Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Biology

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Topsoil restoration of three construction sites in central Norway: Comparing restoration outcome by species composition and soil characteristics in relation to three reference communities

Master's thesis in Natural Resources Management
Supervisor: Dagmar Hagen
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Abstract

Ecological restoration is a tool that can be used to ease the inevitable pressures that the construction of infrastructure induces onto our landscapes and nature. In this study, I conducted an analysis of the species composition and soil characteristics between three categories of reference ecosystems and restored construction sites. The purpose of the study was to determine which reference ecosystem is associated with the restored site, and what drivers explain their association. In addition, I wanted to identify the predictors that best explained the species composition between the restored sites over a three-year timespan. I used a species and functional cover screening approach, along with quantitative measures of soil density, pH, gravel content, and root weight, to compare species composition between restored and reference sites in three construction areas related the to development of electrical power stations in Norway. The reference sites (undisturbed, disturbed, and novel) were chosen to represent positive, negative, and alternative novel references. Finally, species composition in restored sites was compared between two sampling years (2019 and 2022). For the analysis, I applied multivariate statistics in the form of generalized linear latent variable models (GLLVMs). The results yielded statistical evidence indicating the presence of a shared response amongst restored sites relative to the reference sites. Gravel content (g), pH and soil density varied in their effects but described the same changes in species composition between restored sites and reference sites, and they described them well ($R^2 = 70.6\%$). A multitude of unique species (49) were found in single configurations of study sites and study areas. This indicated that comparison across large distances and unique habitats surrounding each station affected the classification of reference sites. Ruderal species such as *Tussilago farfara* and *Taraxacum limnanthes* were prominent in the restored sites. The disturbed site in Åfjord was the reference site most similar to the restored sites in both species composition and soil characteristics. This reference was a disturbed naturally revegetated gravel roundabout. The species composition in restored sites changed the most due to changes in moss cover, sampling year, and litter cover. From the perspective of the use of reference systems in ecological restoration, this study emphasizes that the inclusion of several reference sites and their soil characteristics will make decisions about restoration treatment more precise, as mitigation can be focused on environmental factors most affected by the construction of infrastructure.

Sammendrag

Økologisk restaurering er et verktøy som kan brukes til å lette det uunngåelige presset som bygging av infrastruktur medfører på vårt landskap og natur. I denne studien gjennomførte jeg en analyse av artssammensetning og jordegenskaper mellom tre kategorier av referanseøkosystemer og restaurerte bygg-områder. Hensikten med studien var å finne ut hvilket referanseøkosystem som relaterer mest til de restaurerte områdene, og hvilke miljøvariabler som forklarer assosiasjonen deres. I tillegg ønsket jeg å identifisere hvilke funksjonelle grupper som best kunne forklare artssammensetningen mellom de restaurerte lokalitetene over en treårsperiode. Jeg brukte en artsdekning og dekning av funksjonelle grupper sammen med kvantitative mål på jordtetthet, pH, grusvekt og rotvekt, for å sammenligne artssammensetning mellom restaurerte områder og referanseområdene i tre byggeområder knyttet til utbygging av elektriske kraftstasjoner i Norge. Referansestedene (uforstyrret, forstyrret og menneskeskapt) ble valgt til å representere en positiv, negativ og alternativ referanse. Til slutt ble artssammensetningen i restaurerte områder sammenlignet mellom to prøvetakingsår (2019 og 2022). For analysen brukte jeg multivariat statistikk i form av generaliserte lineære latent variabel modeller (GLLVM). Resultatene ga statistisk indikasjon om tilstedeværelsen av en delt respons blant restaurerte steder i forhold til referanseområdene. Grusinnhold (g), pH og jordtetthet varierte i deres effekter, men beskrev de samme endringene i artssammensetning mellom restaurerte lokaliteter og referanselokaliteter, og de beskrev dem godt (R^2 = 70.6%) Et mangfold av unike arter (49) ble funnet i enkeltkonfigurasjoner av studiesteder og studieområde. Dette indikerte at sammenligning over store avstander og unike habitater rundt hver stasjon påvirket klassifiseringen av referansesteder. forstyrrelsestolerante arter som *Tussilago farfara* og *Taraxacum limnanthes* var fremtredende i restaurerte lokaliteter. Den negative referansen i Åfjord var mest lik de restaurerte lokalitetene både i artssammensetning og jordegenskaper sammenlignet med resten av referansene. Denne referansen var en forstyrret, naturlig revegetert grusrundkjøring. Artssammensetningen i restaurerte områder endret seg mest på grunn av endringer i mosedekke, år og død vegetasjon. Men endringen var ikke stor. Fra perspektivet til bruk av referansesystemer i økologisk restaurering, understreker denne studien at inkludering av flere referanselokaliteter og deres jordegenskaper vil gjøre beslutninger om restaureringsbehandling mer presise, ettersom avbøtende tiltak kan fokuseres på miljøfaktorer som er mest påvirket av bygging av infrastruktur.

Acknowledgements

First and foremost, I want to thank my main supervisors Dagmar Hagen (NINA) and Bente Jessen Graae (NTNU) for their amazing support and guidance throughout the last two years. They have been extraordinarily patient with my independent working style, giving me space to develop at my own pace. They have always given their time and support when I have needed it. I also want to thank my co-supervisors Anne Catriona Mehlhoop (NINA), and Bert van der Veen (NTNU). Anne was there when I needed her most in the first days of my fieldwork. Throughout the whole field season, she always picked up the phone when I had questions, even though I think she was quite busy with her academic endeavors. I also want to thank Bert for being an outstanding supervisor. The sheer number of hours he has invested into my curiosity has to be, I dare say, rarely matched amongst any master student supervisors across NTNU. They truly are a bunch of academics you can look up to. Finally, I want to thank Solveig, for being there through thick and thin. Without her, I don't think I would ever have made it this far in the first place.

Trondheim, 03.05.2023

Markus Andersen

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1 Introduction

One of the main drivers of global biodiversity loss is land-use change, with 75% of all land area now being pressured by several types of anthropogenic activity (IPBES, 2019). Because of this rapid decrease in biodiversity, and increased habitat degradation, ecosystem services are starting to dwindle (IPBES, 2018). This development propagates challenges in both social and natural situations, as both humans and wildlife suffer from the loss of natural resources (IPBES, 2019). Land-use change is also estimated to drive 23% of human-induced greenhouse gas emissions globally, in the form of road, power, and renewable energy installations (IPCC, 2019). In Norway, the constant pressures of land-use change are estimated to be the most prominent negative factor for threatened wildlife, with 89% of these species experiencing increased stress as a consequence (Norwegian Biodiversity Information Centre, 2018). To mitigate the land-use impacts, the Norwegian government has committed to restoring 15% of its degraded nature within 2030 (Norwegian Environment Agency, 2020) in cohesion with the UN decade of restoration (UNEP, 2020; CBD, 2022). This signals a strong political will to develop restoration methods, and functions as a request for increased application among actors such as Statnett, who develop renewable energy infrastructure in the form of electrical power grids in nature (Statnett, 2021). Furthermore, this implies expectations towards restoration results and management, which is a considerable duty for such a relatively young scientific field compared to the timescale that ecological processes need to develop (Wortley et al., 2013).

In the international primer on ecological restoration by the Society of Ecological Restoration (SER, 2004), ecological restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed". Instances where restoration is needed are characterized by severe degradation when historic conditions of pre-disturbed ecosystems are out of reach by natural revitalization (SER, 2004). This also relates to the mitigation hierarchy, an action plan for stakeholders to limit the reduction of biodiversity in new development projects (Ekstrom et al., 2015). The hierarchy consists of four steps; (1) avoiding impact, (2) reducing inevitable impact, (3) restoring land within the development area, and (4) compensation by restoring degraded land outside of the development area (Ekstrom et al., 2015). Ecological restoration is incentivized when avoiding and reducing impacts is not an option any longer. Mitigation then appears in the form of moving the degraded ecosystem's trajectory toward a path of recovery by ecological restoration (Gann et al., 2019).

Two of the biggest challenges in ecological restoration are the definition of a restoration target and measuring the quality of ecosystem function before and after treatment (Prach et al., 2019). The specification of a restoration target allows for easier management decisions, as the ecological attributes set through the target are indicators of a predefined "success" (Durbecq et al., 2020). The most common way to approach the selection of a reference community is to use an original, pre-disturbance site to model the desired state. This is called a "positive" reference, and can be recorded pre-degradation for a direct comparison, or post-degradation if the state of the undisturbed site is known and similar undisturbed zones are available in close vicinity to the restored site (Aronson et al., 1995). Another option is to use a "negative" reference, which represents a degraded, non-restored, control. With a negative and a positive reference, the position of the restored site can be calculated more confidently, making it easier to assess recovery (Aronson et al., 1995; Prach et al., 2019).

Measuring the quality of recovery includes identifying reference communities and combining descriptions of biotic and abiotic factors in the restored site for comparison with measurements typical for a specific ecological target (Wortley et al., 2013; Durbecq et al., 2020). Repeated measurements of these factors over a temporal scale will then give a successional trajectory of the restored sites, and could be used to derive the quality and precision of the recovery when compared to the reference information from a reference community (White & Walker, 1997). Since reference information is often sampled in a specific temporal and spatial scale it is important to understand that the observed variation is dependent on these two scales. To further complicate the matter, species may respond differently to these scales. Thus, approximating community variation requires multiple sources of reference information that can clearly define the recovery in a larger ecological context (White & Walker, 1997).

Setting the restoration goal of a historically accurate target might not always be feasible, or even desirable (Hobbs et al., 2009). There are multiple reasons for this, such as temporal constraints, a degraded site unable to regain its former state, or the need to prioritize human requirements over a pristine recovery. An instance of this can be observed in the recovery of roadsides after the construction of new roads. Safety measures take priority in such cases, which means that larger vegetation like trees obstructing sightlines or potentially becoming a colliding hazard is undesirable (Deshmukh et al., 2019). What is needed in those situations is resilient vegetation that can reclaim some of the lost functions, which is not necessarily what was originally there. In the literature, this is described as a “novel” ecosystem, defined as an ecological community that has been significantly altered through human activity, to the point that it is fundamentally different from its original state (Hobbs et al., 2009).

The implications of novel ecosystems have been rigorously discussed in restoration ecology (Miller & Bestelmeyer, 2016). Novel ecosystems offer a way to expand the idea of success beyond a single positive reference point. It could be considered a more pragmatic approach considering the constraints often bound to achieve similarity to a positive reference (Hobbs et al., 2009; Deshmukh et al., 2019). However, some will argue that focusing on novel ecosystems in ecological restoration might distract researchers from the pursuit of treatments that moves the successional trajectory of degraded sites closer to the original habitats, potentially lowering expectations for restoration efforts (Murcia et al., 2014).

Construction of facilities related to the energy sector are often situated in nature, far away from civilians, and out of sight (Hagen et al., 2022a). Power plants are connected by large grids of power lines across vast distances, consuming land area. During the construction phase of power installations nature is directly affected by destruction through heavy machinery, and, indirectly by fragmentation and isolation of populations (Andrews, 2014; Hagen et al., 2022a). The construction phase is especially damaging in these types of interventions, as soil and vegetation are ripped from the ground altering, both soil and vegetation communities. The use of heavy machinery results in an alteration of soil structure (Alberty et al., 1984). Effects may include the mixing of soil horizons with surplus masses like gravel from the construction, adding to the problem of soil densification by heavy machinery traffic (Bassett et al., 2005).

Topsoil as a propagule for restoration has been analyzed in several different types of infrastructure development, such as road construction and mining (Holmes, 2001; Skrindo & Pedersen, 2004; Herath et al., 2009). In theory, topsoil restoration can reintroduce the seed propagule bank, plant nutrients, mycorrhiza, and microfauna from native topsoil, and re-establish the indigenous vegetation through natural succession. Natural succession is defined as a non-seasonal, continuous, and directional pattern of the metapopulation of native species (Hargis & Redente, 1984; Begon et al., 1986). This restoration method paves the way for an inexpensive and practical restoration process. The reuse of topsoil avoids the need for new soil to be transported to the construction area by removing the topsoil from the construction site, storing the soil during the construction phase, and reintroducing it once the intervention is complete (Skrindo & Pedersen, 2004). However, the use of topsoil as restoration treatment has yielded mixed results (Holmes, 2001; Herath et al., 2009; Johansen et al., 2017; Mehlhoop et al., 2018), with soil densification and soil structure alteration still lingering in the wake of restoration processes. Topsoil restoration can be combined with seeding, ripping, or spreading of topsoil in different soil layers (Zimmerman, 2017). Topsoil restoration is therefore an umbrella term that varies between studies and in practical applications (Holmes, 2001; Zimmerman, 2017; Hagen et al., 2022a)

GRAN (Greener Construction Sector) was a Norwegian project with the main goal of developing a green framework for the restoration of construction sites in the future. Through this project, topsoil restoration has been applied, following the development of the Norwegian power grid, to mitigate ecological impacts. The effects of topsoil restoration in these types of construction sites has been assessed and evaluated by the Norwegian Institute of Nature Research (NINA) through a research project in cooperation with the grid industry (Hagen et al., 2022a).

By looking at three topsoil-restored construction sites, I will use species composition and soil characteristics to compare restored sites with three reference ecosystems. These reference ecosystems represent potential restoration outcomes, chosen to represent positive, negative, and novel references. My research seeks to fill the knowledge gap of how these communities react to restoration treatment compared to the set of reference communities that have not been restored in the context of Norwegian power grid development. Since the restored sites in this study are subject to the impacts of heavy machinery and the addition of surplus mass, measuring soil characteristics is a logical approach when assessing the success of the restoration treatment and comparing them to reference targets. This may also provide insight into what we can expect from the restored sites analyzed in this study; a direct path to a positive reference, or an alternative reference resembling a novel ecosystem.

1.1 Research questions

1. How is the species composition in restored sites related to the three categories of nearby reference ecosystems?

2. Which reference (undisturbed, disturbed or novel) mostly resembles the restoration outcome in terms of species composition and soil characteristics, and which variables are most important for driving species composition in reference and restored sites?

3. How has species composition changed within restored sites over a time period of three years, and which changes in the functional groups best explain this change?

2 Methods

2.1 Study areas

The study sites are located close (<100m) to three former construction sites in Åfjord (N 63.89215, W 10.22257), Klæbu (N 63.3272, W 10.42317), and Namsos (N 64.47918, W 11.77799) (Fig. 1). The constructions built in these areas were power grid stations with powerlines redirected from the main stations. In each case, topsoil was involved in the restoration treatments, in addition to a commercial seed mix for Klæbu. The restoration was completed in 2015 for the Klæbu site, and in 2016 for Namsos and Åfjord. In June 2019, a coarse vegetation screening on every restored site was performed by the Norwegian Institute for Nature Research in connection to the GRAN project (Hagen et al., 2022a), recording community response as functional vegetation groups. Soil attributes based on surface observation were included in the screening process. Nearby vegetation was classified in each study area, namely clear-cut forest (Klæbu) peatland forest (Namsos & Åfjord).

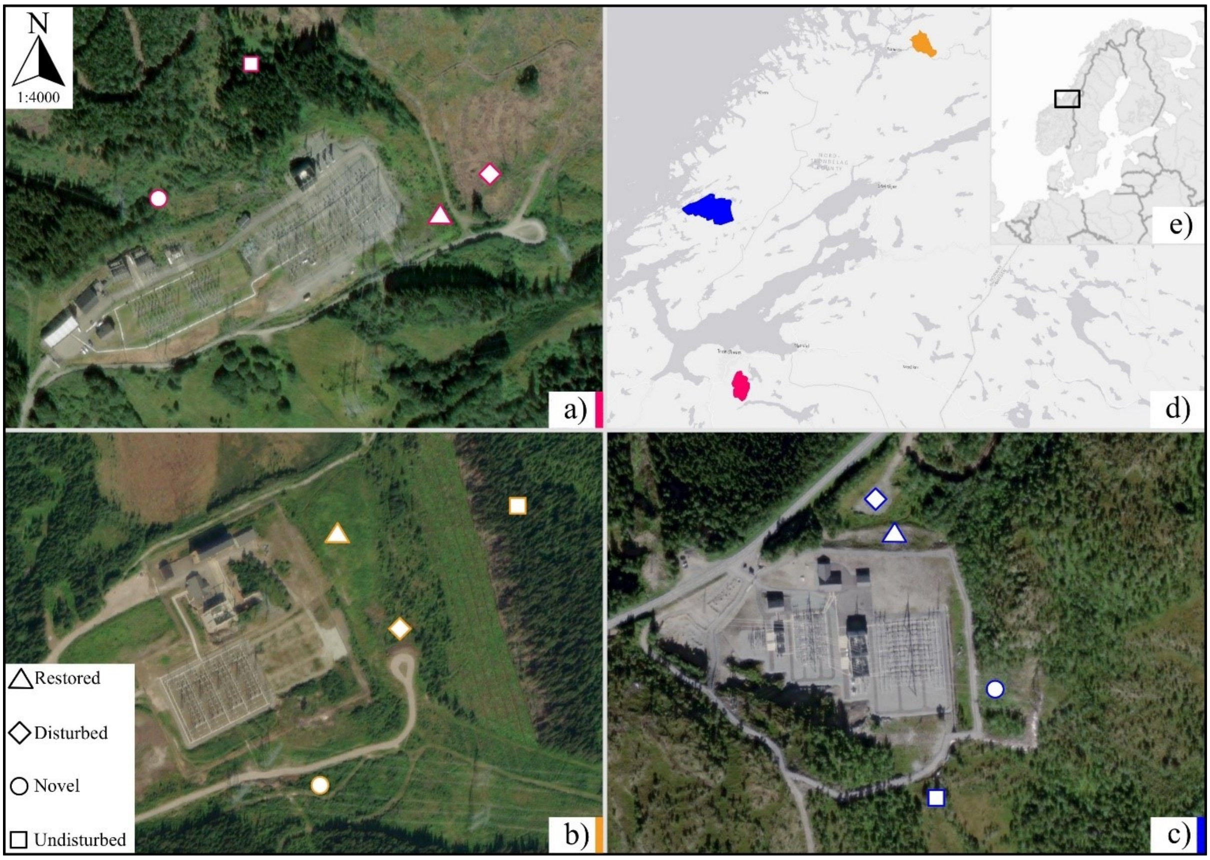

Figure 1: Overview of the study sites and areas included in the study. in the top left corner: Klæbu (N 63,3277875, W 10,4220387), bottom left: Namsos (N 64,4787665, W 11,7775144) and bottom right: Åfjord (N 63,89215, W 10,22257). Coordinates from restored sites. Maps from 2020 made in arcGIS pro and edited with Procreate.

The soil attributes chosen for this study are gravel content (>2mm), pH, and soil density (g/cm^2). These soil attributes have been documented to be altered in relation to common disturbances in restoration and construction sites (Alberty et al., 1984; Bassett et al., 2005; Mehlhoop et al., 2018; Hagen et al., 2022b). The study areas had similar temperatures between 1990 and 2022, but Namsos had slightly higher precipitation (Table 1). However, nearby vegetation of the restored site in Namsos and Åfjord was characterized as peatland forest, indicating a wet climate on ground level in the vicinity of the restored site. The restoration treatments consisted of landfill and reused topsoil (Table 1). Landfill treatments were surplus topsoil, gravel, and rock from the construction phase piled in permanent heaps. Treatments of reused topsoil were cases where local topsoil was removed before the first construction phase, and reintroduced once the intervention was completed (Hagen, 2022a).

Table 1: Mean temperature and precipitation for all research areas (Norwegian Meteorological Institute, 2023), in addition to restoration treatment and the year restoration took place.

Study area	GPS - Restored	Restoration treatment	Restoration year	Mean measurements in June from 1991 – 2022. Mean Temperature	Mean Precipitation
Klæbu	N 63.3272, W 10.42317	Landfill	2016	11.9 ºC SE ± 0.3	87.0 mm SE ± 7.4
Namsos	N 64.47918, W 11.77799	Landfill	2016	11.8 ºC SE ± 0.3	117.8 mm SE ± 9.7
Åfjord	N 63.89215, W 10.22257	Reused topsoil	2015	12.5 ºC SE ± 0.3	98.3 mm SE ± 6.4

2.2 Study design

Soil samples and vegetation data were collected in June 2022 as a supplement to the vegetation screening data of the restored sites from June 2019. Plots were chosen from satellite photos in combination with an in-situ assessment to follow four reference sites, disturbed – novel – restored – original (Fig. 2). Restored sites were pre-determined in connection with the GRAN project. Novel reference plots were always situated under the power lines connected to the power plants, where continuous cutting of vegetation is expected to happen. Disturbed sites were selected by looking at satellite photos of areas where vegetation had been removed or disturbed during the time after restoration. Finally, undisturbed sites were chosen by combining photo records of intact nature and prior classification of nearby ecosystems.

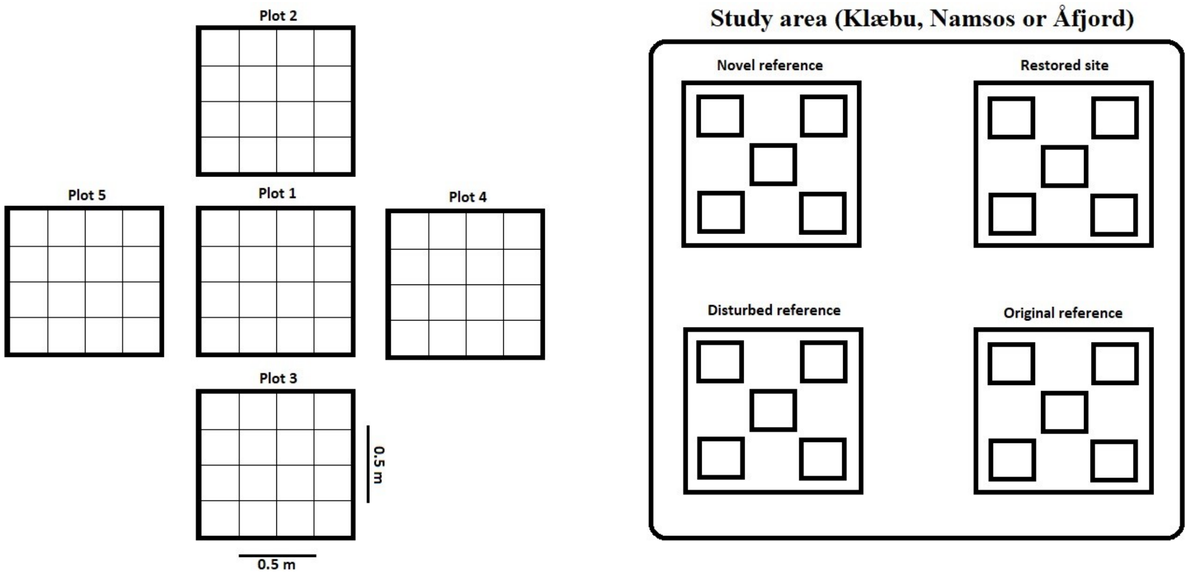

Figure 2: Study design with all sampling levels: Study area, reference (Novel, disturbed, and undisturbed) and restored sites, plot (0.5m x 0.5m) and subplot (0.125m x 0.125m)

2.2.1 Species cover

All sites were analyzed using five plots (0.5m x 0.5m) divided into sixteen subplots (0.125m x 0.125m), across all three research areas (Fig. 2). The exact position of the central plot was obtained by randomly throwing a plastic stick backward over the shoulder from a GPS-center point inside areas for each reference. The landing location of the stick corresponded to the southwestern corner of the plot. The remaining four plots were decided by the same system, with a throw in each direction of the sky (southeast, northeast, and northwest). All species in each subplot were quantified with "presence/absence" where a presence of a species was defined as any part of a species being within the border of the subplot. From the sixteen presence/absence subplots, the cover of each species for the whole plot was calculated, meaning one occurrence weighed 6.25 % of the whole plot (Fig. 2). This method of species frequency is not as strict as rooted species frequency, but it is more structured compared to pure cover measurements which were done for functional groups (see chapter 3.2.2 for details). From here on, the percentage calculated from species occurrences will be referred to as species cover.

2.2.2 Functional group cover

A standardized cover screening protocol was adopted from the GRAN project in 2019 (Hagen et al., 2022a). The protocol was made to record the cover of functional groups, and some soil characteristics. The same plot was used to measure species cover (Fig. 2). Functional groups recorded were tree, shrub, herbaceous, heather, bryophytes, lichen, and graminoids. The cover of litter, bare soil, and rock were also recorded. The total cover was estimated by the cover of all plants except for the canopy cover (tree cover). Trees above 2 meters were classified as tree cover, and below 2 meters as shrub cover. Graminoids included sedge species, grass species, and reeds. The dead grass was excluded from litter cover, as it disappears during the summer. Rocks larger than a closed fist were classified as rock cover.

2.2.3 Soil sampling and soil analysis

Three soil cores were sampled randomly from three corners of the plots (Fig. 2) and photographed alongside a ruler to determine the total length (depth). The total length (depth) was used to derive the soil volume, which in turn was used to calculate soil density. The soil corer was 50 cm long and had a diameter of 21.05 mm. Soil samples were stored in paper bags and frozen from June to November for further analysis.

The soil samples were dried at 60 ºC for 48 hours. The total weight of the dried soil samples was recorded and dry roots (g) and gravel >2mm (g) were extracted with the help of a sieve (2 mm) and then weighed. pH analyses were conducted from 10 mL of dried soil added to 20 mL of distilled water and mixed thoroughly using a pH/Cond-meter. For soil samples with peat, a 1:4 ratio was used to avoid sluggish samples (Margenot, 2021).

2.3 Statistical analysis

All the models fitted for analysis were GLLVMs (generalized linear latent variable models), which are used to analyze multivariate datasets like community composition since it is a joint model of species response. The GLLVM can be used to perform model-based ordinations, with the ability to account for pseudo-replication through random effects, and diagnostic tools to select and evaluate model fit. From here the GLLVM will be referred to as model-based ordination. The concurrent ordination method used in the analysis is a simultaneously unconstrained and constrained ordination. This means that the latent variables in the model are informed by the measured predictors, but not constrained due to the presence of the LV-level (latent variable level) error that accounts for unmeasured residual variation (van der Veen et al., 2022).

2.3.1 Ordinal groups

Because ordinal groups with fewer species and non-zero observations were expected to cause convergence problems, or to result in a different ordination, models with three different configurations were fitted: 1) 10 ordinal groups with intervals of 0.1 from 0 to 1, 2) 8 ordinal groups with merging of group 8, 7 and 6, since these groups had comparatively fewer observations and 3) 6 ordinal groups by the same principle. In principle, a larger number of ordinal groups can be expected to provide the model with more information. However, the models with fewer ordinal groups converged well and resulted in similar ordinations to that of the model with ten ordinal groups, so it was decided to fit all models with 10 groups.

2.3.2 Row effects (random intercepts)

Since all measurements from sites were pseudo-replicated across the three study areas, a random intercept for the area was included in all models. It was confirmed that this resulted in a better fit by comparing models with and without random intercepts. Models with random intercepts had the lowest AICc (corrected Akaike information criterion) and highest log-likelihood (Table S1, Table S2 and Table S3).

2.3.3 Unconstrained model-based ordination

For exploratory purposes a GLLVM (generalized linear latent variable model) was fitted with unconstrained latent variables to model an ordinal response derived from the cover data of species per plot. Species cover data from 2019 and 2022 (75 sites), and species cover data from 2019 (60 sites), were used in the models to produce unconstrained ordination plots. The unconstrained ordinations were used to recognize and explore the patterns in the data of community response and soil characteristics to the latent variables. In addition, this revealed how similar the restored sites are to reference sites purely based on species composition.

2.3.4 Concurrent model-based ordination

To estimate the effect of the predictors and their ability to explain the latent variables, concurrent ordination models were fitted to the data from 2022, and to the data from restored sites between 2022 and 2019. With the concurrent ordination it is possible to confirm the effect on soil predictors, restored and reference site intercept, and the year differences between restored sites. By comparing the unconstrained models to the concurrent models, it is possible to calculate the percentage of variation explained by the predictors of the latent variables.

2.3.5 Infrequent species

While searching for the best model fit it became clear that many of the species occurred exclusively in a single study site and study area, making it harder to accurately estimate all the parameters in the models. This caused parameter estimates to take on extreme values and resulted in overall poor convergence of the models. Because some species were infrequent and therefore lacked variation, their effect sizes became extreme. Removing species from the data that occurred less than three times improved this considerably. This provided more reasonable estimates and the species-specific effects became less extreme across sites. However, after removal of infrequent species the data only contained 50 of the original 98 species. Furthermore, several plots with communities characterized by infrequent species ended up containing few species to define the site scores, which resulted in a new set of problems. Thus, reducing the number of species seemed to just move the problem elsewhere contrary to fixing it. The next paragraphs show proper solutions to this issue.

2.3.6 Interaction between areas and sites

A model with site and area interaction was run with all species to account for the species occurring in one site and area. However, by looking at the species estimates and standard errors for the interaction model, it became apparent that the model overfitted with the additional parameters for all the species, which already were sparse in occurrences.

2.3.7 Regularization – predictor effects as random slopes and intercepts

There is a method in the gllvm R-package to account for collinearity between predictors by regularization (van der Veen et al., 2022), so that the parameter estimates for unimportant predictors are shrunk toward zero. The gllvm R-package implements this by specifying the canonical coefficients (predictor effects in the ordination) as random effects. This can be done in two ways; either by specifying that the variances of the random slopes are unique to each latent variable (so that all predictor effects for the same latent variable are shrunk the same amount), or unique to each predictor (so that the effects of the same predictor on different latent variables are shrunk the same amount). Here, variances of the random slopes and intercepts being unique to each latent variable were chosen because this implies covariation between species responses to a predictor. This causes shrinkage, as the model became stricter when treating predictors as random effects, which scaled the extreme effects, making the plots look better.

To assess model fit, Akaike's corrected information criterion was used (Table S1, S2 and S3 Burnham et al., 2011; Niku et al., 2019). Bar plots were produced using base R, while the ordination diagrams and caterpillar plots were made with the native plotting functions from the gllvm R-package (Niku et al., 2023). All data processing, model fitting, and analysis were done using R version 4.2.2 (R Core Team, 2020) and RStudio (RStudio, 2020).

3 Results

The species cover analysis provided 118 species and genera, along with 75 cover records for each functional group across the two years. In the end there were 767 species cover observations distributed across the observed 118 species and genera (Fig. 3). For the 60 plots screened in 2022 98 total species and genera were observed. Some species were not included in the analysis because the classification was too uncertain. Most often these were single leaves or tiny grasses that were impossible to identify. Species that were unidentified, but distinct, were still included, as there was no risk of counting them twice.

3.1 Species richness and cover data

Species richness in restored sites was higher compared to the reference sites, with an observed mean of 25.3 species per study area and a total number of 58 occurring species. Restored sites held the highest number of species (58), followed by Disturbed (51), Undisturbed (46), and the least species rich reference being Novel (35) (Table 2). The unique species for these sites had a slightly different order with more species being unique to undisturbed than to disturbed. In total, there were 49 species unique to one configuration of study site and study area.

Table 2: Species richness in all restored and reference sites from 2022, along with an area-specific number of species.

		Species Richness		
Study site	**Study area**	**Unique species in study site per study area**	**Total species richness in study sites per study area**	**Total species richness in study sites across study area**
Restored	Klæbu	11	28	58
	Namsos	8	25	
	Åfjord	2	23	
Disturbed	Klæbu	5	19	51
	Namsos	1	24	
	Åfjord	2	23	
Novel	Klæbu	0	17	35
	Namsos	1	19	
	Åfjord	3	18	
Undisturbed	Klæbu	5	14	46
	Namsos	1	14	
	Åfjord	10	29	
Combined		49	118	118

Species that had high occurrences in the plots were often grass species such as *Avenella flexuosa* and *Argostis capillaris*. Shrubs and trees such as *Alnus incana* and *Picea abies* were also prevalent when they occurred, often covering most of the sampling grid due to their sizes. Reference sites (novel, disturbed, undisturbed) experienced more dominating species or species of high coverage, skewing the number of observations to the right, while the observations from the restored sites are skewed towards the left (Fig. 3).

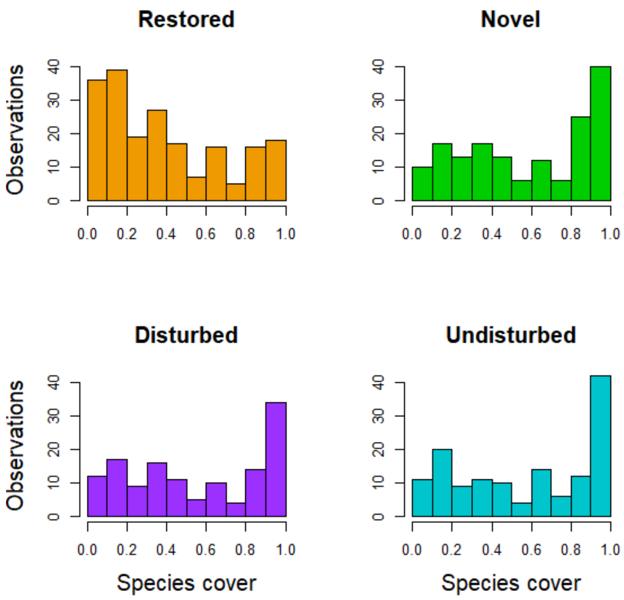

Figure 3: Distributions of observations across all study sites in 2022. Reference sites (novel, disturbed,

3.1.1 Total cover

Across study sites, the total cover varied more in disturbed, novel, and restored compared to undisturbed. The largest observed mean of total cover between study sites was 78.7% ± 4.0 SE (undisturbed) followed up by 75.3% ± 6.4 SE in disturbed reference 67.3% ± 5.0 SE in novel reference sites and 66.7% ± 5.7 SE in restoration treated sites (Fig. 4a). The total cover was also observed between years (Fig. 4b), where the observed mean of total cover had increased from 50.2% ± 9.2 SE to 66.7% ± 6.6 SE since the first vegetation recording in 2019 (Fig. 4b).

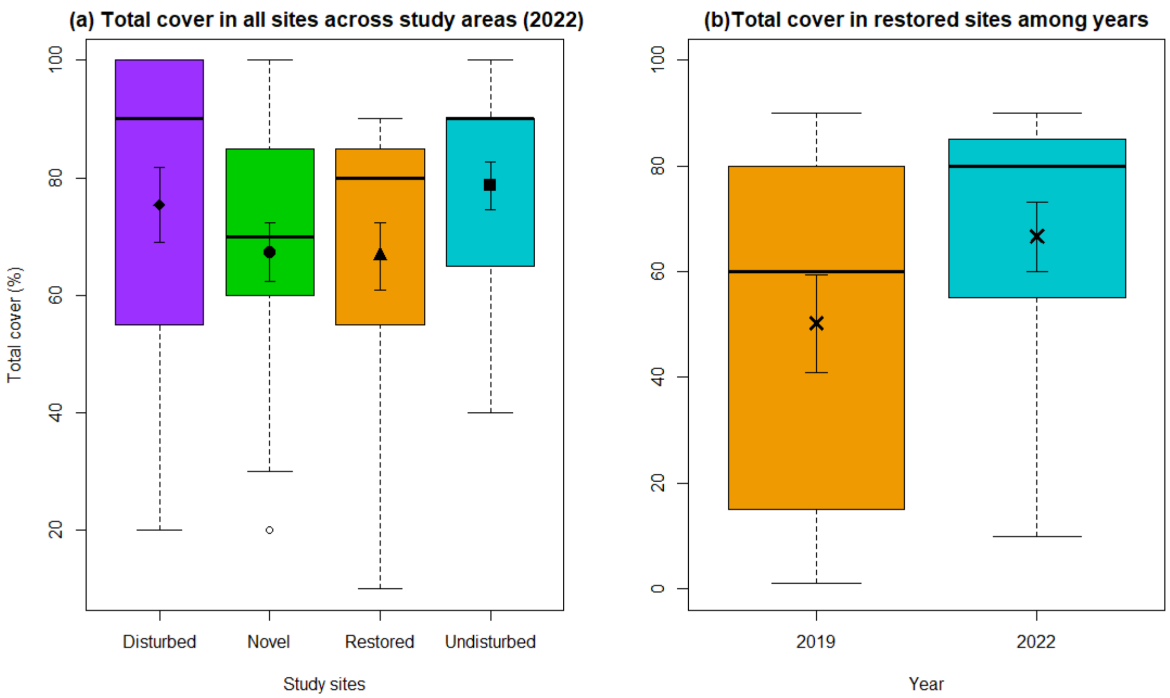

Figure 4: a) Total cover for each site (treatment) for all areas combined (n = 20 per site). b) Total cover of restored sites between 2019 and 2022 (n = 15 per year). Symbols signify the mean. The solid horizontal lines indicate the median and the vertical solid lines show observed standard errors.

3.2 Exploratory analysis of community composition

The unconstrained ordination model with two latent variables fitted the data best, as measured by AICc (Table S1). The ordination visually displayed in Figure 6 showed clustering of restored sites in larger values along latent variable two, and towards the middle of latent variable one (Fig. 5). This suggested that the variation that latent variable two explained was related to whether the study sites are restored sites or not. The exception was a cluster of disturbed plots, which were in the same location in ordination space as restored sites with prediction regions that encompassed only other restored sites (Fig. 5a). The placement of novel

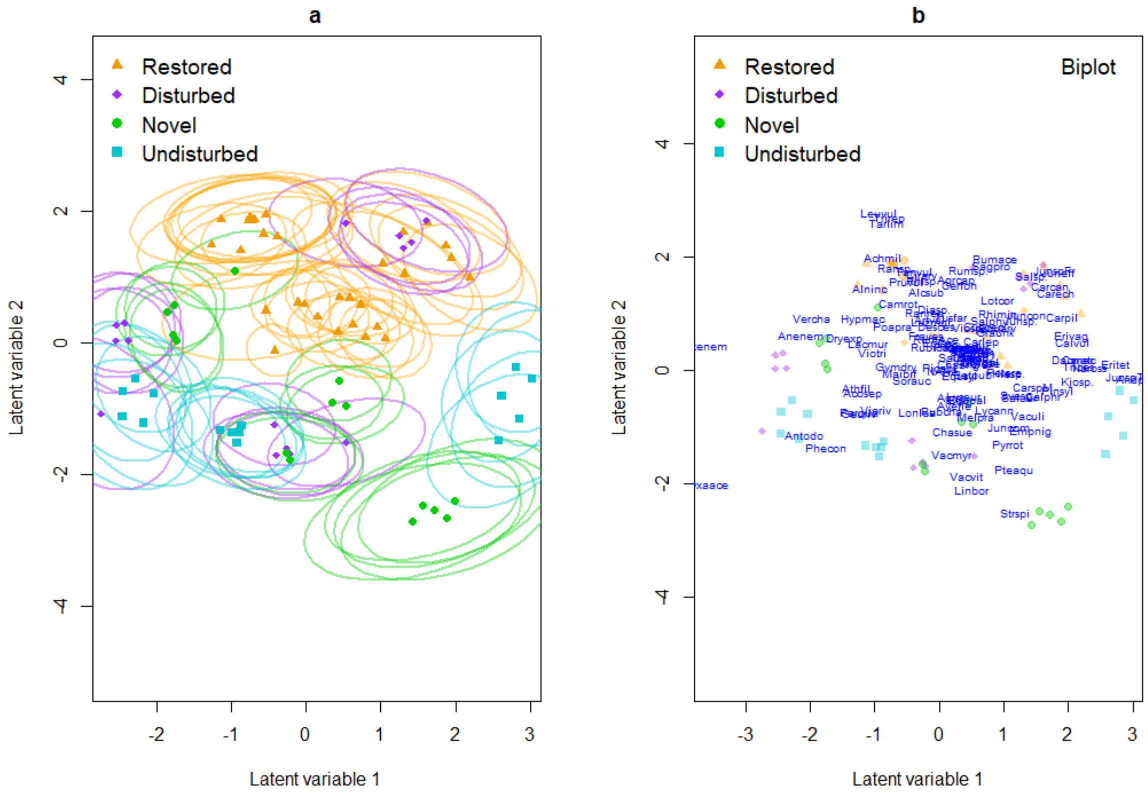

Figure 5: Unconstrained ordination from a GLLVM with study area as a random variable to account for pseudo-replication of sites. a) shows sites with 95% prediction regions and b) is the biplot of the unconstrained model.

and disturbed reference plots varied across both latent variables, while the undisturbed plots exhibit a larger spread on latent variable one but were all in the same position on latent variable two (Fig. 5a). This pattern represented a variation among reference site variation, but in figure 6a it was less clear how latent variable one structured the site response. However, coloring the plots by area revealed that study area is one of the patterns that could be represented along the first latent variable (Fig. 6). However, the effect of study areas was accounted for in the random effect of the model, but the pattern along latent variable one is still prominent and cannot be ignored in further interpretation (Fig. 6). Sites from Klæbu are situated to the left of latent variable one, followed up by Namsos in the middle, and Åfjord to the right (Fig. 6). Species responses are similarly distributed on latent variable one, that described variation between study areas, and latent variable two that explained the threshold for restored sites (Fig. 5a). The disturbed plots placed among the restored cluster in figure 5 was revealed to originate from the disturbed site in Åfjord (Fig. 6). In Klæbu and Namsos, the references that were located closest to the restored sites were the novel reference, while in Åfjord the disturbed site associated more with the restored site. This implied that there may not be a single type of reference site that is more analogous to the restored sites based on the location in the ordination plot (Fig. 5 and 6). The undisturbed plots from the Klæbu and Namsos areas were located closer together compared to the undisturbed plots from

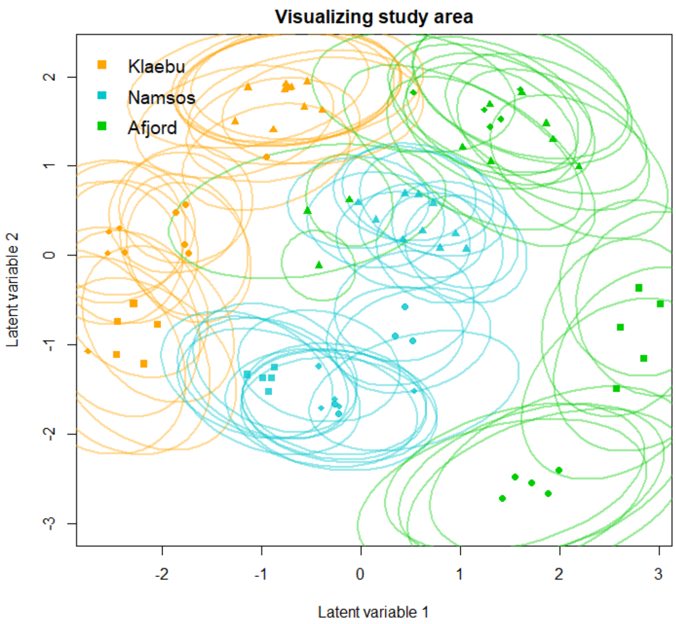

Figure 6: Unconstrained ordination with plots colored by study area. Ellipses show 95% prediction regions.

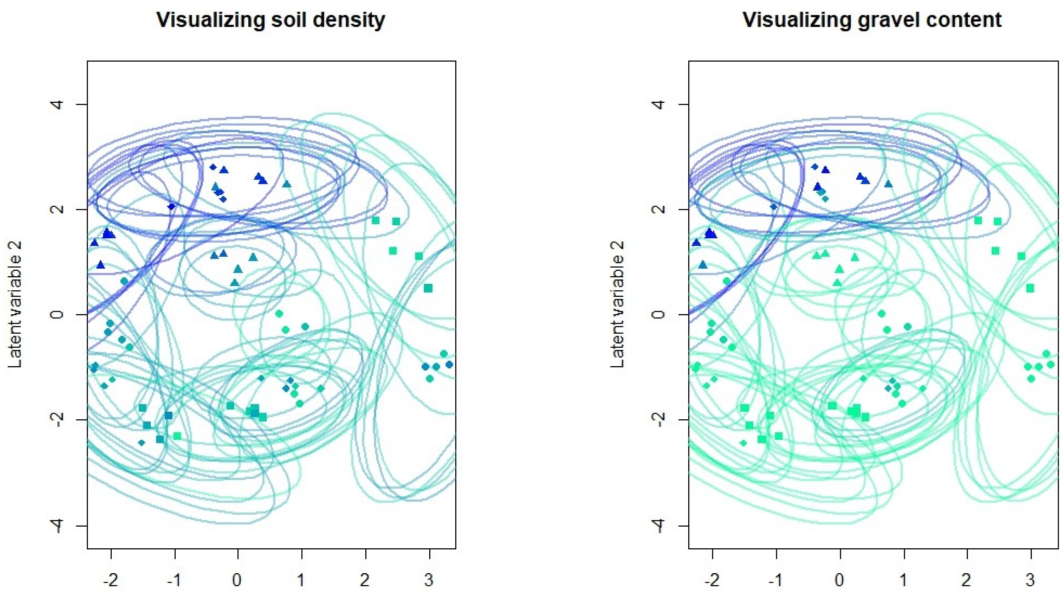

Figure 7: Higher values of soil density and gravel content is shown as a color gradient in an unconstrained ordination with the species from 2022. Darker shade of blue means higher values of the predictors. Ellipses show 95% prediction regions.

Åfjord (Fig. 5 and 6). In figure 7, values of predictor variables are visualized in the same manner as study areas in figure 6. Gravel content and soil density increased as latent variable two increased (Fig. 7). This is also the case for pH and bare soil (Fig. S5). From figure 6 and 5a the pattern in figure 7 suggested that these soil variables could be responsible for the similarities observed in the community response of restored sites compared to the references. Canopy cover and moss cover increase when latent variable two decreases, but the gradients are not as clear compared to the soil predictors (Fig. S4). Unconstrained ordination plots with the rest of the predictor gradients are available in figure S4 located in the supplementary material.

3.3 Explanatory analysis of species composition

A concurrent ordination, with three informed latent variables, and random effect to account for pseudo-replication of area fitted the data best according to Akaike's corrected information criterion (Table S2). Three latent variables and random effect of area in the model gave the best fit. In figure 8 the ordination from the model is depicted (Fig. 8).

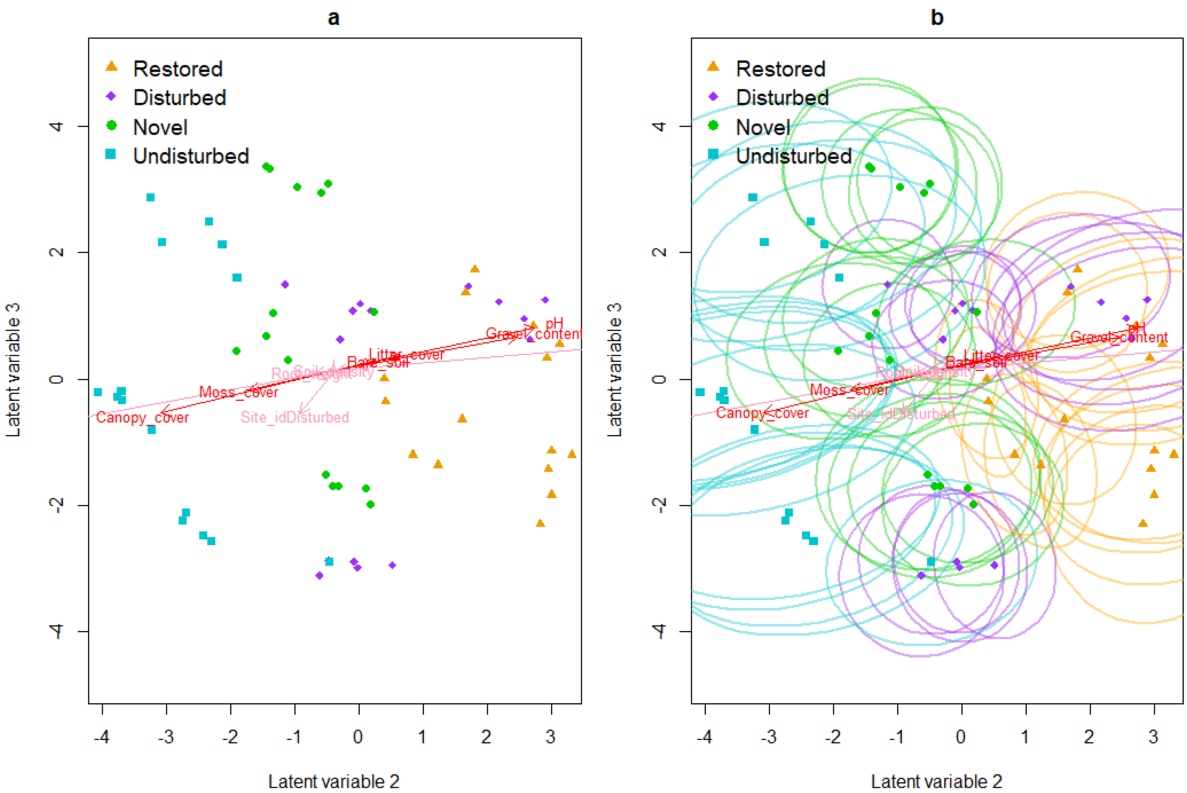

Figure 8: Ordination plots from a concurrent gllvm with three latent variables, random slopes for the predictors per latent variable, and with a random intercept for area. Displayed ellipses are 95% prediction regions. Latent variables 2 and 3 are the constrained axes in all plots. 8a) Arrows show relationship between predictor and axes. Red arrow indicates significant individual differences in the effect of the predictor on the latent variable. 8b) Prediction regions, overlap means non-significant difference (uncertainty) in species composition between sites.

In the concurrent ordination plots, the clustering of the disturbed study site in Åfjord and the restored sites was persistent. And it was confirmed that their relationship observed in the unconstrained plots could be partly explained by the increased pH, soil density and gravel content (Fig. 8 and Table 3). The latent variables were weakly explained by soil density in this configuration of the fitted model, in contrast to the expectation formed from figure 7 (Table 3). The Biplot from the model showed the distribution of species along the second and third latent variable, where species to the right in the ordination plot correspond more to the environment found in restored sites (Fig. 9).

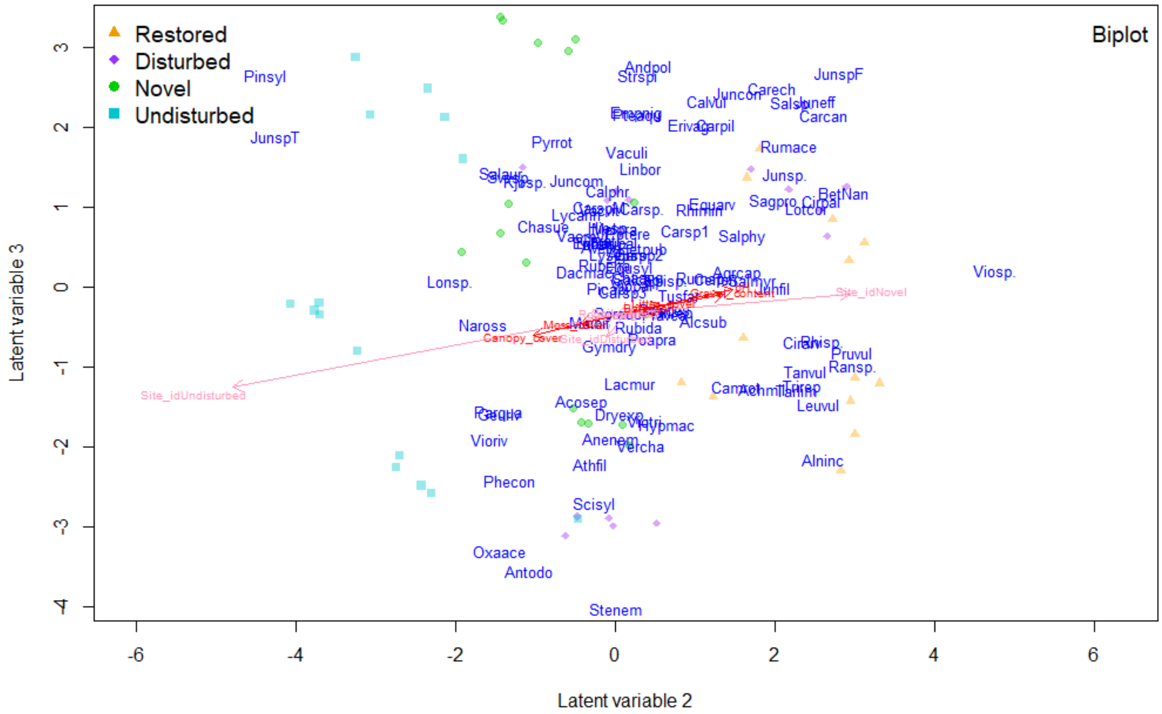

Figure 9: Biplot with all species. Species are located close to the sites where they are most prevalent. Arrows show relationship between predictor and axes. Red arrow indicates significant individual differences in the effect of the predictor on the latent variable.

According to Table 3, the undisturbed site intercept had the largest effect in explaining latent variable two (-0.53 ± 0.31 PE), with pH (0.35 ± 0.10 PE) being the second largest effect followed by canopy cover -0.33 ± 0.11 PE). For latent variable three, the novel (8.92 ± 3.35 PE) and disturbed (6.27 ± 2.48 PE) reference sites had the largest effect, followed by canopy cover (2.53 ± 1.05 PE), the undisturbed intercept (-2.46 ± 1.78 PE) and gravel content (1.57 ± 1.09 PE) (Table 3). The effects of bare soil and soil density are the smallest among the predictors, but arrows for the random slopes were all aligned and stacked on top of each other, which could signify collinearity between the predictors. A soil density gradient could for example be visualized by plotting with color of increasing soil density in another configuration of the latent variables (Fig. S8). The standard deviation of the LV-level (latent variable level) error was 0.76 for the first latent variable, and 0 for the second and third latent variables, which means that two latent variables were almost fully explained by the predictors, and latent variable one was informed by residual variation not explained by the predictors.

Table 3: Summary table for the concurrent model depicted in figures 8 and 9. Estimates for informed latent variables (CLV) 1, 2 and 3 are shown alongside their predicted error (PE). The model explained 70.8% of the variation in the residual model (unconstrained model with three latent variables).

Soil predictor	**LV**	**Estimate**	**PE**	**LV**	**Estimate**	**PE**	**LV**	**Estimate**	**PE**
pH	CLV1	0.00	0.00	CLV2	0.35	0.10	CLV3	-0.64	0,79
Soil density	CLV1	0.00	0.00	CLV2	0.00	0.05	CLV3	0.17	0,41
Gravel content	CLV1	0.00	0.00	CLV2	0.30	0.09	CLV3	1.57	1,09
Bare soil	CLV1	0.00	0.00	CLV2	0.07	0.03	CLV3	0.04	0,26
Functional cover									
Root weight	CLV1	0.00	0.00	CLV2	-0.03	0.04	CLV3	-0.70	0,28
Moss cover	CLV1	0.00	0.00	CLV2	-0.16	0.07	CLV3	0.65	0,44
Litter cover	CLV1	0.00	0.00	CLV2	0.12	0.04	CLV3	-0.61	0,34
Canopy cover	CLV1	0.00	0.00	CLV2	-0.33	0.11	CLV3	2.53	1,05
Intercepts									
Disturbed	CLV1	0.00	0.00	CLV2	-0.10	0.18	CLV3	6.27	2,48
Novel	CLV1	0.00	0.00	CLV2	0.22	0.26	CLV3	8.92	3,35
Undisturbed	CLV1	0.00	0.00	CLV2	-0.53	0.31	CLV3	-2.46	1,78
Residual standard deviation of informed latent variables	0.76			0.00			0.00		
Pseudo R^2 = 70.8 %									

Species estimates along with confidence intervals were collected to plot species - site association (Fig. 10 and Fig. 11a and b). Because many species were infrequently observed, the results need to be interpreted carefully, as most of the species had fewer non-zero observations than there are parameters in the model. Compared to the undisturbed site, ruderal species, common in road ditches, were more likely to occur in restored plots. This included species such as *Rumex acetosa*, *Prunella Vulgaris*, *Alnus Incana*, *Tussilago Farfara, Tanacetum Vulgare* and *Ranunculus Repens* (Fig. 10). The disturbed and novel species responses were almost identical to each other when looking at the structure of the caterpillar plots (Fig. 8b and c). For the aforementioned ruderal species, the differences between their probability to occur in plots with restored and disturbed or novel site is smaller (Fig. 11a, b).

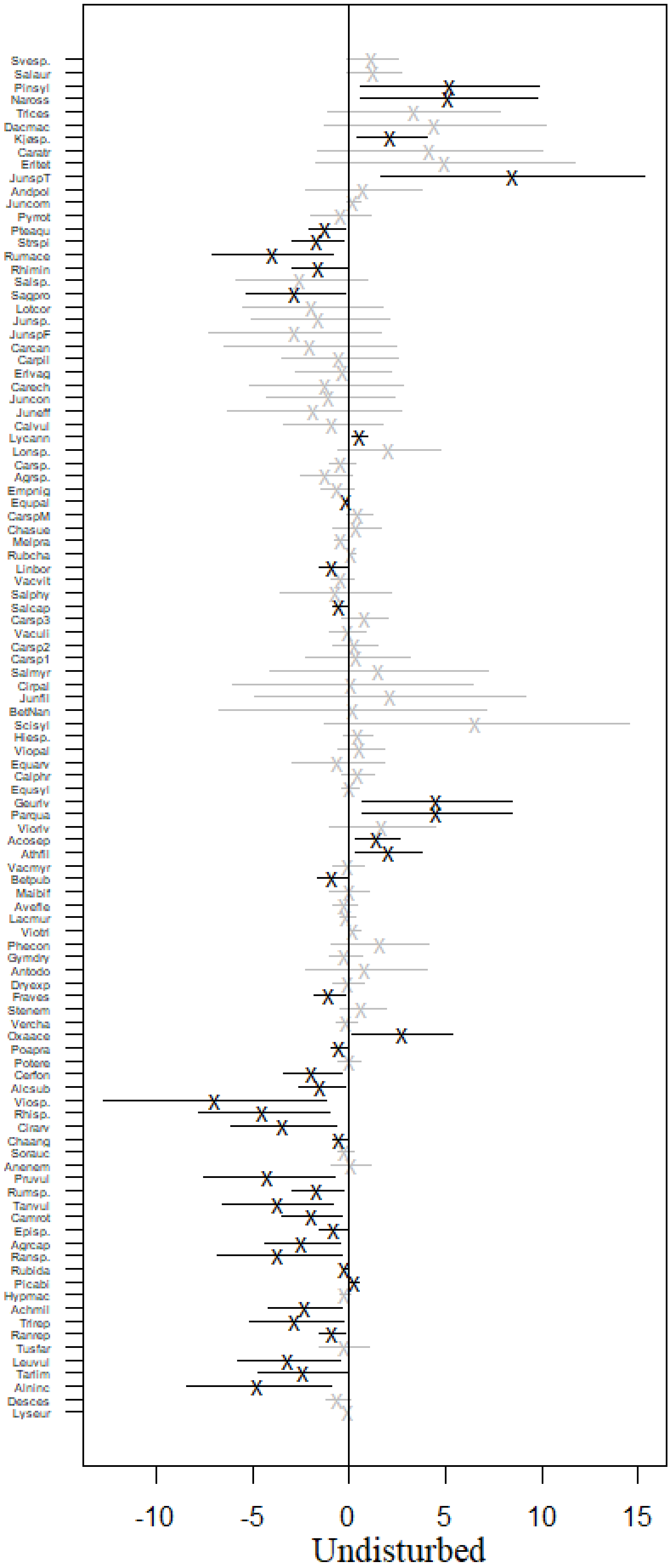

Figure 10: Species association between restored sites and undisturbed reference sites. Negative estimates means that the species is more prominent in the restored sites. 95% confidence intervals (CI) included, where significance is shown as black lines when CI does not span 0.

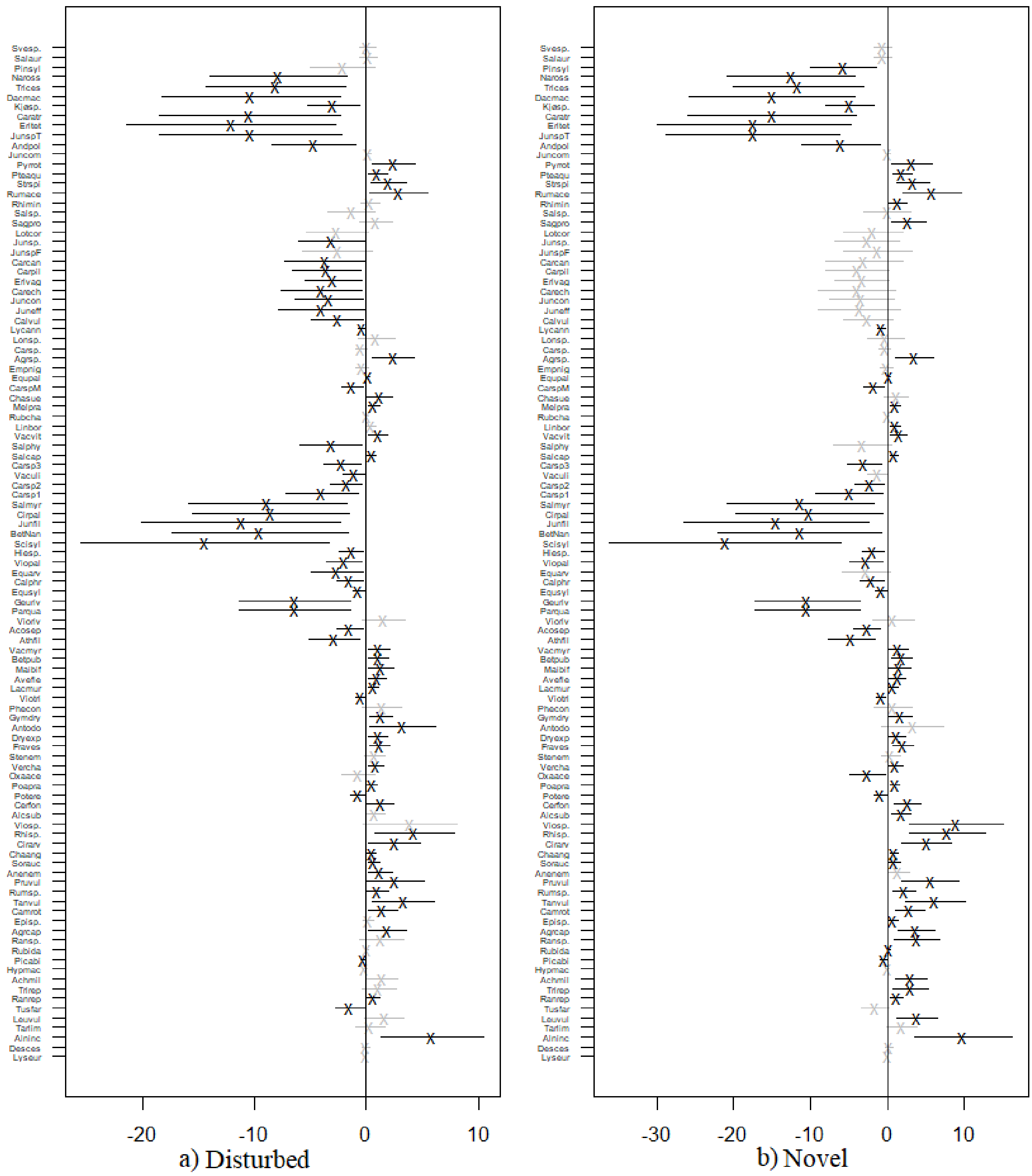

Figure 11: Species association between restored sites and a) Disturbed reference sites and b) Novel reference sites. Crosses represent parameter estimates, with negative estimates meaning that the species is more prominent in the restored site. Horizontal bars represent 95% confidence intervals (CI), where significance is shown as black lines if the CI does not span 0.

3.4 Year effect on restored sites

Plots from 2022 had larger prediction regions compared to plots from 2019. Predictor arrows were perfectly horizontal in the ordination plot, so all vertical variation is generated from unobserved variables (Fig. 12).

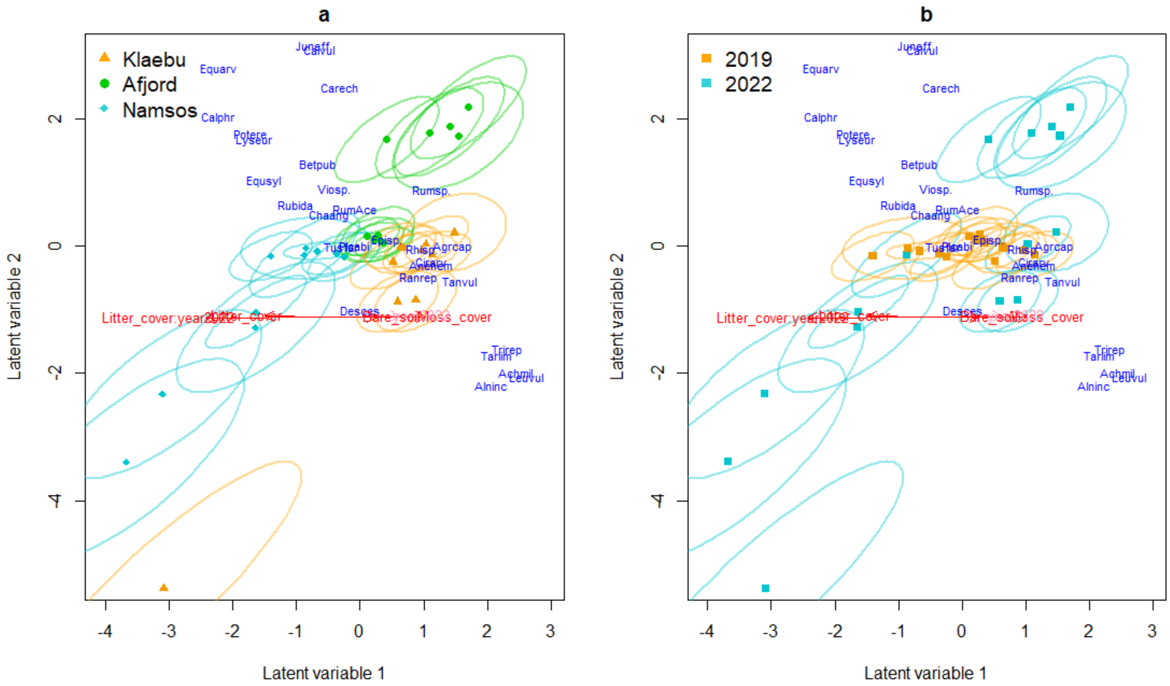

Figure 12: The concurrent ordination fitted to analyze year effect in the restored sites. The model was fitted with random slopes and intercepts per the predictor to shrink the smaller effects to zero. The predictors used were functional cover measurements of litter and moss cover, bare soil, sampling year plus a year and litter cover interaction. a) shows study areas as colors and b) shows sampling year as colors.

The species composition in the plots from 2022 (Fig. 12b) were spread in separate directions from the 2019 cluster in the centre of the ordination space. Restored plots from Namsos shifted towards the bottom left, Klæbu had a slight drift to the right, and Åfjord had completely detached from the 2019 cluster and had moved diagonally along in the positive direction of both axes (Fig. 12). One of the plots from Klæbu stretched out from the 2019 cluster similarly to the plots from Namsos, but from the confidence ellipses the four remaining plots were not significantly different from 2019 (Fig. 12).

Moss cover had the largest effect (1.18 ± 0.22 PE) in explaining latent variable one, followed by the interaction effect between litter cover and year (-1.15 ± 0.42 PE) (Table 4). Overall effect by year was the lowest from all of the predictors (0.45 ± 0.32 PE), suggesting that the species composition has not changed to drastically between years.

Table 4: Summary table for the concurrent GLLVM in figure 12. parameter estimates for informed latent variables (CLV) one and two are shown alongside their predicted error (PE). The model explained 61.3 % of the variation from the null model (Unconstrained model).

Predictor	**LV**	**Estimate**	**PE**	**LV**	**Estimate**	**PE**
Moss cover	CLV1	1.18	0.22	CLV2	0.00	0.00
Litter cover	CLV1	-0.71	0.30	CLV2	0.00	0.00
Bare soil	CLV1	0.61	0.13	CLV2	0.00	0.00
Litter cover:Year (2022)	CLV1	-1.15	0.42	CLV2	0.02	0.00
Intercept						
Year (2022)	CLV1	0.45	0.32	CLV2	-0.01	0.00
Residual standard deviation of LVs	0.71			0.00		
Pseudo R^2 = 61.3%						

4 Discussion

In this study, I found that restored plots, in the aftermath of power plant construction, are defined by similar types of disturbances in soil characteristics which resulted in a shared community response. Increased pH, soil density, and gravel content generated increased relatedness in community composition between restored sites, compared to their association with the three categories of nearby reference ecosystems. Additionally, I found that the reference plots with the highest resemblance to the restored sites originated from the negative reference in Åfjord. Within restored sites I found that moss cover was the best predictor for species composition followed by an interaction between litter cover and sampling year.

4.1 Species richness and disturbance patterns

Restored sites were observed to have the highest species richness in this study, but the species here exhibited lower cover compared to the references. This could be attributed to their earlier successional stage, providing space for ruderal species to emerge in the restored sites. However, utility of species richness as a metric for assessing restoration success has been called into question, as they fail to account for the species identities (Brudvig et al., 2017; Mehlhoop et al., 2022). The ruderal species found in this study, such as *Tussilago Farfara,* were common in restored sites, along with several species known to inhabit roadsides in the Norwegian landscape (Mehlhoop et al., 2022). This indicated that the types of soil alteration identified in this study might be associated with other types of infrastructure developments such as road construction.

4.2 Comparing species composition between restored and reference sites

In the analysis of species composition between the restored and reference sites, I discovered that there was a considerable overlap in species composition among the restored sites. The first latent variable from the unconstrained ordination is suspected to represent a gradient describing differences in study areas. Latent variable two segments the species response in a less obvious pattern, with the exception of separating restored sites from the majority of reference sites. Due to the first latent variable acting as a proxy for the differences induced by study area, it was unexpected that the restored sites clustered along it. The separation induced by compositional similarities seen in reference sites from the same study areas was considerably weaker for the restored sites. The effect of different study areas has previously been shown to be a good predictor for functional group response in restoration treatment on similar infrastructure development (Hagen et al., 2022a), but that was without reference sites. Thus, details about the relatedness of restoration sites in contrast to undisturbed sites is new knowledge in the context of ecological restoration in Norwegian power grid construction. There were a few points where the prediction regions connected reference sites between study areas. These were between a disturbed plot in Namsos and an undisturbed plot in Åfjord, and between the undisturbed plots in Klæbu and Namsos. This is explained by the variation amongst selected reference sites. In Klæbu, similarly to Namsos, the undisturbed site was a forest. The similarities in the species composition are apparent, as both forests have high occurrence of forest floor species such as *Oxalis Acetosella* (Table 5S). The undisturbed site in Åfjord was not a developed forest, but an open peatland forest, explaining the variation between the undisturbed references. Though the similarities between Klæbu and Namsos are supported by many overlapping species, the same is not the case for the overlap between Åfjord and Namsos. This could be explained by similarities in genera and not species, with one example being *Hierarcium sp.* Since it has not been classified on a species level, some uncertainty should be added to the interpretation of similarities produced by genera alone. However, this was not typical throughout the dataset, and is random error induced by the sampling procedure.

4.3 Species composition between restored and reference sites explained by predictors

In the analysis of the models with predictors I confirmed that the observed clustering of restored sites in ordination space could be explained by soil variables. Higher levels of gravel content, pH and soil density were all positively correlated to the right along the second axis, which is where the cluster of restored sites was located in ordination space. Values of pH, gravel content and soil density were larger in the restored sites because of the disturbance related to the construction phase and restoration treatments. Examples of such factors are heavy machinery traffic, mixing of soil horizons and the addition of surplus mass (Alberty et al., 1984; Bassett et al., 2005; Bulot et al., 2017; Hagen et al., 2022a). This is further implied by the overlap between the cluster of restored sites and the negative reference from Åfjord. This disturbed site was distinct, since it was a spontaneously revegetated roundabout made of gravel as opposed to the disturbed sites in Klæbu and Namsos which were both classified as clear-cut forest.

Litter cover was positively correlated, while moss and canopy cover were negatively correlated with the second latent variable. This explained why the undisturbed sites were located towards the left in the ordination space, since later successional stages allow for taller vegetation in the form of trees (Mehlhoop et al., 2022). In addition, undisturbed sites mostly contained no gravel, and exhibited more organic matter in the soil, reducing the density and pH. The soil predictors therefore appear suited as priors to investigate and predicting similarity to the positive reference sites in this study. The reference site closest to the undisturbed, novel, and clear-cut disturbed references was located in Namsos. This was the largest of the restored areas, and contained less gravel and had a lower soil density. However, this varied across the whole landfill, as some parts were more affected by construction traffic.

In hindsight the roundabout did not correspond to the level of degradation we see in its counterparts. However, it has given valuable inputs on what soil characteristics and species composition we can expect from restored sites in grid development, with the topsoil restoration methods utilized in connections to these projects. Higher concentration of pH gravel content, and increased soil density made it harder for less disturbance and stress tolerant species to establish (Alberty et al., 1984; Bassett et al., 2005; Bulot et al., 2017).

In broad terms, the second latent variable represented the degree of disruption described by increased pH, gravel content, soil density, litter cover and bare soil to the right and increased moss cover and canopy cover to the left. The distribution of species we see along this gradient is characterized by more ruderal species on the right in line with the disturbed soils. pH had the largest estimated effect, but most of the predictors are parallel to each other, indicating that they are describing the same gradient.

4.4 Species composition within restored sites is changing

The effect of sampling year was small and uncertain compared to the functional groups included in the analysis. This might be due to the limited timescale of three years, and that the changes observed are simply natural fluctuations. However, the increase in vegetation cover and species richness support the interpretation of changes in the vegetation between the years. This is especially visible in the increased species number and cover of the restored site in Åfjord, as in 2019 there were a recording of an empty plot. Since there are only 5 plots per site, this could also be a random difference because of the patchy vegetation in that specific restored site. From the results I found that the restored sites are changing, but whether the change in trajectory is directed towards a positive reference system is unclear.

4.5 Implications for restoration practices in grid line construction

Hagen et al. (2022) discussed the challenges connected to evaluating the outcome of restoration treatment on a large spatial and intervention type scale. Consequently, the authors call for studies utilizing a more detailed approach, with replicated species response and soil characteristics in contrast to visual evaluation. The results from the smaller scale in this study show that species level sampling also suffers from the same consequences of sites and areas being the best predictors to explain differences in species composition. However, it does shed light on details that might have been missed without the inclusion of references, which is the similarities in restored sites regardless of the clustering of study area, caused by alteration of soil characteristics. The management implications that emerge from these details are

5 Conclusion

The practice of choosing reference ecosystems and evaluating restoration outcomes is necessary for ecological restoration to improve at mitigating impacts and reclaiming lost ecosystem functions. The specific cases of restoration in this study show that there is a common pattern in restored sites' species composition, regardless of location. When compared to the reference sites, they ultimately had more in common with the vegetation and soil characteristics of an abandoned roundabout. Soil variables are important to describe the disturbance gradient we observe along study sites, with gravel content and pH as the biggest drivers in explaining species composition. However, the restored site in Namsos had less impact of construction induced disturbances. This suggests that if done right, a novel ecosystem that still contributes to some ecological functions is possible through restoration and is shown in this study to be the most feasible target along with the negative references. In the light of management, including additional reference ecosystems provides crucial details about the response of species composition. Positive, negative, and novel references will improve our understanding of what reference information is important to consider during topsoil restoration in construction sites. Further, it facilitates the implementation of directed mitigation measures in the contexts of grid line infrastructure development. Future research should aim at setting positive, negative and novel reference ecosystems on a larger temporal scale. This would identify ecological trajectories along with changes in the soil characteristics typical for construction work.

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Supplementary material

Table S1: Model selection pipeline for the unconstrained GLLVM. Difference in AICc (Corrected Akaike information criterion) for each test is shown (ΔAICc).

Model		Model selection	
Number of latent variables	Random effect of area	AICc	ΔAICc
2	False	7186.1	
3	False	7284.8	98.6
2	False	7186.1	
2	True	5269.2	62.2

Table S2: Model selection pipeline for the concurrent GLLVM. Difference in AICc (Corrected Akaike information criterion) for each test is shown (ΔAICc).

Model		Model selection	
Number of informed latent variables	Random effect of area	AICc	ΔAICc
2	False	5496.6	
2	True	5428.6	68.0
2	False	5496.6	
3	False	5269.2	219.7
2	True	5428.6	
3	True	5208.9	219.7
Regularization (randomB = "LV")			
3	False	5541.9	
3	True	5461.3	80.6

Table S3: Model selection pipeline for the constrained GLLVM with only restored sites. Difference in AICc (Corrected Akaike information criterion) for each test is shown (ΔAICc).

Model		Model selection	
Number of latent variables	Random effect of area	AICc	ΔAICc
2	False	2820.1	
2	True	2778.0	42.1
2	False	2820.1	
3	False	2828.9	-8.8
Regularization (randomB = "LV")			
2	False	2872.7	
2	True	2840.2	32.4

Table S4: List of species names and abbreviations for all collected species (2019 and 2022)

Scientific species names	Abbreviations
Achillea Millefolium	Achmil
Aconitum Septentrionale	Acosep
Agrostis Capillaris	Agrcap
Agrostis sp.	Agrsp.
Alchemilla Subcrenata	Alcsub
Alnus Incana	Alninc
Andromeda Polifolia	Andpol
Anemone Nemorosa	Anenem
Anthoxanthum Odoratum	Antodo
Artemisia Vulgaris	Artvul
Athyrium Filix-femina	Athfil
Avenella Flexuosa	Avefle
Betula Nana	BetNan
Betula Pubescens	Betpub
Calamagrostis Phragmitoides	Calphr
Calluna Vulgaris	Calvul
Campanula Rotundifolia	Camrot
Carex Atrata	Caratr
Carex Canescens	Carcan
Carex Echinata	Carech
Carex Leporina	Carlep
Carex Pilulifera	Carpil
Carex sp.	Carsp.
Carex sp1.	Carsp1
Carex sp2.	Carsp2
Carex sp3.	Carsp3
Carex spM.	CarspM
Cerastium Fontanum	Cerfon
Chamaenerion Angustifolium	Chaang
Chamaepericlymenum Suecicum	Chasue
Cirsium Arvense	Cirarv
Cirsium Palustre	Cirpal
Cucurbita Pepo	Cucpep
Cystopteris Fragilis	Cysfra
Dactylorhiza Macultata	Dacmac
Deschampsia Cespitosa	Desces
Dianthus sp.	Diasp.
Dryopteris Expansa	Dryexp
Empetrum Nigrum	Empnig
Continued	

Scientific species names	Abbreviations
Equisetum Arvense	Equarv
Equisetum Palustre	Equpal
Equisetum Sylvaticum	Equsyl
Erica Tetralix	Eritet
Eriophorum Vaginatum	Erivag
Festuca sp.	Fessp.
Fragaria Vesca	Fraves
Geum Rivale	Geuriv
Gymnocarpium Dryopteris	Gymdry
Hieracium sp.	Hiesp.
Hypericum maculatum	Hypmac
Juncus Conglomeratus	Juncon
Juncus Effusus	Juneff
Juncus Filiformis	Junfil
Juncus sp.	Junsp.
Juncus spF.	JunspF
Juncus spT.	JunspT
Juniperus Communis	Juncom
Kjolgress sp.	Kjosp.
Lactuca Muralis	Lacmur
Leucanthemum Vulgare	Leuvul
Linnea Borealis	Linbor
Long leaves sp.	Lonlea
Lotus Corniculatus	Lotcor
Luzula Multiflora	Luzmul
Lycopodium Annotinum	Lycann
Lysimachia Europaea	Lyseur
Maianthemum Bifolium	Maibif
Melampyrum Pratense	Melpra
Mini grass sp.	Mingra
Molinia Caerulea	Molcae
Myrica Gale	Myrgal
Narthecium Ossifragum	Naross
Oxalis Acetosella	Oxaace
Paris Auadriflora	Parqua
Phegopteris Connectilis	Phecon
Picea Abies	Picabi
Pinus Sylvestris	Pinsyl
Poa Pratensis	Poapra
Poa sp.	Poasp.
Potentilla Erecta	Potere
Prunella Vulgaris	Pruvul
Continued	

Scientific species names	Abbreviations
Pyrola Rotundifolia	Pyrrot
Ranunculus Repens	Ranrep
Ranunculus sp.	Ransp.
Rhinanthus Minor	Rhimin
Rhinanthus sp.	Rhisp.
Rubus Chamaemorus	Rubcha
Rubus Idaeus	Rubida
Rumex Acetosa	Rumace
Rumex Acetosella	RumAce
Rumex sp.	Rumsp.
Sagina Procumbens	Sagpro
Salix Aurita	Salaur
Salix Caprea	Salcap
Salix Myrsinifolia	Salmyr
Salix Phylicifolia	Salphy
Salix sp.	Salsp.
Scirpus Sylvaticus	Scisyl
Sorbus aucuparia	Sorauc
Stellaria Nemorum	Stenem
Struthiopteris Spicant	Strspi
Sveve sp.	Svesp.
Tanacetum Vulgare	Tanvul
Taraxacum Limnanthes	Tarlim
Trichophorum Cespitosum	Trices
Trifolium Repens	Trirep
Tussilago Farfara	Tusfar
Vaccinium Myrtillus	Vacmyr
Vaccinium Uliginosum	Vaculi
Vaccinium Vitis-idaea	Vacvit
Veronica Chamaedrys	Vercha
Viola Palustris	Viopal
Viola Riviniana	Vioriv
Viola sp.	Viosp.
Viola Tricolor	Viotri
End	

Table S5: list of species occurrences in study sites nested in study area.
Abbreviations: Klæbu = K, Namsos = N, Åfjord = Å, Restored = R, Disturbed = D, Novel = N and U = Undisturbed

	K-R	K-D	K-N	K-U	N-R	N-D	N-N	N-U	Å-R	Å-D	Å-N	Å-U
Alnus_incana	1		1									
Taraxacum_limnanthes	1											
Leucanthemum_vulgare	1											
Tussilago_farfara	1				1				1	1		
Ranunculus_repens	1	1					1		1			
Trifolium_repens	1											
Achillea_millefolium	1											
Hypericum_maculatum	1	1										
Picea_abies	1		1		1	1		1		1		
Rubus_idaeus	1	1	1		1	1						
Deschampsia_cespitosa	1	1	1		1	1	1			1		
Ranunculus_sp.	1											
Agrostis_capillaris	1	1	1				1		1	1		
Epilobium_sp.	1				1	1				1		
Campanula_rotundifolia	1											
Tanacetum_vulgare	1											
Rumex_sp.	1		1						1	1		
Prunella_vulgaris	1											
Anemone_nemorosa	1	1	1	1								
Sorbus_aucuparia	1	1	1	1		1	1	1				
Chamaenerion_angustifolium	1				1	1	1					
Cirsium_arvense	1											
Rhinanthus_sp.	1											
Viola_sp.	1									1		
Alchemilla_subcrenata	1											
Cerastium_fontanum	1									1		
Potentilla_erecta	1		1		1	1	1		1	1	1	1
Poa_pratensis		1								1		
Oxalis_acetosella		1		1				1				
Veronica_chamaedrys		1										
Stellaria_nemorum		1		1								
Fragaria_vesca		1	1							1		
Continued	**K-R**	**K-D**	**K-N**	**K-U**	**N-R**	**N-D**	**N-N**	**N-U**	**Å-R**	**Å-D**	**Å-N**	**Å-U**

	K-R	**K-D**	**K-N**	**K-U**	**N-R**	**N-D**	**N-N**	**N-U**	**Å-R**	**Å-D**	**Å-N**	**Å-U**
Dryopteris_expansa		1										
Anthoxanthum_odoratum		1										
Gymnocarpium_dryopteris		1	1	1		1						
Phegopteris_connectilis		1		1								
Viola_tricolor		1										
Lactuca_muralis		1										
Avenella_flexuosa			1			1	1	1		1	1	1
Maianthemum_bifolium			1			1		1				
Betula_pubescens			1		1	1	1		1	1	1	
Vaccinium_myrtillus			1	1		1	1	1			1	1
Lysimachia_europaea			1	1	1	1	1	1	1		1	1
Athyrium_filix-femina				1								
Aconitum_septentrionale				1								
Viola_riviniana				1								
Paris_quadriflora				1								
Geum_rivale				1								
Equisetum_sylvaticum					1	1		1				
Calamagrostis_phragmitoides					1	1	1				1	1
Equisetum_arvense					1				1	1		
Viola_palustris					1							
Hieracium_sp.					1							1
Scirpus_sylvaticus												
Betula_Nana					1							
Juncus_filiformis					1							
Cirsium_palustre					1							
Salix_myrsinifolia					1							
Carex_sp1.					1							
Carex_sp2.					1							
Vaccinium_uliginosum					1							1
Carex_sp3.					1							
Salix_caprea					1		1					
Salix_phylicifolia					1				1			
Vaccinium_vitis-idaea						1	1	1			1	1
Continued	**K-R**	**K-D**	**K-N**	**K-U**	**N-R**	**N-D**	**N-N**	**N-U**	**Å-R**	**Å-D**	**Å-N**	**Å-U**

	K-R	K-D	K-N	K-U	N-R	N-D	N-N	N-U	Å-R	Å-D	Å-N	Å-U
Linnea_borealis						1					1	
Rubus_chamaemorus						1	1	1				
Melampyrum_pratense						1	1				1	1
Chamaepericlymenum_suecicum						1	1	1			1	
Carex_spM.						1						1
Equisetum_palustre						1						
Empetrum_nigrum						1					1	1
Agrostis_sp.							1					
Carex_sp.							1		1			1
Long leaves_sp.								1				
Lycopodium_annotinum								1			1	1
Calluna_vulgaris									1	1	1	1
Juncus_effusus									1	1		
Juncus_conglomeratus									1			
Carex_echinata									1			
Eriophorum_vaginatum									1			1
Carex_pilulifera									1			1
Carex_canescens									1	1		
Juncus_spF.									1	1		
Juncus_sp.									1			
Lotus_corniculatus									1			
Sagina_procumbens									1	1		
Salix_sp.									1	1		
Rhinanthus_minor										1		
Rumex_acetosa										1		
Struthiopteris_spicant											1	
NA_NA (empty plot)									1			
Pteridium_aquilinum											1	
Pyrola_rotundifolia											1	
Juniperus_communis											1	1
Andromeda_polifolia												1
Juncus_spT.												1
Erica_tetralix												1
Continued	**K-R**	**K-D**	**K-N**	**K-U**	**N-R**	**N-D**	**N-N**	**N-U**	**Å-R**	**Å-D**	**Å-N**	**Å-U**

	K-R	K-D	K-N	K-U	N-R	N-D	N-N	N-U	Å-R	Å-D	Å-N	Å-U
Carex_atrata												1
Kjolgress_sp.												1
Dactylorhiza_macultata												1
Trichophorum_cespitosum												1
Narthecium_ossifragum												1
Pinus_sylvestris												1
Salix_aurita												1
Sveve_sp.												1
End	**K-R**	**K-D**	**K-N**	**K-U**	**N-R**	**N-D**	**N-N**	**N-U**	**Å-R**	**Å-D**	**Å-N**	**Å-U**

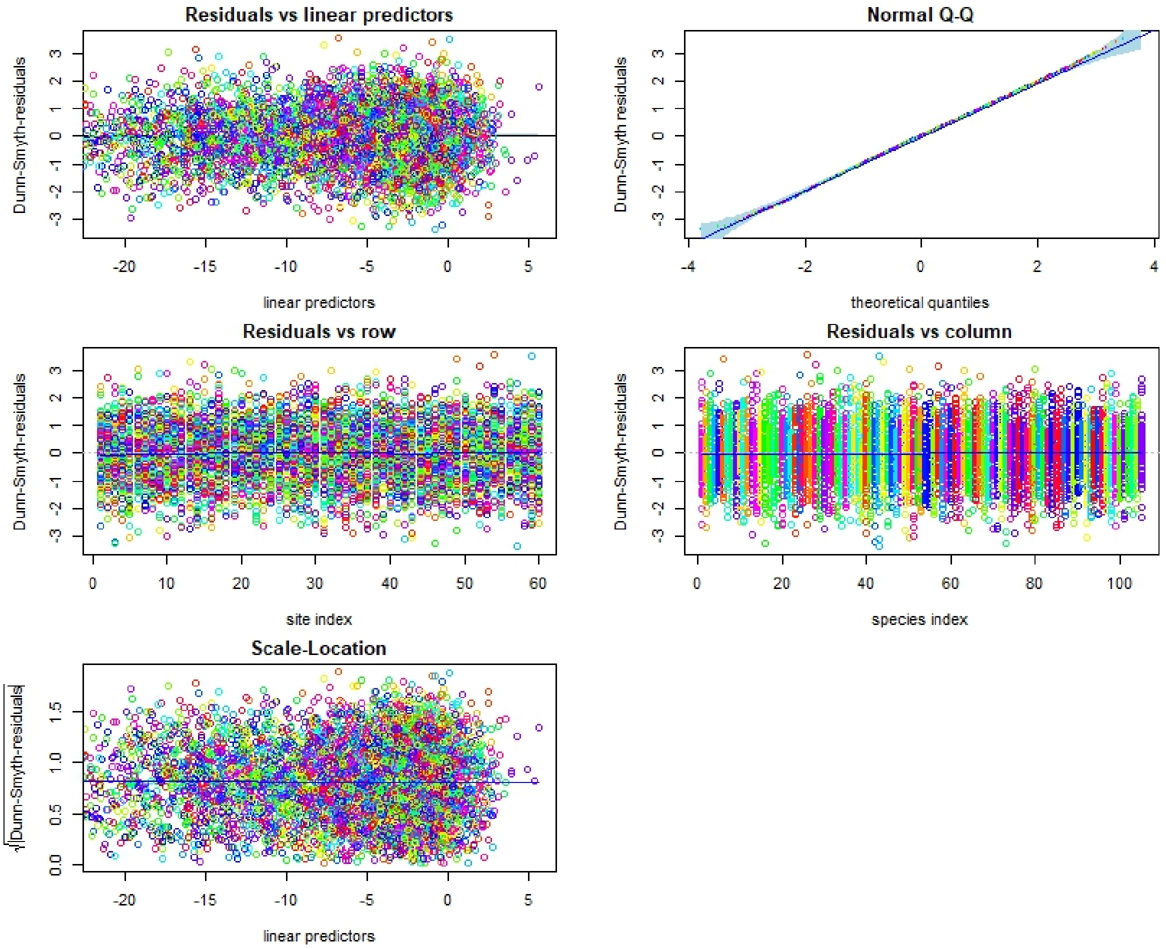

Figure S1: Diagnostics plot for the concurrent model fit to explain species composition in sites.

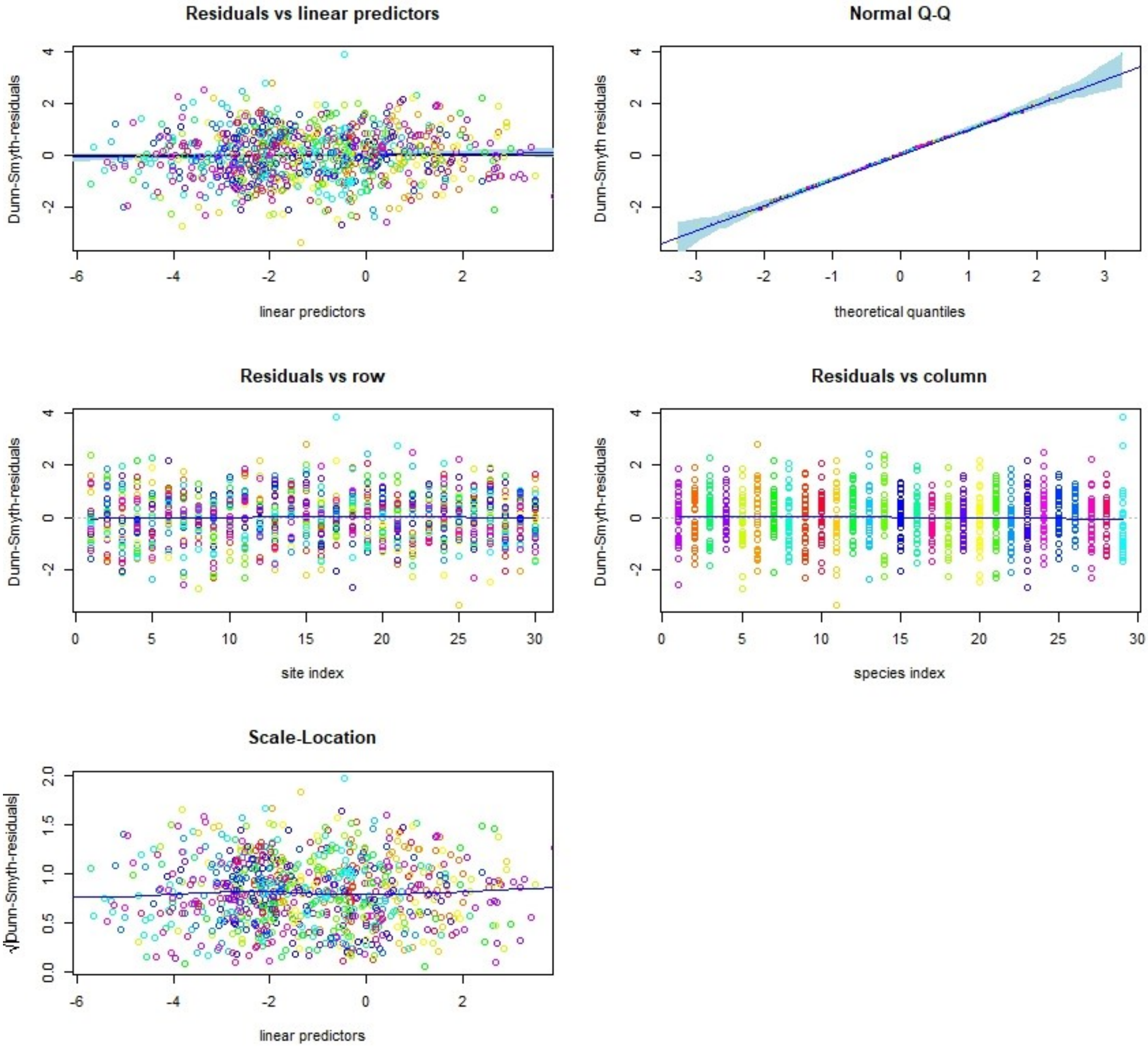

Figure S2: Diagnostics plot for the concurrent model fit to explain species composition in restored sites between sampling years.

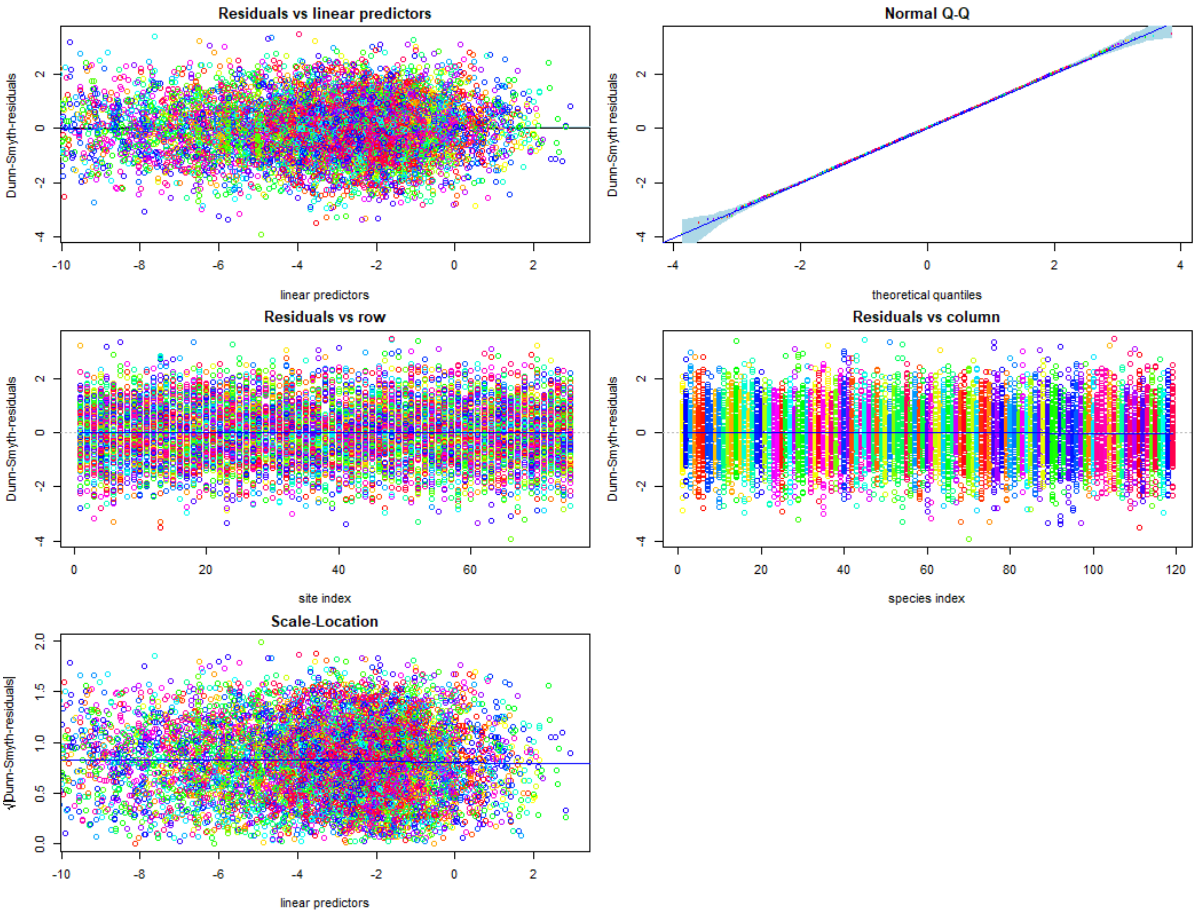

Figure S4: Diagnostics plot for the unconstrained model fit to explore species composition in restored sites and reference sites.

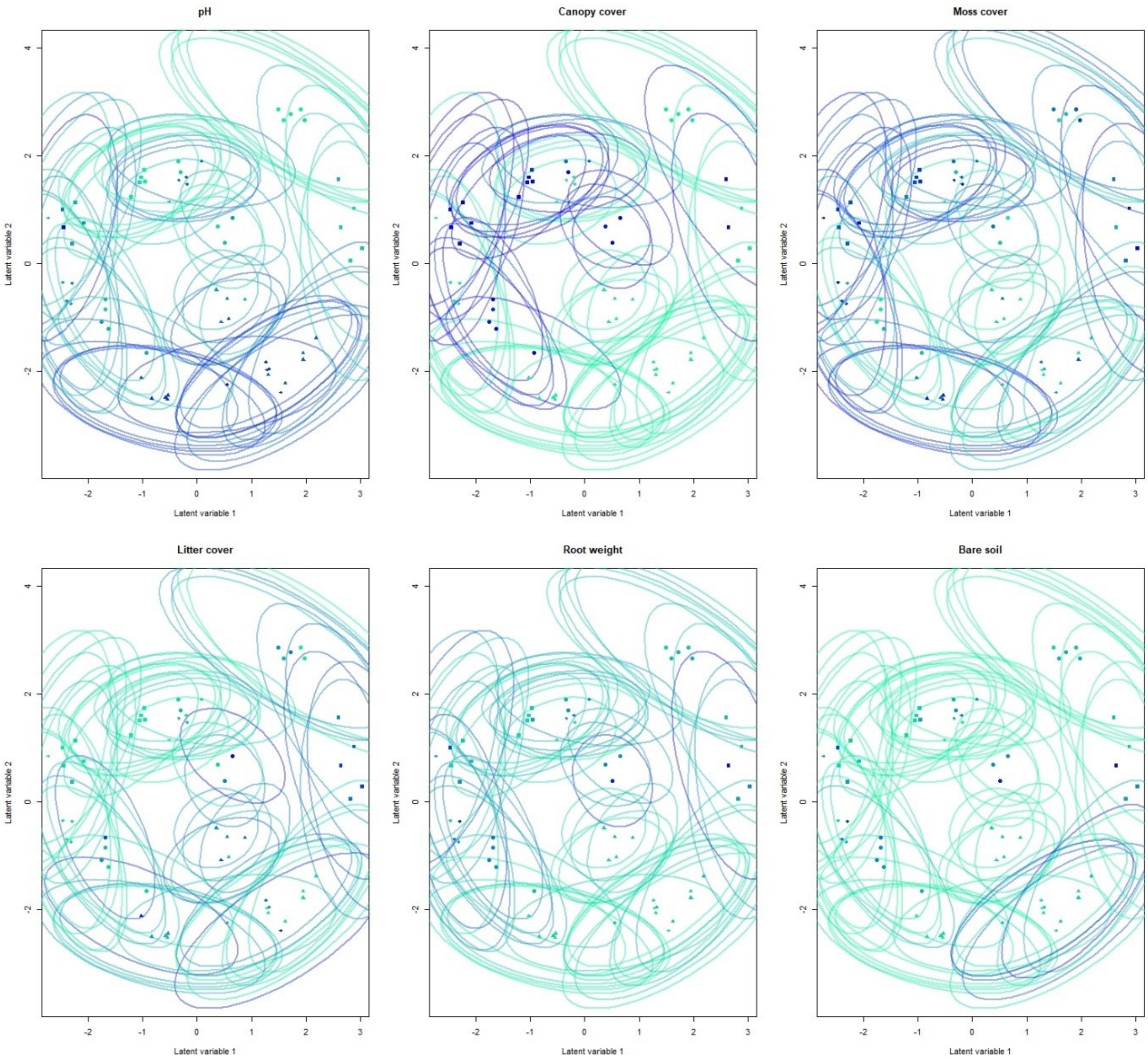

Figure S5: Increasing values of predictor variables shown as color gradients. The darker the color, the higher the value of the measured predictor variables.

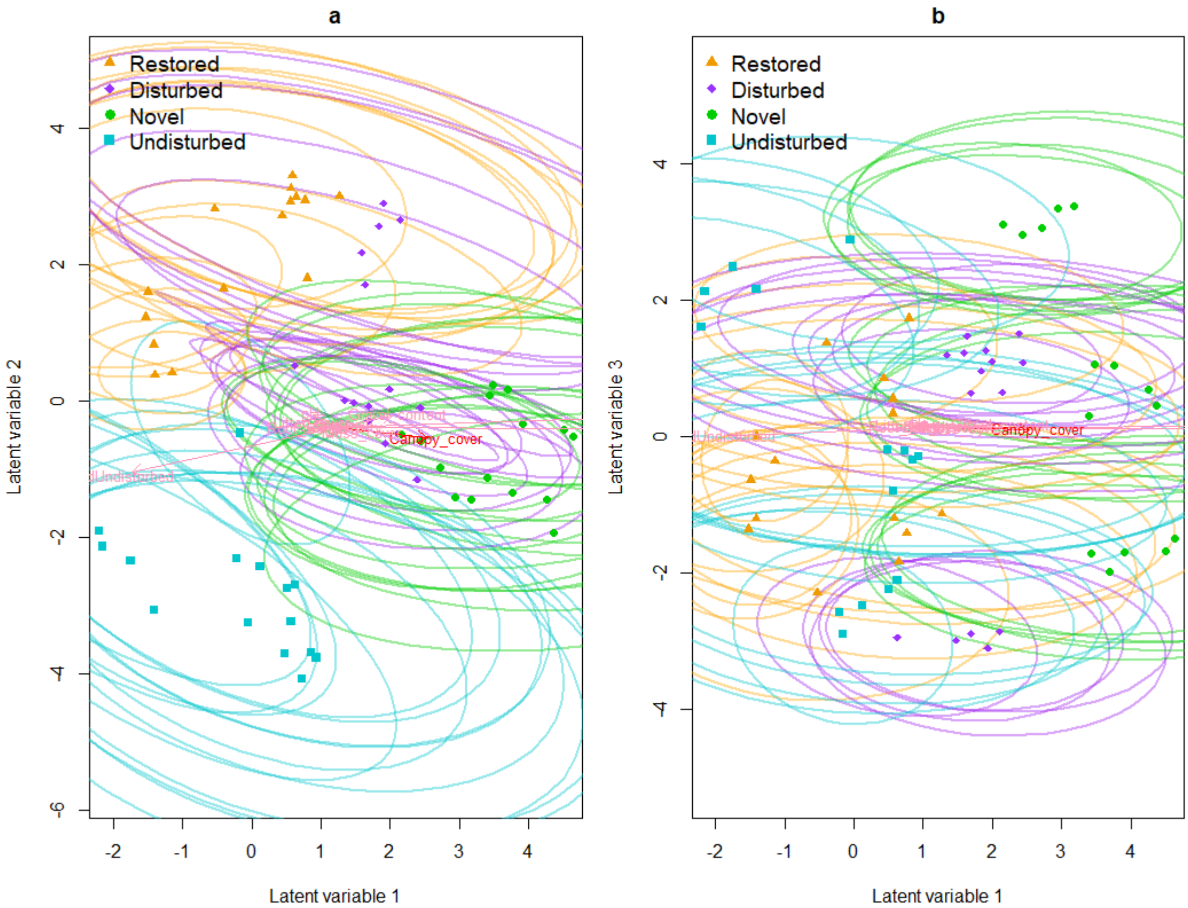

Figure S6: Ordination plot of the concurrent ordination for site effect with the remaining combinations of the latent variables a) 1, 2 and b) 1, 3.

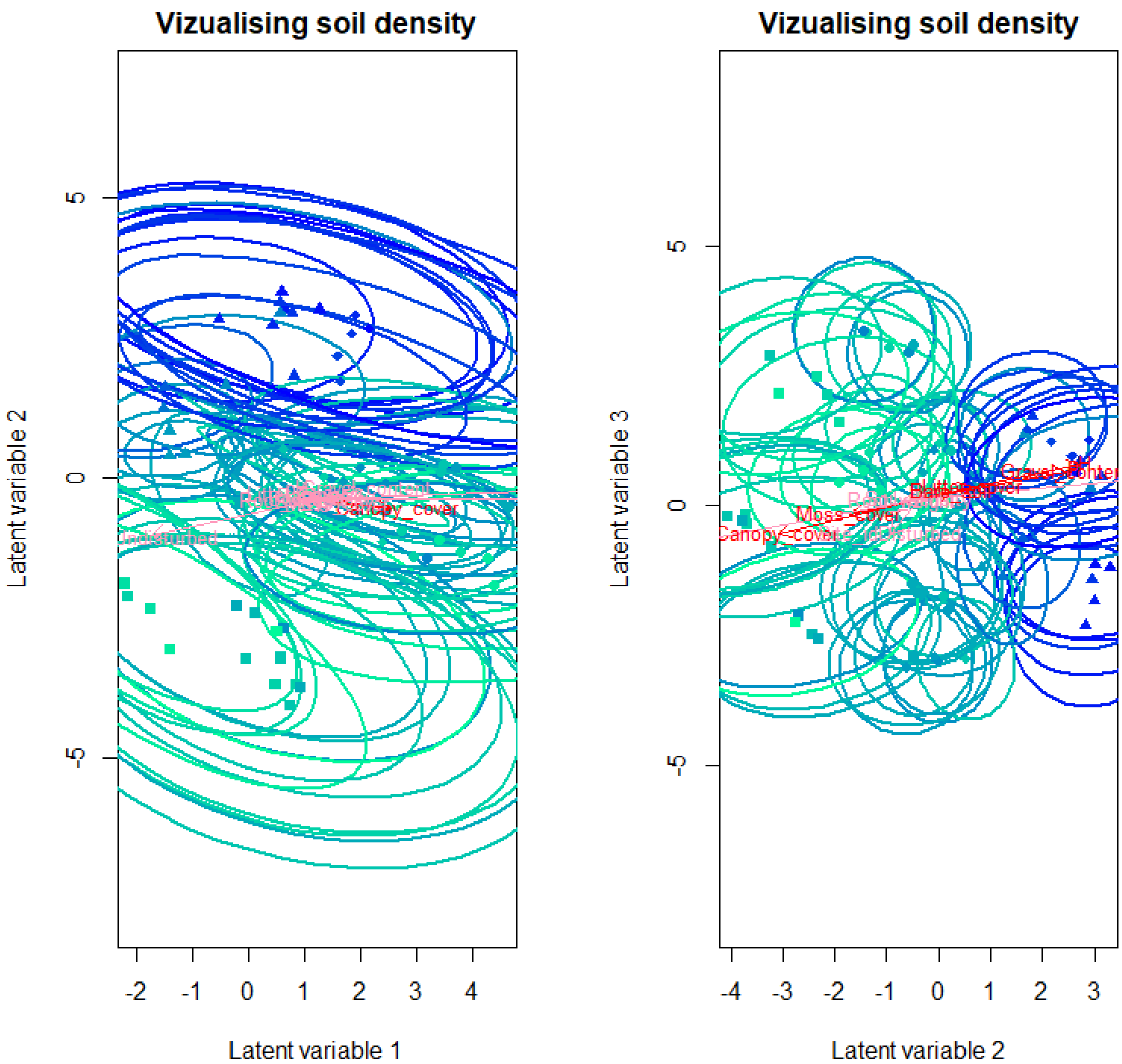

Figure S7: Ordination plot of the concurrent ordination for site effect with the combinations of the latent variables a) 1, 2 and b) 2, 3. Increasing values of predictor variables shown as color gradients. The darker the color, the higher the value of the measured predictor variables

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