Optimising green roofs in the Netherlands: effects of mineral wool and compost additions on flowering success

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Abstract

The continuous increase of the global human population living in cities has significantly impacted various aspects of nature and climate worldwide. One initiative to promote the urban green space and its biodiversity is the construction of green roofs. Despite the basic structure of these green roofs being similar around the world, the optimal design can depend greatly on local environmental conditions. In the Netherlands, it remains unclear how the flowering performance of green roofs can be enhanced beyond the relatively short flowering period of commonly used *Sedum* species. This study investigates the effects of adding mineral wool and compost to experimental green roof systems in the Netherlands. Mineral wool was applied as a water-retentive substrate layer, while compost was added as a nutrient-amending component. Flower and seed production, as well as plant species richness, were used as indicators of flowering performance on the green roofs at ground level. The results showed that mineral wool significantly increases the number of flowers and seeds, and the overall richness of plant species, stimulating both sown and spontaneously colonising species. The addition of compost did not affect these parameters. These results reveal that green roof designs incorporating water-retentive substrate components can enhance flowering performance, and suggest an expansion of the flowering period of green roofs in the Netherlands. This study evaluates these results in the context of the current state of green roof construction and management in urban areas.

Introduction

In recent years, humanity has experienced a rapid shift towards urban living; more than half of the world's population now lives in urban environments (United Nations, 2018). This urban expansion is expected to continue, due to the increasing global population and the rising urbanisation rate (Grimm *et al.*, 2008; Alberti, 2015). In the process, this urban expansion has also precipitated major environmental changes around the world (Johnson & Munshi-South,

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2017). These include the destruction of habitats and the reduction in total green coverage, both of which are widely reported in urban areas and directly affect flora and fauna communities worldwide (McKinney, 2008). The effects of urbanisation on local flora and fauna communities can also work more indirectly, for instance through the effects of fragmentation on the population genetics of local communities (Dickman, 1987; Fischer & Lindenmayer, 2007). In addition, various studies have described urban areas as hotspots for the introduction of invasive species, which may contribute to local extinctions of native species (Sax & Gaines, 2003; Shochat *et al*., 2010). Many studies have reported that, as a result of these various effects, the abundance and diversity of native plant and animal species in urban areas might be strongly reduced (McKinney, 2008; Aronson *et al*., 2014), leading to the simplification and homogenisation of local urban food webs (McKinney, 2006; Aronson *et al*., 2017; Start *et al*., 2020). However, these studies have also reported increases in the richness of species in urban areas due to the creation of novel habitats and the presence of non-native and urban-adapted species.

Because of these global developments, there is an increasing interest from science and society in ways to improve the urban green space and its biodiversity (Elmqvist *et al*., 2013; Wu, 2014). In particular, many recent efforts to ensure sustainability focus on improving the green and blue infrastructure and enhancing ecological connectivity through the implementation of natural and semi-natural landscape elements within urban areas (Krivtsov, 2025). One approach to strengthening the urban green infrastructure is through the construction of green roofs. Various reports have emphasised the potential role of green roofs in different aspects of sustainability, including water and energy management (Berardi *et al*., 2014; Francis & Jensen, 2017). The vegetation on green roofs can help to counter the urban heat island effect – the phenomenon by which temperatures are higher in urban environments than in nearby rural areas (Susca *et al*., 2011; Razzaghmanesh *et al*., 2016). In addition, green roofs have been linked to various ecological benefits for a wide variety of local species (Oberndorfer *et al*., 2007; Threlfall *et al*., 2017; Mayrand & Clergeau, 2018). Utilising the vacant roofs of buildings and transforming them into green infrastructure could play a major role in stimulating urban biodiversity in the future, as this will increase the essential connectivity (Beninde *et al*., 2015), provide habitats for plants (Faeth *et al*., 2011; Aloisio *et al*., 2020), and supply habitats and food for animals. Earlier studies concluded that an 'extensive' design of green roofs can already support the spontaneous growth and spread of native plant species in the UK and France respectively (Bates *et al*., 2013; Madre *et al*., 2014). In addition, Wooster *et al*. (2022) concluded that extensive green roofs contained a significantly more diverse group of birds and arthropod species than regular, non-vegetated roofs in Sydney (Australia), while Fabián *et al*. (2021) showed that arthropod species richness on green roofs in Argentina was positively related to roof size and connectivity, with greater richness observed on larger and less isolated roofs. However, these studies also indicated that the composition of the substrate appeared to be crucial in the success of the green roof. The potential of green roofs for promoting biodiversity is thus well attested in the literature, but it is still not certain how the design of these green roofs can be optimised for promoting diversity in different urban environments around the world.

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At present, most (subsidised) green roofs have an extensive design with a thin substrate layer, while the vegetation is mostly *Sedum* species (Jungels *et al*., 2013; Blanusa *et al*., 2013). This set-up reduces the load on the structure due to substrate weight and water retention, and because it is relatively inexpensive and easy to maintain (Getter & Rowe, 2006). However, green roofs can also be enriched by planting species from a seed mix or by letting the growth of spontaneous species occur (Koroxenidis & Theodosiou, 2021). Accordingly, Faeth *et al*. (2011) argue that a focus on plants is essential to promote urban biodiversity, as animals can benefit indirectly from the increased availability of habitats and food. Various studies have shown that this intensive approach towards green roofs is potentially more biologically effective than more extensive green roofs because the roofs have a thicker substrate layer, allowing for the growth of herbs and shrubs. In the Netherlands, it is uncertain how extensive green roofs and their substrates can be optimised. A key question that remains is how the flowering period can be extended beyond the relatively short flowering peak of the *Sedum* species (late spring to mid-summer), to make them more attractive to insects. Previous studies have indicated that the optimal design of green roofs can vary for different types of ecosystem around the world, as the influence of variables such as (soil) moisture, temperature and nutrient availability on plant growth differs (Vijayaraghavan, 2016; Dusza *et al*., 2020). Earlier studies in Western Europe have proved that the substrate of the green roof is extremely important for the successful establishment of herb species on these roofs (Bates *et al*., 2013; Madre *et al*., 2014). Wang *et al*. (2022) concluded that drought is often an important factor in the development of plants on green roofs in Western Europe. Further research into these aspects of green roofing would not only improve our understanding of the impact of green roofs in urban areas in Western Europe, but also support efforts to manage these green roofs throughout the year. This involves both theoretical and practical challenges regarding the optimal design of green roofs, as well as implementation and management issues.

This study addresses several knowledge gaps concerning the design of green roofs and focuses on the effects of incorporating substrate amendments that influence water retention and nutrient supply on the flowering period of green roofs in the Netherlands. Specifically, it investigates the effect of incorporating mineral wool as a water-retentive substrate layer and compost as a nutrient-amending component on flowering performance in green roofs. Mineral wool has been shown to be suitable as a water-retentive layer in green roof systems (Pérez *et al*., 2025), and can contribute to regulating heat and moisture dynamics within the substrate (Kostadinović *et al*., 2022), thereby potentially influencing substrate moisture dynamics and flowering performance in green roofs. However, despite these proposed functional benefits, the ecological effects of incorporating mineral wool layers into green roof systems have received limited experimental attention, particularly with respect to vegetation performance and flowering dynamics. In addition, the thickness of water-retentive layers may play an important role in determining water storage capacity, drainage dynamics and plant water availability over time, which could ultimately affect flowering continuity and vegetation performance on green roofs.

As indicators of flowering performance and reproductive output, we quantified the number of flowers and seeds on adapted green roof set-ups at ground level. For these plant parameters, we examined the effects on sown herb species, the spontaneously arriving species and the *Sedum* species supplied as plugs. We also link this to whether these treatments influence the flowering period of these adapted green roofs. As drought has frequently been identified as a key limiting factor for plant establishment on green roofs (Vijayaraghavan, 2016; Wang *et al.*, 2022), we hypothesise that the addition of a mineral wool layer, which increases water retention in the substrate, will enhance flowering success, expressed in terms of number of flowers and seeds and the richness of species in constructed green roofs. Based on previous pilot studies suggesting that nutrients are generally not limiting in this system (Moerland, 2011; Tanis, 2020; De Grooth, 2024), we expect that compost addition will have no significant effect on flowering success.

Materials and methods

Study site and experimental set-up

This study was performed at the facility of Universal Greenfields in Katwijk aan Zee, Zuid-Holland, in the Netherlands. Here, the set-up of an extensive green roof was imitated within 12 separate roofs at ground level (Fig. 1). Each of the roofs measured 3.5 × 3.5 m and was divided into four

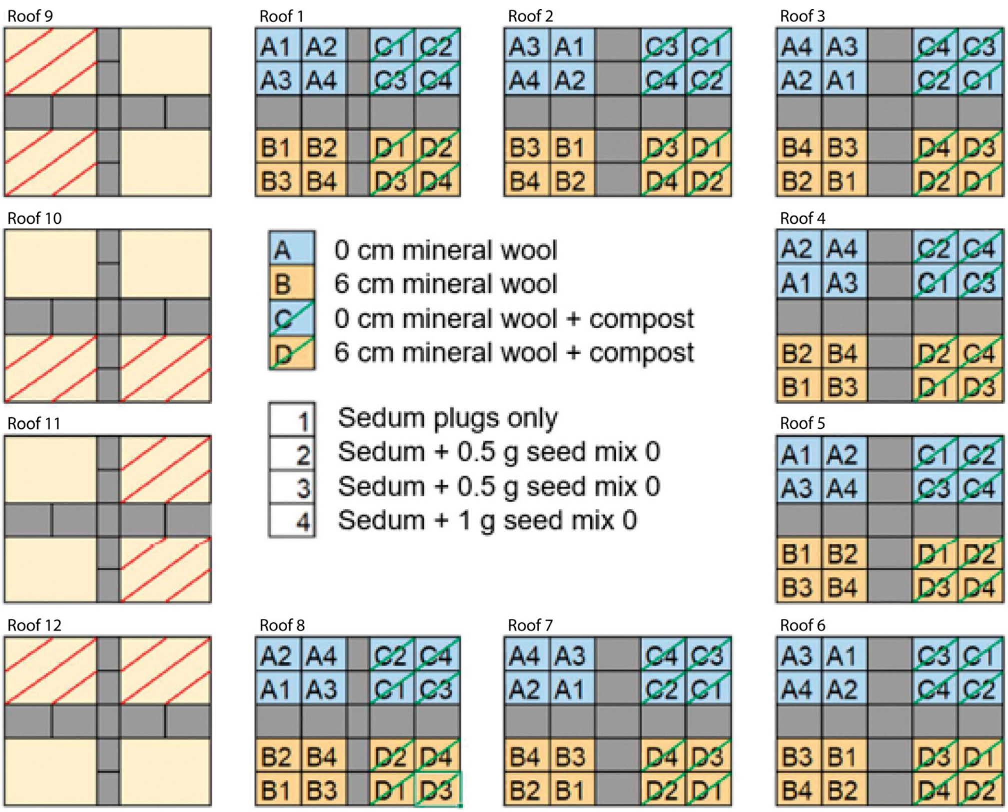

Fig. 1 Experimental green roof set-up at Universal Greenfields. Details of the set-up of roofs 1–8 and the treatments used in this experiment. Diagram drawn by Dirk Roosendaal.

quadrants of 1.5 × 1.5 m. In between the four quadrants, a cross of tiles (each tile being 30 × 30 × 5 cm) was constructed as a walkway. The outer edge of each roof was fenced off with 10 cm of wooden sleepers. The construction further consisted of a drainage layer (11 mm), a substrate layer (5 cm) and a vegetation layer (Fig. 2). The four quadrants in each roof were trimmed off with a plastic cord. Roofs 1–8 of this set-up were used for this experiment (Fig. 1). Each of the roofs was divided into quadrants designated A, B, C and D (Fig. 1) and different treatments using mineral wool and compost were applied. All quadrants A contained no mineral wool but a 6-cm Styrofoam® layer; quadrants B contained 6 cm of mineral wool (130 kg/m^3); quadrants C contained no mineral wool but a 6-cm (neutral) Styrofoam® layer plus a layer of compost (0.5 cm); and quadrants D contained 6 cm of mineral wool (130 kg/m^3) plus a layer of compost (0.5 cm). For all quadrants, a seed mix containing 14 endemic plant species was sown (seed mix 0; see Table 1), with different quantities throughout (0, 0.5 or 1 g, in accordance with Fig. 2), although these different quantities were not taken into account further in the results. Also, in all eight roofs, sedum plugs were planted.

Parameters of plant performance

All roofs were analysed eight times between March and September 2024 (Table 2). During each sampling round, the number of flowering units and seeds within each quadrant for every plant species was counted. This also allowed the number of flowering species per quadrant to be determined. All measurements were conducted by one trained observer, who was following a standardised protocol to ensure consistency across sampling rounds. Within this protocol, the number of flowers per species was counted according to the following assumptions: flowering units are defined as all the distinct, individual flowers of a plant species. For flowering heads (inflorescences), the number of flowers was estimated as accurately as possible.

The green roofs used in this study were originally part of an earlier experiment that also included subquadrant-level treatments, such as variation in the quantity of seeds sown in the plot and whether weeds were removed (as indicated by the numbers following the letters A, B, C and D in Fig. 1). However, these additional treatments were not part of the objectives of the present study, which focused on overall flowering responses

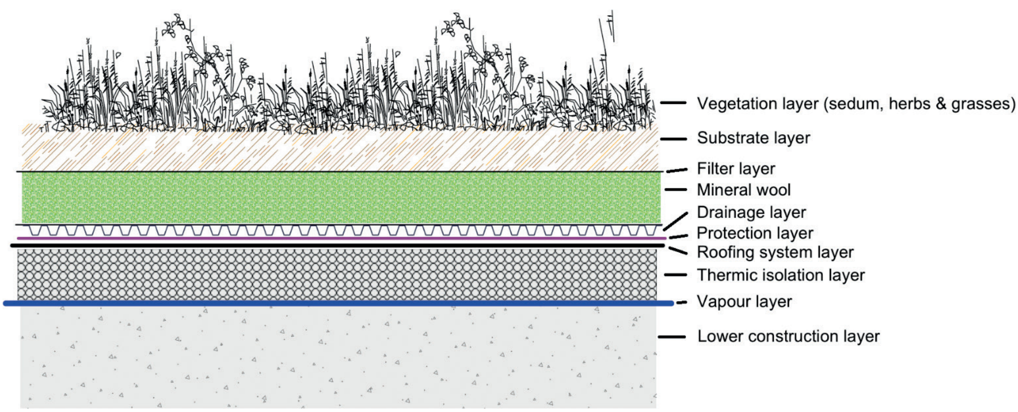

Fig. 2 General set-up of the green roofs at Universal Greenfields. Diagram drawn by Dirk Roosendaal.

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Table 1 Species in the seed mix (seed mix 0) sown in this experiment.

Species	Common Dutch name	Flowering period	Height (cm)
Veronica chamaedrys	Gewone ereprijs	April–June	10–30
Hieracium pilosella	Muizenoor	May–June	5–20
Plantago media	Ruige weegbree	May–July	25–40
Lotus corniculatus	Rolklaver	May–September	10–40
Prunella vulgaris	Bijenkorfje/Brunel	May–September	5–40
Thymus pulegioides	Grote tijm	May–September	5–10
Jasione montana	Zandblauwtje	June–August	10–30
Origanum vulgare	Wilde marjolein	June–September	30–60
Dianthus deltoides	Steenanjer	June–September	15–35
Trifolium arvense	Hazenpootje	June–October	10–35
Campanula rotundifolia	Grasklokje	June–October	15–40
Dianthus armeria	Ruige anjer	July–August	30–45
Clinopodium vulgare	Borstelkrans	July–September	30–60
Teucrium chamaedrys	Echte gamander	July–September	15–30

Table 2 Details of the eight sampling rounds.

Sampling round	Roof	Sampling date
R1	1–8	16-3-2024
R2	1–8	13-4-2024
R3	1–8	26-4-2024
R4	1–8	23-5-2024
R5	1–8	20-6-2024
R6	1–8	18-7-2024
R7	1–8	13-8-2024
R8	1–8	12-9-2024

of green roof systems. Preliminary analyses indicated no meaningful differences in the number of flowers between subquadrants 1, 2, 3 and 4 for the considered response variables. Consequently, only subquadrants 1 and 3 were used as the primary experimental units, as these represented the most consistent configuration across roofs and allowed for a simplified and standardised comparison of flowering metrics.

Based on these counts, the total numbers of flowers, seeds and species per treatment were calculated and used as indicators of flowering performance and reproductive output for each sampling round. Flower counts were not interpreted as direct measures of plant growth, but as indicators of reproductive output and flowering activity. Next, the trends for each treatment were visualised over time with line graphs, using the mean and the standard deviation (SD) over all the roofs (repetitions), to distinguish between the treatments. In addition, the total number of species was also divided into species from the seed mix, spontaneously growing species and *Sedum* species in a secondary analysis, in order to differentiate these plant groups. These values

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were visualised in clustered stacked bar graphs, allowing an assessment of whether the treatments promoted one of these plant groups specifically. Finally, the flower units of the *Sedum* species were examined to investigate whether these species also benefit from the treatments in terms of flowering.

Parallel exploratory experiment (Appendix)

In addition to the main experiment (6-cm mineral wool layer), a parallel exploratory experiment was conducted using a 3-cm mineral wool layer (on roofs 9–12 within the same experimental set-up; Fig. 6) to assess the effect of reduced substrate thickness on flowering performance. However, this parallel experiment also included additional variation in (1) seed mix composition and (2) sedum establishment, which prevented direct statistical comparison with the main experiment. These exploratory results are therefore presented separately in the Appendix.

Data analysis

All statistical analyses were conducted in R (version 4.5.1) (R Core Team, 2025). The effects of the experimental treatments on the plant response variables (flower count, seed count and the number of species) was analysed using generalised linear mixed models (GLMMs), to account for the experimental design and repeated measurements over time. Because the response variables consisted of count data and exhibited overdispersion, models were fitted using a negative binomial error distribution with a log link function (function glmer.nb() in the package lm4). Treatment effects were analysed in a factorial framework, in which treatments were decomposed into two experimental factors: compost addition (present/absent) and mineral wool addition (present/absent). This allowed for the estimation of the main effects of compost and mineral wool, as well as their interaction. For each response variable, compost, mineral wool and their interaction were included as fixed effects. To account for spatial and temporal non-independence in the data, roof (8 levels) and sampling date (8 levels) were included as random intercepts. The models for each response variable were structured as follows (where 'response' refers to the number of flowers, seeds or total number of species):

*glmer.nb(Response ~ Compost * Mineral Wool + (1|Roof) + (1|Date), data = Test)*

Model assumptions were evaluated by inspection of residual diagnostics and by confirming that overdispersion was adequately accounted for by the negative binomial distribution. For comparison, the non-parametric Kruskal–Wallis tests and Dunn's post-hoc tests were initially explored for the plant parameter data, but these were not used for final inference because they do not account for the roof structure or repeated measurements over time.

Results

Plant performance parameters

The number of flowers, seeds and species differs greatly among the treatments over time (Fig. 3). For all three parameters of vegetational success (flowers, seeds and species), the peak in summer is substantially higher in the treatments with mineral wool (B and D) compared to the treatments without mineral wool (A and C). This disparity is especially prominent for the number of flowers, where the peaks in R6 for treatments B and D are approximately 3–4 times higher than for the two treatments without mineral wool (Fig. 3A). Interestingly, the number of flowers, seeds and species is fairly similar across the four treatments throughout the first few sampling rounds (R1–R3/4), but the treatments start to produce different results from about R5 onwards. For the number of species (Fig. 3C), there is a difference from the start, in favour of the treatments with mineral wool, but this difference becomes greater over time. During sampling rounds 7 and 8, the trendlines of the four different treatments converge slightly but remain higher for the treatments with mineral wool. For all three variables, the presence of the mineral wool layer has a distinct effect. The addition of compost did not increase or decrease any of these response variables.

A series of GLMMs, with a negative binomial distribution and log link, were used to assess the effects of adding compost and mineral wool on plant performance. Flower production was significantly affected by mineral wool addition ($p < 0.001$), whereas adding compost had no significant effect ($p = 0.263$). The interaction between compost and mineral wool was not significant ($p = 0.528$), indicating that the combination of compost and mineral wool does not further affect the number of flowers compared to the presence of mineral wool on its own. A similar pattern was observed for species richness, where mineral wool significantly increased the number of species ($p < 0.001$), whereas compost had no significant effect ($p = 0.159$). The interaction term was marginally non-significant ($p = 0.055$). For seed production, the presence of mineral wool also had a significant effect ($p < 0.001$). Compost had no significant effect ($p = 0.160$), but a significant interaction between compost and mineral wool was also detected ($p = 0.041$).

The variance attributed to the specific roof (1–8) was small for all three response variables (flowers: $\sigma^2 = 0.022$; seeds: $\sigma^2 = 2.982 \times 10^{-11}$; species: $\sigma^2 = 0.002$), indicating limited spatial variation among roofs. In contrast, variation among sampling dates was more pronounced:

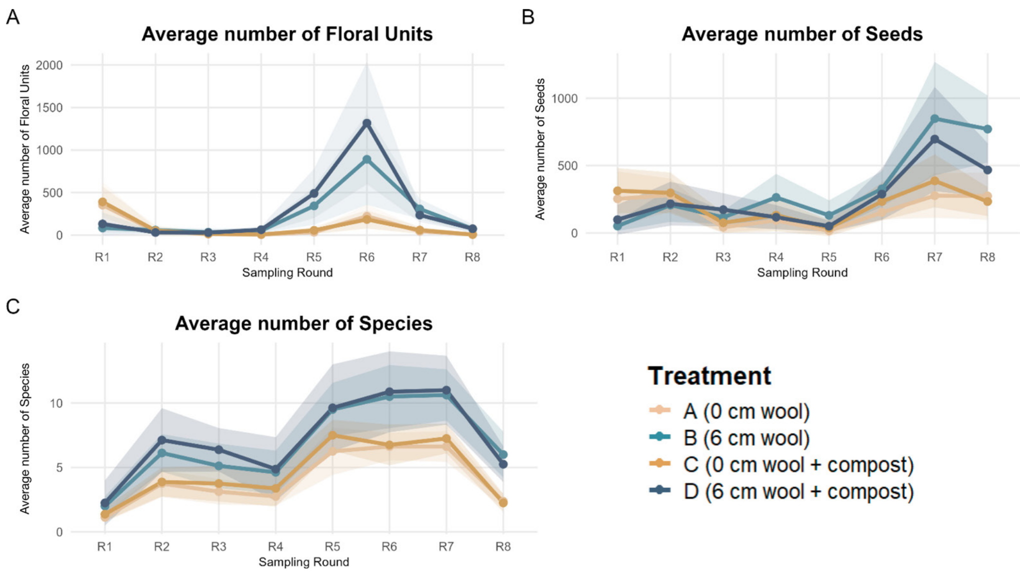

Fig. 3 Development of the number of floral units (**A**), seeds (**B**) and flowering *Sedum* species per treatment (**C**) over time. Each line represents the data from a specific treatment (A, B, C or D), whereas the colour represents the thickness of the mineral wool layer and the addition of compost, according to the legend in the bottom right corner. The transparent frame around the lines represents the standard error.

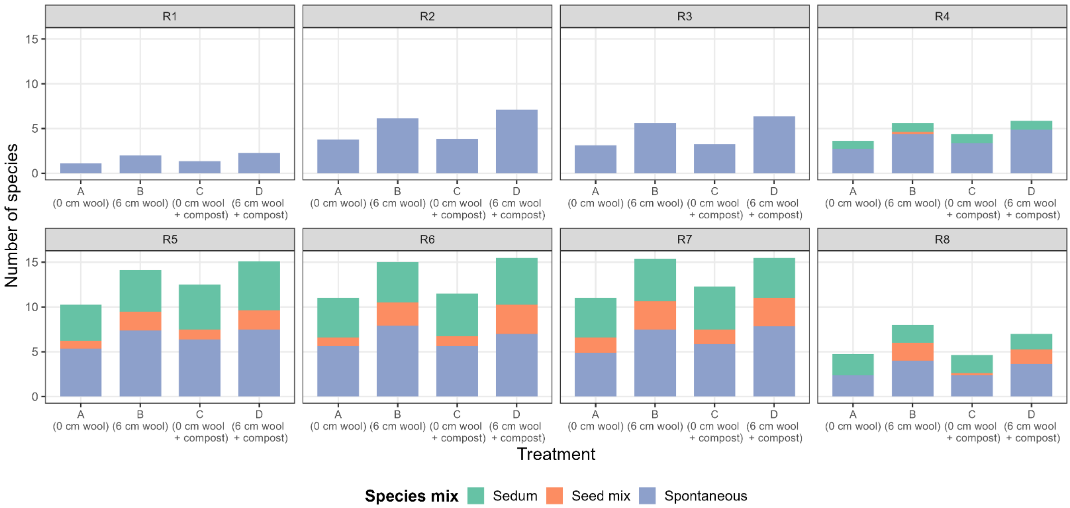

Fig. 4 Distribution of the number of plant species into species from the seed mix, spontaneously growing species and *Sedum* species shown as distinct colours in each bar as per the legend. Each panel represents one of the sampling rounds, whereas the categories represent the four treatments.

for flower counts ($\sigma^2 = 1.400$), for seeds ($\sigma^2 = 0.431$) and for species richness ($\sigma^2 = 0.148$).

Breakdown of the number of species

If the total number of species is further divided into species from the seed mix, spontaneously growing species and *Sedum* species, there are notable differences in the species composition of the four treatments (Fig. 4). Most interestingly, the number of spontaneous growing (and flowering) species was higher in the treatments with mineral wool (B and D) than in the treatments without mineral wool (A and C). This pattern is already prominent in the first few sampling rounds, and the distinction persists or increases further throughout the season. Although it is slightly less evident, this is also the case for the seed mix species, whereas the number of *Sedum* species is similar among the four treatments.

A series of GLMMs with a negative binomial distribution and log link were used to assess the effects of adding compost and mineral wool on the species composition. Mineral wool significantly increased the number of spontaneous species ($p < 0.001$), whereas compost had no significant effect ($p = 0.459$). No significant interaction was found between compost and mineral wool ($p = 0.804$). A similar pattern was observed for species originating from the seed mix. The quadrants with mineral wool contained significantly more seed mix species ($p < 0.001$), whereas the addition of compost had no significant effect ($p = 0.661$). The interaction between compost and mineral wool was also not significant, indicating that the addition of compost did not have any additional influence (positive or negative) on the presence of the mineral wool. In contrast, the number of *Sedum* species did not differ significantly among treatments. Neither compost ($p = 0.666$) nor mineral wool ($p = 0.464$) had a significant effect and no interaction between the two factors was found ($p = 0.884$). The variance was very low for all three species groups (spontaneous species: $\sigma^2 = 0.009$; seed mix species: $\sigma^2 = 0.020$; *Sedum* species: $\sigma^2 = 3.83 \times 10^{-10}$). Variation among sampling dates was higher for the seed mix species ($\sigma^2 = 8.882$) and

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Sedum species ($\sigma^2 = 12.140$), whereas it was comparatively lower for spontaneous species ($\sigma^2 = 0.248$), suggesting stronger temporal dynamics in the planted species group compared to the other two groups of species.

Sedum analysis

Peak sedum flower production in roofs 1–8 was substantially higher in the treatments containing mineral wool (B and D) compared to the treatments without mineral wool (A and C) (Fig. 5). No sedum flowered during the first three sampling rounds, but from sampling round 4 onwards the lines of the treatments began to diverge. Although flower numbers declined towards the final sampling rounds, the treatments with mineral wool (B and D) maintained slightly higher numbers than treatments without mineral wool (A and C) in the last sampling round (R8). The number of sedum flowers was also analysed using a GLMM, with a negative binomial distribution and log link function. However, no significant effects of mineral wool or compost were found, nor was there an interaction between the two factors (all $p > 0.05$). The model indicated a very strong effect of sampling round ($\sigma^2 = 31.61$), whereas variation among roofs was relatively small ($\sigma^2 = 0.096$). This suggests that sedum flowering dynamics were driven primarily by temporal variation, which is evident from Fig. 5, as the number of flowers was generally very low outside its peak.

Discussion

This study examined the effects of incorporating mineral wool and compost into experimental green roof systems in the Netherlands. These effects were assessed by analysing flowering-related parameters within adapted green roof set-ups, including flower production, seed production and species richness. The results showed that the quadrants with 6 cm mineral wool had a significantly higher number of flowers, seeds

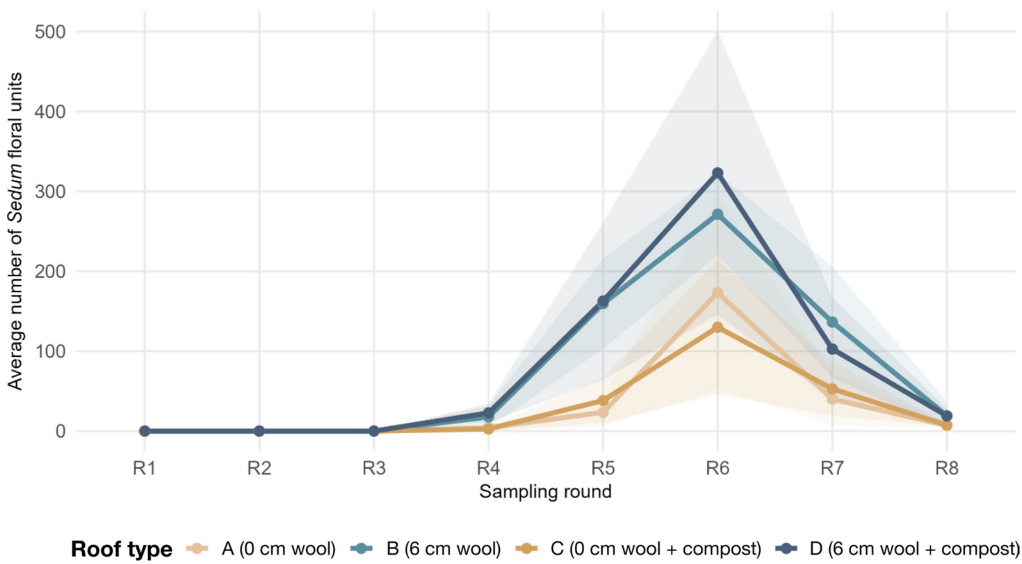

Fig. 5 Average number of *Sedum* floral units counted in each roof over time. Each line represents the data from a specific treatment, whereas the similar colours represent the thickness of the mineral wool layer: yellow illustrates the treatments with 0 cm wool and blue the treatments with 6 cm mineral wool. The transparent frame around the lines represents the standard error of the mean.

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and plant species than the quadrants without mineral wool, and that this distinction was especially notable during the summer months. In contrast, the addition of compost did not significantly affect any of the measured flowering period parameters. Mineral wool also significantly enhanced both the establishment of species from the sown seed mix and that of spontaneously colonising species, resulting in a more abundant and diverse flower community overall, explaining the increased species richness. Although *Sedum* species richness did not increase, the number of flowers was higher in the treatments with mineral wool. However, these differences were not statistically significant, probably because flowers were absent during a substantial part of the sampling period, resulting in many identical values across treatments outside the flowering peak. The findings indicate that incorporating water-retentive substrate layers can enhance flowering performance and species richness in experimental green roof systems in the Netherlands, whereas compost addition showed no measurable effects within this set-up.

During the initial sampling rounds in spring, the three plant performance parameters (number of flowers, seeds and species) were similar across the four treatments, although slightly more spontaneous colonisation was observed in the treatments containing mineral wool. However, clear differences emerged during the summer sampling rounds, when the treatments containing mineral wool consistently outperformed the treatments without it. Not only were the peak numbers of flowers, seeds and species substantially higher, but these values also remained elevated during the later sampling rounds, indicating a modest extension of the flowering period, which was one of the aims of this study. This suggests that the incorporation of the mineral wool layer may have helped to maintain favourable growing conditions during the warmer and drier summer months, thereby sustaining flowering activity over a longer period of time. The experiment also indicated that both sown species and spontaneously colonising species benefited from the presence of the mineral wool, as reflected in their species richness. The higher number of unique spontaneously occurring species in the mineral wool treatments further suggests that the conditions may have increased the suitability of the habitat for spontaneous colonisation. Although there was probably competition for the limited space, there was still space for both seed mix growth and spontaneous colonisation. Although substrate moisture was not directly quantified throughout the experiment (due to technical limitations with installed iButton sensors), the observed vegetation responses were consistent with the expected water-retentive properties of mineral wool described in previous studies (Pérez *et al*., 2025; Kostadinović *et al*., 2022).

An important next step would be to further investigate the optimal thickness of the mineral wool layer, as a fully saturated 6-cm layer may exceed the load-bearing capacity of common roof constructions. The parallel exploratory experiment explored this and showed a higher peak in flower, seed and species numbers (Fig. 7) than the 6-cm treatment. However, there was no clear extension of the flowering period in the final sampling rounds, unlike the 6-cm treatment. These contrasting flowering dynamics between the 3-cm and 6-cm layers may be explained by the hydraulic properties of mineral wool: a thinner layer may saturate more rapidly and makes water immediately

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available to plants, thereby promoting high short-term productivity. However, it may also dry out more quickly, limiting sustained flowering later in the season. Moreover, the number of species in the seed mix and the presence of sedum scatter appeared to have a small influence on spontaneous colonisation of other plant species (Figs 8–9), suggesting that there is increased competition for the limited space within this green roof set-up. Overall, these exploratory findings suggest that the ecological effects of mineral wool in green roof systems may depend not only on its presence, but also on layer thickness.

The patterns observed in this study are consistent with a substantial body of research about green roofs, highlighting the importance of substrate characteristics for vegetation performance and biodiversity. Various studies have demonstrated that water-holding capacity and substrate composition are key determinants of plant performance, species richness and vegetation dynamics on vegetated roofs (Durhman *et al*., 2007; Tan *et al*., 2017; Young *et al*., 2017). The importance of substrate characteristics – including depth, composition and water-holding capacity – has been widely emphasised in studies demonstrating the influence of green roofs on plant survival, diversity and ecosystem functioning (Getter & Rowe, 2009; Bates *et al*., 2013; Madre *et al*., 2014). Deeper and more water-retentive substrates generally buffer more water during peak evapotranspiration, reduce plant drought stress, and thereby support greater plant coverage and species richness compared to shallow, low-moisture substrates typical of extensive green roofs (Thuring *et al*., 2010; Van der Kolk *et al*., 2023). Besides, previous research in Western Europe has likewise identified drought mitigation as an important determinant of green roof performance and long-term vegetation persistence (Wang *et al*., 2022). By enhancing water availability without drastically increasing substrate depth, the incorporation of mineral wool may offer a feasible strategy for improving plant performance and floral resource continuity, emphasising its ecological potential in green roof systems. While previous studies have primarily focused on vegetation cover, or species richness, fewer have explicitly examined flowering dynamics and seasonal continuity of floral resources in relation to engineered water-retention layers.

By improving the conditions for vegetation establishment, mineral wool treatments could also indirectly support urban pollinator communities on green roofs (MacIvor & Lundholm, 2011; Lönnqvist *et al*., 2021; Drukker *et al*., 2025). Studies comparing extensive and intensive green roof systems consistently show that greater substrate depth and structural complexity are associated with higher biodiversity, including invertebrate species (for example, Moerland, 2011; Nevermann *et al.,* 2025). Preliminary pilot studies alongside our experiments have observed higher numbers of insect visitors in the treatments containing mineral wool than in the ones without (Tanis, 2020; De Grooth, 2024). At the same time, various studies have described how green roof performance can also be dependent on the surrounding environment (for example, Kazemi & Mohorko, 2017). Consequently, while the general patterns observed in this study may be broadly applicable, the magnitude and speed of vegetation responses are likely to vary across environments and climatic conditions. Besides, our experimental modules were located at ground level, whereas dispersal limitations and rooftop microclimatic conditions may constrain spontaneous colonisation on elevated roofs in urban settings. Previous studies have likewise shown that green roof plant communities change over time and are influenced by factors such as roof height, water-holding capacity and plant traits (Ksiazek-Mikenas & Köhler, 2018).

Green roofs thus have the potential to stimulate urban biodiversity while simultaneously contributing to climate adaptation and ecosystem functioning in cities. By increasing habitat availability and structural heterogeneity, green roofs can support a community of (native) plant species, invertebrates, pollinators and birds that is capable of colonising rooftop environments (Oberndorfer *et al*., 2007). In the context of ongoing urban biodiversity loss (McKinney, 2008; Aronson *et al*., 2017), optimising green roof design represents a promising strategy for strengthening urban green infrastructure. In addition, expanding the number of vegetated surfaces within urban areas contributes to stormwater retention, mitigation of the urban heat island effect and improved building energy performance (Berardi *et al*., 2014; Francis & Jensen, 2017; Krivtsov, 2025). Nevertheless, while increasing the thickness of a water-retention layer may enhance flowering duration, practical considerations – such as roof load capacity and aesthetic preferences regarding taller spontaneous vegetation – are also important. Management regimes may therefore need to be adapted depending on desired vegetation structure and local acceptance of less conventional, more dynamic plant communities. However, continued optimisation of substrate composition and structural design will be key factors in maximising their long-term ecological and climatic benefits.

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Appendix: Parallel exploratory experiment with 3 cm of mineral wool

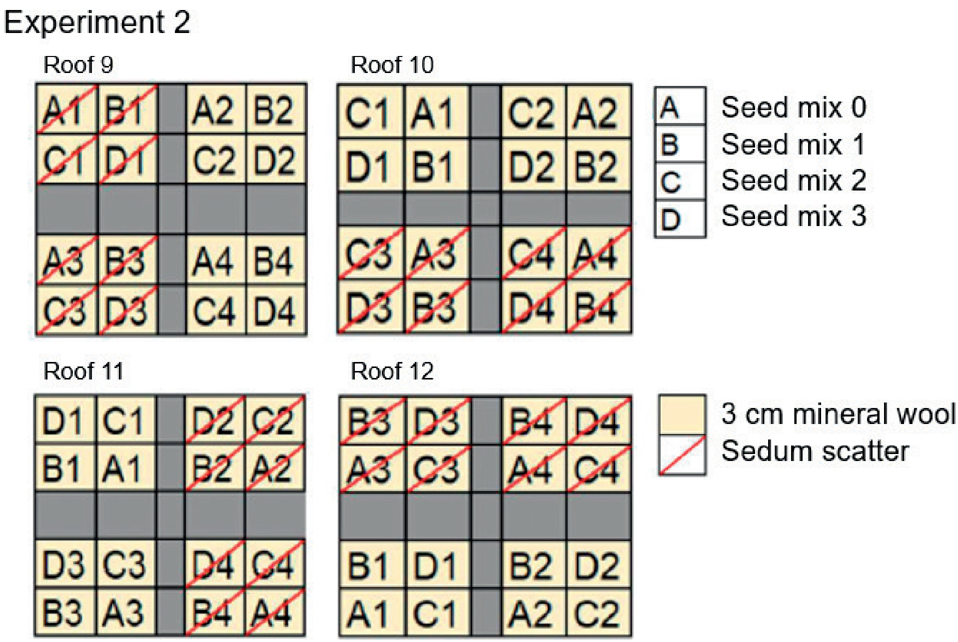

Fig. 6 Set-up of roofs 9–12 used for a separate experiment. The treatments, the sown seed mix (A–D) and the presence of *Sedum* scatter were double randomised in the quadrants (that is to say, each of A1, A2 etc. is in a different plot in each roof set-up).

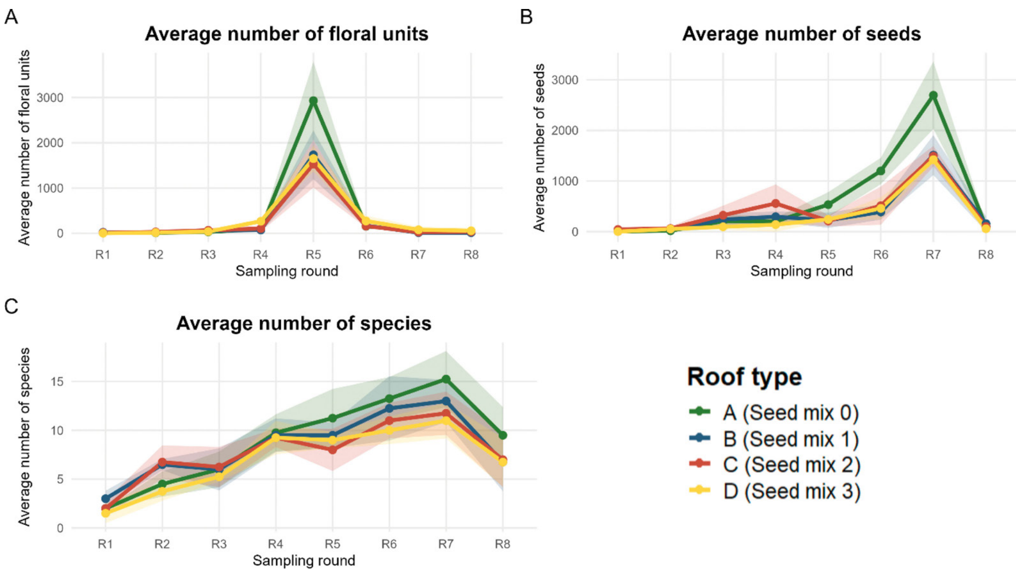

Fig. 7 Average number of floral units, seeds and plant species on the four roofs in Experiment 2. Each colour represents the data from a specific treatment (A, B, C or D) – in this case, different seed mixes according to the legend in the bottom right corner. Treatment A (seed mix 0) contained 14 species, while the others contained 7 species. For details, see Table 3. The transparent frame around the lines represents the standard error.

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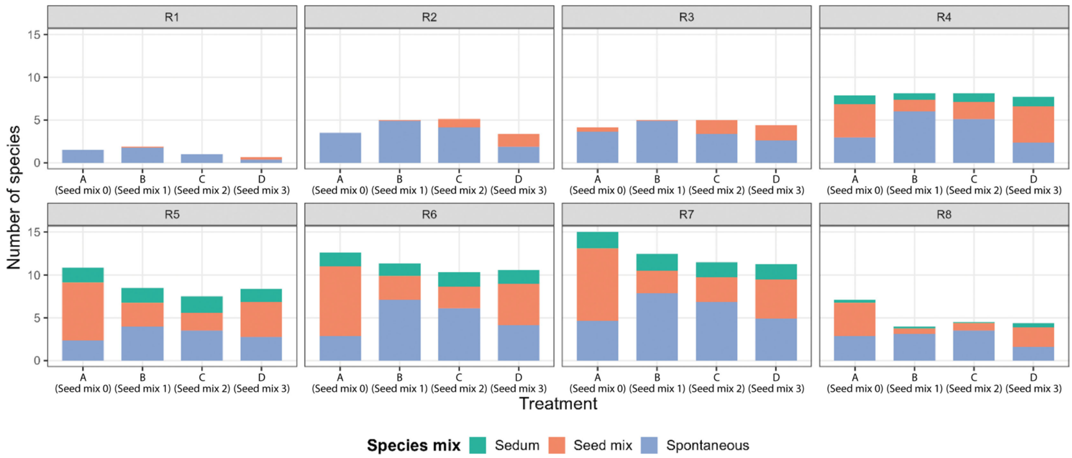

Fig. 8 Distribution of the number of species in roofs 9–12 (3 cm mineral wool) into species from the seed mix, spontaneously growing species and *Sedum* species. Each panel represents one of the sampling rounds, whereas the categories represent the four treatments. (Seed mixes: mix A contained 14 species; mixes B, C and D each contained 7 species. For details, see Table 3.)

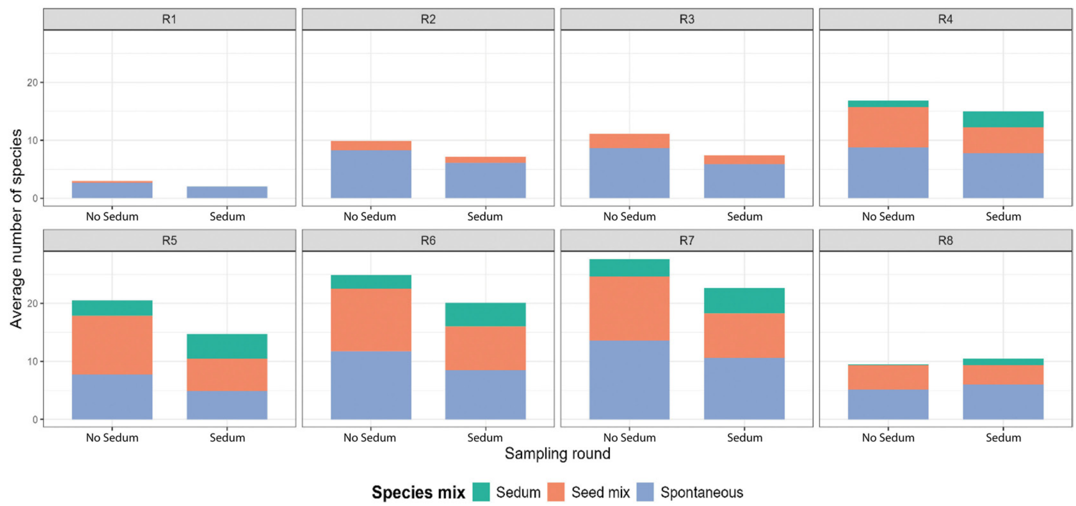

Fig. 9 Distribution of the number of species in roofs 9–12 (3 cm mineral wool) into species from the seed mix, spontaneously growing species and *Sedum* species. Each panel represents one of the sampling rounds, whereas the categories indicate whether *Sedum* was planted in a quadrant or not.

Table 3 Seed mixes used in the second experiment.

Seed mix	Species	Common Dutch name	Flowering period	Height (cm)
0	*Veronica chamaedrys*	Gewone ereprijs	April–June	10–30
	Hieracium pilosella	Muizenoor	May–June	5–20
	Plantago media	Ruige weegbree	May–July	25–40
	Lotus corniculatus	Rolklaver	May–September	10–40
	Prunella vulgaris	Bijenkorfje/Brunel	May–September	5–40
	Thymus pulegioides	Grote tijm	May–September	5–10
	Jasione montana	Zandblauwtje	June–August	10–30
	Origanum vulgare	Wilde marjolein	June–September	30–60
	Dianthus deltoides	Steenanjer	June–September	15–35
	Trifolium arvense	Hazenpootje	June–October	10–35
	Campanula rotundifolia	Grasklokje	June–October	15–40
	Dianthus armeria	Ruige anjer	July–August	30–45
	Clinopodium vulgare	Borstelkrans	July–September	30–60
	Teucrium chamaedrys	Echte gamander	July–September	15–30
Seed mix				
1	*Veronica chamaedrys*	Gewone ereprijs	April–June	10–30
	Bellis perennis	Madeliefje	April–September	5–15
	Prunella vulgaris	Bijenkorfje/Brunel	May–September	5–40
	Thymus pulegioides	Grote tijm	May–September	5–10
	Hypochaeris radicata	Gewoon biggenkruid	June–September	15–80
	Centaurea jacea	Knoopkruid	June–September	30–120
	Achillea millefolium	Gewoon duizendblad	June–October	15–70
Seed mix				
2	*Geranium pyrenaicum*	Bermooievaarsbek	April–September	20–60
	Silene dioica	Dagkoekoeksbloem	April–October	30–90
	Plantago lanceolata	Smalle weegbree	May–September	10–80
	Origanum vulgare	Wilde marjolein	June–September	30–60
	Hieracium umbellatum	Schermhavikskruid	July–September	30–120
	Scabiosa columbaria	Duifkruid	July–September	30–80
	Campanula rotundifolia	Grasklokje	June–October	15–40
Seed mix				
3	*Erodium cicutarium*	Reigersbek	April–October	10–60
	Hieracium pilosella	Muizenoor	May–June	5–20
	Echium vulgare	Slangenkruid	May–September	30–120
	Linaria vulgaris	Vlasbekje	May–October	30–60
	Origanum vulgare	Wilde marjolein	June–September	30–60
	Dianthus deltoides	Steenanjer	June–October	15–35
	Achillea millefolia	Gewoon duizendblad	June–October	15–70

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