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Establishing a biodiverse meadow roof in Oslo, Norway:

An evaluation of the effect of soil type and soil depth on sown native and local species and spontaneously colonizing species

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Natural Resource Management

Preface

This thesis marks the end of my master's degree within Natural Resource Management at the Norwegian University of Life Sciences (NMBU).

I would like to especially thank the two supervisors who have supported me the most; Jonathan Colman (NMBU) and Hans Martin Hanslin (NIBIO). Your help has been essential, and I could not have done it without you. Also a special thanks to my field work partner, Songweh Thierry. Furthermore, a thank you to Diress Tsegaye Alemu (UiO) for helping with the statistics, to Alexius Folk and Leif Ryvarden (UiO) for assisting in species determination, to Tore Krokstad (NMBU) and Trond Børresen (NMBU) for guidance regarding soil analyses, to Irene Dahl (NMBU) and Claus D Kreibich (NMBU) for assisting in soil analyses, to Erik Trond Aschehoug (NMBU) for assisting in AGB analyses, and a big thank you to Tore Faller for letting us use a space within Geitmyra skolehage for the experiment. Also thank you to Kjetil Flydal (UiO) for advice regarding the experiment setup, and his wife, Monica Jenstad (lector at Ullern vgs), for letting us teach your high school students at the experimental site. A last thanks to friends and family who have helped with the practicals surrounding the experimental setup and for all emotional support.

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Abstract

The loss of biodiversity is happening faster now than ever in human history, being mainly driven by changes in land use. Concurrently, cities are expanding and are expected to reach over 1.2 million km^2 within 2030. The question arises as to whether urban architecture can provide win-win solutions benefitting urban expansion, economic growth and preservation of biodiversity. Green roofs have the benefit that they do not compete with other building activity, simultaneously supporting ecosystem services like storm water management, temperature regulation and those related to green vegetation. Now, scientists are requesting that green roofs are considered as a tool for preserving biodiversity to a higher extent.

This main aim of this study was to investigate how three soil types in factorial combination with two soil depths affected the establishment of a biodiverse meadow roof in Oslo, the capital of Norway. Twenty-six native and local meadow species were sown with 15 seeds each in 18 plots simulating green roofs in summer 2019. The six treatments mainly manipulated soil nutrients, soil pH, soil water-holding capacity and soil moisture. Meadow roof establishment was evaluated based on seedling emergence, survival and death, and flowering probability and mortality, as well as diversity indices and above ground biomass (AGB). Both sowed species and spontaneously colonized seedlings were recorded.

The results demonstrated that it is possible to establish meadow roofs in Oslo, but supplementary irrigation in dry periods seem necessary to prevent seedling death. 21 out of 26 sowed species and at least 21.2% of all sowed seeds emerged and survived the summer. 1058 colonized seedlings were recorded, representing 37 different species. It may seem like colonized seedlings can affect green roof vegetation considerably, as the domination of two colonized species reduced the Shannon Wiener diversity in the plots they inhabited. Few interactions between soil type and soil depth were recorded, and no singular treatment was best in terms of the variables measured. Based on the results, soil type SC and soil depth 30 cm seem most promising in terms of meadow roof establishment, relating to the highest nutrient content and water-holding capacity. The results suggest that meadow roofs need to have a higher soil water and nutrient content than meadow ground sites. Yet, a multitude of research done on green roofs recommend carefulness when interpreting data from new established roofs, as succession and interspecies competition imposes changes in plant communities over time. Consequently, this experiment should be followed over the next years to determine the long-time effect of the treatments on meadow roof performance.

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1. Introduction

Both nature and nature’s contributions to people are vital for human existence and well-being (Bowman et al., 2018; IPBES, 2019). Now, we are facing two major global challenges threatening human societies; climate change and the loss of biodiversity, both driven by human activity (IPBES, 2019; IPCC, 2013).

The loss of biodiversity is happening faster now than ever in human history (IPBES, 2019), and various scientists are claiming we are currently facing the sixth major extinction event in the history of the Earth (e.g. Barnosky et al., 2011; Ceballos et al., 2015). The main driver of global population decline and extinction is changes in land use (IPBES, 2019). Changes in land use affect species as habitats are being degraded, reduced, fragmented or removed entirely (Bowman et al., 2018). Changes in land use is also the main driver of extinctions of species in Norway, where 90% of all threatened species are evaluated to be negatively affected by changes in land use (Henriksen & Hilmo, 2015).

Cities and infrastructure linked to a growing population represent the second biggest form of land use change globally, following conversion to agricultural land (IPBES, 2019). Even if there is a high variety of habitats in many cities, housing many unique species, studies show that urban areas impose changes in community compositions (Kowarik, 2011). For example, the number of local species, species demanding large areas and specialist species are declining, while the number of invasive species and generalist species are increasing (Kowarik, 2011). Research indicate that this is because of an unnaturally high number of small patches, increasing habitat heterogeneity but simultaneously reducing habitat area and habitat connectedness (Kowarik, 2011). The increase in number of invasive species is likely caused by human-mediated dispersal combined with an increase in edge effects following habitat fragmentation (Kowarik, 2011).

The land area consisting of cities and urban areas is expected to increase (UNFPA, 2007). Seto et al. (2012) predicted that the urban land cover will reach 1.2 million km^2 within 2030, nearly tripling the global land area of year 2000. The challenge for planners is to find solutions that can unify urban expansion, preservation of biodiversity and conservation of the ecosystem services that nature provides. The question arises as to whether urban architecture can help in countering the environmental problems cities brings them, and whether there exist win-win situations where urban expansion and economic growth in cities can be fulfilled in a way that also reduces the negative effects of climate change and preserves or at the best increases biodiversity (Francis & Lorimer, 2011; Rosenzweig, 2003).

Green (vegetated) roofs represent such a possibility (Francis & Lorimer, 2011). Green roofs benefit an urban environment in that they do not compete with other building activity, and do not contribute to land-use pressure (Madre et al., 2014). Moreover, some studies have found that green roofs are mostly regarded as aesthetical and can promote human well-being in urban areas (Jungels et al., 2013). Additionally, there is substantial research supporting evidence of green roofs having benefits to both the economy and the environment (Getter & Rowe, 2006). Getter and Rowe (2006), reviewing the knowledge regarding the benefits of green roofs, found that green roofs can help in stormwater management, energy conservation and mitigation of the urban heat island effect, reducing the negative effects of abundant impervious surfaces in cities. Current research regarding biodiversity on green roofs argue that green roofs can provide suitable habitat for animal and plant species which have the mobility to reach green roofs and are adapted to extreme local conditions (moisture stress, extreme temperatures, high light and wind intensities (Dunnett & Kingsbury, 2008, cited in Oberndorfer et al., 2007)) (Brenneisen, 2006). Some birds (Baumann, 2006) and an array of plants (Gabrych et al., 2016; Madre et al., 2014) and invertebrates (Braaker et al., 2014; Kadas, 2006) have been documented on a variety of green roofs in several countries, and some studies have even found rare and endangered plant and insect species inhabiting green roof structures (Brenneisen, 2003, cited in Brenneisen, 2006; Gabrych et al., 2016; Kadas, 2006).

While green roofs have several socioeconomical and environmental benefits, the properties of the roof, where substrate type and depth seem to be the main drivers, are regulating many of the ecosystem services provided (Dusza et al., 2017; Lata et al., 2018). The majority of green roofs globally are vegetated by succulents (*Crassulaceae* family), mostly being *Sedum* species (Dunnett & Kingsbury, 2008, cited in Nagase & Dunnett, 2010; Oberndorfer et al., 2007). *Sedum* species are favoured because they are very drought tolerant and can survive on shallow substrate (~ 3-10 cm), as some species have been found to survive without irrigation for 88 days and on substrate as thin as 2-3 cm deep (Vanwoert et al., 2005). Additionally, the vegetation is easily installed as vegetated mats and can be retrofitted to already existing roofs (NIBIO, 2016). Yet, *Sedum* roofs have been criticized for being too monocultural, leading to poor plant diversity (Brenneisen, 2006; Lata et al., 2018), and research has found that succulent roofs are significantly less species rich with lower functional diversity than systems containing more diverse vegetation (Van Mechelen et al., 2015). In the Oslo area in Norway, an additional problem is that the *Sedum* mats have assisted in spreading invasive plant species, especially *Phedimus hybridus* and *Sedum spurium* (NIBIO, 2016). Now, various scientists are requesting that green roofs are considered as a tool for preserving and restoring biodiversity to a higher extent (Brenneisen, 2006; Williams et al., 2014), implementing ecological principles to maximize biodiversity gains (Williams et al., 2014) and considering those species providing the greatest ecosystem service potential (Vaz Monteiro et al., 2017).

Another successful green roof option, which is arguably better in terms of conserving biodiversity, is installing vegetation mimicking hay meadows (Gabrych et al., 2016; Nagase & Dunnett, 2013). Hay meadows are habitats dominated by open fields containing herbaceous plants and grasses (Høiland, 1996). They are generally maintained by mowing, which separates them from semi-natural grasslands which are generally maintained by grazing (Eriksson et al., 1995; Høiland, 1996). Both hay meadows and semi-natural grasslands are recognised as being among the habitats with the highest vascular plant species richness in western, northern and central Europe (Myklestad & Sætersdal, 2004), and they are associated with a high arthropod diversity (Albrecht et al., 2010). They have traditionally had the function of feeding livestock, where the grasslands were mainly used as pastures in the summer while hay from the meadows was used in wintertime (Eriksson et al., 1995; Høiland, 1996). During the past decades, these traditional agricultural habitats have been in decline (Eriksson et al., 1995; Hodgson et al., 2005), as demonstrated in a study from England, where the decline in total grassland area was 33% from 1930-1984 (Fuller, 1987). The main driver was the conversion to modern agricultural fields with the rise of artificial fertilizers, while some areas were converted to forestry and other areas, now being economically unsustainable, were abandoned and left to natural reforestation (Eriksson et al., 2002). Some semi-natural grasslands persist in Scandinavia, whereas the old managed meadows are very rare (Eriksson et al., 1995). Today, hay meadows are regarded as critically endangered in Norway, housing a multitude of threatened species (Miljøstatus, 2019).

Even if there is a great potential to conservation of meadow habitat and meadow species and increased biodiversity in terms of plants and arthropods in cities, there are still many unknowns as to how meadows are best supported on a green roof. The primary goal in this study was to examine how soil type and soil depth could help facilitate native and local meadow species on sustainable green roofs in Oslo, the capital of Norway. While soil depth is examined in many studies of vegetation on green roofs, there is a lack of studies investigating soil types. It is important to understand how both of these soil variables affect meadow roofs as it is the quality of the soil which largely determine plant ecosystems (Brady & Weil, 2014). The study design was inspired by restoration ecology, but it is challenging to use natural meadows as reference systems (see SER, 2004) because conditions on the ground cannot be directly transferred to green roofs (Olly et al., 2011). Roofs are more prone to drought then ground sites as they have a waterproof membrane at the bottom, affecting water storage and water availability (Olly et al., 2011; Skjeldrum & Kvande, 2017). Additionally, roofs only receive nutrients from the soil or from precipitation, while natural systems can get dissolved nutrients from water received horizontally (Brady & Weil, 2014). Having this as a background, I conducted an experiment manipulating soil water-holding capacity, nutrient content and pH to test the effect on native and local meadow vegetation on green roofs in Oslo.

The seeds used in the experiment were collected from dry calcareous meadows and "open calcareous ground with shallow soil" in Oslo and Ringerike municipality (Ryvarden, L., personal communication, April 1th, 2020). These habitats have in common that they are prone to drought, have low nutrient content and are associated with medium alkaline ground (DN, 2009; NINA, 2011). Dry meadows are linked to low nutrient content as the mowing gradually relocates biomass and nutrients elsewhere (Eriksson et al., 2002). It is the shallow depth of "open calcareous ground with shallow soil" which restrains the water capacity and reduces nutrient content (NINA, 2011). The alkaline ground is caused by high limestone levels in the bedrocks created in Cambrian – Silur (SNL, 2020). Similarly to hay meadows, "open calcareous ground with shallow soil" is threatened (NINA, 2011). The nature type is considered a hotspot habitat in the Oslo area with many hundreds threatened species, where 445 are vascular plants (NINA, 2011).

The treatments were based on a soil composed of garden waste compost and natural sand (onwards called sand compost mixture, SC), which was already high in pH (Renovasjonsetaten, n.d.). This soil was altered to make three different soil types and applied in two different depths as treatments for the experiment.

One soil type intended to resemble natural systems the most, with a mixture of 50% SC and 50% natural sand by volume (SCS). The aim was to reduce nutrient content and soil water-holding capacity, as sand creates bigger pores in the soil, and larger pores are more easily drained from water containing dissolved nutrients (Brady & Weil, 2014). The second soil type simply constituted of the sand compost mixture. With higher content of soil organic matter (SOM) and of smaller mineral particles (silt and clay), theory would suggest that the nutrient content and soil water-holding capacity were higher than in SCS (Brady & Weil, 2014) . In the third soil type, 95% SC was mixed with 5% rock dust by volume (SCRD). Rock dust is tailings from quarries with a grain size <4 mm (UMB, 2006). The aim was to increase soil water-holding capacity, nutrients and pH compared to the original soil (UMB, 2006).

The two soil depths (18 and 30 cm) were based upon research where it is consistent through all scientific literature that deeper substrate is better at facilitating herbaceous annual and perennial plants (e.g. Heinze, 1985, cited inDunnett et al., 2008; Gabrych et al., 2016; Monterusso et al., 2005). Scientists have theorised that it might be due to less severe temperature fluctuations than in thinner roof substrates (Eksi et al., 2017) or to higher soil water-holding capacity in deeper substrate (Buccola & Spolek, 2011; Olly et al., 2011). The aim was to refine the understanding of “deeper soil”, further examining meadow roof performance of two relatively deeper soil depths.

The measurements were done over the same season as the sowing of the seeds. Seedling emergence (seedlings that have appeared from the soil), mortality and survival were measured, in addition to flowering and seed production. In addition to the sowed seeds, spontaneously colonized seedlings were allowed to establish, and these were registered too. Colonized seedlings are interesting because they can affect species diversity on roofs, and the colonization of wild plant communities on green roofs remains poorly described (Madre et al., 2014). Soil properties (particle size distribution, soil organic matter content, nutrient content, pH and soil water-holding capacity) and soil moisture were determined to explore relationships between response variables and soil measurements.

I hypothesized that

1. Mixing the sand compost mixture with 50% sand would decrease nutrient content, and reduce soil water-holding capacity and soil moisture
2. Mixing the sand compost mixture with 5% rock dust would increase nutrient content, pH, water-holding capacity and soil moisture
3. Increasing soil depth would increase nutrient content, water content and soil moisture.
4. That the treatments (soil types and soil depth) would affect the first year of meadow roof establishment through
    - Seedling emergence
    - Seedling mortality
    - Seedling survival
    - Seedling flowering ability
    - Species diversity indices
    - Above ground biomass

   regarding both
    - Originally sowed seedlings
    - Spontaneously colonized seedlings
5. That there would be relationships between the seedling response variables and soil measurements (nutrient content, pH, soil water-holding capacity and soil moisture).

2. Materials and methods

2.1 Study site

2.1.1 Geography and climate

The experimental site was located in Geitmyra skolehage in Oslo, the capital of Norway (59°56'07.0"N 10°44'47.8"E). The climate in Oslo is classified as humid and continental (Dfb) by the Köppen climate classification system (Arnfield, 2020). The average temperature (calculated from normal period 1961-1990) is 5.7 °C, where July is the warmest month, averaging 16.4 °C, and January is the coldest month, averaging -4,3 °C. Yearly average rainfall is 763 mm, where most precipitation falls in September with an average of 90 mm, while precipitation is lowest in February with an average of 36 mm (calculated from normal period 1961-1990) (SNL, 2019). The growing season ranges from 150-210 days (calculated from normal period 1971-2000) (Norsk.Klimasenter, n.d.).

2.1.2 Site description

Geitmyra skolehage is an urban green space (45 000 m^2) in Oslo, Norway. Geitmyra consists of both park-like areas and fields for urban agriculture. The experimental site was placed north-east within Geitmyra skolehage, in levelled terrain at 72 m.a.s.l. The experimental site was 50 m^2, where there was a gravel road and a roadside with weeds to the south-east, a compost pile to the north-east, a vegetable field to the north-west and a small house to the south-west (Fig. 1). There were two full grown *Betula pendula* trees three meters east to the site. Typical species in a five meter distance were *Achillea millefolium*, *Aegopodium podagraria*, *Allium schoenoprasum*, *Anthriscus Sylvestris*, *Artemisia vulgaris*, *Borago officinalis*, *Fraxinus excelsior*, *Galinsoga quadriradiata*, *Lamium album*, *Leucanthemum vulgare*, *Malus domestica*, *Matricaria discoidea*, *Pyrus* sp., *Solanum tuberosum*, *Taraxacum officinale*, *Trifolium* sp., *Urtica* sp, and the invasive species *Myrrhis odorata* (Artsdatabanken, 2018a).

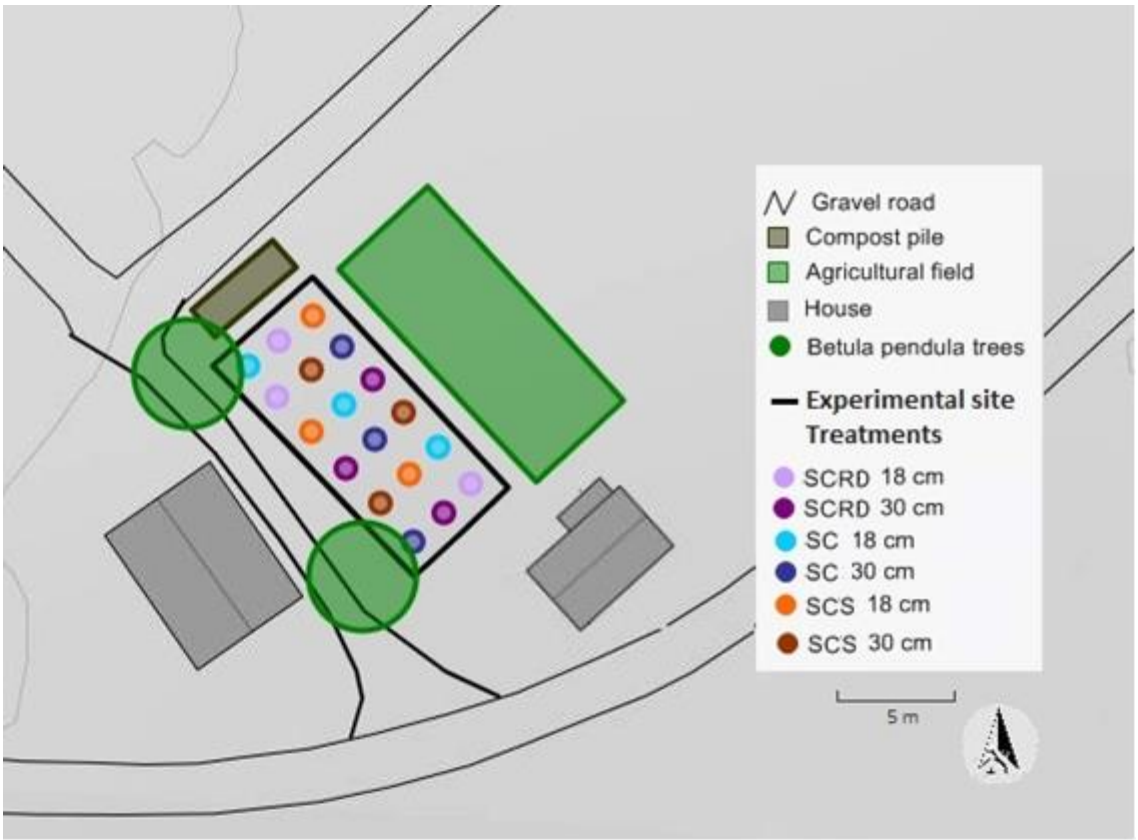

Figure 1 An overview of the experimental site, being the rectangular space containing 18 plots. The experiment had 6 different treatments with three replicates each: 3 soil types (1) SCRD = sand compost mixture 95%, rock dust 5%, (2) SC = sand compost mixture 100%, (3) SCS = sand compost mixture 50%, natural sand 50% in two soil depths (1) 18 cm = 18 cm depth, (2) 30 cm = 30 cm depth.

2.2 Experiment setup

2.2.1 Study biotope and study species

The study biotope for the experiment was dry calcareous meadows. The study species in the experiment were meadow species related to the Oslo area on Cambrian Silurian bedrock. The seeds from the 26 species used were collected in year 2016 – 2018, mainly from Bygdøy and Kalvøya in Oslo, but also from Ringerike. Before sowing, the seeds had been dried for three weeks, then cooled in 1-2 months in +5-6 °C, then frozen at -18 °C for 4 months before being placed into +5-6 °C for another month. For full species list see Appendix Table S1.

2.2.2 Study setup

The experiment consisted of six treatments with three replications each (Table 1). The treatments constituted of three different soil types in factorial combination with two different depths, mainly manipulating **1)** soil nutrients, **2)** soil pH, **3)** soil water-holding capacity and **4)** soil moisture. The reference in the statistical models was soil type “sand compost mixture”

(SC) in 18 cm depth. SC is a garden waste compost-natural sand mixture produced by Oslo municipality. The benefits by using SC is that it is homogenous in big volumes, free from seeds and easily accessible for both private households and big companies (Renovasjonsetaten, n.d.). Second soil type was made by mixing 50% SC with 50% natural sand by volume ("0/4 pussesand", Appendix Figure S1 (NPS, n.d.)), to reduce nutrient content and soil water-holding capacity, onwards called SCS. The third soil type was 95% SC mixed with 5% rock dust (grain size <4 mm), a mix aiming at increasing pH slightly and increasing nutrients and soil water-holding capacity, onwards called SCRD. Soil depths 18 cm and 30 cm were chosen based upon a study of multiyear old green roofs in Helsinki by Gabrych et al. (2016). Their recommendation was to have a substrate depth of 15-25 cm when the goal is to establish a meadow roof. The soil depth 30 cm was applied keeping in mind that the soil compacts with time.

Table 1 The six different treatments with 3 soil types in 2 soil depths. * used as reference level in data analyses.

Treatment	Replications	Soil type	Soil depth	Abbreviation
1	3	Compost sand mixture (100%)	18 cm	SC 18 cm*
2	3	Compost sand mixture (100%)	30 cm	SC 30 cm
3	3	Compost sand mixture (50%) + natural sand (50%)	18 cm	SCS 18 cm
4	3	Compost sand mixture (50%) + natural sand (50%)	30 cm	SCS 30 cm
5	3	Compost sand mixture (95%) + rock dust (5%)	18 cm	SCRD 18 cm
6	3	Compost sand mixture (95%) + rock dust (5%)	30 cm	SCRD 30 cm

The experimental site consisted of 18 plots (80x120 cm), placed in an 5x10 meter area (Fig. 1). The site was prepared by levelling the soil then superimposing a 5x10 meter weed barrier fabric. Each plot consisted of one or two stacked pallet collars. These were installed in 6 rows with three in each row, having 40 cm distance between them and the surroundings to minimize interactions amongst plots and between plot and the immediate surroundings. The plots were randomized and numbered from 1-18. To replicate conditions on green roofs and intercept the hydrological connections between the underlying soil and the soil within the plots, a dimpled plastic sheet (75x115 cm) was placed with dimples facing upwards in the bottom of each pallet collar. Soil types SCS and SCRD were mixed by volume using a cement mixer, then soil was filled into plots being levelled regularly in-between fillings to be equally compact throughout the depth.

On the 7th of June 2019, 15 seeds from 26 species (full species list in Appendix Table S1) were sown per plot. That makes up a lower seed density than what is recommended by Norwegian Institute of Bioeconomy Research (NIBIO) to establish new meadows (2.5-5g/m^2)

(NIBIO, 2018), but data collection required such low numbers in order to identify individual plants as they emerged. The seeds were mixed and broadcast evenly on the surface, resembling a natural growth pattern. Then they were raked 0.5 cm into the soil and the soil was compressed lightly creating soil contact. A 10 cm edge was left unsown to avoid edge effects. Finally, each plot was covered with chicken wire for protection (Appendix Figure S2).

In addition to the 18 plots, another pallet collar was installed, where all 26 species were sown systematically in labelled rows (Appendix Figure S3). This pallet collar was used as a reference when identifying small seedlings in the experiment, onwards called reference plot.

The plots were irrigated ad-hoc when the soil felt dry from project start, but an irrigation regime was established the 17th July based upon observations and soil moisture measurements. The water regime was watering five litres per plot (equals to 5 mm precipitation) if the mean moisture volume was <12% in plot 6, 10 and 17 (soil type SC, SCS and SCRD, 18 cm depth). Irrigation was done by a watering can with an attached boom sprayer (Appendix Figure S4).

The experiment ended the 8th of November. Leaf debris was removed using a leaf blower to simulate green roof conditions, chicken wire was removed, and the vegetation was cut down to soil level to measure above ground biomass.

2.3 Data collection

2.3.1 Seedling emergence and mortality, flowering and seed producing individuals

Seedling emergence (seedlings that emerged from the soil) and death were registered every fifth day from 19th of June 2019 until 7th of October 2019, with some exceptions where registrations were delayed by one day due to rain. Emerged seedlings were marked with a toothpick labelled with a unique ID number, and ID number and emergence date were recorded. As the experiment proceeded, most seedlings were identified to species and were recorded to the assigned ID number (Appendix Figure S5 and S6). If a seedling was absent, then the death date was recorded. As individuals flowered or produced seeds, the date was registered.

2.3.2 Soil moisture

Soil moisture was measured simultaneously with seedling emergence and death; normally every fifth day from 24th of June 2019 to 7th of October 2019. Soil moisture was also measured in dry periods to determine whether it was necessary to irrigate. The instrument used was a Stevens hydra-probe (S/N 216485) and the measuring was done once per plot. Soil moisture was recorded in unit Fv, which translates to volume percent moisture when multiplied by 100 (Børresen, T., personal communication, November 11th, 2019).

2.3.3 Above ground biomass

Above ground biomass (AGB) was collected by cutting down vegetation to soil level from 6th-8th of November 2019. The vegetation was placed into marked paper bags according to plot number. The paper bags were dried in a drying oven at 60 degrees Celsius for 72 hours, then the total weight per plot was recorded.

2.3.4 Soil properties

Samples of the three soil types (SC, SCS, SCRD) were put in separate 10 litre buckets with airtight lids and stored at room temperature for about 6 months before analysis. The pF analysis was done with four replications per soil type, while all other soil analyses were done with three replications per soil type. They were all prepared and analysed according to the methods described in Krogstad et al. (2018) by the NMBU soil science laboratory. The following soil analyses were done:

1) **Particle size distribution**, which determined the weight percentage of clay (<0.002 mm), silt (0.002-0.060 mm) and sand (0.060-2.000 mm) of total mineral material.
2) **Soil dry matter and loss on ignition**. Soil organic matter (SOM) (vol%) was estimated by subtracting the value of 1 from the loss on ignition results, as soil clay content was <15% of mineral material (Krogstad et al., 2018).
3) **Aluminium extraction** (diluted 10 times), used to determine Calcium (Ca), Potassium (K), Magnesium (Mg) and Phosphorus (P) content (mg/kg) in the soil.
4) **pH in water.**
5) **pF analysis,** used to estimate soil water-holding capacity**.** Samples to measure pF 1, pF 1.5, pF 2 and pF 3 were made by packing soil into cylinders equally dense. Packed rings were used to measure pF 4.2. pF 0-2 is defined as percent air volume and pF >2 is defined as soil water content. pF 2-4.2 is defined as percent plant available water, where pF 2-3 is readily available water, pF 3-4.2 is slowly available water. pF >4.2 is water so tightly bond it is unavailable to plants.

2.4 Data analysis

The interactive effects of soil type (three levels: SC, SCS, SCRD) and soil depth (two levels: 18 and 30 cm) were used as treatments to estimate seedling emergence, death and survival, flowering seedlings, diversity indices, AGB and soil moisture. When a significant interaction between soil type and soil depth was lacking, an additive model was applied instead.

Other soil properties (particle size distribution, OM content, nutrient content, pH and water-holding capacity) were estimated in relation to soil types only. In the models used, SC and 18 cm (SC regarding soil properties), were used as reference levels for the categorical fixed effect factors soil type and soil depth, respectively.

For the count response variables (emerged, dead and survived seedlings), a general linear model (GLM) with a Poisson link was applied. The proportion of dead vs. survived (mortality) and flowered vs. non-flowered seedlings of emerged seedlings was analysed using GLM with a logistic regression. The effect of treatments on the continuous response variables AGB, diversity indices and soil properties was analysed using a linear regression model. The effect of treatments on the soil moisture measurements was analysed using a linear mixed effect model, with recorded date as random effect with lme function using nlme package.

The analyses regarding the seedlings were done in three groups: all seedlings, originally sowed seedlings and spontaneously colonized seedlings (with and without *Rumex acetosa and Rumex acetosella*).

Diversity indices estimated were species richness, Shannon Wiener diversity and Pielou evenness (using Shannon Wiener index as diversity value), using the plyr and vegan package. Species that were hard to separate were grouped into being one species, to rather underestimate than overestimate the number of unique species.

One spontaneously colonized species, *Rorippa sylvestris*, occurred in just plot 11 as the second most numerous spontaneously colonized species and was removed from the analyses (plot 11 was removed from AGB analysis) because it was an outlier in the data. See results for more information.

Model residual plots and R^2 values were used to check lack of fit. The plots are based upon the raw data and illustrate the effect of treatment 1-6, with three replications per treatment, or six replications per soil type and nine replications per soil depth. A significance level of 0.05 is used. All analyses were done in R version 3.5.2 (R Core Team 2019).

3. Results

Both the sowed seedlings and spontaneously colonized seedlings emerged and established themselves in the plots of the experiment, with a majority being sowed seedlings (52,5 %). Some seedlings were not identified (10.9 %) due to early death among other things. The soil manipulations that were done changed the composition of the soil and the soil measurements, resulting in treatments which affected meadow roof establishment. Yet, no singular treatment had best performance in terms of all variables measured to evaluate the first year of meadow establishment on green roofs.

There were very few significant effects of the interaction between soil type and soil depth. An additive model was used in the majority of the results, but the results from the interactive models can be found in Appendix Table S2-S5, together with the results from the additive models.

3.1 Soil measurements

The manipulation of the soil, mixing the sand compost mixture (SC) with 50% sand (SCS) or 5% rock dust (SCRD), changed the composition of the soil (Fig. 2). There were bigger differences between soil types SC and SCS than between soil types SC and SCRD.

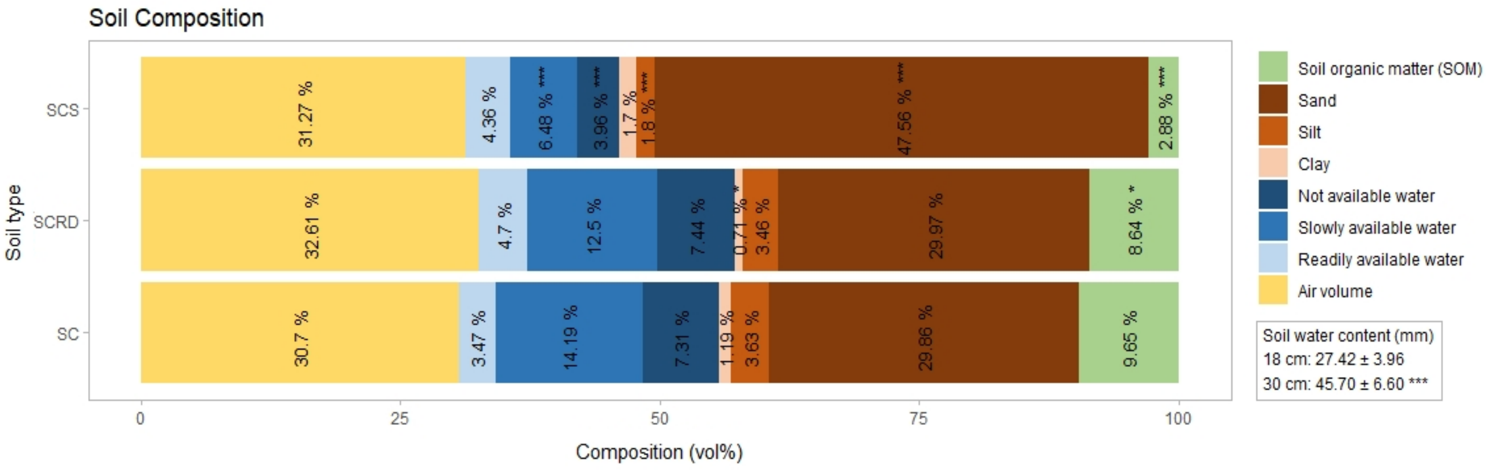

Figure 2 Soil composition (vol%) and soil water content (mm, mean ± SE) across soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust). Not available water is pF > 4.2, slowly available water pF 3 - 4.2 and readily available water pF2 - 3. Water content is pF >2. Air volume is < pF 2. * indicates that P < 0.05, ** that P < 0.01 and *** that P < 0.001. SC is the reference level. N = 3 for vol% SOM, sand, silt and clay, while N=4 for water and air volume.

Mixing 50% SC with 50% sand (SCS) led to a lower proportion of soil organic matter (SOM) (-6.767, P < 0.001) to below a third, and of silt (-6.933, P < 0.001) (Fig. 2). The sand content was higher than in soil type SC (7.067, P < 0.001), making up almost 50% of the total soil volume or 93% of the mineral material. The total pore volume was lower than in soil type SC (-9.605, P < 0.001). While the air volume remained statistically unchanged, there was significantly less volume of pores holding water. This was specifically the pores holding the slowly plant available water (-7.709, P < 0.001) and those holding water so tightly bond it is not plant available (-3.315, P < 0.001). Mixing in 95% SC with 5% rock dust (SCRD) led to lower proportion of SOM (-1.013, P = 0.046), but the difference was smaller than between soil types SCS and SC. Additionally, soil type SCRD had a lower proportion of clay than soil type SC (-1.3667, P = 0.032). However, no significant differences between soil types SCRD and SC regarding soil air volume or soil water-holding capacity were detected. The amount of soil water increased with depth, and was significantly higher in 30 cm than 18 cm soil depth (21.194, P <0.001).

The mean pH of all soil types was 7.88. Contrary what was predicted, no effect of mixing in rock dust was detected on the soil pH (P = 0.883) (Appendix Table S3).

Soil nutrients were generally lower in soil type SCS than in soil type SC, as hypothesized (Fig. 3a). While the calcium content remained statistically unchanged (P = 1.000), the potassium (K), magnesium (Mg) and phosphorus (P) content was lower (K: -833.333, P < 0.001, Mg: -256.667, P < 0.001, P: -54.000, P < 0.001). However, contrary to the hypothesis, a very small yet significant negative effect was found for some nutrients in soil type SCRD (Ca: P = 0.563, K: P = 0.134, Mg: -33.333, P = 0.002, P: -10.000, P < 0.001).

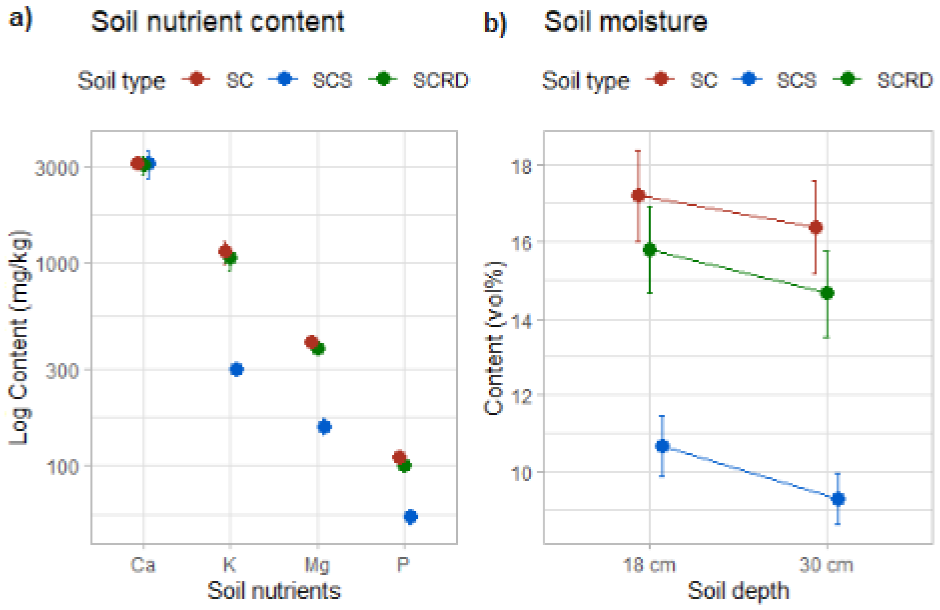

Figure 3 Soil nutrient content (Log mg/kg), calcium (Ca), potassium (K), magnesium (Mg) and phosphorus (P), and soil moisture (vol%) across 6 treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

As hypothesized, soil moisture measurements (fV) were statistically lower in soil type SCS than in soil type SC (-0.065, P < 0.001) (Fig. 3b). However, similarly to both soil water-holding capacity, pH and soil nutrients, the effect on soil moisture was not as predicted in soil type SCRD. Rather than having a higher soil moisture, the measurements in soil type SCRD was slightly lower than in soil type SC (-0.014, P < 0.001). Also contrary to the hypothesized, the effect of depth was negative on soil moisture, where 30 cm soil depth had lower values than 18 cm soil depth (-1.120, P < 0.001).

3.2 Emerged, dead and survived seedlings

3.2.1 All seedlings

A total of 2922 emerged seedlings were recorded during the summer, where 1533 of these were originally sowed seedlings, 1072 spontaneously colonized seedlings and 317 were seedlings not classified as either sowed or colonized (unclassified seedlings). While the seeds were sown evenly in the plots with 10 cm distance to the edge, they emerged fairly clustered over the entire plot, as the seeds had likely been moved by heavy rainfall (Appendix Figure S7). The highest number of emerged seedlings was recorded in soil type SC and in 18 cm soil depth (Fig. 4a). The number of emerged seedlings was significantly lower in soil type SCRD (-0.471, P < 0.001), and lowest in soil type SCS (-0.843, P < 0.001). There was a smaller yet significantly negative effect of 30 cm soil depth on the number of emerged seedlings (-0.273, P < 0.001).

A total of 252 dead seedlings were registered at the end of the experiment, where 41 of these were recorded as sowed seedlings and 14 as colonized seedlings, while the majority, 197 (78%), were unclassified. There were observed multiple causes of death; drying out, malnourishment, dying from fungi and being eaten by insects like larvae. The number of dead seedlings was lowest in soil type SCRD (-0.775, P < 0.001), and highest in soil type SCS (0.315, P = 0.024) (Fig. 4b). Plots with 30 cm soil depth had a higher number of dead seedlings than those with 18 cm soil depth (0.337, P = 0.009).

Mortality (proportion dead of all emerged seedlings) is reflective of the number of dead seedlings (Fig. 4b and 4c). Concurrently, soil type SCRD had the lowest mortality (-0.402, P = 0.039) and soil type SCS had the highest mortality (1.191, P < 0.001). Furthermore, 30 cm soil depth had higher mortality than 18 cm soil depth (0.561, P < 0.001).

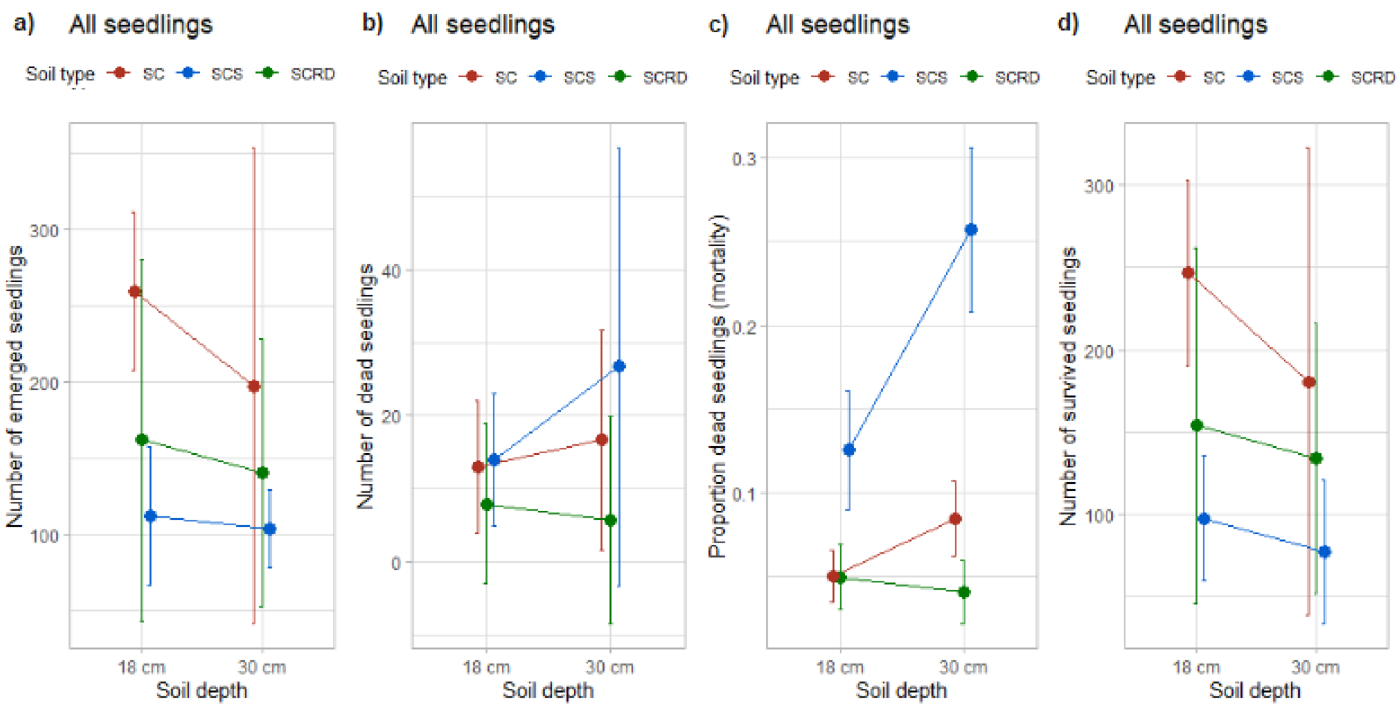

Figure 4 Number of all emerged, dead and survived seedlings, and proportion dead of all emerged seedlings (mortality) across 6 treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

A total of 2670 seedlings survived until the end of the experiment, of which 1533 were sowed seedlings, 1058 were colonized seedlings, and the remaining 120 were unclassified. The effect of treatments on the number of survived seedlings mirrors the effects on number of emerged seedlings (Fig. 4a and 4d). Soil type SC supported the highest number of survived seedlings, the number being lower in soil type SCRD (-0.393, $P < 0.001$) and lowest in soil type SCS (-0.894, $P < 0.001$). Plots with 30 cm soil depth supported a lower number of survived seedlings than plots with 18 cm soil depth (0.239, $P = 0.001$).

3.2.2 Originally sowed seedlings

As a high proportion of dead seedlings was left unidentified (n = 197, 78%), there is a considerable possibility of unrecorded emerged and dead sowed seedlings. Hence, these statistical analyses have been left out, and only the statistical analyses of number of seedlings which survived is included.

Overall, at least 21.84% (n=1533) of all sowed seeds emerged as seedlings over the experimental period, representing 21 out of the 26 sowed species (Fig. 5). Data for the identified sowed seeds suggest that there were variations in the proportion that emerged among species. Out of the identified seedlings, there were five species (*Trifolium arvense*, *Anthoxanthum odoratum* and *Trifolium pratenese/medium/ hybridum*[1]) where 1-10% of the sowed seeds emerged. There were eight species (*Viscaria vulgaris, Galium album/verum, Hypericum perforatum/maculatum, Silene dioica, Hieracium pilosella/umbellatum* [2] and *Pimpinella saxifraga/Seseli libanotis*[3]) where 10-30% of the sowed seeds emerged. There were five species (*Barbarea vulgaris, Leucanthemum vulgare, Luzula multiflora* subsp. *Multiflora, Dianthus deltoides* and *Solidago virgaurea*) where 30-50% of the sowed seeds emerged. *Barbarea vulgaris* seedlings were weeded when >10 cm diameter to prevent then from flowering as the species was recognized as invasive (Artsdatabanken, 2018b). Three species were recorded with >50% emergence of the sowed seeds (*Festuca ovina, Phleum pratense* and *Tripleurospermum inodorum*). The five species with no identified emerged seedlings were *Allium oleraceum, Angelica Sylvestris, Filipendula ulmaria, Lathyrus Sylvestris* and *Scrophularia nodosa*.

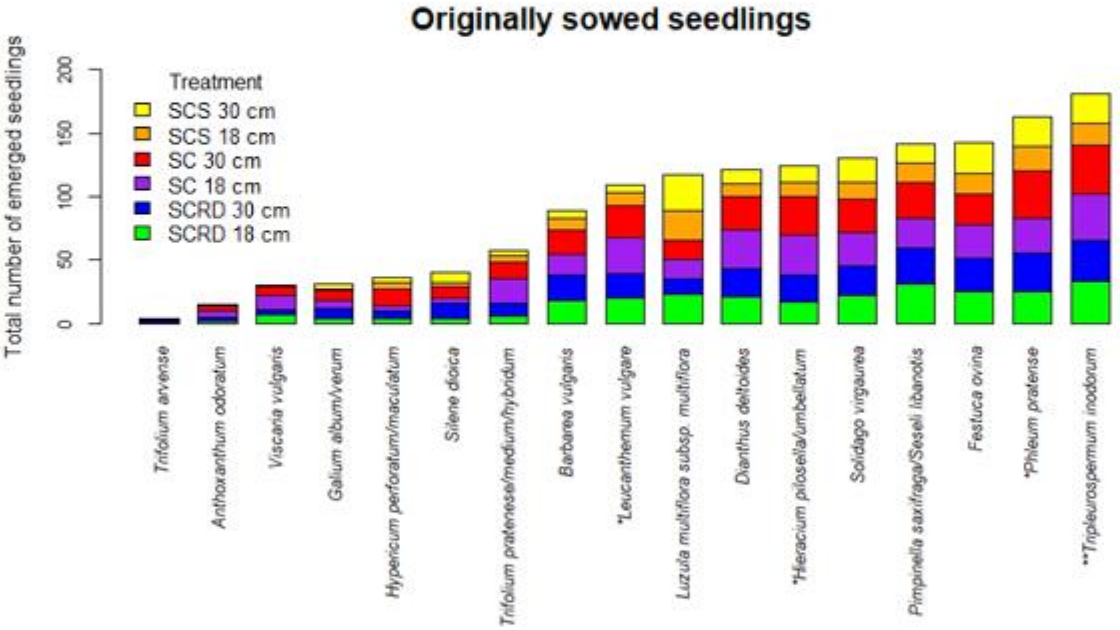

Figure 5 All emerged originally sowed seedlings across 6 treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. 15 seeds were sown per species. *Trifolium pratense/ medium/ hybridum, Hieracium pilosella/ umbellatum* and *Pimpinella saxifraga/ Seseli Libanotis* were sown as different species (respectively 45, 30 and 30 seeds sown). * indicates that ≥1 individual flowered, ** that ≥1 individual produced seeds.

Most of the 1492 surviving sowed seedlings emerged within 3 weeks after sowing (Julian date 178) followed by a lower but steady rate during the remaining experimental period

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[1] Sowed as three different species

[2] Sowed as two different species

[3] Sowed as two different species

(Fig. 6). Similar to the results regarding all survived seedlings (Fig. 4d), the highest number of surviving sowed seedlings was in soil type SC, being lower in soil type SCRD (-0.142, P = 0.015) and lowest in soil type SCS (-0.654, P < 0.001). However, in contrast to the results regarding all seedlings, no effect of soil depth was detected (P = 0.234).

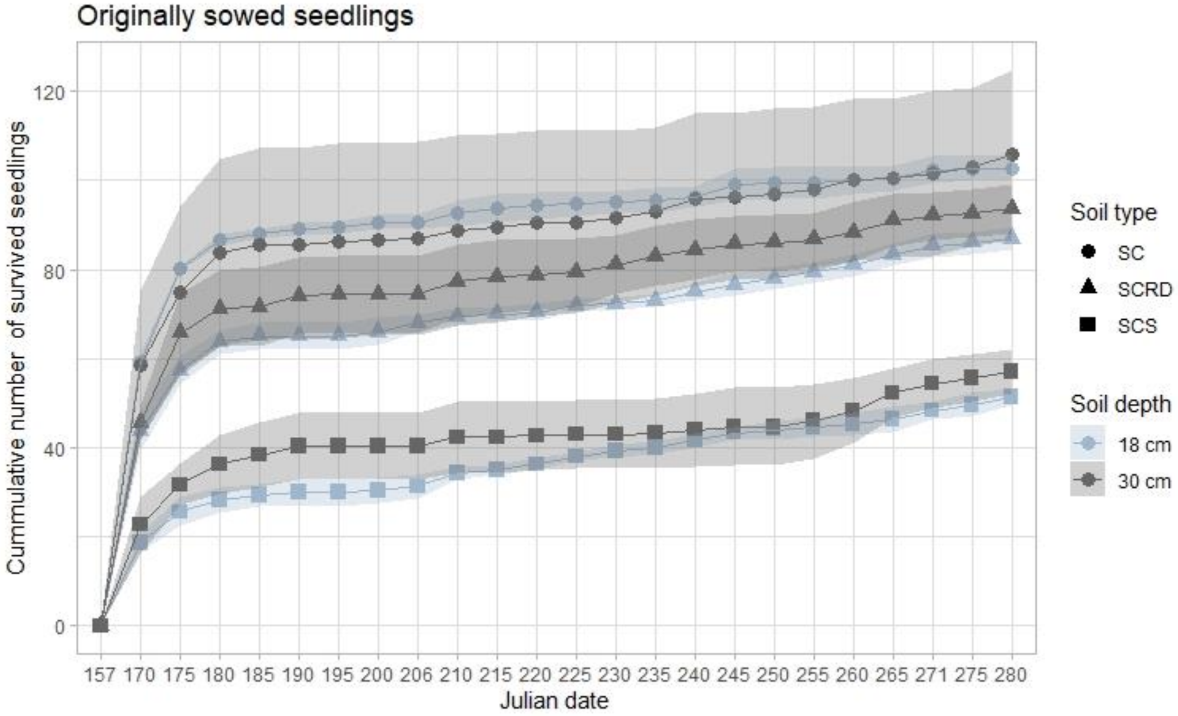

Figure 6 Cumulative number of emergence of surviving originally sowed seedlings across 6 treatments**:** soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm from sowing date (Julian date 157) to project end (Julian date 280). Ribbons indicate SE (standard error), N=3 for treatment 1-6.

3.2.3 Spontaneously colonized seedlings

As for the sowed seedlings, only the statistical analyses for the spontaneously colonized seedlings that survived are presented.

A total of 1072 colonized seedlings were recorded, representing 37 species that could be identified (Fig. 7). The number of emerged colonized seedlings ranged from 1-659 individuals per species, with 24 species supporting ≤5 seedlings, 9 species supporting 6-25 seedlings and four species supporting >25 seedlings. *Fraxinus* sp. was the fourth most common colonized species (Fig. 7) being observed dispersing from neighbouring trees, and was present in all plots except plot seven, ranging from 1-23 individuals per plot. The third most common species, *Senecio vulgaris*, was present in all plots, ranging from 1-25 individuals per plot. The second most common species, *Rorippa sylvestris*, only emerged in one plot (plot 11) with a total of 254 individuals spread by vegetative propagation as the seedlings lacked cotyledons.

This species has been removed from all results and analyses as it represents an outlier where occurrence is not a function of treatment but location. The most common colonized species by far was *Rumex acetosella/ acetosa* (grouped due to being hard to differentiate as seedlings), with 659 registered emerged seedlings in total, making up 61.47% of all registered colonized seedlings. The species was present across all treatments and in 15 out of 18 plots, ranging from 1-119 individuals per plot. Another species that emerged in all plots was *Betula pendula*, being dispersed from the neighbouring trees. This species was left out from registrations due to immensely high numbers. They were not weeded, but the majority died and the remaining stayed < 3 cm tall during the entire experimental period.

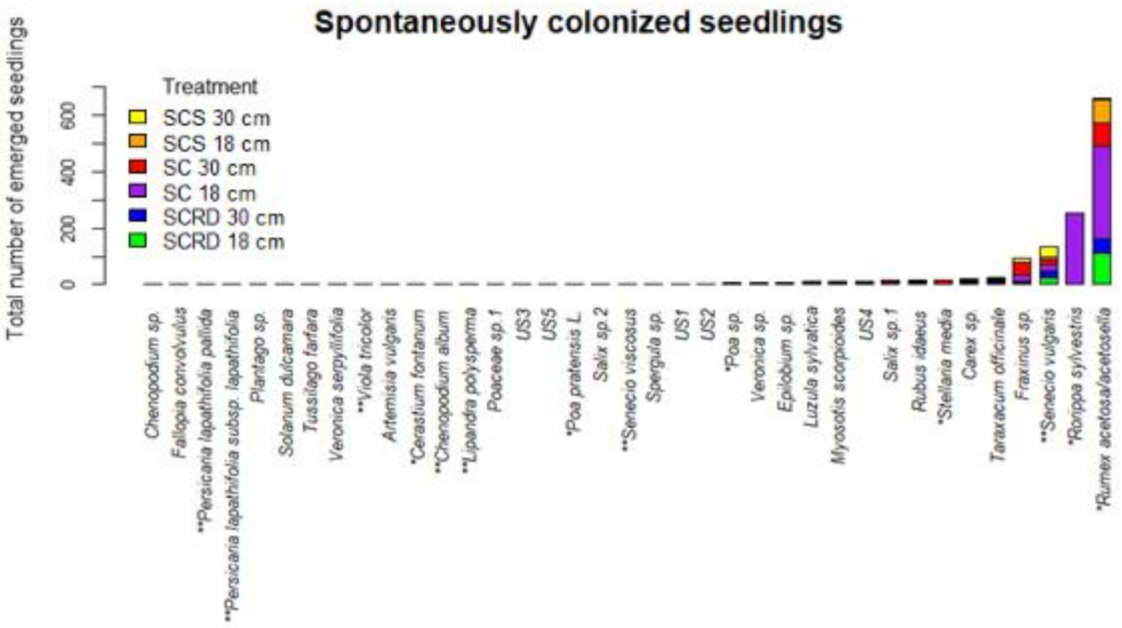

Figure 7 All emerged spontaneously colonized seedlings across 6 treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. US1-US4 are abbreviations for "unknown species 1-4". * indicates that ≥1 individual flowered, ** that ≥1 individual produced seeds.

The surviving colonized seedlings (N = 1072) emerged slowly in the beginning of summer (Fig. 8). The rate increased for all treatments around 10 weeks after project start (Julian date 227), but the increase was especially high in plots with soil type SC and 18 cm soil depth. The acceleration caused a similar trend for surviving colonized seedlings as the trend for all survived seedlings (Fig. 4d). The highest number of survived colonized seedlings was supported in soil type SC, being lower in soil type SCRD (-0.741, P < 0.001) and lowest in soil type SCS (-1.249, P < 0.001). Plots with 30 cm soil depth supported a lower number of survived colonized seedlings than plots with 18 cm soil depth (-0.654, P < 0.001).

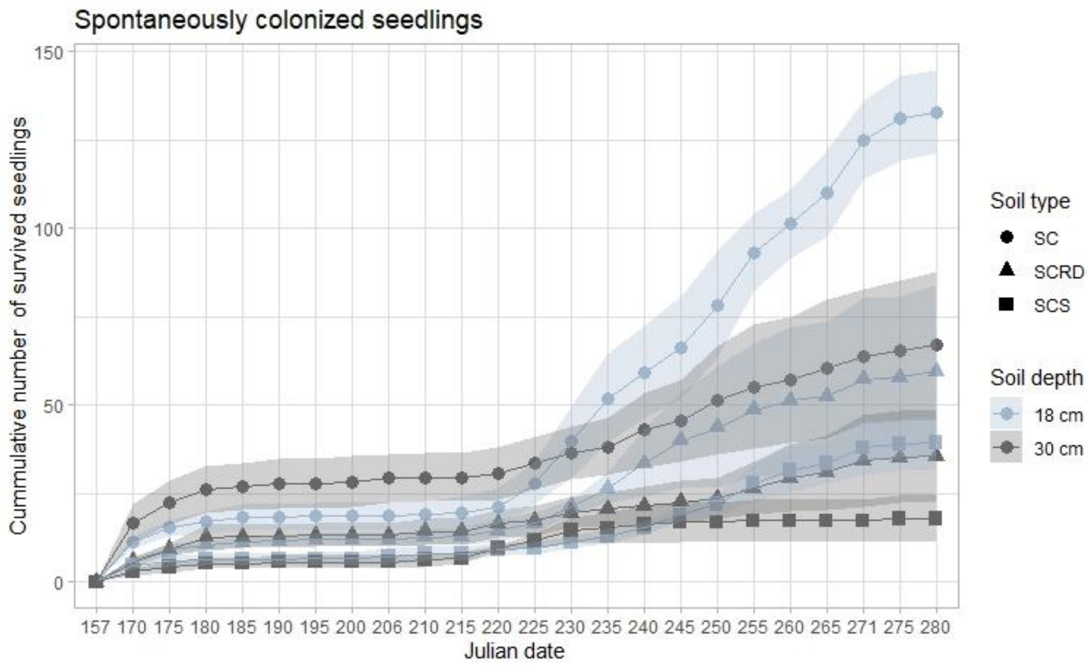

Figure 8 Cumulative number of emergence of surviving spontaneously colonized seedlings across 6 treatments**:** soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm from sowing date (Julian date 157) to project end (Julian date 280). Ribbons indicate SE (standard error), N=3 for treatment 1-6.

3.2.4 *Rumex acetosa/ acetosella*

Interestingly, the effect of soil depth on survived colonized seedlings change when the most numerous species, *R. acetosa/ acetosella*, is excluded from the analysis. Without *R. acetosa/ acetosella*, there is a positive effect of 30 cm soil depth on number of survived colonized seedlings compared to 18 cm soil depth (0.503, P < 0.001) (Appendix Table S3). This is because the surviving *R. acetosa/ acetosella* seedlings mostly occupied 18 cm soil depth, especially in plots with soil type SC (30 cm depth: -1.383, P < 0.001, SCS: -1.347, P < 0.001, SCRD: -1.054, P = < 0.001) (Fig. 9). *R. acetosa/ acetosella* seedlings also affected the effect of soil depth on seedling emergence, survival and mortality, where 30 cm soil depth had a positive effect on seedling emergence (0.104, P = 0.014) and survival (0.075, P = 0.095) and no effect on mortality (P = 0.105) when *R. acetosa/ acetosella* seedlings is excluded from the analyses (Appendix Table S3).

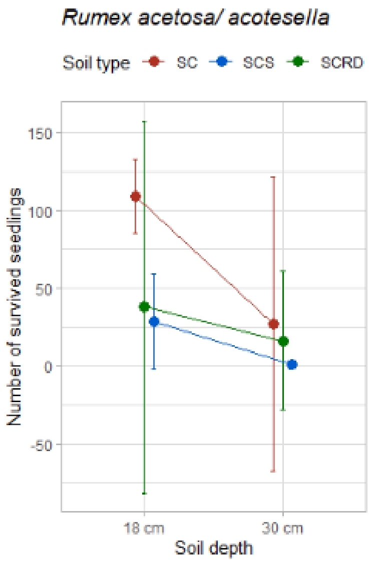

Figure 9 Number of survived *Rumex acetosa/ acetosella* seedlings across treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

3.2.5 Unclassified seedlings

A total of 317 of the emerged seedlings were categorized as unclassified, where some were *Poaceaea* sp. (presumably both sowed species, like *Phleum pratense*, and colonized species) and the rest were left unidentified at project end. Most of the unidentified seedlings died before identification (73%), while the remaining seedlings were too small for identification. No statistical tests regarding solely the unclassified seedlings have been included.

3.3 Flowering and seed production

A total of 42 emerged seedlings (1.4% of all emerged seedlings) from 16 different species flowered over the course of the experiment. Four species and 17 seedlings were sowed (Fig. 5), while 12 species and 25 seedlings were colonized (Fig. 7). Nine emerged seedlings produced seeds, representing one sowed species (Fig. 5) and 7 colonized species (Fig. 7) and 0.3% of all emerged seedlings. Due to low numbers of flowered and seed producing seedlings, the only statistical analyses included are those regarding proportion of flowering seedlings.

There was no significant effect of soil type on the proportion of all flowered seedlings (SCS: P = 0.052, SCRD: P = 0.173) (Fig. 10a). A higher proportion flowered in 30 cm than 18 soil depth (1.682, P = 0.003), mainly due to high flowering probability in 30 cm soil depth combined with soil type SC.

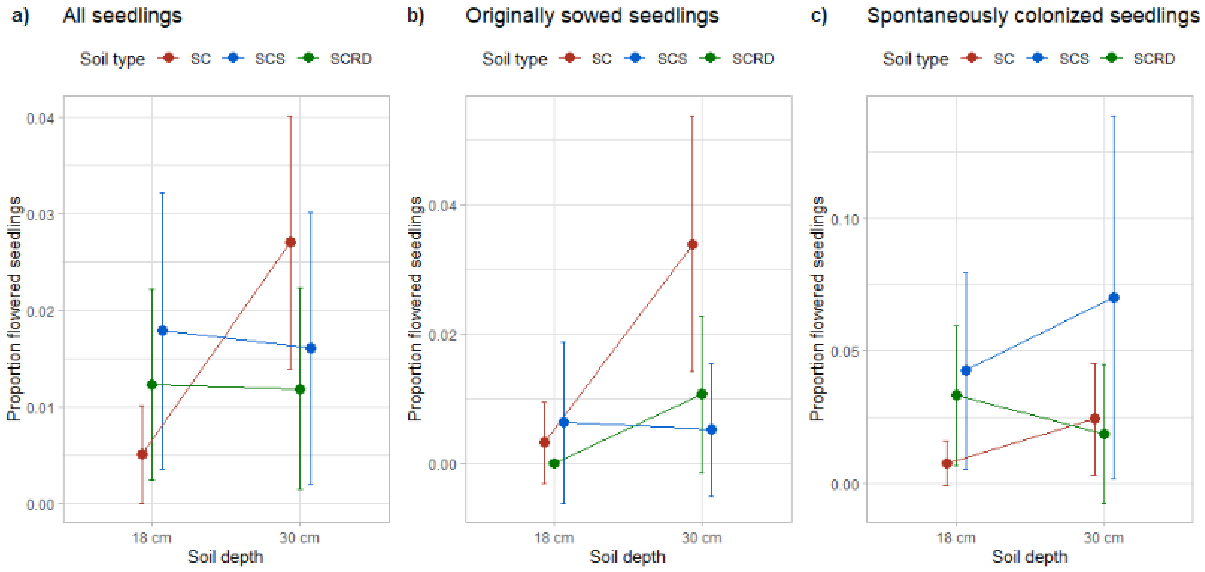

Figure 10 Proportion of flowered seedlings of all seedlings, originally sowed seedlings and spontaneously colonized seedlings across treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

The sowed seedlings had an almost significant negative effect of soil type SCS and SCRD on flowering probability (SCS: -1.275, P = 0.097, SCRD: -1.258, P = 0.053) (Fig. 10b). The effect of depth was positive (1.977, P = 0.009), with a higher proportion of flowered sowed seedlings in 30 cm than 18 cm soil depth.

The colonized seedlings had a higher proportion of flowered seedlings in soil type SCS compared to soil type SC (1.412, P = 0.004) (Fig. 10c). No effect of soil type SCRD or soil depth was detected (SCRD: P = 0.138, 30 cm: P = 0.312).

3.4 Diversity indices

The diversity indices were calculated based upon the surviving seedlings minus the unclassified seedlings, giving more precise estimates. Additionally, as species that were hard to differentiate were grouped, results regarding species richness are conservative.

Species richness (number of unique species) was significantly lower in soil type SCS (-5.500, P = 0.005) compared to soil type SC (Fig. 11a). No effect of soil type SCRD or soil depth was detected (SCRD: P = 0.839 , 30 cm: P = 0.563).

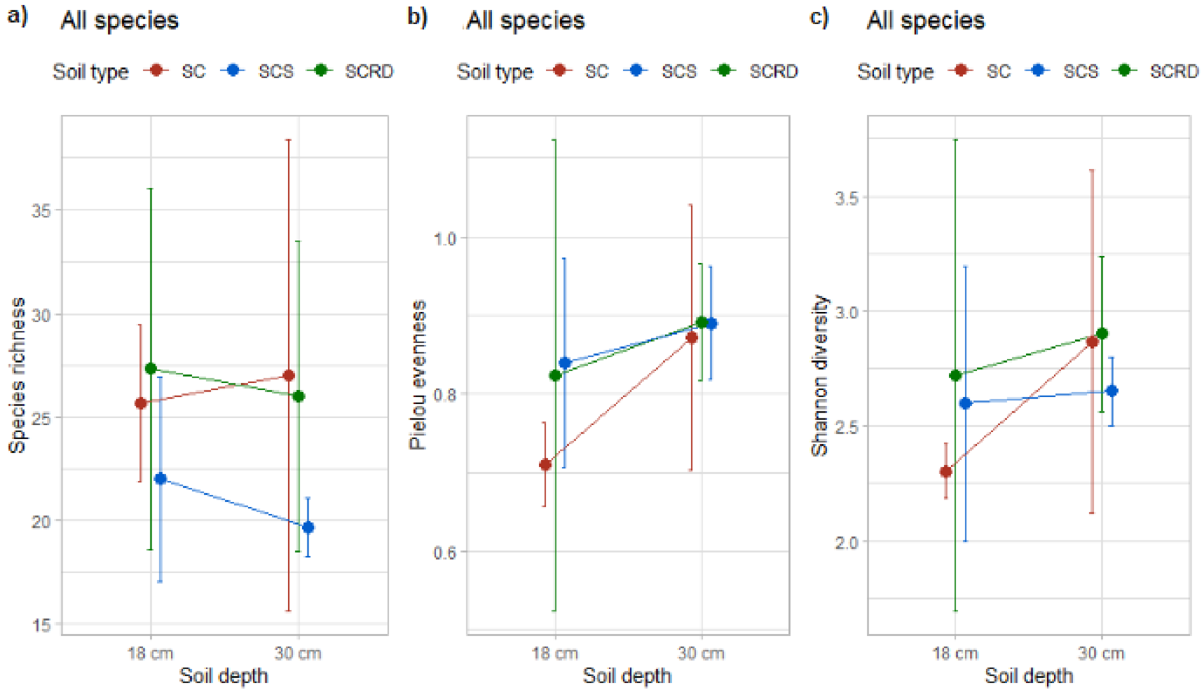

Figure 11 Diversity indices species richness, Pielou evenness and Shannon Wiener diversity calculated from survived identified seedlings across 6 treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

There was a close to significantly positive effect of soil type SCS on Pielou evenness (measuring how homogenous a community is in terms of the abundances of its species) (0.074, P = 0.068) (Fig. 11b). No effect of soil type SCRD was detected (P = 0.097), while 30 cm soil depth led to a significantly higher Pieolou evenness than 18 cm soil depth (0.094, P = 0.009).

Shannon Wiener diversity is an index considering both species richness and evenness. With small recorded differences in species richness and evenness between soil types SCRD and SC, and opposite effects of soil type SCS on species richness and evenness, there was no detected effect of soil type on Shannon Wiener diversity (SCRD: P = 0.145, SCS: P = 0.790) (Fig. 11c). The effect of 30 cm soil depth was significantly positive on Shannon Wiener (0.267, P = 0.042), as higher evenness in deeper plots led to more diverse plant communities.

Analyses without *R. acetosa/ acetosella* leads to a higher Pielou evenness in soil type SC, consequently increasing the Shannon Wiener diversity compared to analyses including *R. acetosa/ acetosella*. This is demonstrated as soil type SCS no longer is having a positive effect on Pielou evenness (SCS: P = 0.750) but is having a negative effect on Shannon Wiener diversity (-0.198, P = 0.008) (Appendix Table S5).

3.5 Biomass

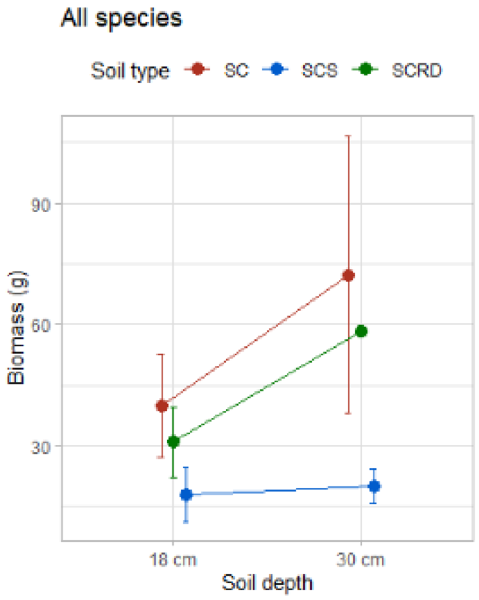

Figure 12 Biomass (g) across treatments: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. Error bars indicate 95% CI and N=3 for treatment 1-6.

The three soil types affected above ground biomass (AGB) similarly to number of all emerged seedlings (Fig. 4a and 12). Soil type SC had highest AGB, being lower in soil type SCRD (-9.000, P = 0.142), and lowest in soil type SCS (-22.000, P = 0.003). Soil depth affected AGB oppositely to number of emerged seedlings, 30 cm soil depth had significantly higher AGB than 18 cm soil depth (32.333, P < 0.001). Soil type SCS in combination with 30 cm depth had close to no positive effect of the deeper soil, contrary to soil types SC and SCRD (-30.333, P = 0.002).

4. Discussion

The results from this experiment demonstrate that, given the treatments and water regime applied, it is possible to establish meadows with native and local herbaceous plant species on green roofs in Oslo, the capital of Norway. Overall, at least 21,2 % of the meadow seeds that were sown emerged as seedlings and survived the experimental period, lasting the first season. This is good news as it uncovers a huge potential to use green roofs in Oslo to increase biodiversity in terms of plants and insects, while simultaneously being capable of preserving some of the many hundreds of threatened plant species related to meadows and "open calcareous ground with shallow soil" in the Oslo area (Miljøstatus, 2019; NINA, 2011). I urge that one should aim at implementing meadow roofs using native and local species on new buildings where the building structure can be made to support the heavier weight of these roofs, instead of implementing lighter *Sedum* roofs, which are possibly invasive and less biodiverse (NIBIO, 2016; Skjeldrum & Kvande, 2017; Van Mechelen et al., 2015).

The results also give an indication that plants can disperse themselves onto green roofs, supporting earlier research (Dunnett et al., 2008; Madre et al., 2014). In this experiment, 39.6% of all survived seedlings were colonized seedlings. The proportion of colonized seedlings is likely to depend on e.g. sowing density (Scotton, 2016) and roof isolation from source vegetation, as habitat connectedness and roof height have been correlated to plant colonization, bird abundance and arthropod richness (Braaker et al., 2017; Madre et al., 2014; Shanahan et al., 2011). In this experiment, the plots were placed on the ground in an urban green space, presumably increasing the abundance of colonizers compared to on a roof.

I detected small effects of the factorial combination of soil type and soil depth, where most analyses lacked a significant interaction between soil type and soil depth. This indicates that soil depth had similar effects on meadow roof establishment independent of soil type, and equally so, that soil type had effects independent of soil depth. Additional research should be done to examine further if the effects of soil depth and soil types act independent of each other on green roofs in general, as no current research (to my knowledge) have investigated these relationships.

Few plants flowered (1.4%) and produced seeds (0.3%) over the experimental period. It is important to stress that the most likely cause is late sowing, and not a response to the treatments. Additionally, some species might need vernalization (live through one winter (SNL, 2018)) to be able to flower, like the sowed species *Pimpinella saxifraga* (Wells, 1987).

To better evaluate the treatments on flowering probability, new recordings should be done in summer 2020.

I have not made any conclusions as to which of the sowed species are most suited for green roof conditions. The difference in emergence between species might be caused by differing seed germination abilities, the need for seed stratification, sowing method etc. Nevertheless, the collected data could have been used to estimate the proportion of the survival of already emerged seedlings per species, giving an indication of the species' fitness on green roofs. However, since I only included the survival of all sowed seedlings, one should not draw conclusions regarding fitness of individual species on green roofs based upon the results presented in this paper.

The wide confidential intervals in the plots are most likely explained by variations of the measured variables among treatments, and not outliers. There were detected significant results in spite of the big CI-s presented in the plots, mainly because each soil type had six replications and soil depth had nine, contrary to treatment 1-6 with three replications each, which were presented in the plots.

4.1 Soil measurements

The soil type consisting of 50% sand compost mixture (SC) and 50% sand (SCS) had a generally lower nutrient content, lower soil water-holding capacity and lower soil moisture measurements than soil type SC, as expected. The reason is likely that a bigger soil volume was attributed to larger mineral particles (sand), and less to smaller mineral particles (silt) and soil organic matter (SOM), which increase nutrient availability and small pores holding water (Brady & Weil, 2014). According to the results, the volume percent of plant available water was similar in soil types SCS and SC short time after irrigation or precipitation (readily available water). However, the volume percent of plant available water was halved in soil type SCS compared soil type SC in longer periods of drought (slowly available water), which makes plots with soil type SCS more prone to drought.

The soil type consisting of 95% SC and 5% rock dust (SCRD) had different effects on the soil measurements than expected. The pH and soil water-holding capacity were not statistically different from soil type SC, contrary to the hypothesized. Soil moisture measurements and some nutrients (Mg, P) were not higher but statistically lower in soil type SCRD compared to soil type SC, although the negative effect was much smaller than compared to soil type SCS. One explanation for the soil chemical results (pH and soil nutrients) can be that the soil was stored for about 6 months (in an airtight bucket) before analysis, where soil processes can have altered the soil chemical properties. Another explanation can be that the rock dust used in this experiment had more neutral chemical properties, giving a smaller response than expected. A lower nutrient content can also be explained by a lower content of both SOM and clay in soil type SCRD, also explaining lower soil moisture measurements, as both SOM and clay improve water storage and nutrient content in soils (Brady & Weil, 2014). Future research should consider how assumed positive effects of adding rock dust, like higher nutrient content and soil moisture (UMB, 2006), is ultimately depending on the physical and chemical properties of the rock dust, and consider how some of the positive effects might diminish in organic-rich soils.

The water content was higher in 30 cm soil depth compared 18 cm soil depth, which is logical, as water content is a function of depth. However, soil moisture measurements were lowest in 30 cm soil depth, contrary to what was expected. One explanation is that the instrument that measured soil moisture was inserted at about 4 cm soil depth, as it is likely that water was drained through the soil and remained more at the bottom of the plots, thus reducing moisture levels in the soil surface with deeper soil. It might also be explained by the observed relationship between 30 cm soil depth and higher biomass, as studies have found that bigger leaves correspond to higher evaporation from leaves leading to lower soil moisture (Vanwoert et al., 2005). I did not estimate nutrient and temperature differences between 30 cm soil depth and 18 cm soil depth. Yet, it is reasonable to assume that the nutrient content increase with soil depth, as the soil will have higher SOM content, and that temperature fluctuations decrease with soil depth, as found in a study by Eksi et al. (2017).

4.2 Soil depth

There were recorded benefits to having both 18 cm and 30 cm soil depth in terms of the measured variables evaluating meadow establishment on green roofs. The number of emerged and survived seedlings was highest in 18 cm soil depth, with lowest mortality and number of dead seedlings. However, the Pielou evenness was highest in 30 cm soil depth resulting in a higher Shannon Wiener diversity compared to 18 cm soil depth, as no effect of depth was detected on species richness. Plots with 30 cm soil depth also had higher above ground biomass (AGB) and a higher probability of seedlings flowering than plots with 18 cm soil depth.

A closer examination of the data reveals that most benefits regarding 18 cm soil depth are attributed to the correlation to a higher abundance of two species; *Rumex acetosa* and

Rumex acetosella, especially in combination with soil type SC. In analyses without *R. acetosa*/ *acetosella*, the opposite effect of depth is detected on seedling emergence and survival, and no effect of depth is recorded on seedling mortality. This is because most colonized seedlings except *R. acetosa*/ *acetosella* survived in 30 cm soil depth, additionally to a higher mean number of survived sowed seedlings, although not significant. Furthermore, 0 out of 659 *R. acetosa*/ *acetosella* seedlings died, which reduced mortality in the plots they occupied the most with 18 cm soil depth. However, the high number of *R. acetosa*/ *acetosella* seedlings had a negative effect on the Shannon Wiener diversity in 18 cm soil depth, demonstrating how the dominance of a few species can reduce the Pielou evenness, ultimately reducing species diversity.

R. acetosa/ *acetosella* seedlings influenced the results by being very numerous, making up 22.55% of all emerged seedlings. It is the species' ability to spread through vegetative propagation which led to its dominance (Korpelainen, 1992), confirmed by the observations of most seedlings lacking cotyledons. Even if *R. acetosa*/ *acetosella* seedlings were found across all treatments, there was a significantly higher number 18 cm soil depth and in soil type SC. This suggests that the vegetative propagation of *R. acetosa*/ *acetosella* requires high levels of soil moisture in the soil surface, as measured soil moisture was highest in 18 cm soil depth and in soil type SC. This is supported by research finding correlations between higher soil moisture content and higher biomass in *R. acetosella* (Zimmerman & Lechowicz, 1982).

Plots with 30 cm soil depth supported the highest number of survived colonized seedlings regarding species other than *R. acetosa*/ *acetosella*, and possibly also a higher number of survived sowed seedlings. More replications of each treatment are required to conclude on whether sowed seedlings actually sprout and survive better in 30 cm soil depth, similar to most of the colonized species.

Plots with 30 cm soil depth also had significantly higher AGB than plots with 18 cm soil depth, supporting earlier research showing correlations between soil depth and plant productivity (e.g. Dunnett et al., 2008; Dusza et al., 2017; Köhler, 2006; Rowe et al., 2012). I found no relation between AGB and number of survived seedlings, suggesting that the plants grew bigger with deeper soil. Bigger plants might explain highest flowering probability of sowed seedlings in 30 cm soil depth. Yet, there was no difference in AGB and flowering probability in 30 cm depth when combined with soil type SCS, suggesting that depth cannot improve productivity if the soil has very low water-holding capacity and nutrient content.

The number of dead seedlings was highest in 30 cm soil depth, which can be explained by a lower measured soil moisture near the soil surface in the deeper soil. My theory is that newly emerged seedlings with small roots were more unable to reach for the water that was drained down the soil profile in deeper soil, ultimately causing a higher number of dead seedlings due to drought. Another possibility is that there was higher competition in deeper soil as it was correlated to higher AGB, but that is unlikely because as soil type SCS correlated with both highest number of dead seedlings and lowest AGB values.

4.3 Soil type

Soil type SC generally did best in terms of meadow establishment on green roofs, while a lower performance was observed in soil type SCRD, and lowest in soil type SCS. Unlike the effect of soil depth, the abundance of *R. acetosa*/ *acetosella* seedlings did not affect the ranking or strength of the correlations regarding soil type considerably. The only exception was in the results regarding Shannon Wiener diversity, where the high number of *R. acetosa*/ *acetosella* seedlings in soil type SC led to the lowest Pielou evenness among the soil types, ultimately reducing the diversity. This indicates that *R. acetosa*/ *acetosella* seedlings did not outcompete other seedling, contrary to what the results of soil depth may suggest.

Soil type SC supported the highest number of emerged and survived seedlings, both overall and when analysing survived sowed and colonized seedlings separately. Soil type SC also had highest AGB, confirming the discussion on soil depth and AGB, where more nutrients and/or water-holding capacity seem to increase productivity on green roofs.

The number of dead seedlings and the proportion of dead seedlings (mortality) were lowest in soil type SCRD. This together with other significant differences between soil types SC and SCRD is surprising, given that no difference in general nutrient content and water-holding capacity between the two soil types was detected. I did detect a lower measured soil moisture in soil type SCRD compared to soil type SC, but the difference in vol% water was very small (1.4% +- 0.3%) and is probably not sufficient to explain the big difference in number of dead seedlings and mortality. Further investigations should be done to understand how additional rock dust is related to lower mortality in herbaceous seedlings on green roofs.

The soil type that presumably resembled the soil properties at meadows and “open calcareous ground with shallow soil” the most, SCS, supported the lowest number of emerged and survived seedlings, regarding both sowed and colonized seedlings. Soil type SCS also had the highest number of dead seedlings and highest mortality, additionally to lowest species richness and AGB. The results suggest that dryer conditions and lower nutrient content, as observed in soil type SCS, prohibited seed germination while also decreasing survival of emerged seedlings and constraining AGB production. Yet, the proportion of flowering colonized seedlings was significantly higher in soil type SCS compared to soil type CS. This is because the three soil types had similar number of flowering plants, while soil type SCS supported a lower number of emerged seedlings. The results suggest that some species (like *Senecio Vulgaris*) have a good chance of flowering regardless of the range in soil property values applied in this experiment. The results regarding soil type SCS are in concordance with those of (Olly et al., 2011), strengthening the theory that soil properties need to be different on roofs than on ground sites to support meadow species. Roof sites seem to require more nutrients and moisture, as they do not receive water horizontally and do not access ground water.

4.4 Future recommendations

No singular treatment had best performance in terms of all variables measured to evaluate the first year of meadow establishment on green roofs. Nevertheless, 30 cm soil depth and soil type SC seem most promising in terms of meadow roof establishment. Plots with 30 cm soil depth had highest AGB and Shannon Wiener diversity, while plots with 18 cm deep soil were dominated by two singular species (*R. acetosa*/ *acetosella)* illustrating how colonized species may reduce diversity. Soil type SC had the most surviving sowed and colonized seedlings, as well as highest AGB. Most *R. acetosa*/ *acetosella* seedlings also preferred soil type SC, but predominantly in combination with 18 cm depth.

There is a multitude of research done on green roofs recommending carefulness when interpreting data from new established roofs, as both succession and interspecies competition imposes changes in plant communities on green roofs over time (e.g. Bates et al., 2015; Dunnett et al., 2008; Gabrych et al., 2016; Rowe et al., 2012). The question arises as to how indicative these results are regarding the future development of the meadow roof in this experiment, and whether the initial results can be generalized to include all meadow roofs.

Results presented in other green roof research suggest that the trends observed in this experiment are likely to change over time. In a 6-year study done in the UK by Dunnett et al. (2008), they found that species which initially had higher survival in shallower substrate (10 cm) (e.g. *Sedum acre* and *Dianthus deltoides*), later decreased in abundance and had higher survival in deeper substrate (20 cm). Their study demonstrates that species which have higher seedling emergence in one soil depth, might have better long-time survival in another soil depth. Bates et al. (2015) found that plant community traits like biomass and species richness only started to diverge among treatments after a drought period four years after plant establishment. It seemed like the species that initially did best in the experiment and had high leaf mass were the ones most vulnerable to drought. The study illustrates how one can wrongly conclude about meadow roof success after as long as 3 years. Results from Hölzel and Otte (2003) on ground site flood meadows demonstrated how colonizers might outcompete target species and halter meadow restoration. I observed how the high abundance of one plant species (*Rorippa sylvestris*) served as a source patch to larvae predators who selectively foraged on this species. This illustrate that predators may act as a biological balancing factor decreasing abundance of dominating species. The conclusion is that this experiment should be followed over the next years to better determine the effect of the treatments on long-time success of meadows on green roof.

Some of the results from this experiment can arguably be generalized to meadow roofs. Target species can be sown onto green roofs and germinate and survive, and colonizing species will establish themselves. The observations of colonized tree seedlings (*Fraxinus* sp. and *Betula pendula*) highlights the need of hay mowing on meadow roofs to prevent succession. The correlation between higher productivity and deeper soil is probably general to green roofs, as a multitude of earlier research have found the same correlation (e.g. Dunnett et al., 2008; Dusza et al., 2017; Köhler, 2006; Rowe et al., 2012). Yet, the results from this study reveal how plant productivity might be haltered even in deep soil if the soil type is substantially nutrient poor and prone to drought. The experimental site was irrigated in dry periods due to observations of high seedling mortality, which suggests that supplementary irrigation is necessary to prevent death of emerged target species in the establishment phase. This is supported by research which have found a positive correlation between watering and establishment of vegetation on green roofs (Nagase & Dunnett, 2010; Nagase & Dunnett, 2013; Vanwoert et al., 2005). It is also probable that meadow roofs need to have a higher soil water and nutrient content than meadow ground sites, as the soil type with lowest nutrient content, water-holding capacity and soil moisture, had no benefits in terms of the variables measured to evaluate meadow roof establishment.

Yet, one issue is that the soil depth results in the present study were influenced considerably by the dominance of *R. acetosa*/ *acetosella* seedlings. While *R. acetosa*/ *acetosella* is wide-spread in Norway (Artsdatabanken, 2020a; Artsdatabanken, 2020b) and wind dispersed, the seeds are generally too heavy to facilitate long-distance dispersal (CABI, 2019), suggesting that it may be unlikely that this species will disperse onto green roofs. As no other research (to my knowledge) have found relationships between soil depth at ~ 18 cm and the occurrence of dominating species, there is a possibility that soil depth 18 cm might be better in terms of meadow roof establishment elsewhere, also keeping in mind that the mortality was lower in shallower soil. Ultimately, each meadow roof will be dissimilar to some degree based upon the surrounding colonized species that can establish themselves onto the roof, which, based on this study, seem to be able to have a considerable influence on the green roof vegetation.

5. Conclusions

The results demonstrate that it is possible to establish meadows with native and local herbaceous plant species on green roofs in Oslo, promoting local and threatened biodiversity. A total of 37 colonized species established themselves. It seems like colonized seedlings can influence green roof vegetation considerably, as two species spread through vegetative propagation, reducing the Shannon Diversity in the plots they were dominating.

The highest number of emerged and survived seedlings was in soil type SC and in 18 cm soil depth, related to a higher soil surface moisture. The results were considerably affected by the colonizers *Rumes acetosa* and *Rumex acetosella*, as other colonized species had most survivors in soil type SC and in soil depth 30 cm, relating to higher nutrient and water-holding capacity values. Sowed species seemingly did best in the same soil type and soil depth, but further research is needed due to a lack of significance. The lowest mortality and number of dead seedlings were recorded in soil type SCRD and in 18 cm soil depth. There seem to be a relation between high seedling death and low soil surface moisture, due to a correlation between deeper soil, SCS, seedlings death and low soil moisture values. Still, no good explanation exists as to why adding rock flour might reduce seedling death on green roofs, and further research is needed. Above ground biomass was highest in soil type SC and in 30 cm soil depth, related to higher nutrient and water-holding capacity values. Yet, no effect of depth was recorded in soil type SCS, suggesting that soil with low nutrient, water-holding capacity and moisture values can hamper plant production even in 30 cm deep soil.

A soil depth of 30 cm in combination with soil type SC seem most promising in terms of meadow roof establishment, suggesting that meadow roofs need to have a higher soil water and nutrient content than meadow ground sites. However, a multitude of research done on green roofs recommend carefulness when interpreting data from new established roofs, as succession and interspecies competition imposes changes in plant communities over time. Consequently, this experiment should be followed over the next years to determine the long-time effect of the treatments on meadow roof performance.

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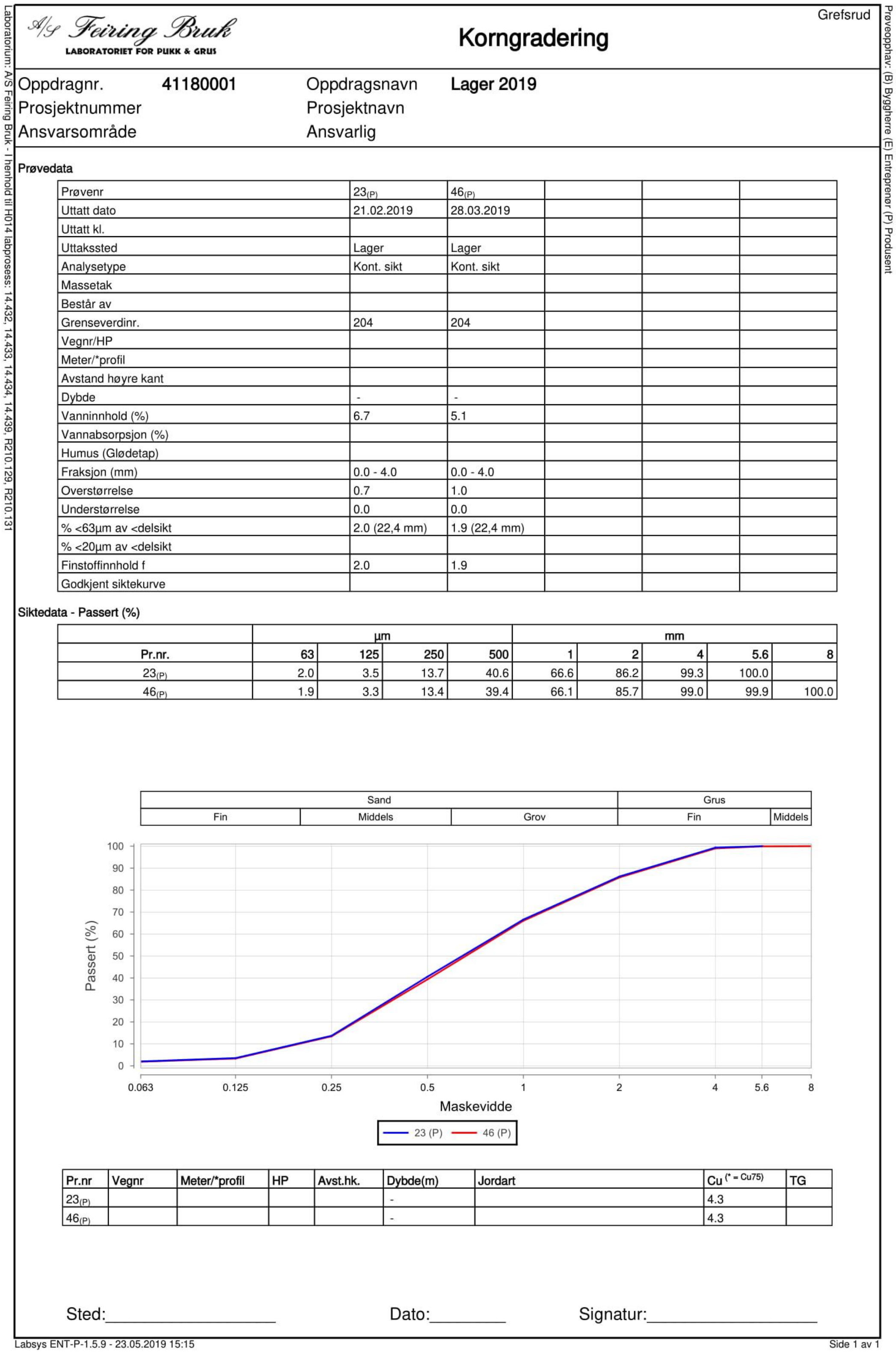
Appendix

Table S1 Full species list of the 26 native and local meadow species used in the experiment.

	Common name	**Latin name**	**annual/ perennial**
1	field garlic	*Allium oleraceum*	perennial
2	wild angelica	*Angelica sylvestris*	perennial/biannual
3	sweet vernal grass	*Anthoxanthum odoratum*	perennial
4	yellow rocketcress	*Barbarea vulgaris*	perennial/biannual
5	maiden pink	*Dianthus deltoids*	perennial
6	sheep fescue	*Festuca ovina*	perennial
7	mead wort	*Filipendula ulmaria*	perennial
8	yellow bedstraw	*Galium verum (/album)*	perennial
9	mouse-ear hawkweed	*Hieracium Pilosella*	perennial
10	narrowleaf hawkweed	*Hieracium umbellatum*	perennial
11	St John's-wort/ spotted St. Johnswort	*Hypericum perforatum/maculatum*	perennial
12	flat pea	*Lathyrus sylvestris*	perennial
13	oxeye daisy	*Leucanthemum vulgare*	perennial
14	many-flowered woodrush	*Luzula multiflora* ssp. *multiflora*	perennial
15	meadow cat's-tail	*Phleum pratense*	perennial
16	burnet	*Pimpinella saxifraga*	perennial
17	figwort	*Scrophularia nodosa*	perennial
18	mountain stone-parsley	*Seseli libanotis*	perennial/biannual
19	Melandrium rubrum	*Silene dioica*	perennial/biannual
20	European goldenrod	*Solidago virgaurea*	perennial
21	hare's-foot clover	*Trifolium arvense*	annual
22	alsike clover	*Trifolium hybridum* ssp. *hybridum*	perennial
23	zigzag clover	*Trifolium medium*	perennial
24	red clover	*Trifolium pratense*	perennial
25	scentless false mayweed	*Tripleurospermum inodorum*	biannual
26	sticky catchfly	*Viscaria vulgaris*	perennial



Laboratorium: A/S Feiring Bruk - I henhold til H014 labprosess: 14.432, 14.433, 14.434, 14.439, R210.129, R210.131

Prøveopphav: (B) Byggherre (E) Entreprenør (P) Produsent

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LABORATORIET FOR PUKK & GRUS

Grefsrud

Korngradering

Oppdragnr.	**41180001**	Oppdragsnavn	**Lager 2019**
Prosjektnummer		Prosjektnavn	
Ansvarsområde		Ansvarlig	

Prøvedata

Prøvenr	23(P)	46(P)			
Uttatt dato	21.02.2019	28.03.2019			
Uttatt kl.					
Uttakssted	Lager	Lager			
Analysetype	Kont. sikt	Kont. sikt			
Massetak					
Består av					
Grenseverdinr.	204	204			
Vegnr/HP					
Meter/*profil					
Avstand høyre kant					
Dybde	-	-			
Vanninnhold (%)	6.7	5.1			
Vannabsorpsjon (%)					
Humus (Glødetap)					
Fraksjon (mm)	0.0 - 4.0	0.0 - 4.0			
Overstørrelse	0.7	1.0			
Understørrelse	0.0	0.0			
% <63µm av <delsikt	2.0 (22,4 mm)	1.9 (22,4 mm)			
% <20µm av <delsikt					
Finstoffinnhold f	2.0	1.9			
Godkjent siktekurve					

Siktedata - Passert (%)

	µm				mm				
Pr.nr.	**63**	**125**	**250**	**500**	**1**	**2**	**4**	**5.6**	**8**
23(P)	2.0	3.5	13.7	40.6	66.6	86.2	99.3	100.0	
46(P)	1.9	3.3	13.4	39.4	66.1	85.7	99.0	99.9	100.0

Pr.nr	Vegnr	Meter/*profil	HP	Avst.hk.	Dybde(m)	Jordart	Cu (* = Cu75)	TG
23(P)					-		4.3	
46(P)					-		4.3	

Sted:__________________ Dato:________ Signatur:__________________

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Side 1 av 1

Figure S1 Particle distribution of “0/4 pussesand”; the natural sand used in soil type SCS (50% sand compost mixture and 50% natural sand).

Figure S2 The experiment setup.

Figure S3 Reference plot with species sowed systematically in rows

Figure S4 Watering with the boom sprayer achieving even irrigation

Figure S5 Emerged seedlings marked with toothpicks and their own unique ID number

Figure S6 Seedlings some time after emergence when identification to species was possible

Figure S7 Plot number 8 as an example of how the seedling emerged fairly clustered despite being sowed evenly

Table S2 Results from statistical analyses regarding soil measurements: soil organic matter (SOM), particle size distribution (clay (<0.002 mm), silt (0.002-0.060 mm) and sand (0.060-2.000 mm)), pF analysis (plant available water (pF 2-4.2), unavailable water (pF > 4.2), slowly available water (pF 3-4.2), readily available water (pF 2-3), air volume (pF 0-2) and water content (pF >2)), soil pH, soil nutrients (Calcium (Ca), Potassium (K), Magnesium (Mg) and Phosphorus (P)) and soil moisture. Treatments 1-6 are: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. SC or SC 18 cm depth is the reference level. N = 3 for SOM, particle size distribution, soil nutrient and soil moisture, while N = 4 for the pF-analysis. **.** indicates that P = 0.5-0.1, * that P < 0.05, ** that P < 0.01 and *** that P < 0.001.

Parameter	Reference level (SC or SC 18 cm)	SCS	SCRD	30 cm	SCS*30cm	SCRD*30cm
Soil composition						
Soil organic matter (SOM) (vol%)	9.650 ± 0.286 ***	- 6.767 ± 0.405 ***	- 1.013 ± 0.405 *			
Clay (weight% of total mineral material)	3.433 ± 0.346 ***	- 0.100 ± 0.490	- 1.367 ± 0.490 *			
Silt (weight% of total mineral material)	10.467 ± 0.787 ***	- 6.933 ± 1.113 ***	- 0.333 ± 1.113			
Sand (weight% of total mineral material)	86.100 ± 0.574 ***	7.067 ± 0.812 ***	1.733 ± 0.812 **.**			
Plant available water (vol%)	17.662 ± 0.665 ***	- 6.819 ± 0.940 ***	- 0.468 ± 0.940			
Unavailable water (vol%)	7.313 ± 0.400 ***	- 3.351 ± 0.566 ***	0.125 ± 0.566			
Slowly available water (vol%)	14.192 ± 0.999 ***	- 7.709 ± 1.413 ***	- 1.693 ± 1.413			
Readily available water (vol%)	3.470 ± 0.619 ***	0.890 ± 0.875	1.225 ± 0.875			
Air volume (vol%)	30.700 ± 0.916 ***	0.565 ± 1.2960	1.910 ± 1.296			
Water content (mm)	31.791 ± 1.645 ***	- 12.274 ± 2.326 ***	- 0.842 ± 2.326	21.194 ± 2.326 ***	- 8.183 ± 3.290 *	- 0.561 ± 3.290
Soil nutrients and pH						
pH	7.880e+00 ± 1.540e-02 ***	- 5.666e-18 ± 2.177e-02	3.333e-03 ± 2.177e-02			
Calcium content (mg/kg)	3100.00 ± 76.98 ***	0.00 ± 108.87	- 66.67 ± 108.87			
Potassium content (mg/kg)	1133.33 ± 27.22 ***	- 833.33 ± 38.49 ***	- 66.67 ± 38.49			
Magnesium content (mg/kg)	413.333 ± 4.303 ***	- 256.667 ± 6.086 ***	- 33.333 ± 6.086 **			
Phosphorus content (mg/kg)	110.000 ± 0.667 ***	- 54.000 ± 0.943 ***	- 10.000 ± 0.943 ***			
Soil moisture						
Soil moisture (fV)	0.172 ± 0.009 ***	- 0.0652 ± 0.003 ***	- 0.014 ± 0.003 ***	- 0.008 ± 0.003 *	- 0.006 ± 0.005	- 0.003 ± 0.005

Table S3 Statistical results regarding the seedlings, both with models estimating interactive and additive effects. The white coloured rows have been used in this paper, whereas grey rows represent results from interactive models without any significant effects that have been excluded. Treatments 1-6 are: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. N = 3 for treatments 1-6. **.** indicates that P = 0.5-0.1, * that P < 0.05, ** that P < 0.01 and *** that P < 0.001.

Parameter	Reference level (SC 18 cm)	SCS	SCRD	30 cm	SCS*30cm	SCRD*30cm
All seedlings						
Number emerged seedlings	5.558 ± 0.036 ***	- 0.843 ± 0.065 ***	- 0.471 ± 0.058 ***	- 0.273 ± 0.055 ***	0.199 ± 0.096 *	0.127 ± 0.139
Number emerged seedlings Without *Rumex acetosa/ acetosella*	5.013 ± 0.047 ***	- 0.590 ± 0.079 ***	- 0.193 ± 0.070 **	0.123 ± 0.065 **.**	0.089 ± 0.107	- 0.126 ± 0.098
	5.023 ± 0.039 ***	- 0.542 ± 0.053 ***	- 0.257 ± 0.049 ***	0.104 ± 0.042 *		
Number dead seedlings Equal without *Rumex acetosa/ acetosella*.	2.565 ± 0.160 ***	0.074 ± 0.222	- 0.486 ± 0.259 **.**	0.074 ± 0.222	0.396 ± 0.286	- 0.593 ± 0.382
	2.515 ± 0.130 ***	0.315 ± 0.139 *	- 0.775 ± 0.189 ***	0.337 ± 0.129 **		
Proportion dead seedlings (mortality)	- 2.942 ± 0.164 ***	0.999 ± 0.233 ***	- 0.016 ± 0.266	0.559 ± 0.221 *	0.324 ± 0.305	- 0.767 ± 0.392 **.**
	- 2.943 ± 0.133 ***	1.191 ± 0.149 ***	- 0.402 ± 0.194 *	0.561 ± 0.136 ***		
Proportion dead seedlings (mortality) Without *Rumex acetosa/ acetosella*	- 2.358 ± 0.168 ***	0.758 ± 0.238 **	- 0.317 ± 0.270	0.138 ± 0.224	0.410 ± 0.309	- 0.500 ± 0.400
	- 2.406 ± 0.137 ***	1.002 ± 0.151 ***	- 0.552 ± 0.196 **	0.224 ± 0.138		
Number survived seedlings	5.507 ± 0.037 ***	- 0.925 ± 0.069 ***	- 0.470 ± 0.059 ***	- 0.310 ± 0.057 ***	0.072 ± 0.10460	0.173 ± 0.089 .
	5.476 ± 0.033 ***	- 0.894 ± 0.052 ***	- 0.393 ± 0.044 ***	- 0.239 ± 0.039 ***		
Number survived seedlings Without *Rumex acetosa/ acetosella*	4.922 ± 0.049 ***	- 0.684 ± 0.085 ***	- 0.169 ± 0.073 *	0.110 ± 0.068	- 0.014 ± 0.117	- 0.093 ± 0.102
	4.941 ± 0.041 ***	- 0.691 ± 0.059 ***	- 0.217 ± 0.051 ***	0.075 ± 0.045 **.**		
Originally sowed seedlings						
Number survived seedlings	4.632 ± 0.057 ***	- 0.693 ± 0.099 ***	- 0.166 ± 0.084 *	0.029 ± 0.080	0.076 ± 0.137	0.045 ± 0.117
	4.615 ± 0.048 ***	- 0.654 ± 0.068 ***	- 0.142 ± 0.059 *	0.062 ± 0.052		
Spontaneously colonized seedlings						
Number of survived seedlings	4.890 ± 0.050 ***	- 1.218 ± 0.105 ***	- 0.802 ± 0.090 ***	- 0.686 ± 0.087 ***	- 0.096 ± 0.186	0.171 ± 0.150
	4.880 ± 0.047 ***	- 1.249 ± 0.087 ***	- 0.741 ± 0.072 ***	- 0.654 ± 0.065 ***		
Number of survived seedlings Without *Rumex acetosa/ acetosella*	3.178 ± 0.118 ***	- 0.780 ± 0.210 ***	- 0.102 ± 0.171	0.503 ± 0.149 ***	- 0.048 ± 0.268	- 0.616 ± 0.234 **
Rumex acetosa/ acetosella						

Number of survived seedlings	4.691 ± 0.055 ***	- 1.347 ± 0.122 ***	- 1.054 ± 0.109 ***	- 1.383 ± 0.124 ***	- 2.366 ± 0.726 **	0.539 ± 0.211 *

Table S4 Statistical results regarding proportion flowered seedlings of emerged seedlings, both with models estimating interactive and additive effects. The white coloured rows have been used in this paper, whereas grey rows represent results from interactive models without any significant effects that have been excluded. Treatments 1-6 are: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. N = 3 for treatments 1-6. **.** indicates that P = 0.5-0.1, * that P < 0.05, ** that P < 0.01 and *** that P < 0.001.

Parameter	Reference level (SC 18 cm)	SCS	SCRD	30 cm	SCS*30cm	SCRD*30cm
All seedlings						
Proportion flowered	- 5.265 ± 0.501 ***	1.261 ± 0.649 **.**	0.883 ± 0.648	1.682 ± 0.562 **	- 1.792 ± 0.830 *	-1.719 ± 0.829 *
Proportion flowered Without *Rumex acetosa/ acetosella*	- 5.414 ± 0.709 ***	1.709 ± 0.820 *	1.303 ± 0.820	1.984 ± 0.753 **	- 2.386 ± 0.970 *	- 2.166 ± 0.969 *
Originally sowed seedlings						
Proportion flowered	- 5.743 ± 1.002 ***	0.680 ± 1.418	- 14.823 ± 1095.387	2.392 ± 1.048*	- 2.586 ± 1.763	13.646 ± 1095.387
	- 5.371 ± 0.724 ***	- 1.275 ± 0.768 **.**	- 1.258 ± 0.650 **.**	1.977 ± 0.755**		
Spontaneously colonized seedlings						
Proportion flowered	- 4.890 ± 0.580 ***	1.772 ± 0.738 *	1.517 ± 0.713 *	1.192 ± 0.735	- 0.658 ± 1.009	- 1.779 ± 1.106
	- 4.480 ± 0.398 ***	1.412 ± 0.494 **	0.751 ± 0.506	0.415 ± 0.410		
Proportion flowered Without *Rumex acetosa/ acetosella*	- 4.304 ± 1.007 ***	2.581 ± 1.118 *	1.985 ± 1.094 **.**	1.126 ± 1.105	- 1.949 ± 1.314	- 2.139 ± 1.387
	- 3.243 ± 0.476 ***	1.307 ± 0.544 *	0.730 ± 0.557	- 0.403 ± 0.439		

Table S5 Statistical results regarding diversity indices (species richness, Pielou evenness and Shannon Wiener diversity, estimated from surviving seedlings minus unclassified seedlings) and above ground biomass, both with models estimating interactive and additive effects. The white coloured rows have been used in this paper, whereas grey rows represent results from interactive models without any significant effects that have been excluded. Treatments 1-6 are: soil type SC (sand compost mixture), SCS (50% SC and 50% sand) and SCRD (95% SC and 5% rock dust), in soil depth 18 and 30 cm. N = 3 for treatments 1-6. **.** indicates that P = 0.5-0.1, * that P < 0.05, ** that P < 0.01 and *** that P < 0.001.

Parameter	Reference level (SC 18 cm)	SCS	SCRD	30 cm	SCS*30cm	SCRD*30cm
Species richness						
Species richness	25.667 ± 1.650 ***	- 3.667 ± 2.333	1.667 ± 2.333	1.333 ± 2.333	- 3.667 ± 3.300	- 2.667 ± 3.300
	26.722 ± 1.314 ***	- 5.500 ± 1.609 **	0.333 ± 1.609	- 0.778 ± 1.314		
Species richness Without *Rumex acetosa/ acetosella*	24.667 ± 1.587 ***	- 3.667 ± 2.244	1.667 ± 2.244	1.667 ± 2.244	- 3.333 ± 3.174	- 3.000 ± 3.174
	25.722 ± 1.265 ***	- 5.333 ± 1.549 **	0.167 ± 1.549	- 0.444 ± 1.265		
Pielou evenness						
Pielou evenness	0.710 ± 0.037 ***	0.130 ± 0.052 *	0.114 ± 0.052 *	0.162 ± 0.052 **	- 0.111 ± 0.073	- 0.094 ± 0.073
	0.744 ± 0.031 ***	0.074 ± 0.038 **.**	0.067 ± 0.038 **.**	0.094 ± 0.031 **		
Pielou evenness Without *Rumex acetosa/ acetosella*	0.909 ± 0.010 ***	0.017 ± 0.014	- 0.015 ± 0.014	- 0.011 ± 0.014	- 0.025 ± 0.020	0.025 ± 0.020
	0.909 ± 0.009 ***	0.004 ± 0.011	- 0.002 ± 0.011	- 0.011 ± 0.009		
Shannon Wiener diversity						
Shannon Wiener diversity	2.301 ± 0.138 ***	0.295 ± 0.195	0.418 ± 0.195 **.**	0.565 ± 0.195 *	- 0.510 ± 0.276 **.**	- 0.385 ± 0.276
	2.450 ± 0.119 ***	0.040 ± 0.146	0.226 ± 0.146	0.267 ± 0.119 *		
Shannon Wiener diversity Without *Rumex acetosa/ acetosella*	2.911 ± 0.062 ***	- 0.097 ± 0.087	0.007 ± 0.087	0.021 ± 0.087	- 0.201 ± 0.124	- 0.020 ± 0.124
	2.948 ± 0.053 ***	- 0.198 ± 0.065 **	- 0.002 ± 0.065	- 0.053 ± 0.053		
Above ground biomass						
Above ground biomass (g)	40.000 ± 4.407 ***	- 22.000 ± 5.690 **	- 9.000 ± 5.690	32.333 ± 5.690 ***	- 30.333 ± 7.634 **	- 5.000 ± 7.634

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