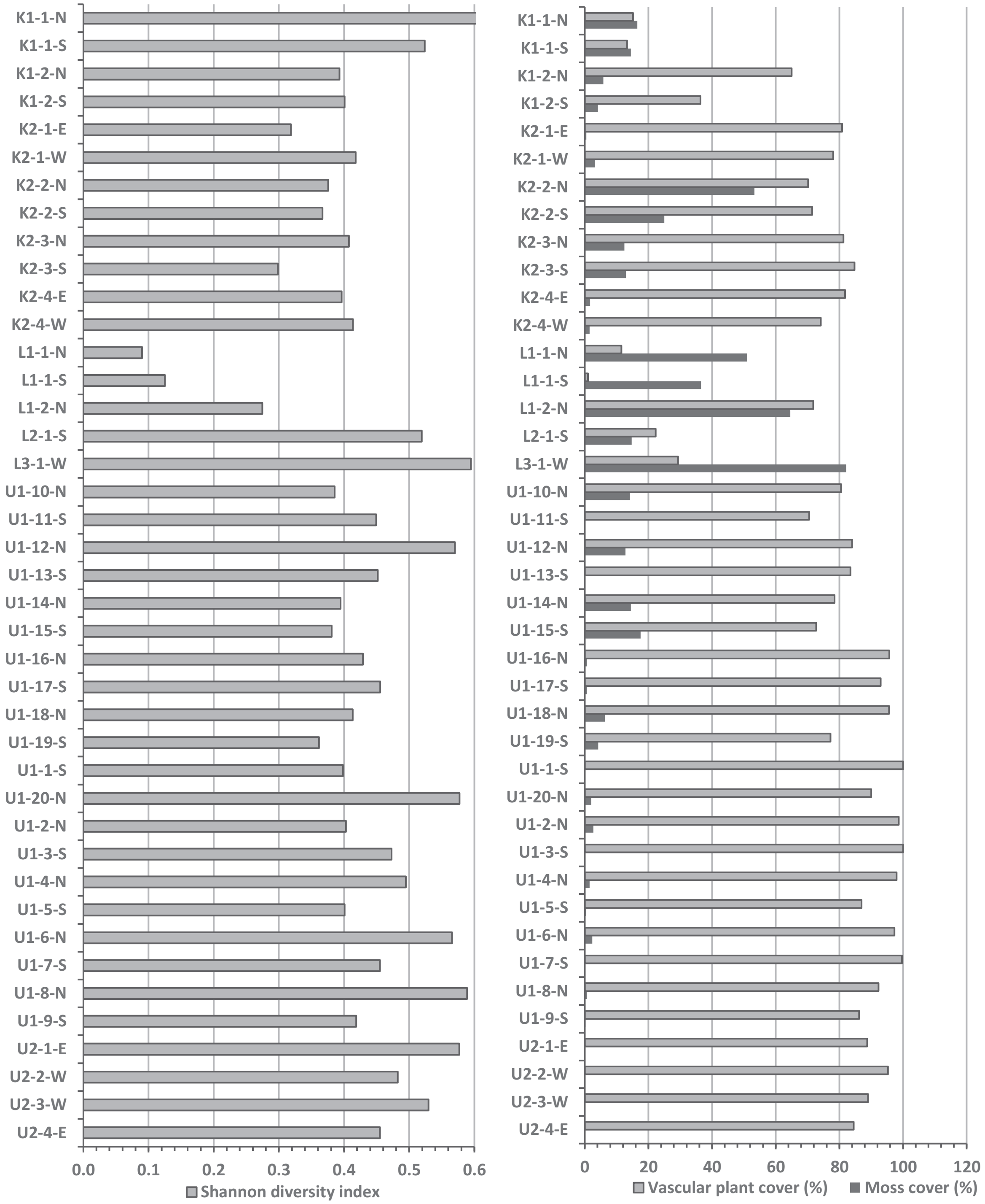

Figure 2: Bar charts of Shannon diversity index (left) and mean vascular plant cover and moss cover (right) of indicated roof sections.

The mean percentages of *intended species* detected in surveys were similar at all three locations (28, 28 and 22% for sections at Kiruna, Luleå and Umeå, respectively). Wilcoxon rank sum tests with pairwise comparisons detected no significant *exposure*-related variations in *vascular plant cover*, *moss cover*, *species richness* or *percent intended vegetation present*.

Substrate depth, diversity and vascular plant cover

Results of the PLS analysis are illustrated in Fig. 5. In the loading plot (right panel in the figure), *vascular plant cover* is located close to *substrate depth* and *slope*, indicating that it is positively correlated to these variables. *Shannon diversity index* and *moss cover* are located on opposite sides of the axis (w*c[1], Fig. 5) of the first PLS component, indicating a strong negative correlation with *vascular plant cover*. The variables *age*, *roof area* and *species richness* are all close to the middle of the loading plot, indicating that they have weaker influence on *vascular plant cover*. The results presented in Fig. 6 indicate that *species richness* is not related either positively or negatively to *vascular plant cover* on the surveyed roofs, and this was confirmed by a

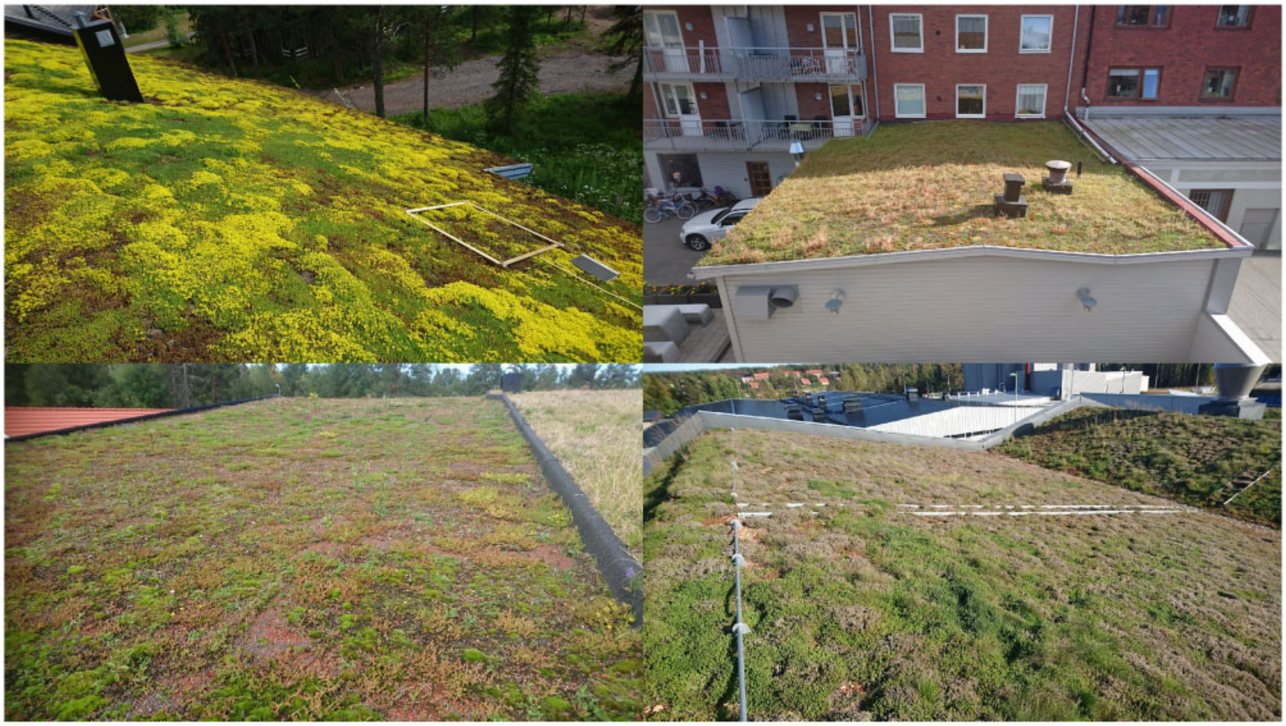

Figure 3: Illustrative images of roof sections included in the study. Upper left: section K2-3-S in the northernmost location, Kiruna; part of a relatively old (13 years) south-facing roof dominated by a single species (*S. acre*), leading to nearly 100% vascular plant cover, but a relatively low Shannon diversity index. Upper right: shaded north-facing section L1-2-N with relatively high vascular plant cover and high species diversity. Lower left: section K1-1-S, with low cover but high species diversity index. Lower right: section U1-5-S in the southernmost location, with high vascular plant cover dominated by *S. acre*, and a relatively low diversity index.

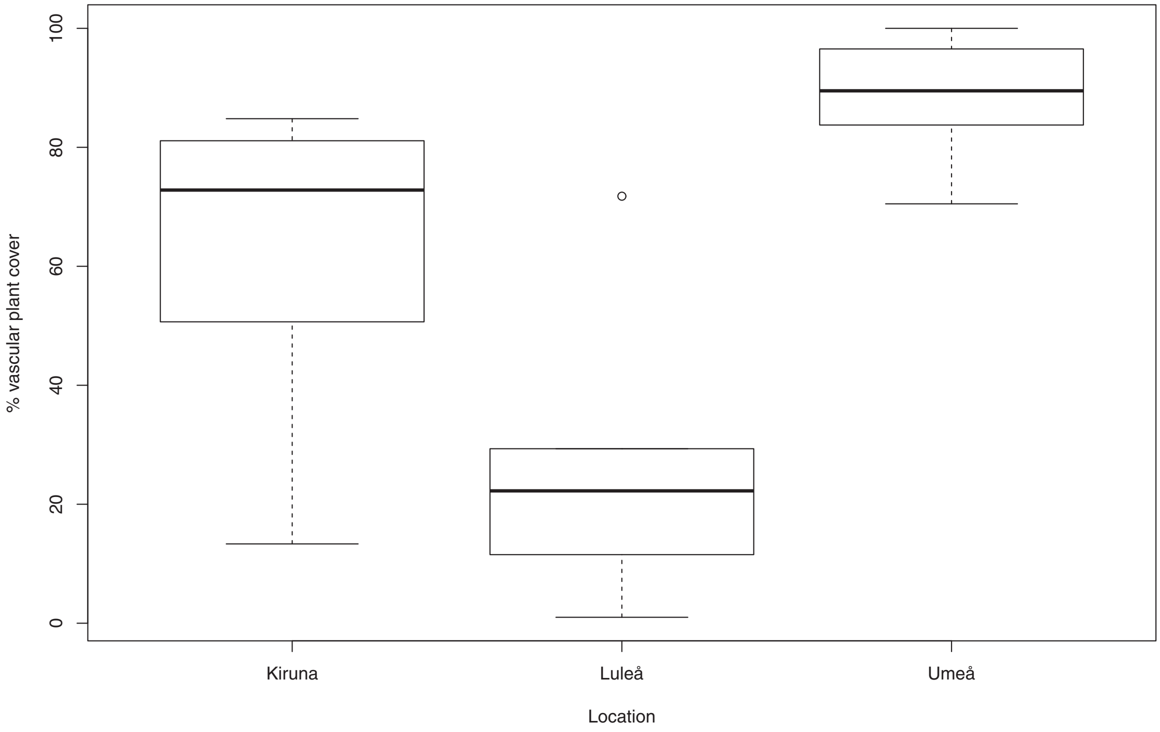

Figure 4: Boxplot of vascular plant cover at the three locations, which had significantly different medians (pairwise Wilcoxon test, $P < 0.05$).

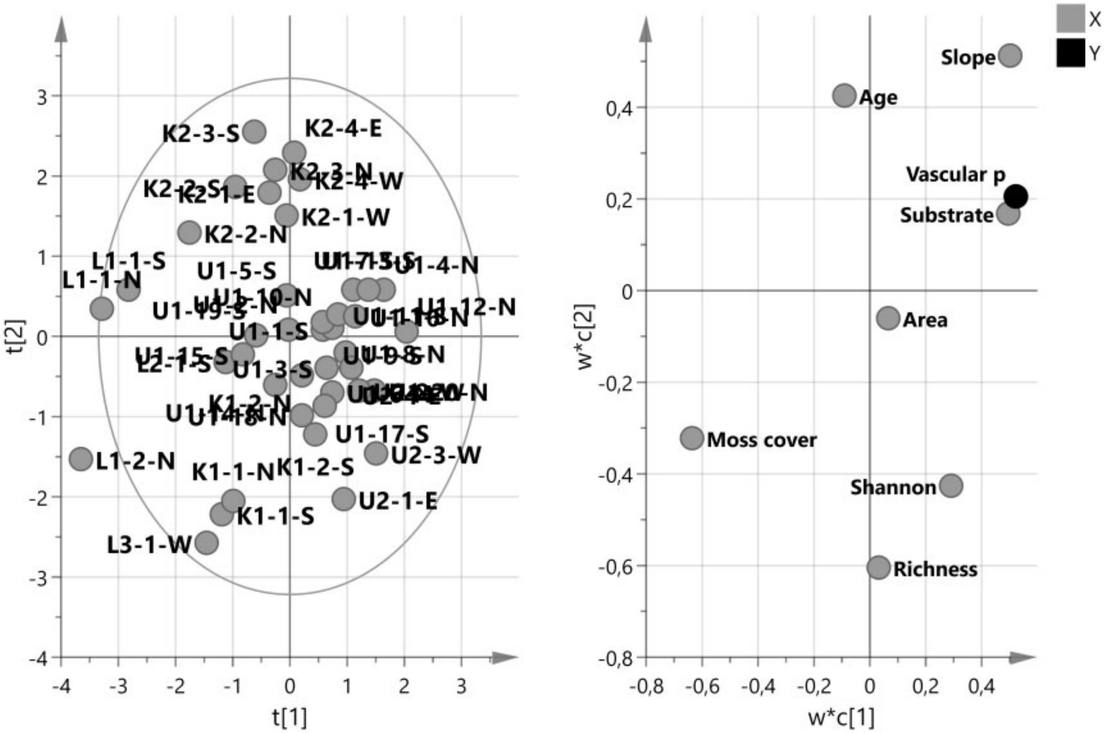

Figure 5: Score (left) and loading (right) plots obtained from PLS analysis with vascular plant cover set as the response variable. Most of the variation in vascular plant cover is explained by the first component on the y-axis: R2Y = 0.46 and Q2 = 0.27. Second component added R2Y (cumulated) = 0.52 and Q2(cumulated) = 0.23. Score plot shows Hotelling's ellipse for 95% confidence. Vascular p = the total vascular plant cover, Shannon = Shannon Diversity Index, Richness = species richness, and Substrate = substrate depth of the roof sections.

Pearson correlation test ($r = 0.01$, $P = 0.97$). However, it indicates that Shannon diversity index and *substrate depth* both have a strong positive relationship with *species richness*. *Age* is located the furthest away from *species richness* in the plot, indicating a strong negative correlation between these variables.

Variables affecting vascular plant cover and species richness

The PLS analysis provided an overview of variables that are apparently correlated with *vascular plant cover* on the surveyed roofs (Fig. 5). To test the significance of their relationships, a GLM with a quasibinomial family and logit link function was applied with *vascular plant cover* as dependent variable and *substrate depth*, *moss cover*, *roof area* and *species richness* as independent variables. The resulting model confirmed the positive relationship between *vascular plant cover* and *substrate depth*, as well as the negative relationship between *vascular plant cover* and *moss cover*. In contrast, *roof area* and *species richness* had no significant effect on *vascular plant cover* (Table 4).

To explore which variables affect the vascular plant *species richness* on the roofs, a GLM with Poisson family and log link function was applied with *species richness* set as the response variable. The results indicate that *substrate depth* and *moss cover* have significant positive effects, *age* has a significant negative effect, and *roof area* no significant effect on *species richness* on the roofs (Table 5).

Discussion

Vascular plant species richness, survival and composition

Between 1 and 25 species were detected on the roof sections. Numbers recorded in previous studies (with varying surveying effort and roof characteristics) have also varied substantially: 9–32 in Germany (Thuring and Dunnett 2014), 9–161 in Hong Kong, China (Deng and Jim 2017), 16 in Lleida, Spain (Bevilacqua et al. 2015), 50 in Sheffield, UK (Dunnett et al. 2008) and 47 in Birmingham, UK (Olly et al. 2011). The high proportions of originally planted species that were not detected in the survey (white bars in Fig. 2) indicate that plants have high mortality rates on roofs included in our study. This may be because many of the species planted on the roofs are native to different climate zones (especially at the northernmost location, Kiruna) and cannot successfully adapt to the low temperatures and short vegetation season. However, similar results have also been recorded in regions with temperate climates, e.g. in Germany, where observations spanning more than 30 years showed that sown species gradually gave way to new colonizing species (Catalano et al. 2016). In another German study, less than half of the originally intended species persisted after 20 years (Thuring and Dunnett 2019). During a more short-term, 5-year experiment, all planted species survived on herb and grass-roof modules in Sheffield, UK (Dunnett et al. 2008). In contrast, in northern Sweden, 76% of the originally intended species were not detected, although most of the roofs were significantly younger than in the cited studies. It should be noted that in such surveys both originally intended and unintended species may be missed if they are only present as propagules in the substrate, waiting to reemerge when conditions become favorable (Vanstockem et al. 2018a). Some of the unintended species found on the K1 roofs in the northernmost location (*Vicia hirsuta*, *Satureja acinos* and *Fumaria officinalis*) are very rare or absent in the surrounding region (Mossberg and Stenberg 2010), but common in southern Sweden, where the suppliers of green roofs are based. This implies that some of the unintended species did not spread to the roofs naturally

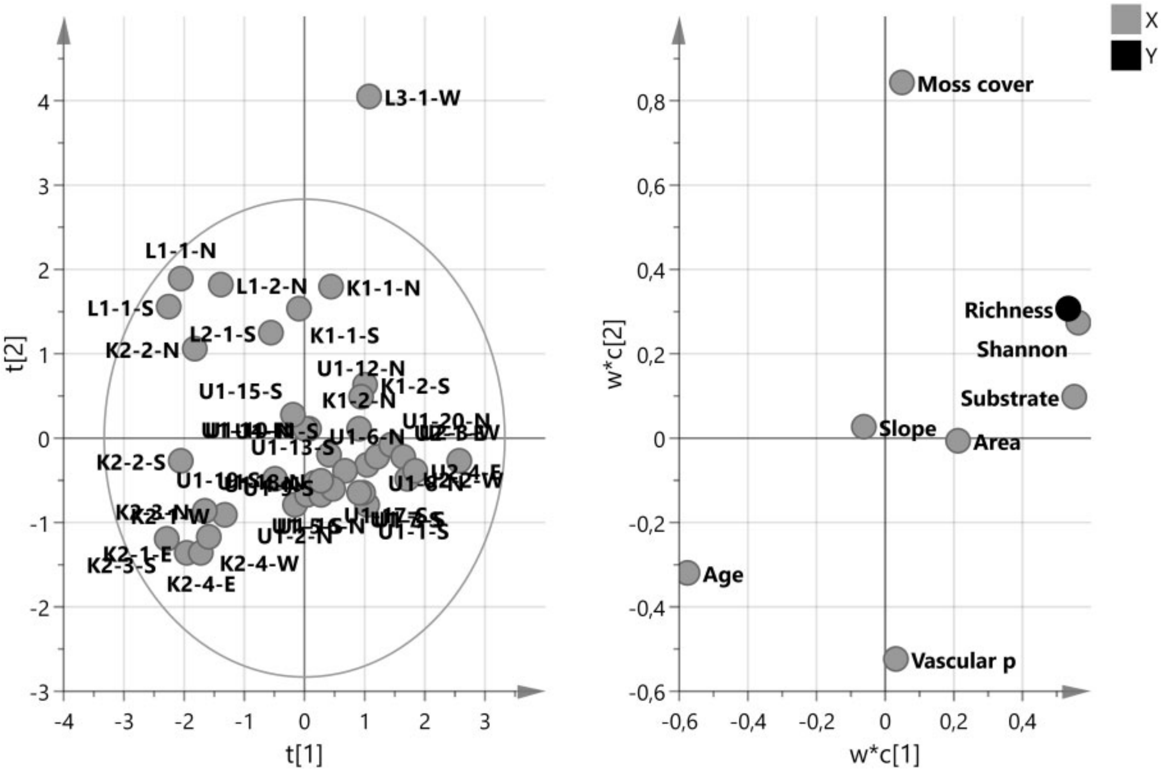

Figure 6: Score (left) and loading (right) plots obtained from PLS analysis with species richness set as the response variable. Most of the variation in richness is explained by the first component on the y-axis where R2Y = 0.48 and Q2 = 0.31. Second component on the x-axis added R2Y (cumulated) 0.59 and Q2 (cumulated) 0.31. Score plot (left) shows Hotelling's ellipse for 95% confidence. Vascular p = total vascular plant cover. Shannon = Shannon Diversity Index, and Substrate = substrate thickness of the roof sections.

Table 4: Summary of the Generalized Linear Model (GLM) with quasi-binomial family and link logit function, with vascular plant cover set as response.

Coefficients	Estimate	Std. error	T value	P value
Intercept	0.06	0.69	0.09	0.93
Substrate depth	0.06	0.01	2.36	**0.02**
Moss cover	−0.03	0.01	−2.77	**0.01**
Roof area	−0.00	0.00	−0.08	0.94
Richness	−0.04	0.04	−1.00	0.32

Significant *P*-values indicated in bold.

Table 5: Summary of Generalized Linear Model (GLM) with Poisson family and link log function, with species richness set as response.

Coefficients	Estimate	Std. error	z-value	*P* value
Intercept	1.90	0.17	11.07	**>0.00**
Age	−0.12	0.02	−5.99	**>0.00**
Substrate depth	0.01	0.00	5.34	**>0.00**
Moss cover	0.01	0.00	4.94	**>0.00**
Roof area	−0.00	0.00	−0.151	0.88

Significant *P*-values indicated in bold.

through wind or animals, but were introduced together with the substrate or seed mix from the suppliers.

Location

The northernmost roofs (K1 and K2) are exposed to the longest and coldest winters (Table 1). Nevertheless, although their *vascular plant cover* was highly variable, it was higher on average than on roofs in Luleå (L1, L2 and L3), where the climate is milder. Consequently, there was no clear relationship between annual mean temperature and *vascular plant cover* (Fig. 4). Roofs in the southernmost location, Umeå, had high *vascular plant cover*, probably partly due to the milder climate. However, they also had significantly thicker substrate (mean 67 mm) than the roofs in Luleå and Kiruna (40 and 52 mm, respectively). The relatively low *age* and possible fertilization after construction may also have contributed to the high vascular plant cover of roofs in Umeå.

Aspect and slope

A roof's exposure to sunlight, and thus the amount of light available to plants on it for photosynthesis, strongly depends on its *aspect* and *slope*. In a cold climate with long winters and short growing seasons, a southerly *aspect* can extend the snow-free period and increase the length of the growing season. Further, with increases in exposure to sun, the temperatures and thus evapotranspiration rates increase. Roofs facing south might retain more rainfall through increased sun exposure and evaporation, but this could also make them more prone to drought than roofs facing north. If water is a factor limiting plant growth, south-facing roofs may dry out faster than others, thereby favoring drought-tolerant species and reducing the number of species that can survive on them. Köhler and Poll (2010) found a negative correlation between vegetation coverage and sun exposure in a study of the long-term development of green roof vegetation in Berlin, Germany. The canopy height of vegetation was not measured in the present study, but visual inspection at all three locations indicated that tall herbaceous species were more abundant on north-facing roofs than south-facing roofs. However, no significant relationship between aspect and either *vascular plant cover* or *species richness* was found. Theoretically, the *slope* of green roofs could be negatively correlated with *vascular plant cover* due to its negative correlation with water storage of the substrate (Köhler and Poll 2010) and positive correlation with risks of erosion by wind, rain and snow (FLL 2008). However, Köhler (2006) found no significant difference in species richness between flat and sloped extensive green roofs they examined in Germany, although erosion caused a need for revegetation on some steeply sloped roofs. In contrast, results of the PLS analysis presented in Fig. 5 indicate that *slope* was positively correlated with *vascular plant cover* on the roofs surveyed in this study. Some U1 sections in the southernmost location (Table 1) had a steep pitch (up to 38°), but most had high *vascular plant cover*. These roofs were dominated by a few species that formed dense cover, particularly of *S. acre*. The roofs were steep but not very wide along the slope (3–10 m wide), which might have helped reduce risks of rain or snow sliding off their steep slopes causing erosion. It should be noted that roofs with the greatest variation in slope had unconventional construction, so the correlation between slope and *vascular plant cover* might not hold for other steep roofs with different construction.

Roof area

According to island biogeography, the size of any kind of island affects its species richness since large islands provide more diverse habitats and can support larger populations, that are less prone to extinction, than small islands (McArthur and Wilson 1967). Green roofs can be viewed as isolated vegetated islands in a sea of impervious urban surfaces, where surrounding urban green spaces (parks, gardens, agricultural areas etc.) provide species pools that colonizers can spread from (Blaustein et al. 2016). The relationship between the diversity of arthropods on green roofs and their isolation has been examined in several studies. It has found to be non-significant in some cases, and consistent with island biogeography theory in others, but no relationship between these variables contrary to expectations based on the theory have been reported (Blank et al. 2017). Similarly, it has been hypothesized that green roofs' size may be important for their plant abundance and diversity (Gabrych et al. 2016). Although humans dictate the intended plant composition on green roofs, high proportions of species present may be members of unintended species (Catalano et al. 2016). These species' ability to immigrate, survive and reproduce may depend on the roofs' size and isolation. Thus, *species richness* and *vascular plant cover* could theoretically be higher on larger roofs. Accordingly, Köhler (2006) found a slight correlation between species richness and roof area, but it was below the significance threshold ($r^2 = 0.67$). Moreover, the most species-rich roof in the cited study was a flat, 160 m^2 lichen-dominated flat roof, which hosted many annual species, and there was high inter-annual variation in species richness, mainly attributed to variation in moisture availability. Thus, other variables related to roofs' location and construction are probably more important and could obscure any effect of roof size. In this study, no significant relationship was detected between roof *area* and either *vascular plant cover* (GLM, $P = 0.94$) or *species richness* (GLM, $P = 0.32$).

Moss cover

Moss co-existed with vascular plants on the roofs. However, the roofs with the highest *moss cover* had sparse *vascular plant cover*, resulting in a significant negative relationship between these variables. Functions of mosses on green roofs have received little attention, relative to those of vascular plants, although they may provide better stormwater retention than vascular plants and several other potential benefits, such as nitrogen and carbon sequestration (Anderson et al. 2010). Moreover, mosses can survive in harsh environments and can both cool the substrate and bind water, but they have also been found to inhibit the germination of vascular plants (Drake et al. 2018). This might prevent vascular plants from recolonizing a roof after passing their permanent wilting points during drought periods, leading to lower *vascular plant cover*, as seen in this study. Thus, further research on mosses' performance in terms of ecosystem services is encouraged.

Substrate depth

The water storage capacity of a green roof generally increases with increases in *substrate depth* (VanWoert et al. 2005b). On non-irrigated roofs, thicker substrates need longer time to exhaust the plant available water between rain events compared to a thinner substrates. Thus, plants reach their permanent wilting points less frequently, and plant *survival rates* are generally higher, on thicker substrates (Thuring et al. 2010). Accordingly, Durhman et al. (2007) found that survival and growth rates of nearly all of 25 succulent species tested in Michigan, USA, were higher on thick substrates, and Gabrych et al. (2016) found corresponding relationships in southern Finland. Similarly, in the survey presented here, a significant positive relationship was found between *substrate depth* and *vascular plant cover*. Madre *et al.* (2014) also investigated colonizing plants on green roofs in northern France, and effects of *substrate depth*, height, surface, *age*, maintenance and proximity to surrounding natural habitats on the Shannon diversity index of the vegetation. The only variable found to have a significant positive effect on the *Shannon diversity index* was *substrate depth*. However, no such relationship was detected in the survey presented here. Instead *substrate depth* was positively correlated with *species richness*. These results emphasize the importance of *substrate depth* not only for the water storage capacity and *vascular plant cover* but also for sustaining biodiversity on roofs.

Age

As green roofs age, the species composition changes and heterogeneity of the substrate may also change (Köhler and Poll 2010; Thuring and Dunnett 2014; Catalano et al. 2016). Risks of long drought events exceeding the plants' permanent wilting points inevitably increase with time, possibly leading to sparser cover and even extinction of the intended species. In a study of green roof development over 20 years, Köhler (2006) initially observed unintended species (brought in as propagules in the substrate at planting), but they declined in the years following establishment. After this initial decline, species richness varied from year to year with no apparent trend linked to age. Conversely, possibilities of colonization by new species, which could potentially restore both plant cover and diversity, gradually increased. By providing more microhabitats, this could lead to higher *species richness* and *Shannon diversity* on old roofs than on younger roofs, but no such relationships were observed in this study. Instead, on the roofs considered here, *age* had no significant effect on *vascular plant cover* and a negative relationship with *species richness* (Table 5). This was probably due to increases in mortality of both intended and unintended species as nutrient availability and the propagule bank in the original substrate declined.

Practical implications

The original plant species composition on the evaluated roofs in Northern Sweden was the same as in material commercially supplied to southern parts of Scandinavia and Central Europe. Thus, there is no consideration of local ambient conditions and associated challenges, despite their harshness. This approach fails to properly mimic the adaptability and resilience of natural ecosystems, often leading to sub-optimal plant development and associated functionality. Hardier green roof vegetation is needed in harsh environments, with original composition that is not necessarily highly diverse if high vegetation cover is a priority, However, if high diversity is requested, spontaneous colonisation of roofs should be encouraged since unintended colonising species will provide most of the species diversity in the long run.

Conclusion

Clearly, there is a need to extend knowledge of the main factors influencing green roof vegetation performance, particularly in non-temperate climates. Thus, this field survey focused on vegetation on 41 extensive green roofs located in three locations with subarctic and continental climates. In accordance with a first hypothesis, on average 76 ± 1% of the intended planted vascular plant species were absent by the time of the survey. Various other unintended species had appeared, and strongly contributed to the *species richness* on the roofs. However, these species contributed much less to the total plant cover than the surviving originally planted species. This highlights a need to use better adapted species to improve survival and cover in demanding climates. Moreover, spontaneous colonization of green roofs should not necessarily be discouraged, as it may contribute significantly to species diversity. Contrary to a second hypothesis, *species richness* was not positively related to *vegetation cover*. In accordance with previous studies and a third hypothesis, *substrate depth* was positively correlated with both *vascular plant cover* and *species richness*. In the cold environments of roofs examined in this study, the originally intended vegetation was highly important for the vegetation cover, but most of the species found (69 ± 3%) were colonizing unintended species. This should be noted when installing green roofs, as it has profound implications for the main objectives (e.g. promotion of urban biodiversity, aesthetic appeal and/or stormwater management), which should preferably be considered by stakeholders from the start.

Supplementary data

Supplementary data are available at *JUECOL* online.

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Conflict of interest statement

None declared.

Data availability

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.bvq83bk4w.

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