Evaluation of an extensive green roof design after 3 years - effect of substrate depth and habitat elements on growth and diversity of vegetation communities

Scientific thesis for attaining the degree M.Sc. of Biology at the University of Regensburg

First Supervisor:	PD Dr. Sebastian T. Meyer Technical University of Munich Chair of Terrestrial Ecology Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising
Second Supervisor:	Prof. Dr. Florian Hartig University of Regensburg Theoretical Ecology Faculty of Biology and Pre-Clinical Medicine Universitätsstraße 31, 93053 Regensburg
Author:	Pia Schumann Niedermayerstraße 5, 81679 München Matricle number: 2139328 Degree program: Biology (M.Sc.) at the University of Regensburg

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Abstract

The relatively isolated, fragmented and unique microclimatic characteristics of rooftops make green roofs potential habitats for biodiverse communities. There is limited knowledge on the effect of green roof characteristics on the development of the rooftop vegetation, however substrate depth has found to be a determining factor for the vegetation composition. In this study I investigated the effects of varying substrate depths and the installation of structural elements on vegetation growth, development and diversity. Within a three years study, an experiment was set up on three neighbouring rooftops with homogenous and heterogenous plots which were initially sown with different seed mixtures and installed with different structural elements. Surveying the vegetation three times during 2022 I found that substrate depth had the strongest impact on the vegetation. Deeper substrate has a higher water storage capacity and retention time and less temperature fluctuations, which is an important factor for the establishment of flora on green roofs with its extreme climatic conditions. Vegetation cover was significantly higher on homogenous plots, and there was a tendency of cover values to be higher on homogenous plots, and species richness and diversity to be higher on heterogenous plots. Cover values were higher on subplots with sand, soil (control) and refuges due to their greater surface area. Plant height, species richness and biodiversity had higher values on subplots with stones and deadwood which are able to retain water and provide protection from high temperature, high solar radiation and wind. More than 60% of the flora consisted of spontaneous vegetation. Compared to the vegetation of 2020, the plots showed an increased number of *Sedum*, grass and herbaceous species. Cover values on plots sown with a typical seed mixture for green roofs consisted roughly of two thirds of meadow species (9% grass and 55 % herbs) and one third of *Sedum* species; roughly 92% of the vegetation cover of plots sown with seeds of heathland species were meadow species (18% grass and 74% herbs) and 8% were *Sedum* species. Plant cover values on plots of the green roof seed mixture were higher in 2022; on heathland plots cover values of *Sedum* decreased, and cover values of herbs increased. Blooming cover was highest in early summer and relatively low throughout the remaining season. The plots of different seed mixtures were rather homogenous regarding their flora on a plot level and represented different vegetation communities. The combination of different seed mixtures, the introduction of the habitat elements stones and deadwood, and a combination of different substrate depths are important elements for increasing floral diversity on green roofs. In conclusion, green roofs - when designed carefully - represent a valid measure to establish habitats and improve biodiversity in urban ecosystems.

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1 Introduction

1.1 Chances and limitations of green roofs

In temperate ecosystems, some of the highest rates of floral biodiversity and endemism occur in calcareous grasslands (Willems 1990; Poschlod & Jackel 1993) and in relatively unproductive habitats such as rock pavements and scree slopes (Larson et al. 2000). Small isolated and fragmented green spaces have found to hold high biodiversity rates in cities (Fuller and Gaston 2009). The relatively isolated, fragmented and unique microclimatic characteristics of rooftops as well as the presence of shallow substrate and gravel make green roofs - when designed carefully - potential habitats for biodiverse communities (Fuller and Gaston 2009; Bates et al. 2013; Gabrych et al. 2016; Ives et al. 2016).

Additional to their role as important urban habitats green roofs have a number of additional environmental advantages. For example, green roofs can lower the temperature inside and around the building by a few degrees. A study measured green roof maximum surface temperatures on average 6°C higher in the winter and more than 19°C lower in the summer (DeNardo et al. 2005). Another positive effect of green roofs is their water storage capacity. Some of the rainwater is being retained and stored in the substrate and the drainage layer, and then partly absorbed by the plants. The remaining water evaporates back into the air, returning to the water cycle. This effect mitigates the overloading of the sewer system, thus reduces flooding, and improves the urban climate (Brune, Bender, Groth 2017; Berardi et al. 2014; Uhl and Schiedt 2008). Other positive effects of green roofs are the reduction of air pollution and the enhancement of air quality through the plants ability to sequester carbon dioxide, produce oxygen and absorb dust and smog (Li and Babcock 2014; Berardi et al. 2014).

Rooftop conditions are challenging for plant growth and survival and require physiological adaptations. Elevated temperatures and temperature fluctuations, high solar radiation, moisture stress and high wind speeds cause drought and substrate damage (Dunnett and Kingsbury 2010; Oberndorfer et al. 2007). Plant species that are adapted to these conditions are characterized by stress-tolerant qualities including compact growth, evergreen or succulent foliage and CAM (crassulacean acid metabolism) physiology (Grime 2002). These high stressors for rooftop vegetation also favour some ruderal plant species that occupy gaps (Grime 2002). Green roof plant communities are dynamic and likely to change from the original composition with time (Köhler 2006). A study in Michigan found that most of the local herbaceous species planted as plugs on the green roof did not survive after three years, whereas all *Sedum* species persisted (Monterusso et al. 2005). Gabrych et al. (2016) found young green roofs in Helsinki to favour *Sedum* and moss species, and old green roofs to favour meadow species (grasses and herbs). For green roof design it is important to reinvestigate if these trends can be observed with the central European flora (and seed mixture) and in the climatic region of Bavaria.

1.2 Basic structure of green roofs

The basic construction of green roofs consists of a root protection foil at the bottom, which is intended to protect the roof from root damages, followed by a storage fleece layer and a drainage. The two latter layers absorb and store a limited amount of water and slowly release it over time. A layer of filter fleece and a substrate layer complete the construction. The substrate on green roofs has been compounded to have a small weight and an increased water storage capacity. It contains a blend of mineral components (e.g. expanded slate, lava rock) and small amounts of organic material. Development of green roof technology has generated two main types of green roofs, extensive and intensive green roofs. Extensive green roofs are highly functional in purpose and are characterized by shallow substrate (up to 20cm), hardy, drought-tolerant vegetation and require lower maintenance than intensive green roofs which have deeper substrate and elaborated vegetation. As extensive green roofs are more lightweight and cheaper than intensive green roofs and are primarily built as a way to promote biodiversity, this study focuses on extensive green roofs only.

1.3 Green roof design

There is limited knowledge on the effect of green roof characteristics on the development of the vegetation, however substrate depth has found to be a determining factor for the vegetation composition. Due to its water retentive qualities deeper substrate facilitates plant (overwintering) survival (Dunnett and Kingsbury 2010; Dunnett et al. 2008) and favours floral diversity (Madre et al. 2014; Vandegrift et al. 2019; Köhler and Poll 2010; Oberndorfer et al. 2007; Dunnett et al. 2008). Also species abundances, plant height and flower performance was found to be higher on deeper substrate on green roofs in the UK (Dunnett et al. 2008). Again, reinvestigation with the local flora of Bavaria is important for green roof designs. The harsh climatic conditions on extensive green roofs suggest the need of water retention and protection from high solar radiation and strong winds. Gravel stones as well as deadwood can hold water (Klamerus-Iwan et al. 2020; Mandal et al. 2005) and could therefore be suitable elements for green roof designs. Introducing habitat features such as stones and deadwood generating microhabitats have found to increase floral diversity (Chapin et al. 2011). However, this has not been tested on green roofs. Typical components of green roof substrate include sand (30%), lava rock and expanded shale, clay and slate. Due to its unique qualities – sturdy anchorage, low water retention and negligible nutrient source (Dunnett and Kingsbury 2010; Bunt 1988; Handreck and Black 2005) – sand could increase floral diversity when introduced purely and aside other substrate types and habitat elements. Varying substrate depth on green roofs has found to favour the development of different plant species (Coffman and Blackson 2020; Brenneisen 2006; Heim and Lundholm 2014). However, the positive effect of substrate heterogeneity on floral diversity and vegetation cover on green roofs has not been confirmed. Other important aspects of green roof design are the persistance and blossoming periods of occuring plant species. Benvenuti (2014) found a constant blooming cover due to the combination of early, spring, summer and late flowering species. For this experiment a seed mixture with herbaceous perennials and Sedum shoots, suitable for roof greening, was chosen.

1.4 Hypotheses

To establish green roofs on a large scale, rooftop conditions and seed mixtures need to be optimized so that the vegetation can establish itself permanently, attract pollinators and provide habitat for local flora and fauna. The intention of this study is to examine the development of wild and sown plant species in relation to the variables substrate depth, grade of heterogeneity and presence of habitat elements on extensive green roofs over the course of summer. Furthermore, vegetation communities of different seed mixtures and survey dates will be compared, and the vegetation will be compared to the vegetation investigated in 2020. The potential benefit of green roofs for pollinators will be investigated through examination of flowering periods and flower performance.

Based on the results of previous studies I hypothesize that:

1. Deeper substrate (15 cm) and the presence of habitat elements have a positive effect on vegetation cover, plant height and floral diversity.
2. Heterogenous plots have a higher floral diversity than homogenous plots.
3. Cover and richness of herbaceous and grass species have increased after two years.
4. The overall blooming cover does not change significantly within the summer season.

2 Material and methods

2.1 Experimental set-up

The experiment was set up within the project "Animal Aided Design Brantstraße", which is a collaboration between the start-up company "Animal Aided Design" (AAD), the Institute of Terrestrial Ecology (Technical University of Munich), and the "GEWOFAG", one of the largest housing associations of Munich. Constructional densification - as it was the case in the complex of Brantstraße (80687 Munich) - causes habitat loss for floral and faunal species. The project was initiated to create compensatory areas for flora and fauna in an urban context. The experimental set-up consists of a total of 75 plots that were built on the roof tops of three neighbouring houses in the complex of Brantstraße in 2019, 23 plots on the west roof, 26 plots on the middle roof, and 26 plots on the east roof. Plots measure a length of 2.5 meters and a width of 1.5 meters and are divided into three subplots, A, B and C. Subplot A and C are each 1m long and 1.5m wide, Subplot B is 0.5m long and 1.5m wide. For this experiment 10 plots per roof were set up as homogenous with a continuous substrate depth of 10cm on all three subplots, and 10 plots as heterogenous. The substrate of heterogeneous plots measures a height of 15cm on a randomly selected subplot (A or C) and 5cm on the respective other subplot (C or A). Subplots B on both the homogeneous and heterogeneous plots always have a substrate depth of 10cm and were installed with various structural elements:

Table 1: Structural elements

Deadwood	deadwood log (*Acer platanoides*), measuring approx. 80 x 25 cm
Stones	Jurassic limestones piled on an area of 20 x 80 cm
Refuges	inverted plant coasters embedded in the substrate
Sand	sand replacing the substrate
Control	no element installed

Each type of structural element was placed on four plots per roof, two homogenous and two heterogenous plots (Fig. 1, 2). A standard seed mixture (*Optigruen*, see Appendix 8) for green roofs consisting of 30 perennial plant species as well as shoots of various sedum species were sown on 60 plots in late fall 2019 after having removed spontaneous vegetation. These 60 plots are referred to as "Optigruen plots" in the following.

There was an additional seeding experiment established on three (roof West) and six plots (roof East, Middle) per roof respectively. These plots are homogenous, without habitat elements, and were sown with thrashed biomass of two different heathlands, Garchinger Heide and Allacher Heide, or with a special seed mixture consisting of heathland species (*Krimmer*, see Appendix 9), two plots per roof for each seeding type (one plot per seeding type on roof West) (Fig. 1). These 15 plots are referred to as "heathland plots" in the following.

Figure 1: Ground plan of the plots installed with habitat elements (stones, deadwood, sand, refuges, soil=control) and plots of the seed experiment (=heathland plots) on roof East, Middle and West (source: AAD Brantstraße)

Figure 2: Experimental design of homogenous plots and heterogenous plots; treatments: control, deadwood, refuges, stones, sand. Illustration of the roof design (above), schematic design (below; source: AAD Brantstraße).

2.2 Vegetation survey

To investigate seasonal changes of phenology, height and composition of the existing flora on the plots, I examined the vegetation in three rounds between June and October 2022. The survey took three to four days per roof, and the dates were chosen as close to each other as possible. Vegetation cover and the cover of moss and bare ground per subplot were estimated. Plant species were identified using books (Schmeil et al. 2011; Spohn et al. 2021) and the smartphone applications *Flora Incognita* (Mäder et al. 2021) and *PlantNet* (Affouard et al. 2023). Of species that could not be identified on first sight, I took samples and photographs for later identification. To examine the development of each plant species on the plots, the mean height of individuals excluding seedlings, as well as their phenology status were recorded. The phenological categories are vegetative, blooming, seed producing, seed dispersing and after seed dispersing (Tab. 2). The categories were set based on the furthest developed individual on the subplot. Seedlings as well as vegetation that died during the process of reproduction ("cover of species with dead individuals") were noted. To evaluate the benefit of the plots for pollinators, the cover of blooming individuals of each species per subplot was estimated.

Table 2: Phenology states

1	vegetative
2	blooming
3	seed producing
4	seed dispersing
5	after seed dispersing

2.3 Statistical analysis

Aim of the statistical analysis is to test whether the installation of different substrate depths, the introduction of structural elements and the grade of plot heterogeneity have significant effects on vegetation development, growth and diversity, and which treatments have the highest values. Furthermore, I want to test for vegetation (dis)similarity between the treatments to draw conclusions about the treatment effects on species composition.

Plots which were treated with thrashed biomass of heathlands were analysed separately. The variables substrate depth and structural elements were tested on a subplot level, the variable grade of heterogeneity on a plot level. I recorded all parameters for each species separately and aggregated them on a plot or subplot level, respectively. The estimate of the cover of individual species when summed up did not equal the estimate of the plot vegetation cover, and so I standardized the species cover based on the vegetation cover estimate using the following formula:

*standardized species cover [%] = species cover [%] * vegetation cover [%] / sum of species cover [%]*

With the following formula I converted the blooming estimate of individual plant species to an overall blooming cover per subplot:

*blooming cover [%] = species cover [%] * blooming individuals [%] / 100*

For the visualisation of seasonal patterns of blooming quantity, I plotted the values of blooming cover on a plot level against roof and round. For the analysis of the cover of seedlings, I calculated the mean cover value of species of which there were seedlings present on the subplot. Consequently, cover of species with seedlings includes not only seedlings but also mature plants. The same approach was taken for the analysis of the cover of species with dead individuals. This implies that the cover of species with dead individuals includes dead and thriving individuals of the same species. For an authentic mean value, I calculated the community weighted mean value of plant height and phenology status with *group_by* and *summarise* in the package *dplyr* (Wickham et al. 2023). Floral biodiversity indices, i.e. Shannon-index and Simpson-index (Simpson 1949), I calculated using the function *diversity* in the package *vegan* (V.2.6.4) (Oksanen et al. 2009). For the analysis on a plot level, I standardized the cover of blooming vegetation to the respective surface area of the subplot before summing up on plot level. The same method was applied for the analysis of vegetation cover, cover of species with seedlings and diversity indices on a plot level.

I plotted the variables mentioned above (vegetation cover, species richness, cover of blooming vegetation, cover of species with seedlings, plant height, phenology status, shannon and simpson diversity indices, cover of species with dead individuals) against the variables substrate depth, structural elements and the grade of heterogeneity for each round. The following example illustrates the procedure:

*lme (vegetation cover ~ substrate depth * round, random=~1|subplotID/round, data=D)*

To investigate potential effects of the explanatory variables, I performed linear mixed-effect models and analyses of variance (ANOVA). I analysed the variables substrate depth and structural elements on a subplot level, therefore only subplots A and C, or B respectively, are included. I transformed the cover of species with seedlings and the cover of species with dead individuals in the linear mixed-effect models with their logarithm. To test for statistical significance between the individual elements of the explanatory variables I performed Tukey's tests for post-hoc analyses.

For the comparison of the vegetation composition between the plots sown with different seed mixtures as well as between the subplots with different substrate depths, structural elements, and for the comparison of vegetation between the rounds and between 2020 and 2022, I conducted analysis with the non-metric multidimensional scaling (NMDS) in R (*metaMDS*, package *vegan*). For the analysis of vegetation dissimilarities between substrate depth and between habitat elements, only the regarding subplots were considered. For the analysis of vegetation dissimilarities between seed mixtures, I included only homogenous plots of the control group for the Optigruen plots and compared them to plots with thrashed biomass of the heathlands Allacher Heide, Garchinger Heide and the Krimmer seed mixture. Analyses of dissimilarities between the vegetation of 2020 and 2022, of both Optigruen plots and heathland plots, are based on data from previous studies (Wenzel 2021; Rester 2020). I compared the vegetation of only the first round of 2022 to the vegetation of 2020. Furthermore, I conducted analyses of similarity using the Bray-Curtis dissimilarity matrix (*anosim*, package *vegan*).

3 Results

3.1 General community composition

The recorded vegetation on all plots consisted of 92 species from 24 families. The most dominant families were Asteraceae (20) and Poaceae (17), followed by Caryophyllaceae with 12 species. On Optigruen plots 79 species of 20 families were identified. Asteraceae (20), Poaceae (12) and Caryophyllaceae (9) were the families with the most species (Appendix 1). Optigruen plot vegetation consisted of 13.9% of species originating from the Optigruen seed mixture, 12.3% of species originating from the Krimmer seed mixture or from the heathlands, 13.8% of species being on the Optigruen seed mixture list as well as on the Krimmer seed mixture list or part of the vegetation on the heathlands, and 62% of spontaneous vegetation (Appendix 1, 2). The vegetation on the heathland plots consisted of 64 species from 20 families. Again, the most dominant families were Poaceae (14 species), Asteraceae (14 species) and Caryophyllaceae (10 species) (Appendix 1). Heathland plot vegetation consisted of 10.9% of species from the Optigruen mixture, 12.5% species from the Krimmer seed mixture or from the heathlands, 14.1% of species being on the Optigruen list as well as on the Krimmer list or part of the vegetation on the heathlands, and 62.5% of spontaneous vegetation (Appendix 2).

Vegetation outside the plots was not included in the analysis, however species were identified. Plant species of the side vegetation that did not occur at all or rarely on plots are shown in Appendix 3.

3.2 Effects of substrate depth, structural elements and grade of heterogeneity

Regarding the question of the effect of substrate depth on the vegetation I found that substrate depth has a positive effect on all response variables except cover of species with dead individuals (Fig. 3, Tab. 4, Appendix 5). There were statistically significant differences in vegetation cover, plant height, cover of blooming vegetation, species richness and shannon and simpson diversity indices either between all three substrate depths or between 5cm to 10cm/15cm or between 5cm/10cm to 15cm; 15cm containing the highest values (Fig. 3). Compared to 5cm subplots, 15cm subplots held 16% (25%, 32%) more vegetation cover in the first (second, third) round, 6.7% more cover of blooming vegetation, roughly 4 species more, and plants with 9.5 cm more height on average. *Sedum* was most abundant on subplots with 5 cm and 10 cm substrate without habitat elements (Tab. 3). Herbaceous species were most abundant on subplots with 15 cm substrate, followed by 10 cm.

Table 3: Vegetation cover on 5cm, 10cm and 15cm substrate (Optigruen plots, only subplots A and C)

	5cm	10cm	15cm
mean cover of *Sedum* per subplot [%]	51	48.3	37
mean cover of grass per subplot [%]	6.3	29	14.5
mean cover of herbs per subplot [%]	46.4	74.2	102

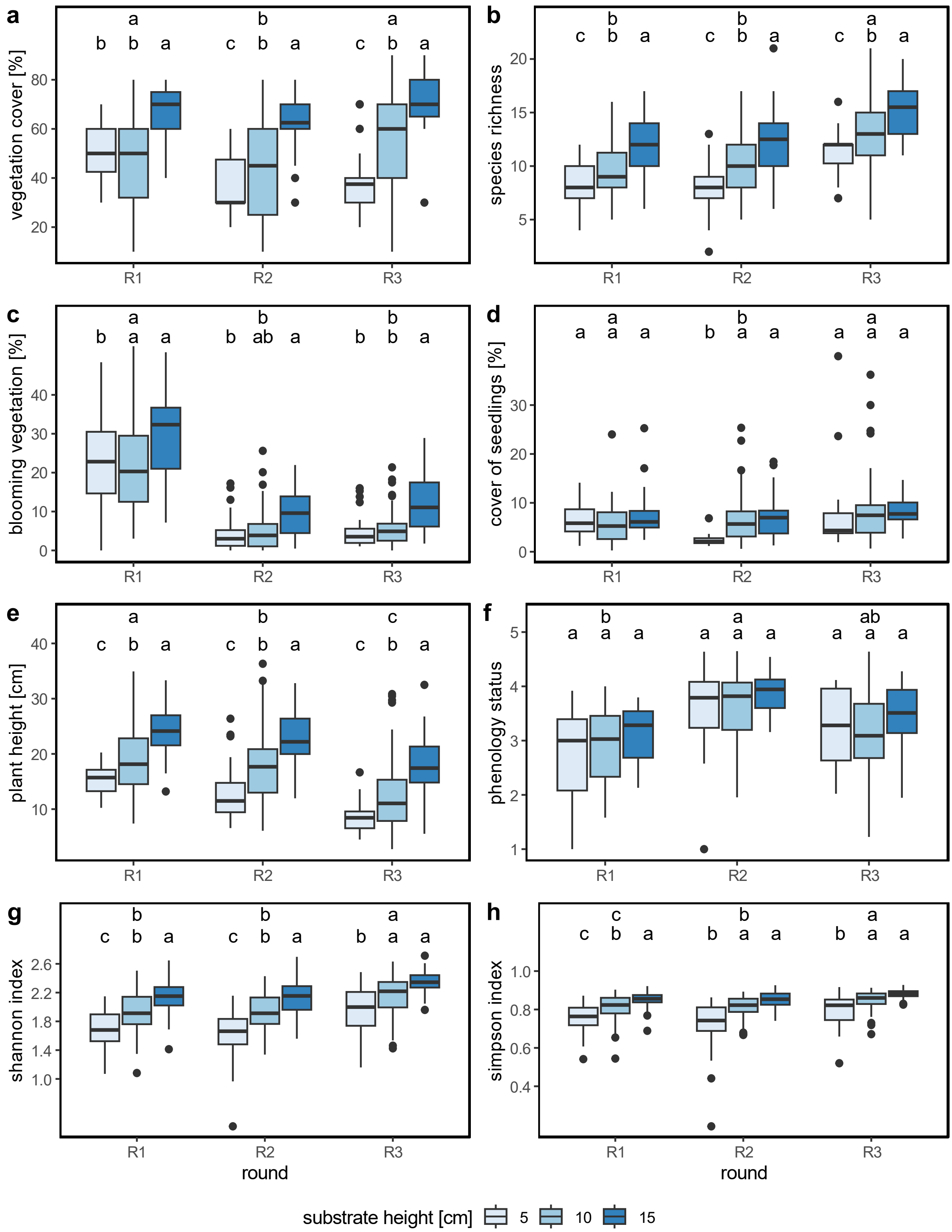

Figure 3: Response variables (a) vegetation cover, (b) species richness, (c) cover of blooming vegetation, (d) cover of species with seedlings, (e) plant height, (f) phenology status, (g) diversity shannon index, (h) diversity simpson index in relation to substrate depth (5cm, 10cm, 15cm). Tukey's test results are presented as letters within and between rounds.

Table 4: Results of the analyses of variance of the linear mixed models: Effect of substrate depth, habitat elements, grade of heterogeneity (individually and combined with round) on the response variables. Significant results are shown in bold.

	substrate depth	substrate depth *round	habitat elements	habitat elements *round	grade of heterog.	grade of heterog. *round
vegetation cover	$F_{1,117}$=98.34; p<**0.0001*** **	$F_{2,232}$=11.94; p<**0.0001*** **	$F_{4,55}$=10.62; p<**0.0001*** **	$F_{8,108}$=1.01; p=0.432	$F_{1,58}$=8.60; p=**0.0048****	$F_{2,114}$=1.79; p=0.172
species richness	$F_{1,117}$=74.91; p<**0.0001*** **	$F_{2,232}$=0.36; p=0.695	$F_{4,55}$=28.77; p<**0.0001*** **	$F_{8,108}$=1.20; p=0.307	$F_{1,58}$=0.52; p=0.473	$F_{2,114}$=0.48; p=0.621
cover of blooming vegetation	$F_{1,59}$=32.94; p<**0.0001*** **	$F_{2,232}$=0.78; p=0.462	$F_{4,55}$=6.55; p=**0.0002*** **	$F_{8,108}$=3.36; p=**0.0018****	$F_{1,58}$=0.36; p=0.549	$F_{2,114}$=1.02; p=0.362
cover of species w. seedlings	$F_{2,104}$=5.34; p=**0.0063****	$F_{4,124}$=3.98; p=**0.0045****	$F_{4,45}$=10.58; p<**0.0001*** **	$F_{8,45}$=0.55; p=0.81	$F_{1,58}$=1.85; p=0.179	$F_{2,114}$=0.29; p=0.75
plant height	$F_{1,117}$=92.78; p<**0.0001*** **	$F_{2,232}$=0.47; p=0.626	$F_{4,55}$=15.68; p<**0.0001*** **	$F_{8,108}$=0.34; p=0.948	$F_{1,58}$=1.35; p=0.25	$F_{2,114}$=0.21; p=0.813
phenology status	$F_{1,118}$=6.44; p=**0.0125***	$F_{2,232}$=0.05; p=0.948	$F_{4,55}$=1.26; p=0.295	$F_{8,108}$=0.63; p=0.755	$F_{1,58}$=0.51; p=0.477	$F_{2,114}$=0.70; p=0.5
shannon index	$F_{1,117}$=64.77; p<**0.0001*** **	$F_{2,232}$=3.12; p=**0.0462***	$F_{4,55}$=8.49; p<**0.0001*** **	$F_{8,108}$=0.89; p=0.527	$F_{1,58}$=1.41; p=0.24	$F_{2,114}$=0.17; p=0.844
simpson index	$F_{1,117}$=52.61; p<**0.0001*** **	$F_{2,232}$=5.93; p=**0.0031****	$F_{4,55}$=6.43; p=**0.0003*** **	$F_{8,108}$=1.19; p=0.314	$F_{1,58}$=0.66; p=0.42	$F_{2,114}$=0.43; p=0.652
cover of species w. dead individuals	$F_{1,12}$=0.23; p=0.797	$F_{4,6}$=0.18; p=0.938			$F_{1,39}$=0.02; p=0.882	$F_{2,18}$=0.56; p=0.58

Regarding the question of the effect of habitat elements on the vegetation I found significant differences of all response variables between structural elements except cover of species with dead individuals and phenology status (Fig. 4, Tab. 4). There was not sufficient data for analysing potential effects of habitat elements on the cover of species with dead individuals. Vegetation cover and cover of species with seedlings had significant higher values in the control group and on subplots with sand and refuges; cover of blooming vegetation was higher on subplots of the control group and on subplots with refuges compared to subplots with sand, stones and deadwood (Fig. 4). Species richness and both shannon and simpson diversity indices were higher on subplots with stones, deadwood and the control group compared to subplots with sand and refuges; plant height had its greatest values on subplots with stones and deadwood.

Regarding question of the effect of plot heterogeneity on the vegetation I did not find significant differences of the response variables between homogenous plots and heterogenous plots, except for vegetation cover (Fig. 5, Tab. 4, Appendix 5). On average, vegetation cover was 6.7% higher on homogenous plots. There was a tendency of cover values to be higher on homogenous plots, and species richness and diversity to be higher on heterogenous plots.

3.3 Seasonal patterns

Vegetation cover, species richness and diversity indices were highest in the third round (Fig. 3-5). Plant height was highest in the first round; cover of species with seedlings were highest in the first and third round. Cover of blooming vegetation on Optigruen plots was highest in the first round (28.2%) and had lower values in the second (6.7%) and third round (7.6%) (Fig. 3-5, Appendix 7). Heathland plots held high blooming vegetation cover values in the first round (16.7%), lower values in the second round (5.4%), and again higher values in the third round (11.6%). Phenology states were highest in the second round (4=seed dispersing) and lower in the first and third round (3=seed producing) on average (Fig. 3-5). The analysis of the phenology shows fluctuations between rounds and roof ranging from 2 (blooming) to 4 (seed dispersing) on average (Appendix 7).

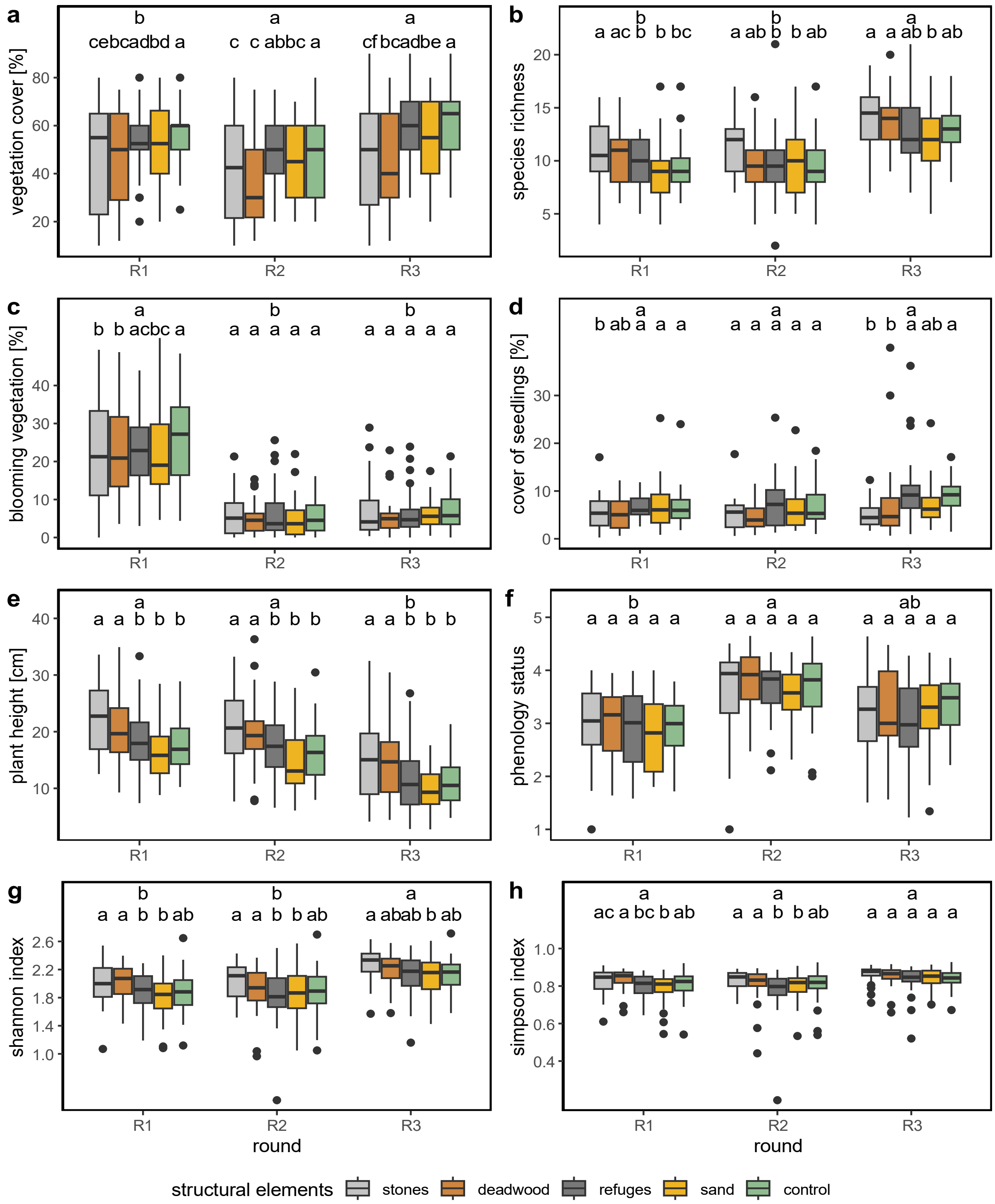

Figure 4: Response variables (a) vegetation cover, (b) species richness, (c) cover of blooming vegetation, (d) cover of species with seedlings, (e) plant height, (f) phenology status, (g) diversity shannon index, (h) diversity simpson index in relation to habitat elements. Tukey's test results are presented as letters within and between rounds.

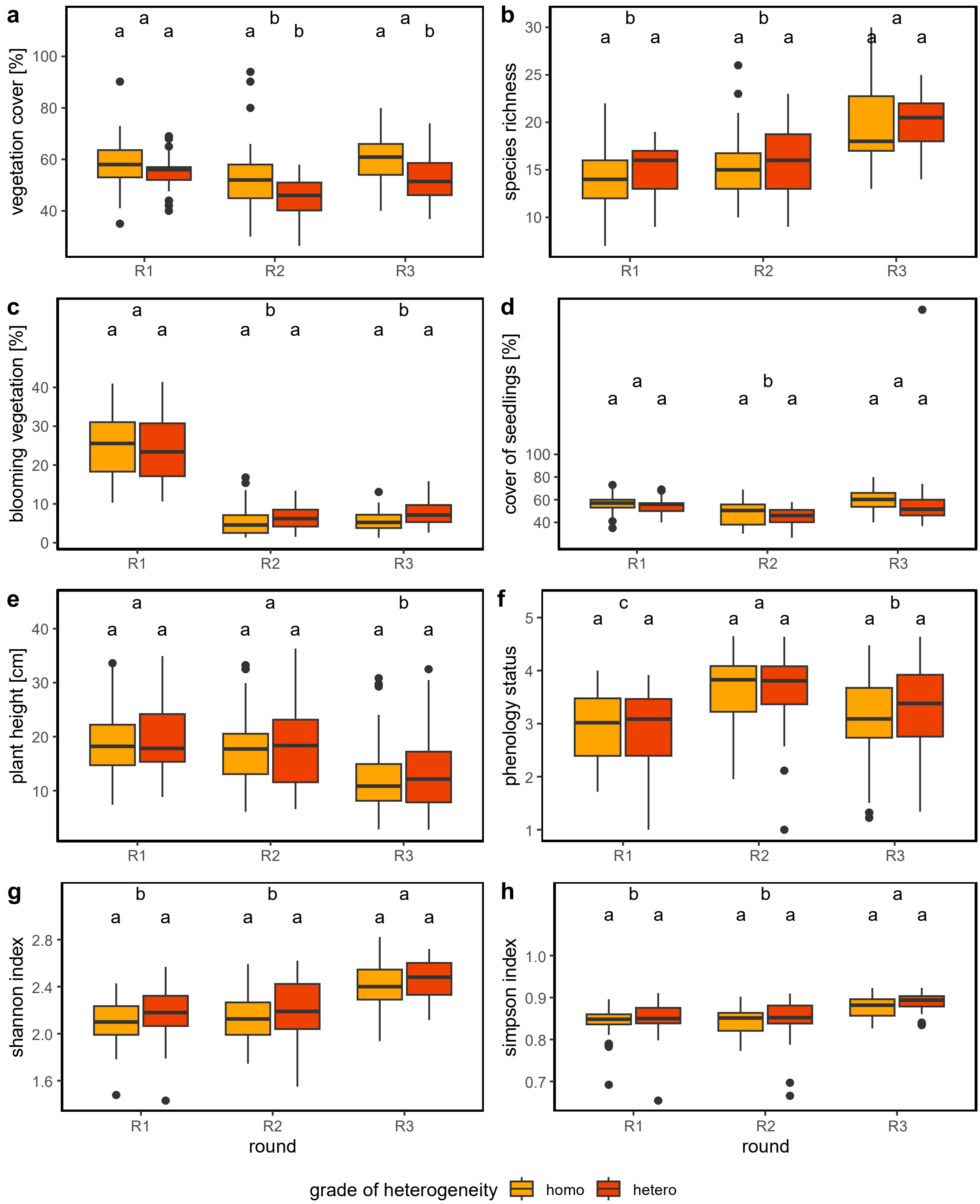

Figure 5: Response variables (a) vegetation cover, (b) species richness, (c) cover of blooming vegetation, (d) cover of species with seedlings, (e) plant height, (f) phenology status, (g) diversity shannon index, (h) diversity simpson index in relation to grade of heterogeneity. Tukey's test results are presented as letters within and between rounds.

3.4 Vegetation composition

To compare the vegetation composition of (sub)plots, I calculated several NMDS. Vegetation composition was rather dissimilar between subplots with 5cm and 15cm substrate depth (Fig. 6A). The NMDS of habitat elements (Fig. 6B) shows rather dissimilar subplot vegetation between stones and sand, between stones and refuges, between stones and the control, and between deadwood and sand. Vegetation on subplots with sand, refuges and the control group were rather similar. The NMDS of seed mixtures (Fig. 6C) shows pronounced dissimilarities of the plot vegetation between the Optigruen seed mixture and all heathland seed mixtures. Plot vegetation of the Allacher seed mixture was rather similar to the vegetation of Krimmer and Garchinger seed mixture. The plot vegetation was dissimilar between the rounds (Fig. 6D) and highly dissimilar between 2020 and 2022 on both Optigruen and heathland plots (Appendix 6).

I calculated p-values for the (dis)similarity between vegetation compositions using the Bray-Curtis dissimilarity matrix (ANOSIM) which reveal high statistically significant differences among the groups (Fig. 6A-D, Appendix 6).

γ -diversity, number of *Sedum* species, grass and herbaceous species as well as the cover of herbaceous species have increased on both Optigruen and heathland plots from 2020 to 2022 (Tab. 5). α-diversity and the mean cover of *Sedum* and grass species have increased on both Optigruen and heathland plots. 38 species occurred in 2020 but not in 2022, such as *Centaurea scabiosa, Erucastrum gallicum, Galium album, Geranium robertianum, Helianthemum nummularium, Hieracium aurantiacum, Phleum pratense* and *Senecio viscosus* (Appendix 1). 45 species that did not occur in 2020 were recorded in 2022, such as *Cerastium arvense, Dianthus armeria, Leucanthemum vulgare, Origanum vulgare, Prunella vulgaris, Silene nutans, Sonchus asper* and *Vicia lathyroides*.

Table 5: Vegetation richness and cover on Optigruen and heathland plots in 2020 and 2022 (all plots)

	2020		2022 (all rounds)	
	Optigruen plots	heathland plots	Optigruen plots	heathland plots
total number of species (γ -diversity)	52	58	79	64
number of succulent species (*Sedum*)	3	1	4	2
number of grass species	6	11	12	14
number of herb species	43	46	63	48
mean species richness per plot (α-diversity)	15	16.1	16.7	17.3
mean cover of *Sedum* per plot [%]	7.5	10.6	14.7	4.0
mean cover of grass per plot [%]	1.3	9.0	4.1	8.6
mean cover of herbs per plot [%]	9.8	15.5	23.7	36.1

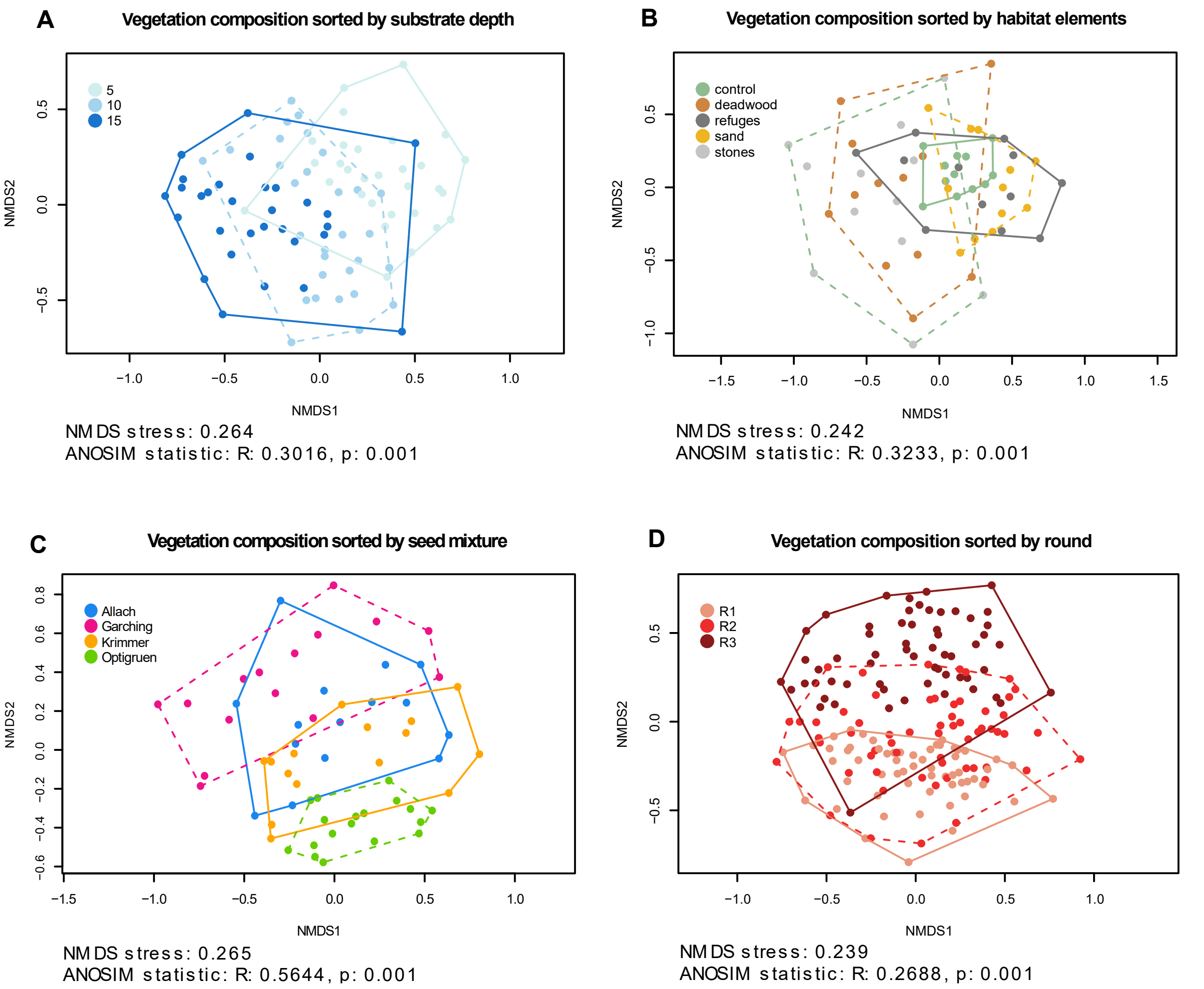

Figure 6: NMDS of vegetation composition: dissimilarities between (A) substrate depth, (B) structural elements, (C) seed mixtures, (D) round. Dots are subplots (A, B) or plots (C, D).

4 Discussion

4.1 Effect of substrate depth and plot heterogeneity

Analyses show that substrate depth had the strongest impact on vegetation growth, development and diversity in this experiment (Fig. 3, Tab. 4). This result was expected as it has been partly found by several studies (Madre et al. 2014; Gabrych et al. 2016; Vandegrift et al. 2019). Due to the extreme climatic conditions on extensive green roofs where water is a strongly limiting factor for plant growth, water retention appears to be an important quality of green roof substrate. Deeper substrate has a higher water storage capacity and retention time (Buccola and Spolek 2011) and therefore benefits vegetation development and diversity. Furthermore, deeper substrate holds higher abundances and diversities of arthropods (Woelfel 2023), which indirectly benefits plant growth. Plant and microbial responses to herbivore and detritivore arthropods have found to be an important factor in increasing nutrient cycle rates (Seastedt and Crossley 1984). Decreased vegetation cover and plant performance in shallower substrate was probably mainly due to more rapid rates of desiccation and temperature fluctuations of the substrate (Oberndorfer et al. 2007).

Subplots with 10 cm substrate had a similar species composition to subplots with 5 cm substrate, however with higher floral abundances. Subplots with 15 cm substrate had a similar species composition to subplots with 10 cm substrate, however with higher abundances of herbaceous species and numerous additional species such as *Bromus hordeaceus, Dianthus deltoides, Linaria vulgaris* and *Verbascum* sp.

Species of *Sedum* had high abundances on subplots with 10 cm and 5 cm substrate without habitat elements (Tab. 3). Belonging to the family of Crassulaceae, *Sedum* is adapted to elevated temperatures and moisture stress and is therefore suitable for green roofs with substrate layers as thin as 2 to 3 cm (Gómez-Campo 1994). On 15 cm subplots and on subplots with habitat elements *Sedum* was outperformed by other taxa probably due to a more moist substrate which favours grass and herbaceous species (Gabrych et al. 2016; Heinze 1985). On subplots with 10 cm and 15 cm herbaceous vegetation was predominant (Tab. 3) (see also: Gabrych et al. 2016).

The results of this study as well as the study of 2020 (Wenzel 2021) suggest that the grade of heterogeneity does not have a big impact on vegetation growth or diversity. Vegetation cover was positively affected by homogenous plots, and there was a tendency of cover of blooming vegetation and cover of species with seedlings to be higher on homogenous plots (Fig. 5). This pattern can be explained by the negative effect of the 5 cm substrate on heterogenous plots having been stronger than the positive effect of the 15 cm substrate on vegetation cover. Compared to 2020 where there was no effect, there was a tendency of species richness and diversity to be higher on heterogenous plots, which confirms the findings of some studies (Coffman and Blackson 2020; Brenneisen 2006; Heim and Lundholm 2014) and implies that the effect of heterogeneity becomes stronger over multiple growing seasons.

Dead vegetation caused by heat and drought does not seem to be reduced by deeper substrate or the grade of plot heterogeneity (Appendix 5). The reason for this could be the drought tolerance of species being the driving factor for survival. Dead vegetation in this study consisted only of a few plant species, mainly *Conyza canadensis, Anthemis tinctoria* and *Epilobium tetragonum*.

4.2 Effect of structural elements

Some response variables were favoured by the elements stones and deadwood, whereas other variables were favoured by the elements sand, refuges and the control group. Cover values such as the total vegetation cover, cover of blooming vegetation and cover of species with seedlings were higher on subplots with sand, soil (control) and refuges (Fig. 4). Greater surface area on these subplots and therefore more habitat for plant development could be a reason for higher cover values.

Sand was introduced to the experiment as one element creating microhabitats alongside the other habitat elements and was intended to increase plant diversity. In 2020, sand was the element with the most effect on the vegetation among all structural elements (Wenzel 2021). Subplots with sand showed increased numbers of individuals of the spontaneous vegetation and a decreased plant height on average. Over time, sand was overgrown by moss and did not have the initial characteristics of sand anymore. This explains the rather small dissimilarities between vegetation on sand, refuges and soil (control) (Fig. 6B). This implies that sand - when introduced as a structural element within a green roof design – needs to be maintained. Refuges were installed with the intention to function as capillary barriers to retain water in the substrate. However, no significant effect of refuges on vegetation growth or diversity was found in this study. The design of refuges as habitat elements might need to be revised.

Plant height, species richness and biodiversity had higher values on subplots with stones and deadwood than on subplots with other elements (Fig. 4). Stones and deadwood were introduced mainly for their ability to retain water (Mandal et al. 2005) and provide protection from high temperature, high solar radiation, wind and other climatic stressors. The capacity of deadwood to absorb and retain water is highly dependent on the tree species as well as the stage of decomposition of the wood (Klamerus-Iwan et al. 2020). Compared to 2020 where the wood log did not show any effect on the vegetation (Wenzel 2021), the results of this study showed an increased vegetation height and greater species richness and diversity on subplots with deadwood. This strengthens the hypothesis that deadwood qualities and therefore its capacity for water retention changes over time depending on its decomposition state.

Subplots with stones and deadwood had a rather dissimilar vegetation to plots with other habitat elements (Fig. 6B), which suggests that due to their protective qualities and their ability to retain water, stones and deadwood create microhabitats and niches for certain plant species that did not occur (as much) on other subplots, such as *Dianthus armeria, Silene otites, Vicia lathyroides* and species of *Verbascum*. Species that occurred only on subplots with stones, deadwood and refuges are *Achillea millefolium, Galium verum* and *Origanum vulgare*.

4.3 Vegetation composition

More than 60% of the vegetation on Optigruen and heathland plots consisted of spontaneous vegetation (Appendix 1, 2), which reveals species turnover to have occurred on the rooftops due to succession, interspecific competition and the occupation of niches (McKinney 2018; Klein and Coffman 2015; Grime 2002). Spontaneous vegetation consisted mainly of short-lived species that typically grow in ruderal and urban areas (Ellenberg 1996). Species turnover could be a reason for the high dissimilarities of the vegetation between 2020 and 2022 (Appendix 6). Studying the vegetation on green roofs on a long term, Ksiazek-Mikenas et al. (2018) found an increase of vegetation cover over time and a stagnation of vegetation richness beyond the first two years. If one differentiates between the total species richness (γ-diversity) and species richness per plot (α-diversity), γ-diversity was found to increase, whereas α-diversity was found to increase in the first years and decrease after 12 years on green roofs (Catalano et al. 2016). In this study, increased α-diversity and γ-diversity imply higher floral heterogeneity on a plot or roof level, respectively, revealing that species turnover occurs as a response to the progressive occupation of niches (Catalano et al. 2016).

The age of green roofs plays an important role in the vegetation composition and diversity (Gabrych et al. 2016; Klein and Coffman 2015). Young green roofs contain large numbers of *Sedum* and moss cover and diversity, whereas older green roofs support meadow plants (Gabrych et al. 2016; Klein and Coffman 2015). The vegetation cover of Optigruen plots consisted roughly of two thirds of meadow species (9% grass and 55 % herbs) and one third of *Sedum* species; roughly 92% of the vegetation cover of heathland plots were meadow species (18% grass and 74% herbs) and 8% were *Sedum* species (Tab. 5). With an increase of *Sedum* species richness and cover on the one hand, and higher γ-diversity and larger numbers of meadow species and cover values - compared to 2 years ago - on the other hand, the Optigruen plots of the green roofs of this study could represent a transitory stage between young and old. In contrary, cover values of herbs on heathland plots have increased by 132,9 % and *Sedum* cover values have decreased by 59,6 %, which indicates these plots to be at a rather old stage.

Numerous species of the original seed mixtures were able to withstand the rooftop’s harsh climatic conditions and interspecific competition, and still thrive after two growing seasons. 21 out of 30 species from the Optigruen seed mixture and 17 out of 48 species from the Krimmer seed mixture were found in this study. The plots of different seed mixtures were rather homogenous regarding their flora on a plot level and represented different vegetation communities. Plots sown with thrashed biomass from the Allacher heathland were rather heterogenous (Fig. 6C). Plots of the different seed mixtures were similar regarding the occurring plant species with high cover values which originate mainly from multiple seed mixtures or spontaneous vegetation. What made the plot vegetation different are the species that occurred in small numbers and probably originated from the regarding seed mixture. *Anthoxanthum odoratum, Hippocrepis emerus, Linum perenne, Rhinanthus minor* and *Echium vulgare* occurred in small numbers and only on plots sown with trashed biomass of the Allacher and Garchinger Heide. A multitude of species including *Achillea millefolium, Campanula rotundifolia, Dianthus* *deltoides, Silene otites, Sedum hispanicum, Origanum vulgare, Linaria vulgaris* and two species of *Verbascum* occurred only on Optigruen plots, however mostly in small numbers. Vegetation communities of the different seed mixtures showed different characteristics and qualities and therefore complemented each other to a diverse green roof community.

4.4 Seasonal patterns

Vegetation has changed over the months of June between October (Fig. 3-5, 6D). Species that occurred in large numbers in all rounds are *Anthemis tinctoria, Conyza canadensis, Dianthus carthusianorum, Leucanthemum vulgare, Petrorhagia saxifraga, Sanguisorba minor, Sedum acre* and *Sedum album*. These species are perennials and part of the Optigruen and/ or Krimmer seed mixture except for *Conyza canadensis*. *Conyza canadensis* likes warm climate and typically occurs in recolonised wasteland mainly in the second and third year (Oberdorfer et al. 2001). *Geranium molle* was present only in the first round, and *Eragrostis minor, Galinsoga parviflora* and *Geranium pusillum* only in the third round. Characteristic for the second and third round were mainly species of the spontaneous vegetation: *Amaranthus blitum, Chaenorhinum minus, Capsella bursa-pastoris, Chenopodium album, Digitaria sanguinalis, Erodium cicutarium, Hypochaeris glabra, Hypochaeris radicata, Sonchus asper, Sonchus oleraceus* and *Vicia lathyroides*. These species mentioned above are geophytes that typically complete their life cycle in a short period when conditions are favourable and survive unfavourable environments (e.g. summer drought) as seeds (therophytes) or through persistence buds which lie on the earth's surface (hemicryptophytes) (Ellenberg 1996).

Besides species turnover, pronounced changes in blossoming patterns were observed. While there were higher blooming cover percentages of Optigruen plots in early summer, blooming cover values were rather low after mid-July (Appendix 7). Heathland plots contained less blooming cover than Optigruen plots. Blooming cover on heathland plots was highest in early summer, decreased during mid-summer, increased again in early autumn (August until early October) prior to decreasing significantly after mid-October (Appendix 7) (see also Nagase et al. 2017). A lack of summer flowering species on the investigated roofs could be a reason for low blooming percentages in mid-summer (cf. Benvenuti 2014). Blooming cover in early autumn consisted partly of species that blossom throughout the season, such as *Thymus pulegioides* and *Petrorhagia saxifraga*, as well as of therophytes which grow and bloom later in the season, such as *Chaenorhinum minus* and *Senecio vulgaris.*

Analysis of the phenology of the flora corresponds to the analysis of blossoming patterns. On average, vegetation was blossoming in June, producing seeds in early July and dispersing seeds in late July (Appendix 7). Vegetation of the third round (late September onwards) consisted mainly of seedlings and of flora that was in or after the state of dispersing seeds.

5 Conclusion and recommendations

To establish green roofs on a large scale, rooftop conditions and seed mixtures need to be optimized so that the vegetation can establish itself permanently, attract pollinators and provide habitat for local flora and fauna. The results of this study give important insights and recommendations for green roof design. The combination of different seed mixtures and thrashed biomass of heathlands, the introduction of the habitat elements stones and deadwood, and a combination of different substrate depths are important elements for increasing floral diversity on green roofs. Therefore, I recommend considering a combination of homogenous plots with a deeper substrate (e.g. 15 cm) and heterogenous plots with a deeper and a lower substrate (e.g. 15cm and 10cm), as well as the installation of stones and deadwood for green roof designs. Furthermore, I recommend introducing different seed mixtures and thrashed biomass of heathlands sown on the substrate of green roofs to increase floral diversity.

However, green roofs are dynamic and individual, therefore green roof design should be adapted to local conditions. For future research I suggest examining the effects of habitat elements and plot heterogeneity on a long term. Furthermore, I suggest a wider study on using different seed mixtures on green roofs, and the question whether there is a need for modifying the standard seed mixture should be addressed. For establishing a more constant bloom on the roofs I suggest experimenting with plant groups of different blooming seasons and maybe considering slight maintenance of the rooftops. To be able to record changes in vegetation cover, richness, diversity and phenology patterns multiple surveys within a growing season should be conducted. In conclusion, green roofs - when designed carefully - represent a valid measure to establish habitats and improve biodiversity in urban ecosystems.

6 Data and code availability

Statistical analysis was performed with R and RStudio (Version 4.2.2; R core team 2018). My data, R code and thesis are stored on a permanent electronic repository (links below).

GitHub: https://github.com/PiaSchumann/green-roofs.git

Zenodo: DOI 10.5281/zenodo.7948378

https://zenodo.org/badge/latestdoi/642393312

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8 Literature

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9 Appendix

Appendix 1: Total species list of roof vegetation on Optigruen and heathland plots. Species are presented with the seed mixtures they originate from: Optigruen (O), Krimmer (K) or thrashed biomass from Garchinger Heide (G) and Allacher Heide (A). Numbers represent the quantity of plots where the species was present (60 Optigruen plots, 15 heathland plots in total).

species	family	seed mixture	2020 Optigruen	2020 heathland	2022 Optigruen	2022 heathland
Achillea millefolium	Asteraceae	O/K/A	30	8	20	0
Allium schoenoprasum	Amaryllidaceae	O	0	0	0	2
Amaranthus blitum	Amaranthaceae	S	0	0	4	1
Amaranthus sp.	Amaranthaceae	S	7	0	0	0
Amaranthus sp.	Amaranthaceae	S	0	0	1	0
Anthemis tinctoria	Asteraceae	O	58	1	60	13
Anthoxanthum odoratum	Poaceae	S	0	0	0	1
Arenaria serpyllifolia	Caryophyllaceae	K	18	12	23	15
Betula pubescens	Betulaceae	S	3	0	1	3
Briza media	Poaceae	K/A/G	0	2	1	0
Bromus erectus	Poaceae	K/A/G	0	9	0	3
Bromus hordeaceus	Poaceae	S	0	0	1	3
Bromus sp.	Poaceae	S	0	1	0	0
Calamagrostis minor	Poaceae	S	0	0	2	3
Campanula rotundifolia	Campanulaceae	O/K	0	0	4	0
Capsella bursa-pastoris	Brassicaceae	S	0	3	3	0
Centaurea scabiosa	Asteraceae	O/K/A	0	1	0	0
Centaurea sp.	Asteraceae	S	0	3	0	0
Cerastium arvense	Caryophyllaceae	S	0	0	2	3
Chaenorhinum minus	Plantaginaceae	S	41	13	34	11
Chenopodium album	Amaranthaceae	S	60	15	58	15
Clinopodium vulgare	Lamiaceae	K	8	4	26	2
Conyza canadensis	Asteraceae	S	60	15	57	15
Crepis molle	Asteraceae	S	0	0	1	0
Dactylis glomerata	Poaceae	S	0	0	0	7
Dianthus armeria	Caryophyllaceae	S	0	0	9	1
Dianthus carthusianorum	Caryophyllaceae	O/K/A/G	58	10	60	15
Dianthus deltoides	Caryophyllaceae	O	0	0	1	0
Digitaria sanguinalis	Poaceae	S	0	0	6	0
Draba verna	Brassicaceae	S	0	0	46	7
Echinochloa colona	Poaceae	S	0	0	1	0
Echium vulgare	Boraginaceae	S	0	6	0	1
Epilobium tetragonum	Onagraceae	S	11	2	18	7
Eragrostis minor	Poaceae	S	13	1	23	5
Erigeron annuus	Asteraceae	S	34	2	21	5
Erodium cicutarium	Geraniaceae	O	0	0	12	9
Erucastrum gallicum	Brassicaceae	S	5	4	0	0
Euphorbia cyparissias	Euphorbiaceae	K/A	0	1	4	0
Festuca ovina	Poaceae	S	0	8	39	13
Galinsoga parviflora	Asteraceae	S	0	0	2	0

Galium album	Rubiaceae	A/G	0	9	0	0
Galium verum	Rubiaceae	O	2	0	18	1
Geranium molle	Geraniaceae	S	2	0	5	2
Geranium pusillum	Geraniaceae	S	0	2	25	8
Geranium robertianum	Geraniaceae	O	1	0	0	0
Helianthemum nummularium	Cistaceae	K	0	2	0	0
Hieracium aurantiacum	Asteraceae	O	5	0	0	0
Hieracium pilosella	Asteraceae	K	5	2	8	4
Hieracium piloselloides	Asteraceae	S	0	0	19	4
Hieracium sp.	Asteraceae	S	1	0	0	0
Hieracium sp.	Asteraceae	S	0	0	6	2
Hippocrepis emerus	Fabaceae	S	0	0	0	1
Holcus lanatus	Poaceae	A	0	1	0	0
Hypericum perforatum	Hypericaceae	S	0	0	1	1
Hypochaeris glabra	Asteraceae	S	0	0	11	1
Hypochaeris radicata	Asteraceae	S	0	0	4	0
Lactuca serriola	Asteraceae	S	0	2	0	0
Lapsana communis	Asteraceae	S	0	0	1	0
Lepidium densiflorum	Brassicaceae	S	0	1	0	0
Leucanthemum vulgare	Asteraceae	O	0	0	51	10
Linaria vulgaris	Plantaginaceae	O	12	0	1	0
Linum perenne	Linaceae	O/K/G	0	1	0	1
Lotus corniculatus	Fabaceae	A	0	1	1	0
Medicago lupulina	Fabaceae	A/G	0	5	19	10
Medicago sativa	Fabaceae	S	0	0	1	0
Origanum vulgare	Lamiaceae	O/K	0	0	19	1
Panicum miliaceum	Poaceae	S	0	0	4	1
Papaver dubium	Papaveraceae	S	1	0	0	0
Persicaria maculosa	Polygonaceae	S	2	0	0	0
Persicaria sp.	Polygonaceae	S	0	1	0	0
Petrorhagia prolifera	Caryophyllaceae	K	1	0	24	12
Petrorhagia saxifraga	Caryophyllaceae	O/K	50	3	60	14
Phleum pratense	Poaceae	G	0	10	0	0
Picris hieracioides	Asteraceae	S	0	0	1	0
Plantago lanceolata	Plantaginaceae	A/G	0	10	4	11
Plantago major	Plantaginaceae	S	2	0	2	0
Plantago media	Plantaginaceae	S	0	0	1	0
Poa annua	Poaceae	S	19	4	2	1
Poa compressa	Poaceae	S	1	2	0	0
Poa sp.	Poaceae	S	5	1	0	0
Polygonum aviculare	Polygonaceae	S	1	0	0	0
Populus sp.	Salicaceae	S	0	1	0	0
Potentilla argentea	Rosaceae	O	0	0	16	1
Potentilla norvegica	Rosaceae	S	5	0	14	4
Potentilla sp.	Rosaceae	S	0	1	0	0
Prunella vulgaris	Lamiaceae	O	0	0	9	0
Rhinanthus minor	Orobanchaceae	S	0	0	0	1
Salix fragilis	Salicaceae	S	0	0	1	0

Salvia pratensis	Lamiaceae	S	0	1	0	0
Sanguisorba minor	Rosaceae	O/K	41	3	48	4
Saponaria ocymoides	Caryophyllaceae	O	0	0	0	1
Saponaria officinalis	Caryophyllaceae	O	38	0	0	0
Sedum acre	Crassulaceae	O/K	60	0	60	14
Sedum album	Crassulaceae	O/K	60	0	60	15
Sedum hispanicum	Crassulaceae	O	22	0	14	0
Sedum sp.	Crassulaceae	O	0	0	2	0
Sedum sp.	Crassulaceae	O/K	0	11	0	0
Senecio inaequidens	Asteraceae	S	7	1	20	3
Senecio viscosus	Asteraceae	A	7	1	0	0
Senecio vulgaris	Asteraceae	S	2	0	44	9
Setaria viridis	Poaceae	S	25	0	42	7
Silene dioica	Caryophyllaceae	S	0	1	0	0
Silene latifolia	Caryophyllaceae	S	1	0	0	0
Silene nutans	Caryophyllaceae	O/K	0	0	0	2
Silene otites	Caryophyllaceae	O	3	0	11	0
Silene vulgaris	Caryophyllaceae	S	57	8	58	14
Solidago canadensis	Asteraceae	S	0	2	0	0
Sonchus asper	Asteraceae	S	0	0	53	12
Sonchus oleraceus	Asteraceae	S	21	0	48	13
Sonchus sp.	Asteraceae	S	0	0	5	1
Taraxacum sp.	Asteraceae	S	2	1	30	6
Thymus pulegioides	Lamiaceae	O/K/A	9	1	34	2
Trifolium campestre	Fabaceae	K/G	0	2	11	9
Trifolium sp.	Fabaceae	A	0	2	0	0
Triticum sp.	Poaceae	S	1	0	0	0
Verbascum sp.	Scrophulariaceae	S	7	5	0	0
Verbascum sp.	Scrophulariaceae	S	0	0	3	0
Verbascum thapsus	Scrophulariaceae	S	0	1	1	0
Veronica arvensis	Plantaginaceae	G	1	1	0	0
Vicia lathyroides	Fabaceae	S	0	0	6	0
Vulpia ciliata	Poaceae	S	0	2	0	0
unknown grass species	Poaceae	S	0	0	9	7
unknown grass species	Poaceae	S	0	0	0	2
unknown grass species	Poaceae	S	0	0	4	1
unknown grass species	Poaceae	S	0	0	0	3
unknown grass species	Poaceae	S	0	6	0	0
unknown species	NA	NA	0	13	0	0
unknown species (dead)	NA	NA	1	0	0	0
unknown species (long leaves)	NA	NA	14	0	0	0

Appendix 2: Origin of plant species on Optigruen and heathland plots

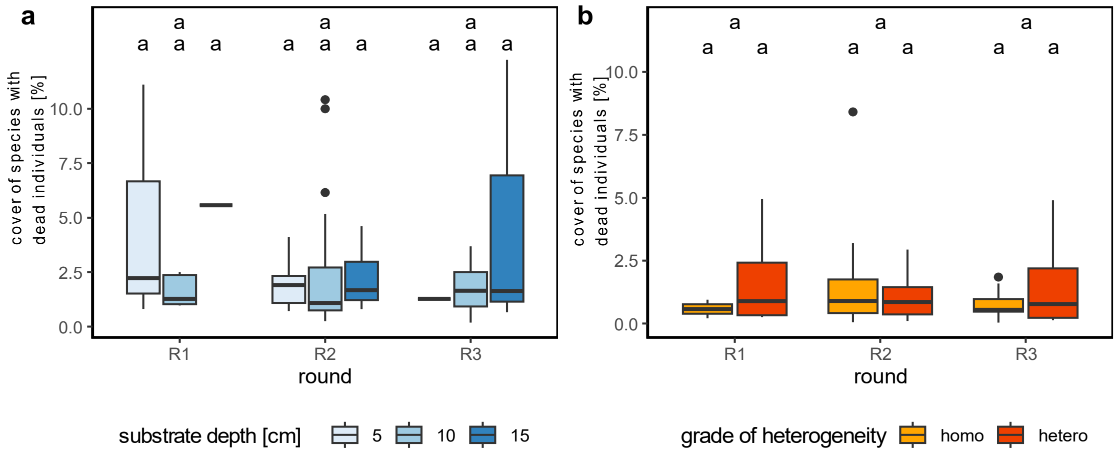
seed mixture	Optigruen plots	heathland plots
Optigruen	13.9%	10.9%
Krimmer/ thrashed biomass from heathland	12.3%	12.5%
Optigruen AND Krimmer/ thrashed biomass from heathland	13.8%	14.1%
spontaneous	62.0%	62.5%

Appendix 3: Side vegetation

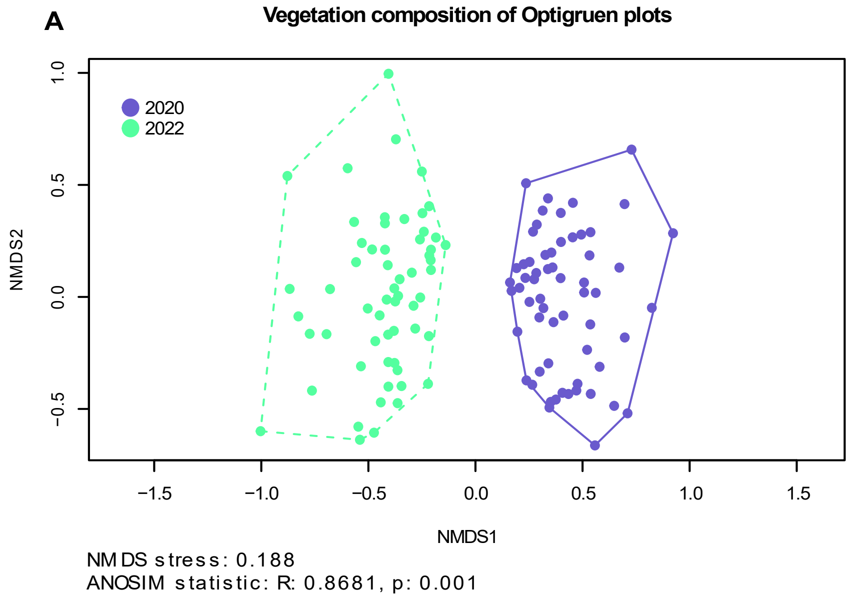
roof	species	family	phenology	seed mixture
E	Linum perenne	Linaceae	sd	O/K/G
E	Daucus carota	Apiaceae	sd	S
E	Allium schoenoprasum	Amaryllidaceae	sd	O
E	Oenothera biennis	Onagraceae	sd	S
E	Geranium pyrenaicum	Geraniaceae	sd	S
E	Verbascum thapsus	Scrophulariaceae	v	S
M	Saponaria ocymoides	Caryophyllaceae	v	O
M	Prunella grandiflora	Lamiaceae	sp	O/K
M	Euphorbia cyparissias	Euphorbiaceae	b	K/A
M	Linum perenne	Linaceae	sd	O/G
M	Potentilla norvegica	Rosaceae	sd	S
W	Linum perenne	Linaceae	sd	O/K/G
W	Campanula rotundifolia	Campanulaceae	sp	O
W	Epilobium tetragonum	Onagraceae	asd	S

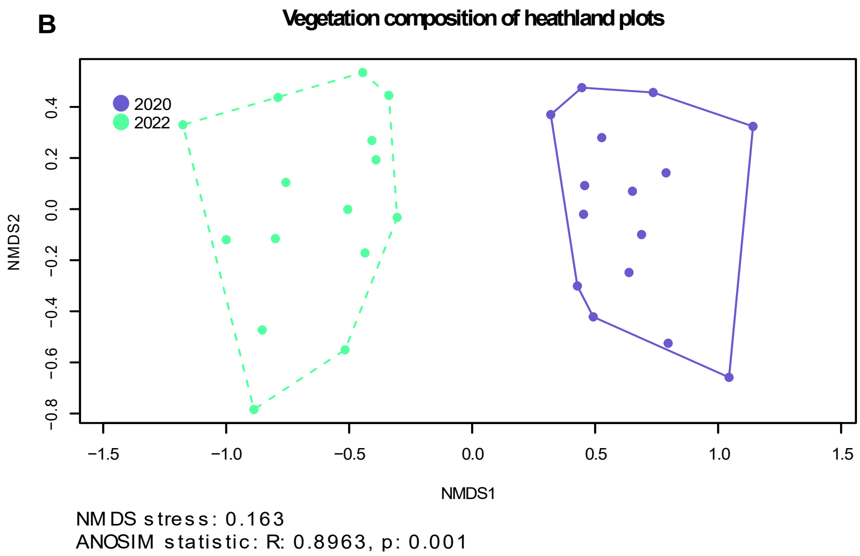
Appendix 4: Dates of data collection 2022 (round 1-3)

roof	R1	R2	R3
E	13 - 28/06	22 - 26/07	30/09 - 04/10
M	30/06 - 05/07	21 - 23/08	06 - 11/10
W	12 - 19/07	28 - 31/08	19 - 25/10

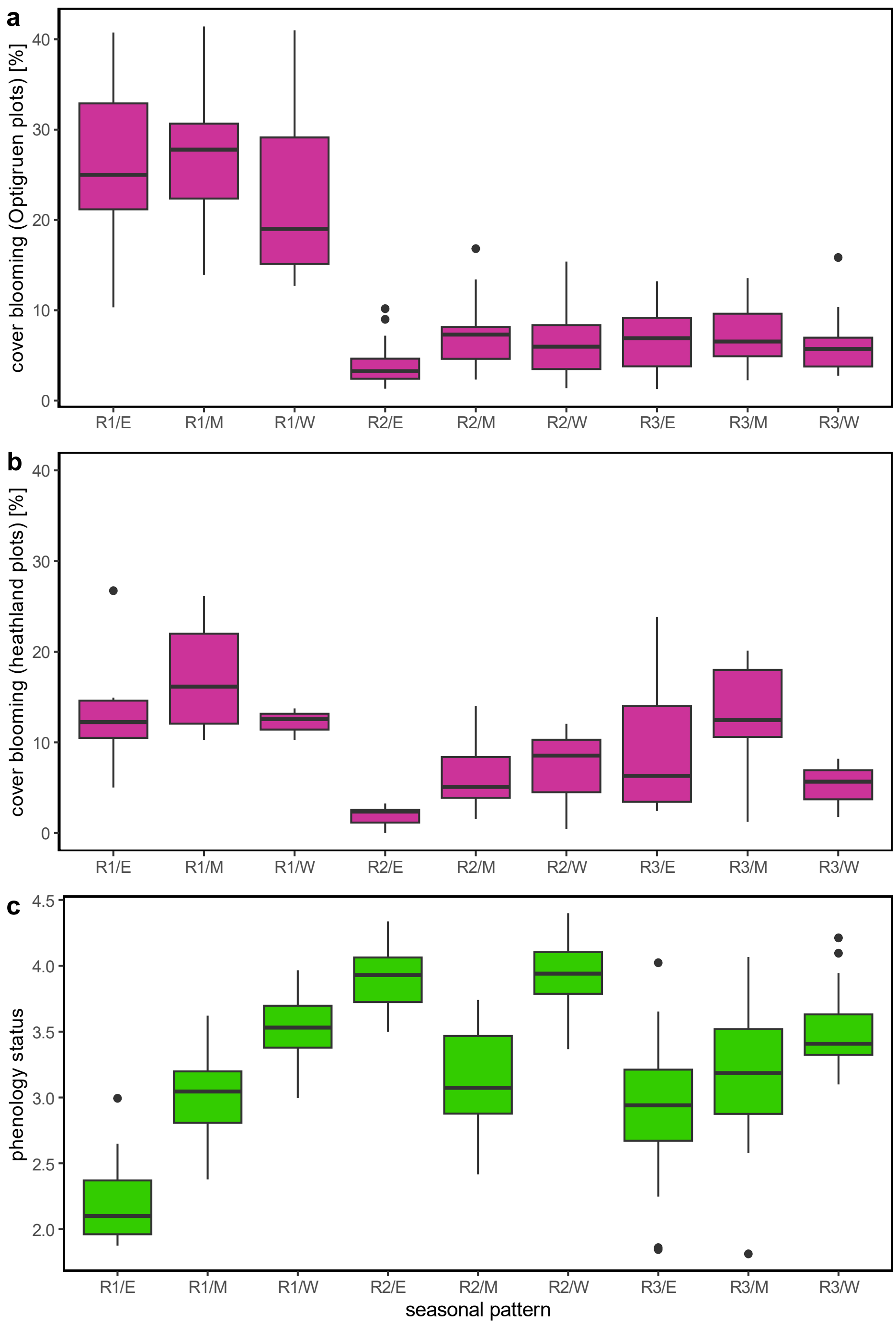


Appendix 5: cover of species with dead individuals [%] in relation to substrate depth and plot heterogeneity





Appendix 6: NMDS: dissimilarities of vegetation composition between 2020 and 2022 on (A) Optigruen plots, (B) heathland plots. Dots are plots.



Appendix 7: seasonal pattern of cover of blooming vegetation [%] on (a) Optigruen plots, (b) heathland plots; (c) mean phenology status (2=blooming, 3=seed producing, 4=seed dispersing)

Optigrün-Saatgutliste Typ EKR

OPTIGRÜN
DIE DACHBEGRÜNER

Wissenschaftlicher Name	Deutscher Name	Blütenfarbe	Höhe	Blütezeit
Kräuter				
Achillea millefolium	Schafgarbe	weiß	15-50	6-8
Allium schoenoprasum	Schnittlauch	rosa	10-40	6-8
Anthemis tinctoria	Färberkamille	gelb	20-50	6-9
Aster amellus	Kalkaster	Weißblauviolett	20-50	8-10
Campanula rotundifolia	Rundblätt. Glockenblume	violettblau	10-40	6-9
Centaurea scabiosa	Scabiosen-Flockenblume	Rotviolett	30-100	6-9
Dianthus carthusianorum	Karthäuser-Nelke	Rosa	15-40	6-9
Dianthus deltoides	Heide-Nelke	Rosa	10-30	6-9
Erodium cicutarium	Reiherschnabel	lila	10-40	4-9
Fragaria vesca	Wald-Erdbeere	weiß	5-20	4-6
Galium vernum	Labkraut	gelb	20-70	6-9
Geranium robertianum	Storchschnabel	rosa	20-50	5-10
Hieracium aurantiacum	Orangerotes Habichtskraut	gelborange	20-50	6-8
Hieracium pilosella	Kleines Habichtskraut	gelb	5-25	5-10
Leucanthemum vulgare	Wiesenmargerite	weiß	10-80	5-9
Linaria vulgaris	Leinkraut	gelb	20-60	6-10
Linum perenne	Staudenlein	hellblau	25-70	6-9
Origanum vulgare	Wildmajoran	lila	20-60	7-10
Petrorhagia saxifraga	Felsennelke	weiß-rosa	10-25	6-9
Potentilla argentea	Silber-Fingerkraut	gelb	10-40	6-9
Prunella grandiflora	großblütige Prunelle	blauviolett	10-30	6-8
Prunella vulgaris	gewöhnl. Prunelle	blauviolett	10-25	6-9
Ranunculus bulbosus	Knolliger Hahnenfuß	gelb	10-30	4-7
Sanguisorba minor	Kleiner Wiesenknopf	rötlich	30-60	5-8
Saponaria ocymoides	Kleines Seifenkraut	rot	10-30	5-7
Saponaria officinalis	Gewöhnliches Seifenkraut	weiß/rosa	30-80	6-9
Silene nutans	Nickendes Leimkraut	weiß	30-60	5-8
Silene otites	Ohrlöffel- Leimkraut	weiß	20-70	5-8
Thymus pulegioides	Feldthymian	Lila	5-30	6-10
Thymus serpyllum	Wilder Thymian	lila	5-15	6-10

Appendix 8: Optigruen seed mixture

Johann Krimmer
Dipl. Ing. FH
Samen und Pflanzen
für naturnahes Grün

Sünzhauser Str. 5 - 85354 Freising-Pulling
Tel.: 08161-490420 - Fax 08161-490421
Mail: info@krimmer-naturnahes-gruen.de
Web: www.krimmer-naturnahes-gruen.de

Mischung	Extensive Dachbegrünung		
Fläche	110 m²	Herkunftsregion	16
Saatgut	4,00 g/m²	Saatgut	0,440 kg
Schnellbegrüner	g/m²	Schnellbegrüner	kg
Schrot	16,00 g/m²	Schrot	1,760 kg
Aussaatstärke	g/m²	Gesamtmenge	kg

Kräuter	Deutsch	Mischungsanteil:	Einwaage:
Ajuga genevensis	Genfer Günsel	0,50 %	0,002 kg
Arenaria serpyllifolia	Quendelbl. Sandkraut	0,90 %	0,004 kg
Asperula cynanchica	Hügel-Meister	1,00 %	0,004 kg
Aster amellus	Kalkaster	1,50 %	0,007 kg
Aster linosyris	Gold-Aster	1,20 %	0,005 kg
Betonica officinalis	Heilziest	2,00 %	0,009 kg
Biscutella laevigata ssp laevigata	Brillenschötchen	3,00 %	0,013 kg
Buphthalmum salicifolium	Rindsauge	2,00 %	0,009 kg
Campanula glomerata ssp glomerata	Knäuel-Glockenblume	0,80 %	0,004 kg
Campanula rotundifolia	Rundblättrige Glockenblume	0,70 %	0,003 kg
Centaurea jacea spp angustifolia	Schmalblättrige Flockenblume	2,50 %	0,011 kg
Centaurea scabiosa ssp scabiosa	Skabiosen-Flockenblume	2,20 %	0,010 kg
Clinopodium vulgare	Wirbeldost	0,60 %	0,003 kg
Dianthus carthusianorum ssp carthusianorum	Kartäuser-Nelke	4,00 %	0,018 kg
Euphorbia cyparissias	Zypressenwolfsmilch	0,50 %	0,002 kg
Filipendula vulgaris	Kleines Mädesüß	1,60 %	0,007 kg
Genista tinctoria	Färberginster	3,00 %	0,013 kg
Gentiana cruciata	Kreuz-Enzian	0,70 %	0,003 kg
Globularia punctata	Echte Kugelblume	0,50 %	0,002 kg
Helianthemum nummularium	Gewöhnliches Sonnenröschen	1,00 %	0,004 kg
Hieracium pilosella	Kleines Habichtskraut	0,30 %	0,001 kg
Hippocrepis comosa	Hufeisenklee	1,80 %	0,008 kg
Inula hirta	Rauhhaariger Alant	0,70 %	0,003 kg
Linum perenne	Blauer Staudenlein	4,00 %	0,018 kg
Origanum vulgare	Wilder Majoran	1,00 %	0,004 kg
Petrorhagia prolifera	Sprossendes Nelkenköpfchen	0,80 %	0,004 kg
Petrorhagia saxifraga	Felsennelke	0,50 %	0,002 kg
Pimpinella saxifraga	Kleine Bibernelle	1,00 %	0,004 kg
Potentilla tabernaemontani	Frühlings-Fingerkraut	0,80 %	0,004 kg
Prunella grandiflora	Großblütige Braunelle	0,50 %	0,002 kg
Ranunculus bulbosus	Knolliger Hahnenfuß	2,00 %	0,009 kg
Salvia verticillata	Quirl-Salbei	3,00 %	0,013 kg
Sanguisorba minor ssp minor	Kleiner Wiesenknopf	1,50 %	0,007 kg
Saxifraga granulata	Knöllchen-Steinbrech	0,30 %	0,001 kg
Sedum acre	Scharfer Mauerpfeffer	0,30 %	0,001 kg
Sedum album	Weißer Mauerpfeffer	0,30 %	0,001 kg
Seseli annuum	Steppen-Sesel	1,50 %	0,007 kg
Silene nutans	Nickendes Leimkraut	1,40 %	0,006 kg
Teucrium montanum	Berg-Gamander	0,40 %	0,002 kg
Thymus praecox ssp praecox	Frühblühender Thymian	0,80 %	0,004 kg
Thymus pulegioides ssp pulegioides	Gewöhnlicher Thymian	1,00 %	0,004 kg
Trifolium campestre	Feld-Klee	0,50 %	0,002 kg
Veronica spicata	Ähriger Ehrenpreis	0,40 %	0,002 kg
	Summe Kräuter: 55 %		

Gräser	Deutsch	Mischungsanteil	Einwaage:
Briza media	Zittergras	25,00 %	0,110 kg
Koeleria pyramidata	Pyramiden-Kammschmiele	5,00 %	0,022 kg
Phleum phleoides	Glanzlieschgras	6,00 %	0,026 kg
Poa angustifolia	Schmalblättriges Rispengras	4,00 %	0,018 kg
Poa compressa	Platthalm-Rispengras	5,00 %	0,022 kg
	Summe Gräser: 45 %		

Appendix 9: Krimmer seed mixture

Declaration of the author

I hereby confirm that the printed copies and the digital version of the thesis submitted are identical; that the thesis is my own work; that I have used only those sources and aids cited; and that I have not already submitted the work to another university to obtain an academic degree. I am aware of the legal consequences of this declaration being inaccurate provided for in accordance with § 26 Para. 5 of the relevant examination regulations.

Munich, 18.05.2023 Pia Schumann