Impacts of forest restoration on avian communities

A passive acoustic monitoring study in Färna Ecopark

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Impacts of forest restoration on avian communities. A passive acoustic monitoring study in Färna Ecopark.

Påverkan av skogsrestaurering på fågellivet – en studie med passiv akustisk övervakning i Färna Ekopark.

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Abstract

Maintaining biodiversity across landscapes requires continuous monitoring. For birds, their sounds play a crucial role in monitoring populations as they facilitate mate selection, resource defence, and species recognition, and can signal divergent speciation. In this study, I aimed to evaluate how restoration measures in a managed forest landscape, affect bird species richness, activity and occurrence of indicator species. The study was conducted in Färna Ecopark, Sweden. This study draws on data from two sources: three restored and three unrestored stands included in a pilot study, and an additional 15 stands that were part of a larger, separate full study. To gather information about birds, one audio box was placed in the center in each stand. In addition to audio recordings of birds, data on forest attributes across the different stands was collected. I identified the bird species in the recordings from each audio box, relying on distinctive vocalizations and established identification methods. The results suggested that the restoration measures influenced the bird activity and species composition, but not species richness. No differences were neither found in species richness among red-listed species or indicator species associated with broadleaf forests. The lack of differences in species richness may indicate that the restoration measures applied have limited immediate impact on species richness. However, bird activity of red-listed species differed significantly between target and unrestored stands. These findings indicate that restoration benefit habitat quality for birds and highlight the importance of continued restoration efforts.

Keywords: passive acoustic monitoring, forest restoration, bird communities, species richness, forest structure, bird activity, audio box, indicator species

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Abbreviations

Abbreviation	Description
PAM	Passive acoustic monitoring
NMDS	Non-metric multidimensional scaling

1. Introduction

Biodiversity is essential for sustaining life on Earth, providing critical services such as clean air, water, soil formation, and climate regulation (Fisher et al. 2009; Hoefer et al. 2023). However, human activities have caused rapid biodiversity loss, with the current extinction rate approximately 1000 times higher than the natural rate (Barnosky et al. 2011; Pimm et al. 2014). Over 99% of the four billion species that have ever existed on Earth are now extinct, highlighting the magnitude of species loss throughout history (Barnosky et al. 2011). Biodiversity loss not only threatens ecosystems but also undermines human well-being, as we rely on these systems for food, medicine, and raw materials (Cardinale et al. 2012). Fragmentation of habitats, as a result of human activities, is an important factor to this rapid decline (Barnosky et al. 2011). Other factors include introduction of non-native species, the spread of pathogens, direct killing of species and climate change influenced by human activities (Barnosky et al. 2011).

As a forest-rich country, the forest industry has played a significant role in Sweden's industrial development (Lindahl et al. 2017). Since the emergence of wood pulp and paper production, along with expanding timber industries in the 1850s, the export has steadily increased, and remains one of the country's most important net export sectors (Berg et al. 2008; Lindahl et al. 2017; Hertog et al. 2022). In Sweden, rotation forestry has for many years been the dominant form of forestry, promoting even-aged monocultures which have a negative effect on bird diversity (Pedley et al. 2019; BirdLife Sverige 2020; Hertog et al. 2022).

The intense use of forest has resulted in fragmentation and loss of old growth structures, which has reduced habitat quality for forest dependent species (Angelstam et al. 2020). This degradation accentuates the critical need for ecological restoration to recover biodiversity and restore ecosystem function. One approach to addressing this has been the establishment of 37 ecoparks, large forest landscapes of at least 1,000 hectares, distributed across Sweden and managed by Sveaskog, the state-owned forest company (Sveaskog 2022). These areas aim to combine continued timber production with enhanced biodiversity. They are managed with a higher level of environmental ambition than in conventional production forests, often including restoration measures. At least 50% of the productive forest land in every ecopark is dedicated to nature conservation.

The Swedish Forestry Act (SFA) was updated in 1993 to emphasize that production goals and environmental considerations should be given equal importance (Jordbruksdepartementet 1993). The revised version of SFA has been criticized by the environmental movement, for shifting the responsibility for sustainable management to private forest owners (Löfmarck et al. 2017). However, in the short term, Sweden observed a remarkable 10% increase in the number of breeding forest-related bird species between 1998 and 2018 (Sveriges Fåglar 2019). This rapid increase is correlated with changes in forestry practices, such as an increased amount of deadwood and a greater proportion of broadleaf trees, introduced by the new Forestry Act (Sveriges Fåglar 2019).

Maintaining biodiversity across landscapes requires continuous monitoring, and indicator species are often used as reliable measures of ecosystem health (Angelstam et al. 2004). Birds, in particular, are well suited as indicators, because their abundance often correlate with variations in other taxa (Basile et al. 2021). Forest fragmentation, management practices, and habitat changes are known to impact bird populations (Basile et al. 2021). Key forest features contributing to habitat heterogeneity, such as mean diameter of living trees, diameter of dead trees, and deadwood volume, impact their abundance (Basile et al. 2021). Habitat consisting of broadleaf or mixed forest cover increases bird abundance and diversity (Basile et al. 2021). Restoration measures within managed forests play a crucial role in enhancing biodiversity by recreating natural habitats and promoting ecological balance (Angelstam et al. 2004). Restoring and creating diverse habitats, such as broadleaf or mixed forests, will not only mitigate the negative impacts of fragmentation but also enhance species richness and support a more resilient ecosystem. Specifically, such measures can provide essential habitats for birds, contributing to their conservation and population resilience (Angelstam et al. 2004). Understanding the theoretical basis of these restoration strategies is pivotal for effective biodiversity management and ecosystem health within managed forest landscapes.

Animals can be challenging to monitor because they are mobile and elusive (Biro and Adriaenssens 2013). For birds, their sounds play a crucial role in monitoring populations as they facilitate mate selection, resource defence, and species recognition, and can signal divergent speciation (Wilkins et al. 2013). Sounds can also be produced for territorial defence, for group interactions and orientation, making them valuable for studying population dynamics and speciation (Obrist et al. 2010; Wilkins et al. 2013). Traditional faunal survey methods based on auditory detection have been completely transformed by the recent introduction of automated audio recorders (Obrist et al. 2010). Most vocalisations have specific characteristics and can be determined by species, which can be used when doing surveys by humans (Obrist et al. 2010). Bioacoustic monitoring is applied to many different groups of animals, but mainly for well-known species like mammals and birds (Obrist et al. 2010). These advancements in bioacoustic monitoring not only enhance our ability to track elusive species but also provide deeper insights into their behavioral patterns and ecological interactions.

The technologies used for wildlife monitoring have dramatically shifted during the last decades (Sugai et al. 2019). Expensive and heavy equipment has been replaced with cheaper and smaller devices that are easier to use and have longer battery life (Pimm et al. 2015). Improvements in bioacoustic technology allow for the collection of data across various locations over extended periods (Blumstein et al. 2011; Sugai et al. 2019). Passive acoustic monitoring (PAM) has increased rapidly and will supplement traditional observation based monitoring (OBM) and citizen science projects (Sugai et al. 2019; Hoefer et al. 2023). Unlike traditional observational methods, PAM enables long-term, cost-effective biodiversity monitoring through unattended audio boxes, recording continuously (Gibb et al. 2019; Sugai et al. 2019; Hoefer et al. 2023). Recently, its application has grown significantly, particularly in studies on bats and birds in northern temperate regions (Gibb et al. 2019; Sugai et al. 2019; Hoefer et al. 2023). The method also allows for detection of species across vast areas and reduces human error (Sugai et al. 2019; Hoefer et al. 2023). Even though PAM is effective, non-vocal birds and animals will be hard to detect using this method (Gibb et al. 2019). Also, databases on species observations have increased quickly and improved our ability to monitor biodiversity changes (Pimm et al. 2015). This development will work as a tool to better understand the rapid change in biodiversity, influenced by human activities (Pimm et al. 2014; Schmeller et al. 2017). To better understand environmental changes, long-term studies are necessary, where the new technique could be used (Magurran et al. 2010). These advancements collectively improve our ability to monitor and respond to ecological shifts more effectively.

1.1 Aim

In this study, I aim to evaluate how restoration measures to increase the share of broadleaf forests in a managed forest landscape, including changes in forest structure, affect bird species richness, bird activity and occurrence of indicator species. Conducted in Färna Ecopark, where the goal is to preserve and develop broadleaf forest shares, this research addresses the following questions:

1. Do restored and unrestored forest stands differ in bird species richness, activity and community composition?
2. What are the effects of restoration measures on the activity and diversity of indicator species and red-listed species?
3. How are variations in understory, deadwood volume and tree species diversity associated with specific bird species?

4. What forest structural features are associated with bird species communities?

2. Method

2.1 Study area

The study was conducted in Färna Ecopark, located 10 kilometres east of Skinnskatteberg, Västmanland county, Sweden (Figure 1). The ecopark spans 4,004 hectares, of which 70% is forest land (Sveaskog 2021). It contains several areas of older forest and has a significant proportion of broadleaf trees. In addition to forested areas, the park is characterized by extensive flat peatlands, which contribute to the bird species richness at the landscape scale (Calmé et al. 2002). The surrounding area also include plenty of lakes, which improve the ecological diversity in the region.

This study draws on data from two sources: three restored and three unrestored stands within Färna Ecopark included in a pilot study (Figure 2), and an additional 15 stands that were part of a larger, separate full study. The 15 forest stands from the full study were categorized as five restored, five unrestored and five target stands of which the latest is defined by have reached a favorable forest condition. The restoration efforts in the restored and target stands primarily focus on removing spruce (*Picea abies*) to encourage the growth of broadleaf forests. Additional measures, such as cutting down aspen (*Populus tremula*) trees, have also been implemented. However, information about the exact timing of these restoration measures has been insufficient. The stands are all classified as NS-stands, which stands for “nature conservation with management”. This classification indicates that the unrestored stands are planned for future restoration within the Swedish forest management. Developing and preserving broadleaf forests is the largest nature conservation investment within the ecopark. Many rare species from different taxa, such as woodpeckers, insects, and lichens, depend on old broadleaf trees in bright, open areas (Sveaskog 2005; Fritz et al. 2008). Additional conservation efforts include recreating wetlands to improve conditions for shorebirds, amphibians, and other threatened species (Sveaskog 2021).

Figure 1. Location of Färna Ecopark in Västmanland County, central Sweden, where all measurements for this study on forest structure and bird data were collected using passive acoustic monitoring.

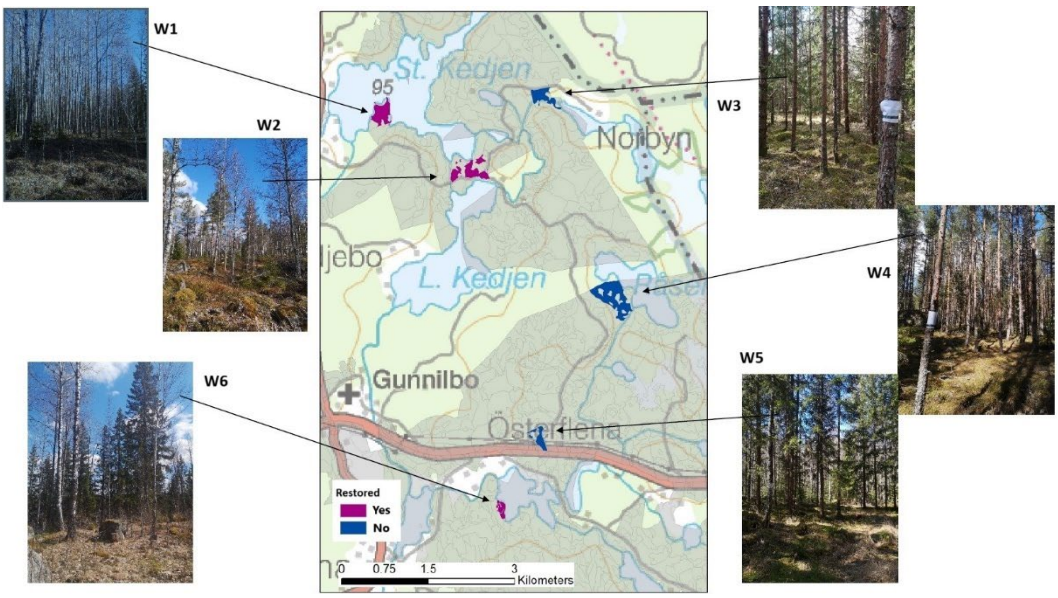

Figure 2. Study area in Färna Ecopark, highlighting the six forest stands in the pilot study. These stands were selected to represent both restored and unrestored areas, and the data collected were used to examine forest composition and bird diversity.

2.2 Bird sampling

To gather information about the bird activity in the six stands, one audio box was placed in the center in each stand. For the pilot study, the devices were deployed during the day on May 5, 2023, and retrieved on May 13, 2023. Each audio box made five one-minute recordings at the beginning of every hour between 3 a.m. and 6 p.m., resulting in a total recording time between 635 and 645 minutes per device.

For the full study, one audio box was also placed in the center in each stand. Recordings began on April 14 and continued until May 18, 2024. Each box made a one-minute recording every ten minutes, throughout the entire 24-hour period. The model used was the AudioMoth, a device first released in 2017 (Open Acoustic Devices 2024). The AudioMoth is a small, low-cost, full-spectrum acoustic logger designed to record sounds across both audible and ultrasonic frequencies. Powered by an EFM32 Gecko processor, it records uncompressed WAV files at sample rates ranging from 8,000 to 384,000 samples per second, storing the data on a microSD card. It measures 58 x 48 x 15 mm and runs on 3 AA batteries. This makes the AudioMoth an efficient and versatile tool for environmental acoustic monitoring.

2.3 Structural measurements

In addition to audio recordings of birds, data on forest attributes across the different stands was collected. This was done to analyze the relationship between birds and forest types.

2.3.1 Selection of sampling points

To document the forest structure within a given forest stand, forest features were sampled at a total of five positions within a given stand. One at place of the audiomoth and four random positions within the stand. To create the four random position, a map was created in QGIS (QGIS.org Association 2024 version 3.10.5-A Corüna) showing all forest stands. By adding a base map to the QGIS project using the QuickMapServices Plugin, a background layer was created. Next, the stands were visualized using a shapefile, along with the locations of the audio boxes from another shapefile. Also, a buffer zone of 25 meters inward from the edge of each stand was created, and 50 meters around the audio boxes, using the "Buffer" tool. Within these buffered areas, the "Random Points Tool" was used to place four random plots, at least 50 meters from each other, for structural measurements in each plot, in addition to the location of the audio box. Finally, the completed QGIS project was transferred to QField (OPENGIS.ch 2024).

During the fieldwork, QField in combination with the phone's GPS was used to navigate to the different plots effectively. If a plot was placed at a non-representative location of the stand, such as in a power line corridor, it was moved 20 meters north from the original position.

2.3.2 Measurements of forest stand structures

In each of the five plots within every stand, structural measurements were conducted, where ArcGIS Survey123 (Esri 2024) was utilized to collect the data and to take notes. Basal area for each tree species was measured from the center of each plot using a relascope. This data was used to calculate the distribution of tree species and to assess differences between restored and unrestored stands.

Within each plot, deadwood, both downed and standing, were measured. The equipment used included a hypsometer, caliper, and measuring tape. The plot radius for deadwood measurements was set to 10 meters. All downed deadwood with a base diameter greater than 10 cm and with the base located inside the plot was measured. The length from base to top was recorded to calculate the volume of each piece of deadwood with the truncated cone formula;

$$V = \tfrac{1}{3} \times \pi \times h \times (R^2 + Rr + r^2)$$

The decay class of the downed deadwood was estimated using the method described by Gibb et al. (2005), while the decay class for standing dead trees was assessed using the method from Thomas (1979). For standing dead trees, diameter at breast height (DBH) and height were measured. A taper formula was used to estimate the volume of standing dead trees (Näslund 1947). Coniferous species (e.g., pine (*Pinus sylvestris*) and spruce) were calculated using the formula:

$$V = 0.09314 \times D^2 + 0.03069 \times D^2 \times H + 0.002818 \times D \times H^2,$$

while broadleaf species (e.g., birch (*Betula spp.*) and aspen) used:

$$V = 0.03715 \times D^2 + 0.02892 \times D^2 \times H + 0.004983 \times D \times H^2$$

Undergrowth composition was assessed by counting the number of understory stems for each species within a plot with a radius of 1,78 meters, centered at the same location as the deadwood plot. In this smaller plot, all trees between 1,3 and 4,5 meters in height were counted. From this data, the mean number of stems per hectare for each stand and each tree species was calculated. I chose these variables to better understand the impact of restoration measures on bird habitat quality, as they are important components of forest structure.

2.4 Analyses

2.4.1 Analysis of bird communities

Using my bird survey experience, I identified the bird species in the recordings from each audio box, relying on distinctive vocalizations and established identification methods. In addition to analyzing all recorded species, I used a list of the most relevant forest birds to compare differences among forest stands (Green 2019) and excluded all remaining species from further analysis. Also, comparisons of different groups of indicator species were conducted, using indicator species lists from Svensk Fågeltaxering (Svensk Fågeltaxering 2024). In Sweden, 16 bird species serve as indicators for the Environmental Quality Objective *Living forests* (Naturvårdsverket 2020), which is one out of 16 to define the desired environmental states in areas, including quality goals on air, water, biodiversity, and climate. Forest-related objectives are closely tied to bird populations, which are influenced by fragmentation, management, and habitat change (Basile et al. 2021). The indicator species were categorized into three ecological groups that were analyzed in this study; *Forests with high conservation values at the landscape scale*, *Dead wood* and *Broadleaf-rich forest* (Svensk Fågeltaxering 2024). The species included in each category are as follows:

- Forests with high conservation values at the landscape scale: Capercaillie (*Tetrao urogallus*), Hazel grouse (*Tetrastes bonasia*), Stock dove (*Columba oenas*), Green woodpecker (*Picus viridis*), Lesser spotted woodpecker (*Dryobates minor*), Three-toed woodpecker (*Picoides tridactylus*), Long-tailed tit (*Aegithalos caudatus*), Coal tit (*Periparus ater*), Crested tit (*Lophophanes cristatus*), Marsh tit (*Poecile palustris*), Willow tit (*Poecile montanus*), Siberian tit (*Poecile cinctus*), Eurasian treecreeper (*Certhia familiaris*), Siberian jay (*Perisoreus infaustus*), Nutcracker (*Nucifraga caryocatactes*), and Bullfinch (*Pyrrhula pyrrhula*).
- Dead wood: Green woodpecker (*Picus viridis*), Lesser spotted woodpecker (*Dryobates minor*), Three-toed woodpecker (*Picoides tridactylus*), Marsh tit (*Poecile palustris*), and Willow tit (*Poecile montanus*).
- Broadleaf-rich forest: Stock dove (*Columba oenas*), Green woodpecker (*Picus viridis*), Lesser spotted woodpecker (*Dryobates minor*), Three-toed woodpecker (*Picoides tridactylus*), Long-tailed tit (*Aegithalos caudatus*), Marsh tit (*Poecile palustris*), and Eurasian treecreeper (*Certhia familiaris*).

The data from the audio boxes in the pilot study were imported into the software Arbimon (Rainforest Connection 2024 beta version). The tools used for this study were the Audio Event Detection (AED) and the Clustering tool. When importing the data into the software, one playlist with all recordings from each audio box was created. Every single playlist was processed in the AED tool to determine the number of audio events for each box (Table 1).

Table 1. Number of audio events detected in each stand.

Stand	Treatment	Audio Events Detection (AED)
W1	Restored	7428
W2	Restored	6590
W3	Unrestored	6682
W4	Unrestored	4794
W5	Unrestored	5671
W6	Restored	6282

The AED tool automatically detects and categorizes sounds in the recordings according to a given sonogram, and these results are then analyzed using the Clustering tool to group similar sounds based on acoustic similarities for each audio box (Appendix 1). These groups could be explored and validated in the software when the clustering process was completed. All the audio events grouped by the Clustering tool were analyzed.

In addition to the cluster analysis, a smaller subset of recorded sounds was examined. Since the bird activity is most frequent in the early morning, the activity was checked in one-minute recordings at 4am, 5am, 6am, 7am and 8am over five days. Five days were randomly selected, using the RAND tool in Excel. The selected days were the 6th, 7th, 10th, 11th and 12th of May, resulting in 25 minutes of recordings for each forest stand. As in the cluster analysis, the total number of species for stand was calculated with the main purpose to quantify the bird frequency in detail (i.e. proportion of recordings with bird species presence).

For the data from the full study the software Kaleidoscope Pro (Kaleidoscope Pro 2024 version 5.6.8) was used. Like the software tools in Arbimon, it grouped sounds with similar characteristics into clusters, using the Clustering Analysis tool. Analyzing the different clusters provided the most comprehensive mapping possible of the number of birds for each audio box. The total number of species was analyzed, along with forest-related birds and indicator species. Additionally,

red-listed species were assessed as part of the full study (SLU Artdatabanken 2020).
To compare bird activity across the full study, 50 one-minute recordings were analyzed. The recordings were selected using the same method as in the pilot study, but ten random days were included to ensure a broader and more representative dataset. The same set of species analyses was conducted, with a primary focus on bird activity and the proportion of recordings in which bird species were present. Also, the mean number of species per recording was calculated for each treatment, based on the presence data from the bird activity analysis.

2.4.2 Data management and statistical analysis

To estimate similarity among forest stands based on bird species composition and forest structure, I applied Non-metric Multi-Dimensional Scaling (NMDS) using the R package vegan (Oksanen et al. 2025). NMDS reduces complex, multidimensional data into a two-dimensional space, where the distance between points reflects dissimilarity between samples. Separate NMDS ordinations were conducted for forest structure and bird species composition across stands.

To explore relationships between forest structure and bird community composition, I used the function "envfit" from the vegan package. This method fits each environmental variable separately to the NMDS ordination through multiple linear regression of the form $env\_var_i \sim NMDS1 + NMDS2$. The resulting vectors illustrate the strength and direction of association between each environmental variable and the ordination. The environmental variables included the number of broadleaf and conifer trees, understory trees, and volume of deadwood. While these regressions are modeled with NMDS axes as predictors, ecological interpretation assumes that forest structure influences bird communities, not vice versa. It is also important to note that because each environmental variable is fitted independently, the resulting vectors do not represent relationships among environmental variables themselves.

To assess differences between restored, target and unrestored stands in forest stand structures and bird data, Wilcoxon-Mann-Whitney, Kruskal-Wallis, Adonis and t-tests were performed. Wilcoxon-Mann-Whitney tests are non-parametric methods suitable for comparing two independent groups, especially with small sample sizes and non-normal data. They assess differences in central tendency without assuming a specific distribution (Happ et al., 2019). Another non-parametric test, Kruskal-Wallis, can be used to compare medians across multiple groups without assuming normality (Venables & Ripley 2002). In contrast, parametric methods such as t-tests are used when assumptions of normality and homogeneity of variances are met, allowing for comparisons of means between two groups (Venables & Ripley 2002). The ADONIS test is used to assess statistically significant differences between two or more groups based on explanatory variables, especially with multivariate data and non-normal distributions, and it can handle both continuous and categorical predictors. However, it assumes homogeneity of multivariate dispersions across groups (Stevens & Oksanen 2024). Wilcoxon–Mann–Whitney tests were used to examine individual forest structural variables in the pilot study, while Adonis tests were applied to test the combined effects of all structural measurements. Adonis tests were also used to evaluate differences in overall bird community composition between stands. T-tests were used to compare the number of species between treatments and bird activity for individual species within the pilot study. Kruskal-Wallis tests were used for structural measurements, number of species and bird activity within the full study.

To statistically identify which species are representative of each treatment group, i.e. can serve as an indicator species, the indicspecies package in R was used (Cáceres et al. 2025). This tool calculates p-values for each species, using a significance level of $\alpha < 0.05$, to determine their association with specific treatment groups. The structural measurement data collected in Färna was processed and visualized using the software R (R Core Team 2024, version 4.4.1).

3. Results

3.1 Structural measurements

3.1.1 Pilot study

The tree species composition, based on basal area data, did not show any significant differences between treatments (p > 0,05, Appendix 2). However, aspen and rowan (Sorbus aucuparia) tended to be more prevalent in the restored stands, and all broadleaf tree species had higher mean basal area values in the restored stands (Figure 3a). While the three restored stands were more uniform in their tree species composition, the unrestored stands showed greater variation. Overall, basal area was slightly lower in the restored stands. Only a small amount of deadwood was found in the unrestored stands, whereas the volume varied considerably among the restored stands (Figure 3.b & Appendix 2). Much of the deadwood in the restored stands consisted of large aspen trees, which contributed substantially to the overall volume. Understory density did not differ significantly between the two treatment groups (Figure 3.c; p = 0,82). However, there was substantial variation within treatments, with birch and aspen being the dominant understory species. Overall, no significant difference was detected in the measured forest structures (Appendix 5; p = 0,1).

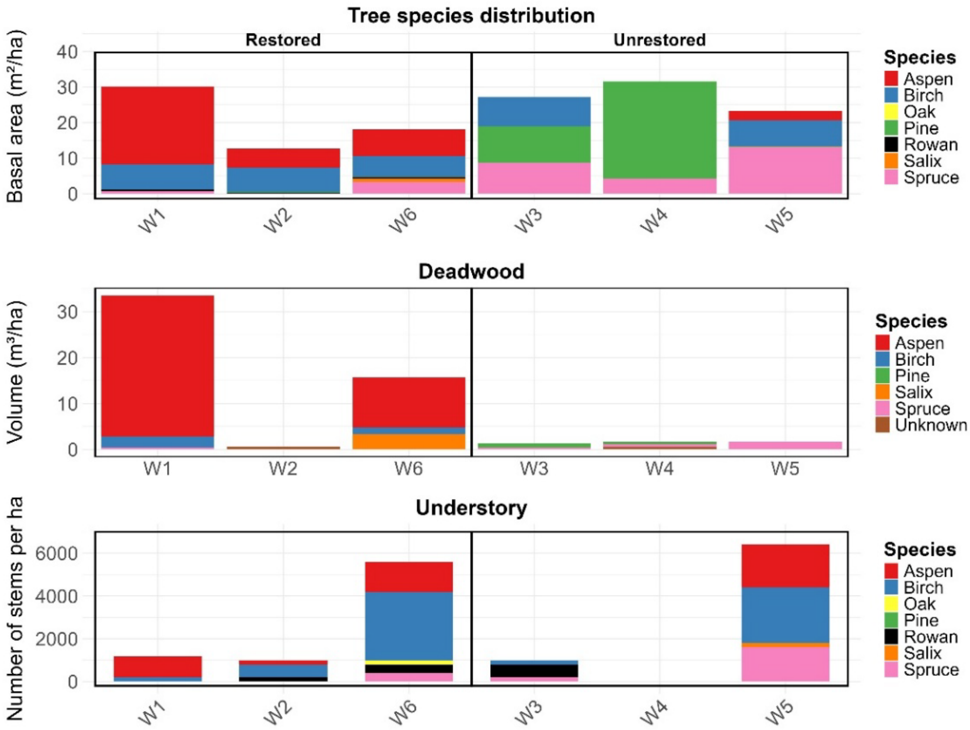

Figure 3. Structural measurements in restored and unrestored forest stands within Färna Ecopark 2024: (a) tree species distribution, (b) deadwood volume, and (c) number of understory stems.

Structural features in the restored stands clustered more closely, while unrestored stands were more dispersed (Figure 4). However, in the NMDS ordination, one restored stand appeared visually closer to an unrestored stand than to another restored one. Structural variables explained 44% of the variation in the data, but this difference between treatments was not statistically significant (Appendix 5; $R^2 = 0.44$, $p = 0.10$).

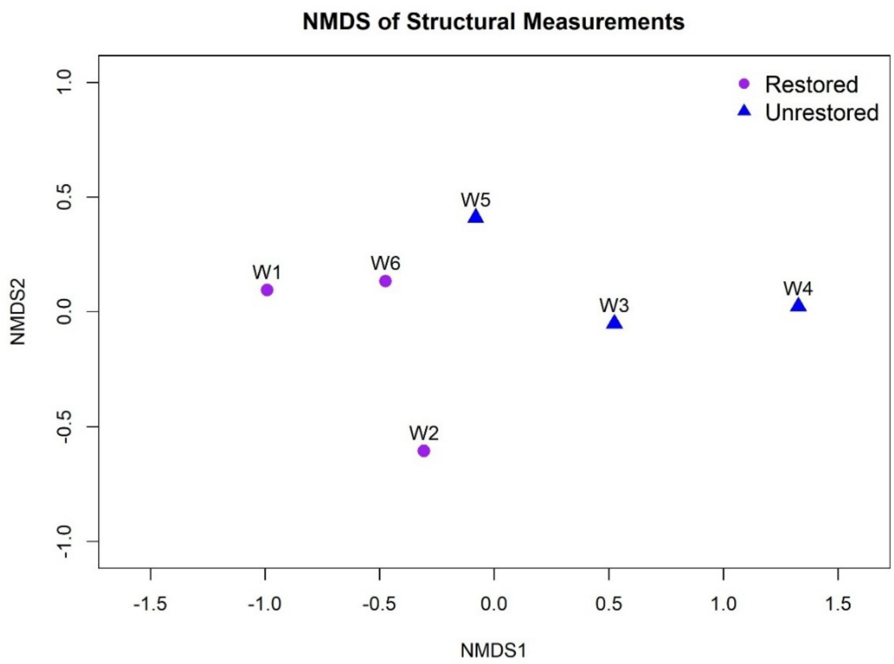

Figure 4. NMDS plot showing the spatial arrangement of forest stands in Färna Ecopark, based on structural measurement data, including deadwood volume, tree species composition, and understory density.

3.1.2 Full study

The target stands were characterized by a dominance of aspen trees and an absence of conifer species (Figure 5.a). The restored stands shared a similar composition, dominated by broadleaf trees, but were primarily influenced by birch. In contrast, the unrestored stands were dominated by spruce and pine. The deadwood volume in the target stands was predominantly composed of aspen (Figure 5.b). In line with tree species distribution, the restored stands had a higher proportion of birch deadwood, while the unrestored stands contained more conifer species. The total deadwood volume was significantly higher in the target stands compared to the unrestored ones (Appendix 3; p = 0,01). The understory tree species composition mirrored the patterns observed in previous figures, with target stands dominated by aspen (Figure 5.c). Both the restored and unrestored stands were more influenced by birch. Salix (*Salix caprea*), rowan, spruce and pine, also contributed to the understory. The number of understory trees did not significantly differ between treatment groups (Appendix 3; p = 0,2). However, the overall forest structure differed between target and unrestored stands (Appendix 5; $p = 0{,}01$).

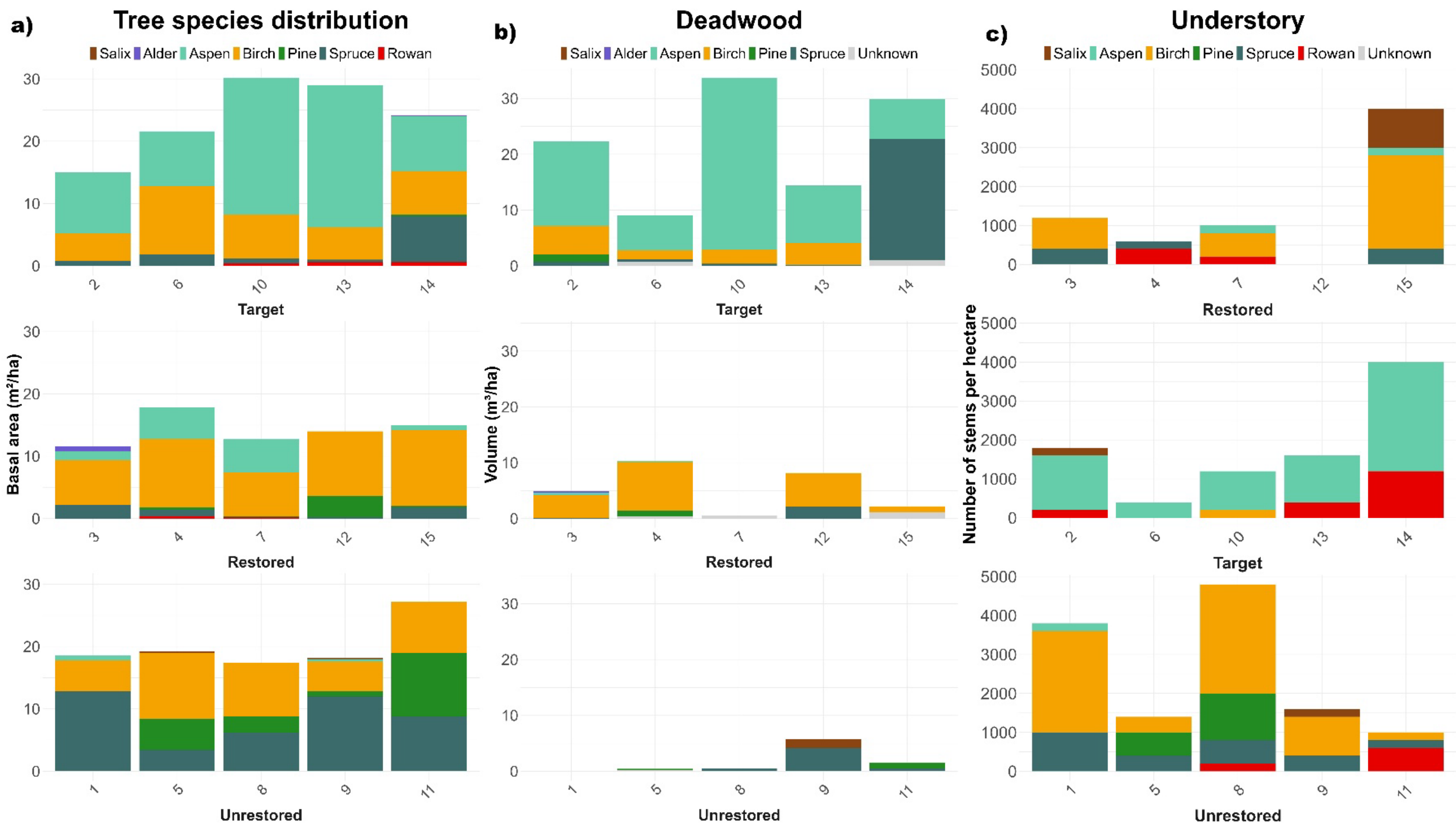

Figure 5. Structural measurements in target, restored and unrestored forest stands within Färna Ecopark 2024: (a) tree species distribution, (b) deadwood volume, and (c) number of understory stems.

The NMDS analysis of structural measurements revealed a distinct grouping of the target stands, placing them close to each other (Figure 6 & Appendix 5; p = 0,01). The unrestored stands were also clustered, although one stand was positioned farther apart. The restored stands were more dispersed across the figure, overlapping with some of the unrestored stands.

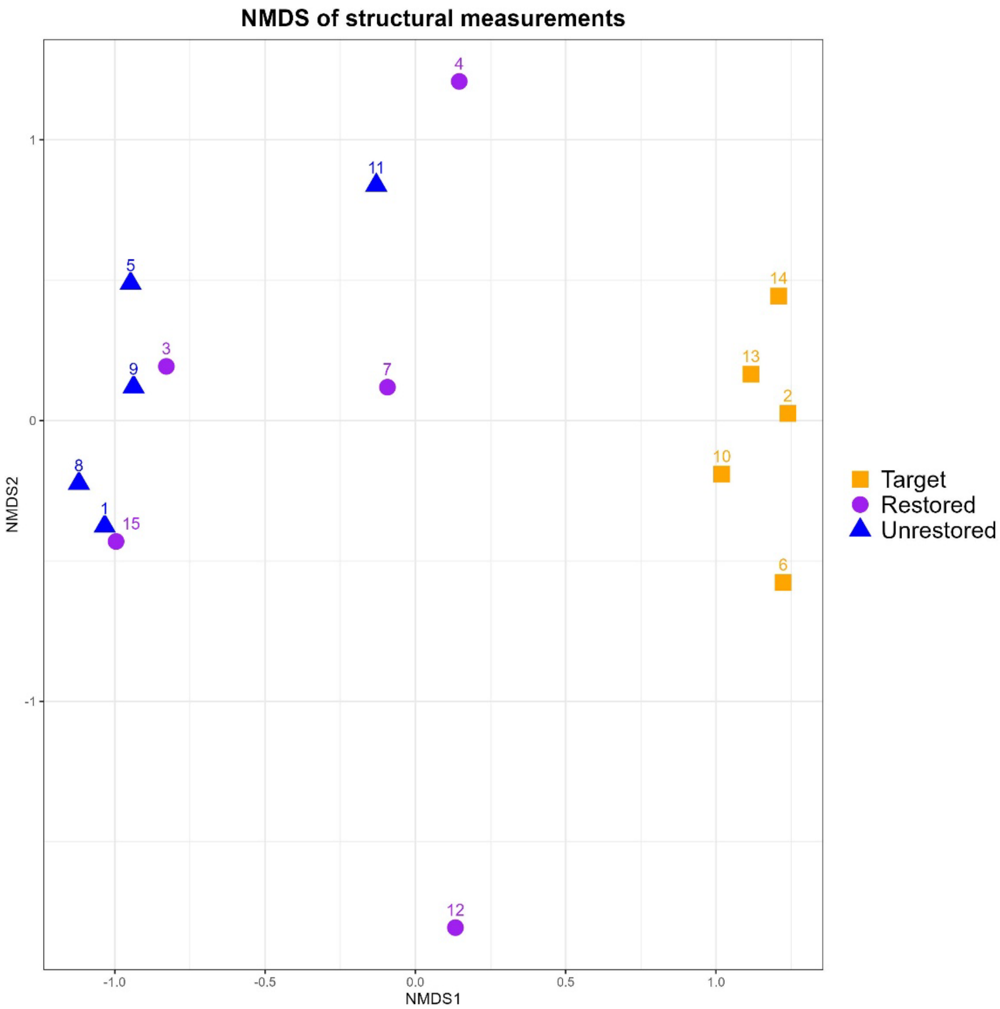

Figure 6. NMDS plot showing the spatial arrangement of forest stands in Färna Ecopark, based on structural measurement data, including deadwood volume, tree species composition, and understory density.

3.2 Bird species presence

3.2.1 Pilot study

The highest total number of birds was found in the restored stands, both for all species and forest associated species (Table 2). The mean number of birds per treatment was also higher in the restored stands, although the difference was not significant (p = 0,44). When examining the groups of indicator species, the number of species varied slightly between treatments, but no significant differences were detected.

Table 2. Number of species identified in each treatment type in the cluster analysis in the pilot study, presented as mean values and standard deviation. Results include p-values from t-tests and the total number of species within each species group.

					Total	**Total**
Treatment	**Restored**	**Unrestored**	**p-value**	**Df**	**Restored**	**Unrestored**
Number of species	38,0 ± (1,7)	36,7 ± (2,1)	0,44	3,87	56	53
Forest related species	28,3 ± (2,1)	26,7 ± (2,1)	0,38	4,00	37	36
Indicator species: forest	4,3 ± (0,6)	5,3 ± (1,2)	0,29	4,00	7	8
Indicator species: broadleaf forest	2,3 ± (0,6)	2,3 ± (0,6)	-	-	3	4
Indicator species: deadwood	2,0 ± (1,0)	1,0 ± (0,0)	1	2,94	3	3

In the NMDS analysis based on bird data, with an environmental fit layer of forest structural variables, restored and unrestored stands tended to cluster separately (Figure 7). Species composition influenced the NMDS ordination, with certain species having a stronger impact on the separation of stands (Appendix 4). Broadleaf trees and deadwood were more associated with restored stands, while conifers were linked to unrestored stands. Understory vegetation showed no clear pattern across treatments. Bird communities tended to differ between treatments, but the variation was not statistically significant (Appendix 5; p = 0,1). Overall, bird presence appeared to be less strongly associated with treatment groups than structural variables were.

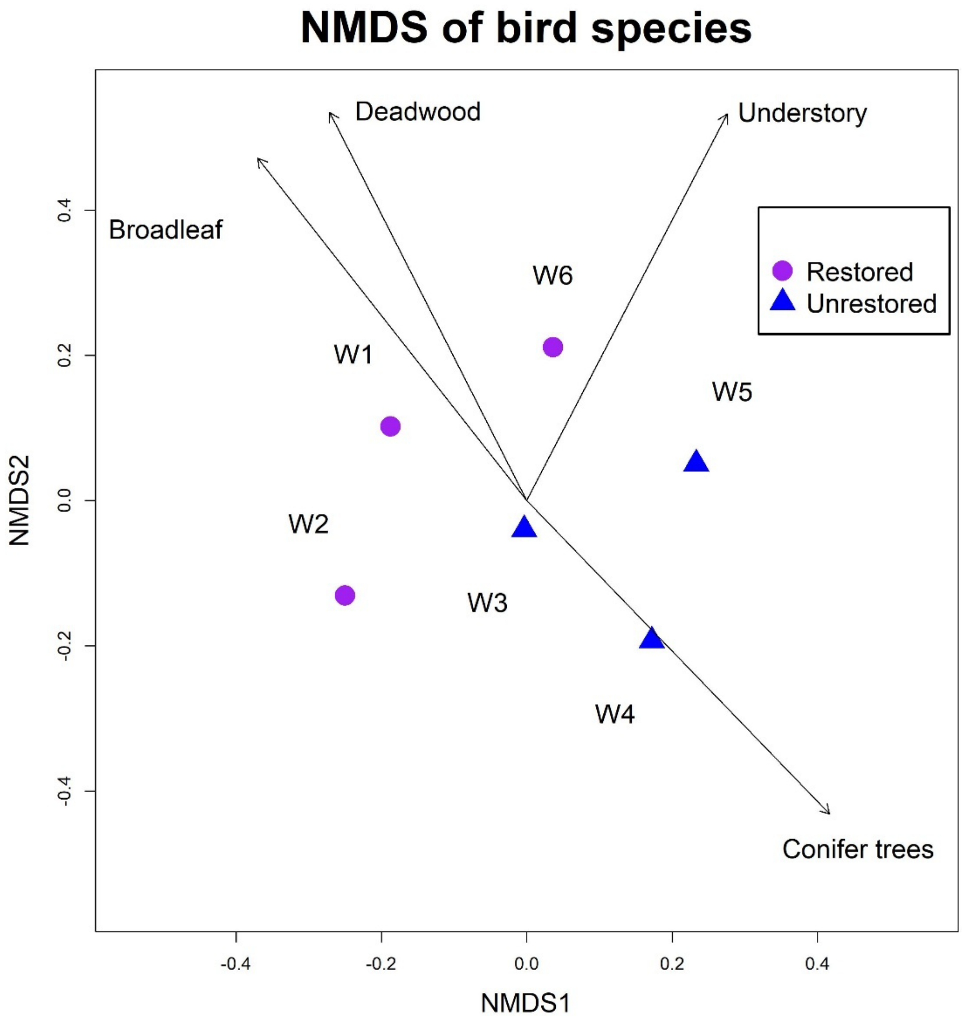

Figure 7. NMDS plot showing bird communities across forest stands in Färna Ecopark. Arrows indicate the direction and strength of correlations between deadwood volume, tree species composition, understory density and the bird community composition.

3.2.2 Full study

The mean number of bird species found was highest in the target stands for all groups of species compared, except indicator species of forest (Table 3). However, no significant difference was found (p > 0,05).

Table 3. Number of species identified in each treatment type, presented as mean ± standard deviation. Results include p-values, chi-squared and df from Kruskal-Wallis tests comparing treatments.

Species	Target	Restored	Unrestored	p-value	chi-squared	df
All species	53,0 ± (2,3)	50,0 ± (2,5)	43,2 ± (7,0)	0,13	4,16	2
Forest-related species	38,0 ± (2,9)	36,8 ± (2,4)	33,8 ± (3,7)	0,18	3,47	2
Red-listed species	12,2 ± (1,3)	10,8 ± (1,3)	9,2 ± (3,7)	0,16	3,73	2
Indicator species - forest	6,8 ± (1,1)	6,6 ± (1,5)	7,4 ± (0,9)	0,76	0,54	2
Indicator species – deadwood	2,8 ± (0,8)	2,6 ± (1,1)	2,4 ± (0,9)	0,85	0,32	2
Indicator species – broadleaf forest	4,6 ± (0,9)	3,4 ± (1,5)	3,4 ± (0,9)	0,17	3,57	2

The results from the NMDS analysis using bird data revealed distinct grouping patterns across all treatments (Figure 8). Bird species composition in the unrestored stands differed from that in the target and restored stands (Appendix 5; p = 0,01). However, one unrestored stand was located far from all other stands, while one target stand was positioned among the restored stands. Some species had a stronger influence on the ordination, with their distribution in the NMDS plot reflecting how their presence or absence contributed to the overall similarity or difference between stands (Appendix 6). Species located near each other in the plot are more likely to co-occur in the same stands, while species further apart are less likely to appear in the same stands. The environmental fit layer showed that conifer trees were associated with unrestored stands while broadleaf trees and deadwood were associated with target and restored stands.

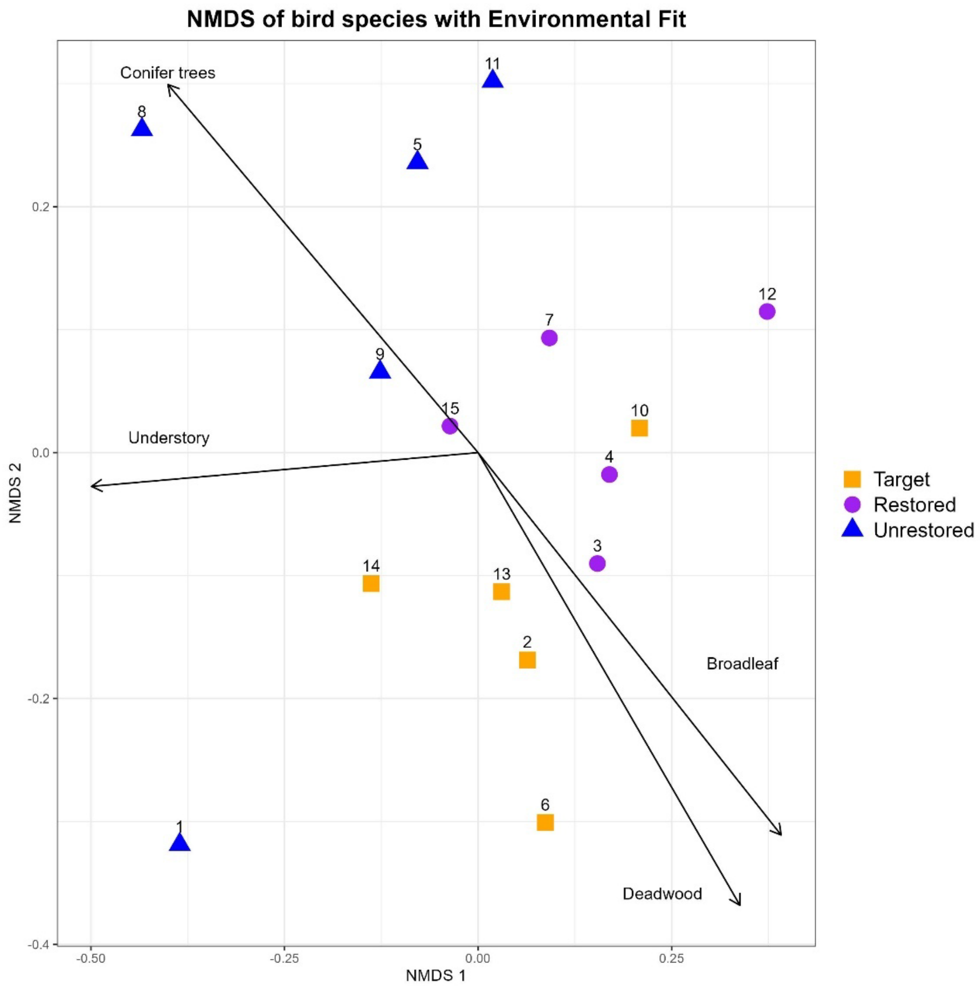

Figure 8. NMDS plot illustrating the spatial arrangement of bird communities across stands in Färna Ecopark. Arrows indicating strength and direction of correlations between deadwood, tree species composition, understory density and bird community composition.

When using bird data for forest associated species in the NMDS plot, the overall pattern remained similar, with distinct clustering by treatment (Figure 9). The forest structures associated with each treatment were also consistent with previous figures.

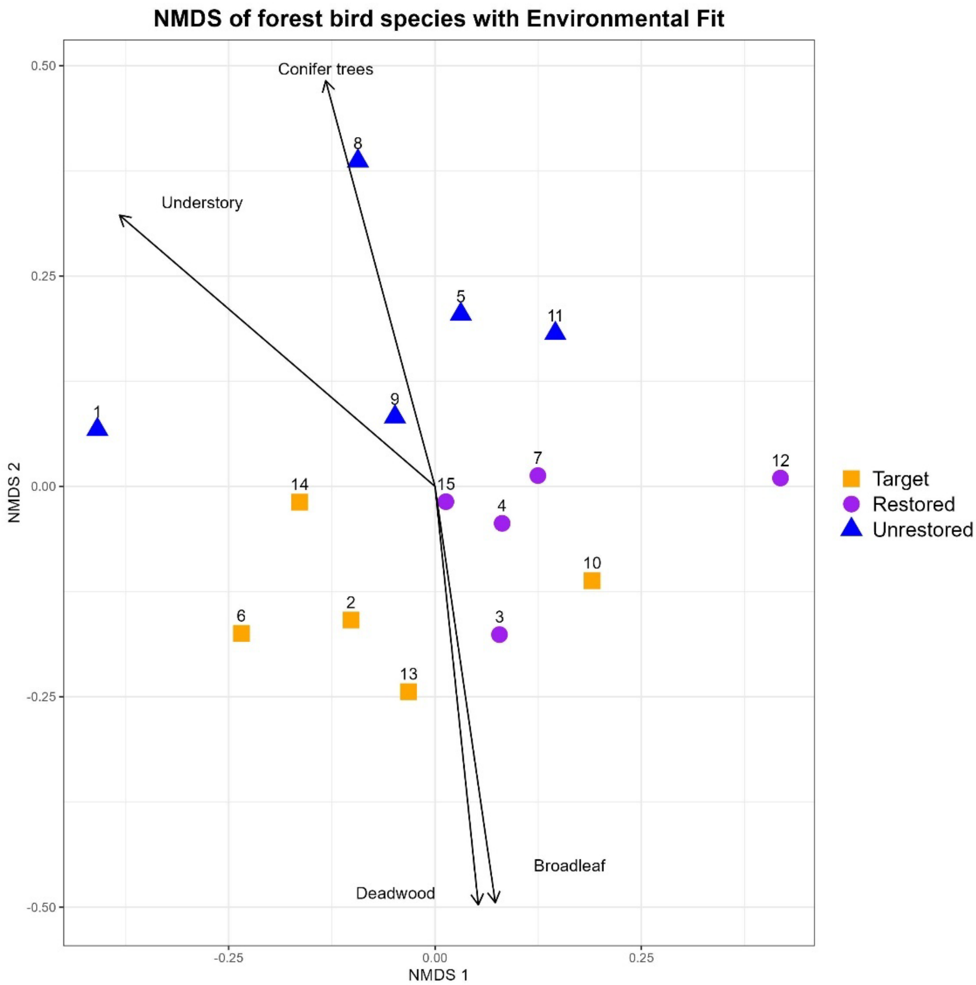

Figure 9. NMDS plot showing the spatial arrangement of forest bird communities across stands in Färna Ecopark. Arrows indicating strength and direction of correlations between deadwood, tree species composition, understory density and bird community composition.

3.3 Bird activity

3.3.1 Pilot study

Bird species activity was similar between restored and unrestored forest stands (Appendix 7). The three most frequently detected species had higher mean proportions in the restored stands (Table 4). However, some species were detected more often in the unrestored stands. Overall, bird activity did not differ between treatments (Appendix 5; p = 0,2).

Table 4. Mean values and standard deviations of the proportion of recordings in which each species was detected across different treatments. The ten most frequently detected species are shown.

Species name	Restored	Unrestored
Willow warbler	0,84 ± (0,07)	0,33 ± (0,31)
Eurasian chaffinch	0,59 ± (0,12)	0,53 ± (0,02)
Song thrush	0,65 ± (0,09)	0,44 ± (0,39)
European robin	0,33 ± (0,19)	0,43 ± (0,15)
Common wood pigeon	0,25 ± (0,12)	0,28 ± (0,12)
Eurasian wren	0,25 ± (0,27)	0,27 ± (0,39)
Eurasian siskin	0,19 ± (0,10)	0,28 ± (0,12)
Tree pipit	0,35 ± (0,27)	0,07 ± (0,08)
Common cuckoo	0,19 ± (0,02)	0,24 ± (0,16)
Great spotted woodpecker	0,28 ± (0,08)	0,05 ± (0,06)

3.3.2 Full study

Similar activity patterns were observed in the target and restored stands, while the unrestored stands exhibited fewer species with high proportions and more with low proportions, resulting in different distributions (Appendix 8). Among the ten most active species, Eurasian wren (*Troglodytes troglodytes*) and Tree pipit (*Anthus trivialis)* were significantly more frequent in the restored stands compared to the unrestored stands (Table 5: p = 0,01 & 0,02). In contrast, Coal tit (*Periparus ater*) was more frequently detected in the unrestored stands (p = 0,02).

Table 5. Mean values and standard deviations of the proportion of recordings in which the ten most frequently detected species were detected. P-values, chi-squared statistics, degrees of freedom and significant pairwise differences are also included.

Species	Target	Restored	Unrestored	p-value (Kruskal-Wallis)	chi-squared	Df	Significant difference
Eurasian chaffinch	0,48 ± (0,10)	0,56 ± (0,10)	0,42 ± (0,10)	0,17	3,46	2	No significant difference
Song thrush	0,42 ± (0,21)	0,44 ± (0,24)	0,35 ± (0,16)	0,83	0,38	2	No significant difference
Willow warbler	0,44 ± (0,08)	0,20 ± (0,20)	0,28 ± (0,22)	0,25	2,80	2	No significant difference
Eurasian wren	0,26 ± (0,11)	0,46 ± (0,20)	0,04 ± (0,03)	0,01*	9,99	2	Restored > Unrestored (Post hoc: p = 0,01)
European robin	0,16 ± (0,08)	0,20 ± (0,16)	0,34 ± (0,17)	0,16	3,73	2	No significant difference
Common blackbird	0,22 ± (0,21)	0,14 ± (0,15)	0,15 ± (0,17)	0,91	0,19	2	No significant difference
Tree pipit	0,16 ± (0,14)	0,27 ± (0,14)	0,03 ± (0,03)	0,02*	7,43	2	Restored > Unrestored (Post hoc: p = 0,02)
Eurasian siskin	0,08 ± (0,08)	0,17 ± (0,06)	0,07 ± (0,03)	0,04*	6,22	2	Significant differences among stands (Post hoc: > 0.05)
Great spotted woodpecker	0,16 ± (0,14)	0,10 ± (0,09)	0,04 ± (0,04)	0,34	2,19	2	No significant difference
Coal tit	0,06 ± (0,03)	0,04 ± (0,03)	0,19 ± (0,10)	0,02*	7,73	2	Unrestored > Restored (Post hoc: p = 0,02)

Among woodpeckers, activity was significantly higher in the target stands compared to the unrestored stands (Table 6; p = 0,02). Wood warbler (*Phylloscopus sibilatrix*) also showed higher activity in the target stands (p = 0,02). No significant differences in activity were found between treatments for tits or indicator species of broadleaf forests (p = 0,09 & 0,08). However, the mean number of species detected per recording was significantly higher in the target stands than in the unrestored stands (p = 0,01).

Table 6. Mean values and standard deviations of the proportion of recordings in which each group of species was detected. P-values, chi-squared statistics, degrees of freedom, and significant pairwise differences are also included.

Species	**Target**	**Restored**	**Unrestored**	**p-value (Kruskal-Wallis)**	**Chi-squared**	**Df**	**Significant difference (post-hoc)**
Woodpeckers	0,25 ± (0,13)	0,12 ± (0,11)	0,04 ± (0,05)	0,03*	6,88	2	Target > Unrestored (Post hoc: p = 0,03)
Tits	0,36 ± (0,23)	0,14 ± (0,05)	0,33 ± (0,14)	0,09	4,90	2	No significant difference
Wood warbler	0,19 ± (0,11)	0,09 ± (0,16)	0	0,02*	7,88	2	Target > Unrestored (Post hoc: p = 0,02)
Indicator species – broadleaf forest	0,11 ± (0,07)	0,03 ± (0,05)	0,04 ± (0,03)	0,08	5,04	2	No significant difference
Red-listed species	0,46 ± (0,12)	0,35 ± (0,28)	0,08 ± (0,07)	0,02*	8,24	2	Target > Unrestored (Post hoc: p = 0,02)
Species per recording	3,70 ± (0,62)	3,42 ± (0,32)	2,46 ± (0,43)	0,01*	9,71	2	Target > Unrestored (Post hoc: p = 0,01)

When using bird activity data for each stand, the grouping pattern resembled previous NMDS plots based on bird presence data (Figure 10). The unrestored stands formed a separate cluster and differed in overall activity compared to the target and restored stands, which showed greater overlap in the NMDS plot than in earlier analyses (Appendix 5: p < 0,01).

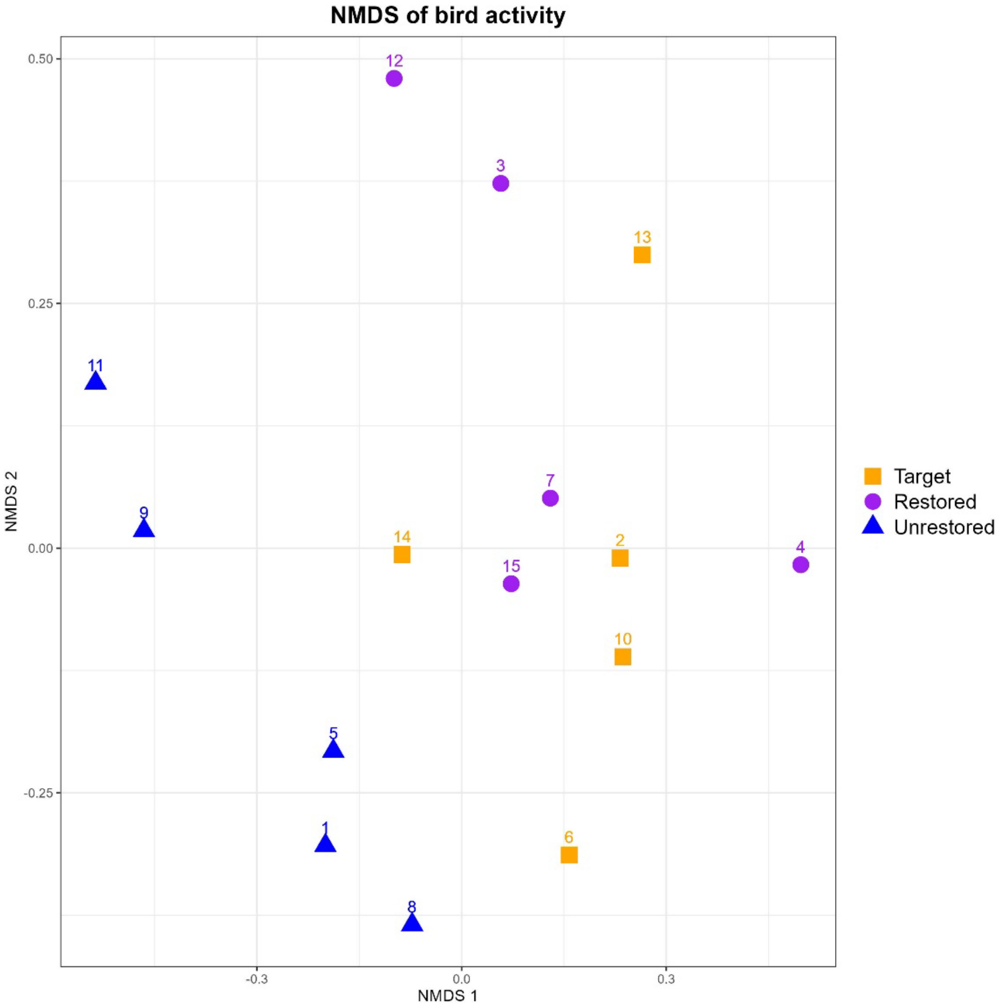

Figure 10. NMDS plot illustrating the spatial arrangement of bird activity across different stands and treatments in Färna Ecopark.

3.4 Indicator species analysis

The indicator species analysis found no significant species in the pilot study, but two species were identified in the full study (Table 7). Garden warbler (*Sylvia borin*) was identified for target stands and Black-throated loon (*Gavia arctica*) for target and restored stands combined (p = 0,02 & 0,01).

Table 7. Species identified as indicators for one or more treatment types. The table presents the indicator values and associated p-values from the indicator species analysis, highlighting species that show a strong association with specific treatment types.

	Treatment	**p-value**	**Indicator value (stat)**
Garden warbler	Target	0,02*	0,76
Black-throated loon	Target + Restored	0,01*	0,87

4. Discussion

Habitat diversification, such as increasing the amount of broadleaved trees, is generally expected to support species richness (Angelstam et al. 2004; Roels et al. 2019), and is a commonly applied restoration measure to enhance biodiversity within managed boreal landscapes (Similä & Junninen 2012). However, there is still limited knowledge on how birds respond to these environmental changes (Versluijs et al. 2017). Analyzing whether bird communities differ in restored compared to unrestored forest stands will provide valuable insight into the effectiveness of this restoration measure. Within my study, I investigated species richness and bird activity across forest stands with different level of restoration (unrestored – restored – target). Four main findings emerged. First, no differences in species richness were found between treatments. This may suggest that the forest structures have not yet fully developed to meet their ecological targets, either requiring more intensive restoration or additional time to mature. Second, bird activity was highest in the target stands, showing significant differences across treatments. Third, no differences were found in species richness among red-listed species or indicator species associated with broadleaf forests. However, bird activity of red-listed species differed significantly between target and unrestored stands with higher activity in the target stands, while no such difference was observed for the indicator species group. Lastly, certain broadleaf-associated species were more strongly linked to the restored stands, suggesting that the restoration measures have benefited some specific species.

4.1 Bird communities

Bird species richness (both all species and the forest associated species) did not differ among stands with different restoration level, which is opposing my expectation. This result was consistent in both the pilot and the full study. In contrast, community composition differed between treatments in the full study, supporting my expectation and indicating that restoration influenced species presence despite similar species richness. This pattern has been observed in previous restoration studies and may depend on multiple factors (Versluijs et al. 2017). This may indicate that the restoration measures applied so far have limited immediate impact on species richness. Different restoration measures can play important roles in promoting biodiversity (Similä & Junninen 2012). However, some species may benefit from the altered conditions, while others may decline or disappear (Guilfoyle et al. 2025). For example, conifer associated species and generalists may continue to breed in surrounding unrestored stands, which could counteract any potential increase in richness in restored areas. There are several plausible explanations why species richness did not differ significantly. First, the surrounding landscape plays a critical role, highly influencing the occurence of bird species in a given place (Betts et al. 2006; Prevedello & Vieira 2010; Crouzeilles et al. 2016). If the broader landscape remains fragmented, degraded, or homogeneous, restoration efforts may not be enough to attract new species. Second, the small sample size and high variation among stands within the treatments may inhibit detecting treatment effects due to insufficient statistical power. This variation may depend on site-specific characteristics, differences in restoration intensity, or the composition and connectivity of the surrounding landscape. Moreover, the effects of restoration are likely to be delayed, as it can take several decades for forest structures and species communities to recover (Uezu & Metzger 2016; Roels et al. 2019; Haslem et al. 2023; Guilfoyle et al. 2025). Third, bird communities may respond after structural features have been developed, such as deadwood and mature forests, a process that takes time, especially in restored stands aiming to resemble target conditions. Also, even if the amount of broadleaf has increased, the restoration may have failed to enhance other key structures, such as cavity trees and canopy openings, needed by certain species (Similä & Junninen 2012). Time is particularly important for species with longer life cycles or slower colonization rates (e.g. Capercaillie and Hazel grouse) (Åberg et al. 2000; Kämmerle et al. 2021). Colonization rates are influenced by landscape structure and habitat connectivity (Pavlacky et al. 2012). The absence of a difference in species richness in my study may reflect the early stage after restoration and limited dispersal opportunities. Restoration is clearly not the only factor influencing bird populations, other environmental and landscape-level factors, such as habitat fragmentation, might also be important components (Betts et al. 2006). Yet, addressing these was beyond the scope of the present study. I recommend further research to incorporate these factors into future analyses and to examine more deeply how birds respond to restoration measures over time, as developing forest structure and connectivity may enhance colonization and potentially increase species richness.

4.2 Bird activity

Bird activity (i.e. number of times a given bird species has been recorded in a subset of the data) tended to be higher in the target stands compared to the unrestored stands in the full study, which supports my expectation. Along with species richness, bird activity may benefit from restoration efforts, although the effects are often subject to a time lag (Roels et al. 2019). The mean number of species detected per recording was significantly lower in the unrestored stands, which could indicate a reduced local-scale activity in these areas (Versluijs et al. 2017). One explanation for the different species activity per recording rate is that bird activity was generally higher in the restored and target stands, potentially increasing the detection probability per recording. In contrast, birds in the unrestored stands may have been less active or occurred at lower densities, resulting in fewer detections per recording despite comparable species richness. These findings suggest that restoration efforts may have contributed to higher bird activity and density in the target stands. In summary, my results do not support that restored and unrestored forest stands differ in bird species richness but indicate an effect of broadleaf restoration on bird activity and community composition in my study area.

4.3 Indicator species

The group of indicator bird species for broadleaf forests (Stock dove, Green woodpecker, Lesser spotted woodpecker, Three-toed woodpecker, Long-tailed tit, Marsh tit, and Eurasian treecreeper) did not differ among stands in terms of species richness or activity, which is opposing my expectations. Indicator species may not always respond uniformly to restoration, and their effectiveness as habitat quality indicators can be context-dependent (Bakker 2008). Although not statistically significant, the mean values for both species richness and activity were higher in the target stands and the overall activity tended to differ between treatments. The indicator group consisted of seven species only, and given the small number of species, the results were likely driven by a few dominant contributors (Bissonette 1999). Notably, the European green woodpecker and Eurasian treecreeper were far more active than the others, meaning the outcome largely reflects patterns for these two species. The result also raises the question of how well the chosen species represent broadleaf forest habitat. For example, the Eurasian treecreeper is described as often inhabiting areas with some conifer presence (Svensson et al. 2010). While this does not exclude it from being considered an indicator species, it may be worth for future research to evaluate whether alternative species would offer a more sensitive or specific signal of habitat quality within my study system, such as Hawfinch (*Coccothraustes coccothraustes*) (Lindbladh et al. 2020; Bakx et al. 2023). Some of the indicator species may be weakly linked to the structural changes promoted by restoration, and including species more closely tied to broadleaf forest structure could improve the sensitivity of the group.

4.4 Red listed species

Similar to previous patterns, no significant difference was found in species richness among the group of red listed species, which has been shown in other restoration studies focusing on this group (Guilfoyle et al. 2025). This trend appears consistent across birds and other taxa in general, suggesting overall species richness itself may be an insufficient indicator of early restoration effects (Basset et al. 2008; Versluijs et al. 2017). However, red listed bird species showed highest activity in the target stands, and the lowest in the unrestored stands, indicating that these species are more active in structural complex forests and may be an effect of the restoration measures. Fourteen different red listed species were detected in my analysis, and most of them were found sparsely, probably because red listed species are typically rare. The two most active species in this group were Wood warbler and European pied flycatcher (*Ficedula hypoleuca*), contributing substantially to the overall activity result. It is important to note that red-listed species are not necessarily rare; the list also includes formerly common species experiencing significant declines, which makes their response complex (SLU Artdatabanken 2020).

4.5 Broadleaf species responses

Some broadleaf-associated bird species were found to higher extent in the target and restored stands, which is in line with the previous shown positive effects from restoration (Versluijs et al. 2017; Roels et al. 2019). The Garden warbler was identified as an indicator species for the target stands in Färna, with its presence being significantly higher in these stands. This species is typically associated with broadleaf forests (Svensson et al. 2010; SLU Artdatabanken 2025). The restoration measures likely benefited the Garden warbler, which prefers open habitats, especially those with shrub layers. The activity of the Wood warbler also differed significantly between treatments. Although it primarily prefers broadleaf forests, it can occur in spruce forests when broadleaved trees are present (Svensson et al. 2010; International 2024). Its higher activity in the restored stands may indicate that the habitat improvements made these areas more suitable. Since the Wood warbler prefer dense, mature broadleaf forests, restoration may have enhanced such conditions within the target stands. The presence of these species suggests restoration benefits certain birds, reflecting their specific ecological needs. This is supported by broadleaf-associated species being closely linked to target stands with high volumes of deadwood and broadleaf trees.

4.6 Restoration outcomes

Previous studies have found that restoration efforts alter bird communities at different restoration levels, indicating that bird species are affected by these measures (Versluijs et al. 2017). One of the measured forest structures, understory trees, has been shown to play an important role in bird community composition (Dagan & Izhaki 2019). Within both the pilot and the full study, no such effect was detected, and the amount of understory stems did not differ between treatments, possibly depending on local conditions such as light availability and soil composition (Ou et al. 2020). A general pattern linking forest structures to bird communities was consistent between the pilot and the full study, where broadleaf trees were connected to the birds in the target and restored stands, while the opposite pattern was observed for coniferous trees. Deadwood has also been shown to influence bird community composition (Bujoczek et al. 2021), and findings from this study revealed an association for the target and restored forest stands. Overall, certain forest characteristics appeared to impact bird communities, likely resulting from the applied restoration measures.

The extent of variation among stands within treatments varied. The target stands from the full study were clustered closely based on structural measurements (Figure 6), indicating similar forest characteristics (Zorz 2024). In contrast, the unrestored and restored stands showed greater overlap, which may reflect the variability within the restoration measures between the stands. It highlights the need for restoration strategies that are more consistently aligned with habitat conditions favourable to bird communities (Haslem et al. 2024). Some restored stands in the plot are positioned near unrestored ones in the ordination, suggesting that they may have undergone only limited restoration. In such cases, the restoration efforts may not sufficiently promote features beneficial to broadleaf-associated species, unlike the conditions found in the target stands. To enhance effectiveness, restoration should aim to emulate the structural attributes of the target stands, supporting greater homogeneity within the treatment group (Larsson Ekström et al. 2024). However, this goal is challenging due to differences in initial conditions, such as tree species composition, vegetation structure, and site history, all of which affect how restoration translates into ecological outcomes (Chase 2003). Understanding and accounting for this variation is important for achieving more consistent restoration outcomes that support the bird communities typical of developed forest habitats. Here, I recommend future research to investigate the causes of variability within treatments and to determine which structural changes are most critical to supporting bird communities.

4.7 Methodological limitations

This study provided valuable insights into the benefits of restoration for avian communities. However, some limitations should be acknowledged. The dataset was small, which may have reduced statistical power and contributed to the lack of significant results (Ioannidis 2005; Button et al. 2013). Although the pilot study findings supported some results from the full study, a larger dataset would have enhanced the reliability and robustness of the conclusions. Next, the analysis focused on stand level differences and did not include a landscape perspective, even though landscape context is known to influence bird communities (Prevedello & Vieira 2010; Crouzeilles et al. 2016). Incorporating landscape variables in the study might have provided further insights into birds' responses to restoration. Also, species abundance was not estimated due to limitations within

PAM (Blumstein et al. 2011; Furnas & Callas 2015). Estimating abundance would have required more time, effort and equipment. Finally, there was some uncertainty regarding the timing and extent of the restoration measures implemented in the study area. A more consistent and well documented restoration design across treatments would have allowed for a better comparison. Addressing these limitations in future studies could contribute to a deeper understanding of restoration effects on avian communities.

5. Conclusion

This study aimed to assess differences in bird species richness, community composition, and activity across forest stands with varying levels of restoration in Färna Ecopark. Restoration measures did not significantly change bird species richness across forest stands but did alter bird activity levels and community composition. These results suggest that restoration affects composition of species and habitat use of certain bird groups before changes in species richness become evident. The findings emphasize the importance of restoration strategies that enhance forest structural complexity to support bird communities. To better understand long-term impacts, future studies should examine how different restoration measures influence bird populations over multiple years and across broader spatial scales.

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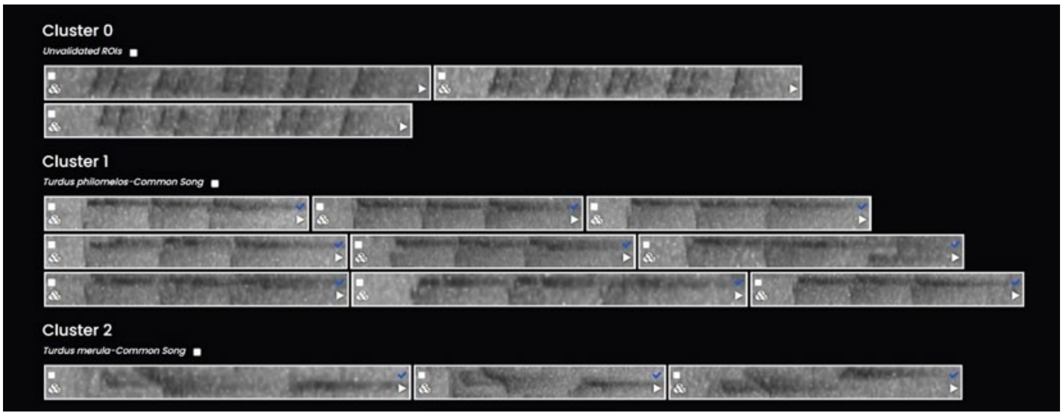
Popular science summary

Forests are home to a rich variety of birds, and restoring damaged forests may help species come back. It is important to create places where birds can live, because they play an important role in nature. In this study I tried to understand whether restored forests have more bird species and higher bird activity than forests that have not been restored. I also looked at whether species linked to broadleaf forests were more common in the restored areas. To compare the different forest types, I measured things like dead wood, tree types, and the number of small trees. Audio boxes were placed in the forest which recorded the birds. These recordings were later analyzed to find out which bird species were present in each type of forest.

I found no clear difference in the number of bird species between restored and unrestored forests. However, bird activity was higher in the restored forests, and the types of species were also different. This suggests that the restoration may not have increased the number of species, but it likely had a positive effect on how often birds were active and which species were present. If more time had passed since the restoration, we might have seen changes in species richness too. These results are promising, as they show that restoration efforts can help improve forest habitats for birds. Continuing restoration work could benefit both birds and the overall health of forest ecosystems.

Appendix 1

Appendix 1. *Similar sounds grouped into clusters, using the Clustering tool in Arbimon.*



Appendix 2

Appendix 2. *Mean values and standard deviations of structural measurements for deadwood, understory and basal area (BA) in restored and unrestored forest stands in Färna Ecopark 2024. The table also includes p-value and test statistics (W-values) from Wilcoxon-Mann-Whitney tests.*

Variable	**Restored stands**	**Unrestored stands**	**P-value (Wilcoxon-Mann-Whitney)**	**W-value**
Deadwood (m^3/ha)	16,6 ± (16,5)	1,6 ± (0,2)	0,77	120
Understory (stems/ha)	2600,0 ± (2600,0)	2466,7 ± (3442,9)	0,82	5,5
Aspen BA (m^2/ha)	11,7 ± (9,0)	0,9 ± (1,5)	0,08	9
Birch BA (m^2/ha)	6,6 ± (0,7)	5,2 ± (4,5)	0,66	3
Oak BA(m^2/ha)	0,1 ± (0,1)	0	0,50	6
Pine BA (m^2/ha)	0,1 ± (0,1)	12,6 ± (13,8)	0,12	0,5
Rowan BA (m^2/ha)	0,3 ± (0,1)	0	0,06	9
Salix BA (m^2/ha)	0,3 ± (0,5)	0	0,50	6
Spruce BA (m^2/ha)	1,4 ± (1,8)	8,7 ± (4,5)	0,10	0
Broadleaf trees (m^2/ha)	18,9 ± (5,3)	6,0 ± (5,3)	0,37	7
Conifer trees (m^2/ha)	1,5 ± (1,7)	21,3 ± (9,3)	0,10	0

Appendix 3

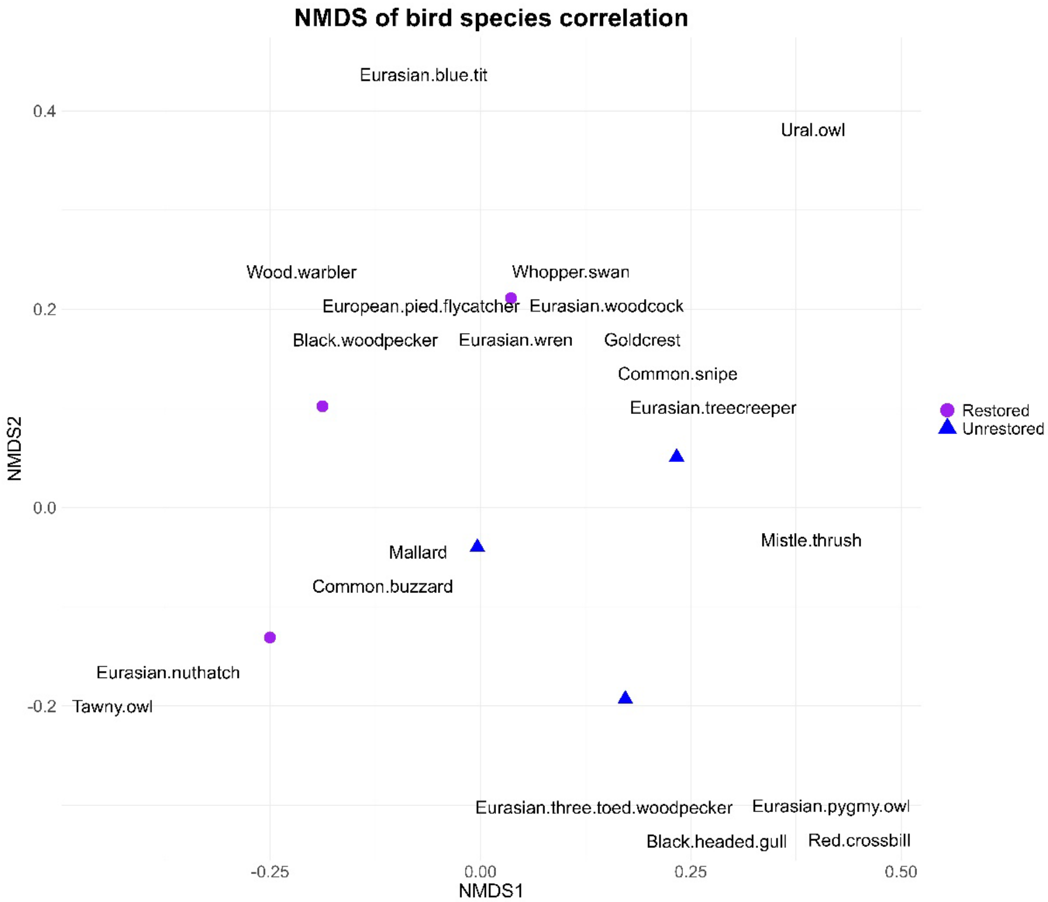
Appendix 3. *Mean values and standard deviations of structural measurements for deadwood, understory and basal area (BA) in target, restored and unrestored forest stands in Färna Ecopark 2024. P-values, chi-squared statistics, and degrees of freedom from Kruskal–Wallis tests are also presented, along with significant pairwise differences between treatments, based on post hoc tests.*

Variable	**Target stands**	**Restored stands**	**Unrestored stands**	**P-value**	**Chi-squared**	**Df**	**Significant difference (post-hoc)**
Deadwood (m^3/ha)	21,9 ± (10,3)	5,2 ± (4,1)	1,7 ± (2,4)	0,01*	10,26	2	Target > Unrestored (p = 0,004)
Understory (stems/ha)	1800,0 ± (1341,7)	1120,0 ± (1664,9)	2520,0 ± (1676,9)	0,20	3,14	2	No significant difference
Aspen BA (m^2/ha)	14,4 ± (7,3)	2,5 ± (2,5)	0,2 ± (0,4)	<0,01*	11,06	2	Target > Unrestored (p = 0,003)

Birch BA (m^2/ha)	6,9 ± (2,5)	9,6 ± (2,3)	7,5 ± (2,5)	0,23	2,91	2	No significant difference
Pine BA (m^2/ha)	0	0,8 ± (1,4)	3,7 ± (4,1)	<0,05*	6,13	2	Unrestored > Target (p = 0,04)
Rowan BA (m^2/ha)	0,3 ± (0,3)	0,1 ± (0,2)	0	0,11	4,45	2	No significant difference
Salix BA (m^2/ha)	0	0	0,1 ± (0,1)	0,12	4,31	2	No significant difference
Spruce BA (m^2/ha)	2,2 ± (2,9)	1,0 ± (1,0)	8,6 ± (3,9)	0,02*	8,14	2	Unrestored > Restored (p = 0,02)
Alder BA (m^2/ha)	0,0 ± (0,1)	0,4 ± (0,4)	0	0,58	1,09	2	No significant difference
Broadleaf trees (m^2/ha)	21,7 ± (6,9)	12,4 ± (2,7)	7,8 ± (2,2)	<0,01*	11,06	2	Target > Unrestored (p = 0,003)
Conifer trees (m^2/ha)	2,3 ± (3,0)	9,4 ± (1,2)	12,4 ± (4,2)	0,01*	9,53	2	Unrestored > Restored (p = 0,04) & Unrestored > Target (p = 0,01)

Appendix 4

Appendix 4. *NMDS plot illustrating the spatial arrangement of bird communities across different stands and treatments in the pilot study, at Färna Ecopark. The plot highlights the 20 most strongly correlated bird species, illustrating their association with different stands.*



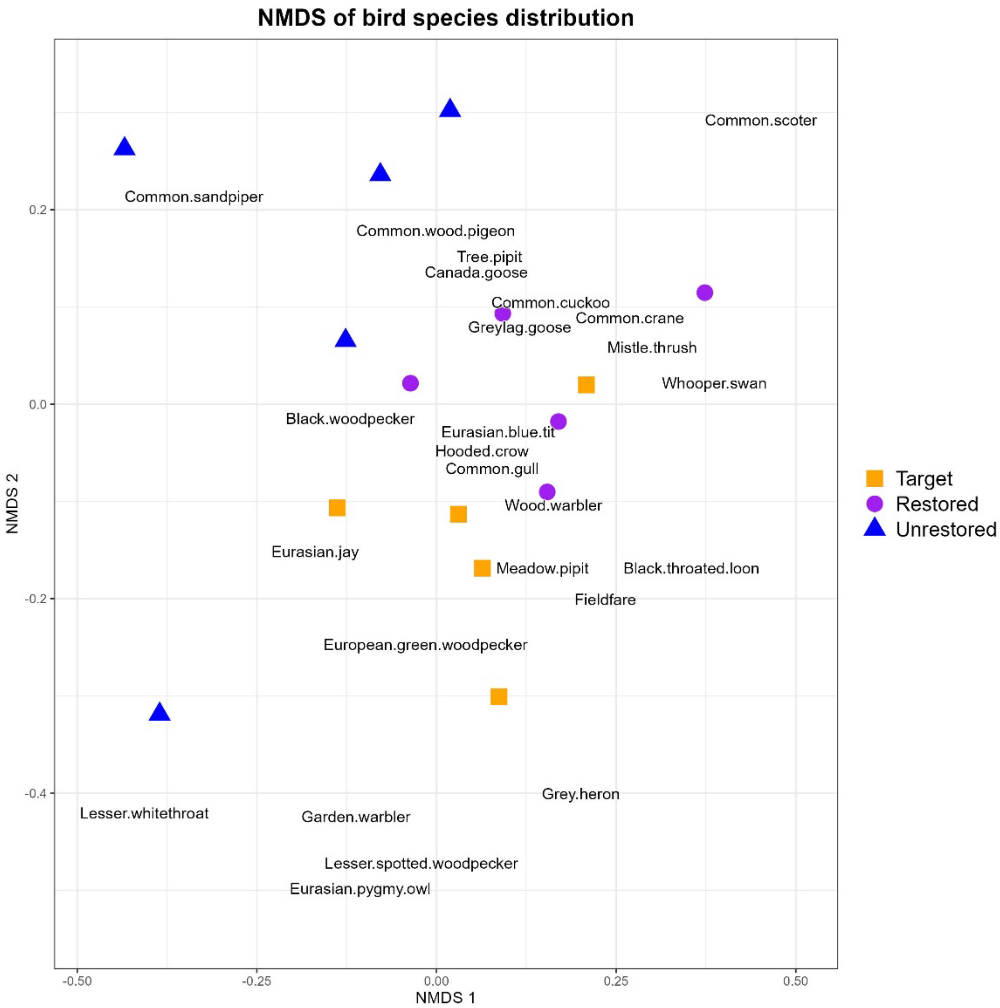
Appendix 5

***Appendix 5**. Results from Adonis tests assessing differences between treatment types. One test evaluates variation in forest structural measurements (e.g., deadwood volume, tree species composition, understory density), while the other examines bird community composition and overall bird activity.*

Variable	Df	SumOfSqs	R2	F	Pr(>F)	Significant difference
Structural measurements – Pilot study	1	0,55	0,44	3,09	0,10	No significant difference
Birds – Pilot study	1	0,08	0,31	1,83	0,10	No significant difference
Bird activity – Pilot study	1	0,12	0,27	1,48	0,20	No significant difference
Structural measurements – Full study	2	11223739	0,41	4,22	0,01*	Target > Unrestored (pairwise MANOVA: p=0,04)
Birds – Full study	2	0,13	0,25	2,05	<0,01*	Target > Unrestored (pairwise Permanova: p=0,02) & Restored > Unrestored (pairwise Permanova: p=0,03)
Bird activity - Full study	2	0,47	0,33	2,90	<0,01*	Target > Unrestored (pairwise Permanova: p=0,01) & Restored > Unrestored (pairwise Permanova: p=0,01)

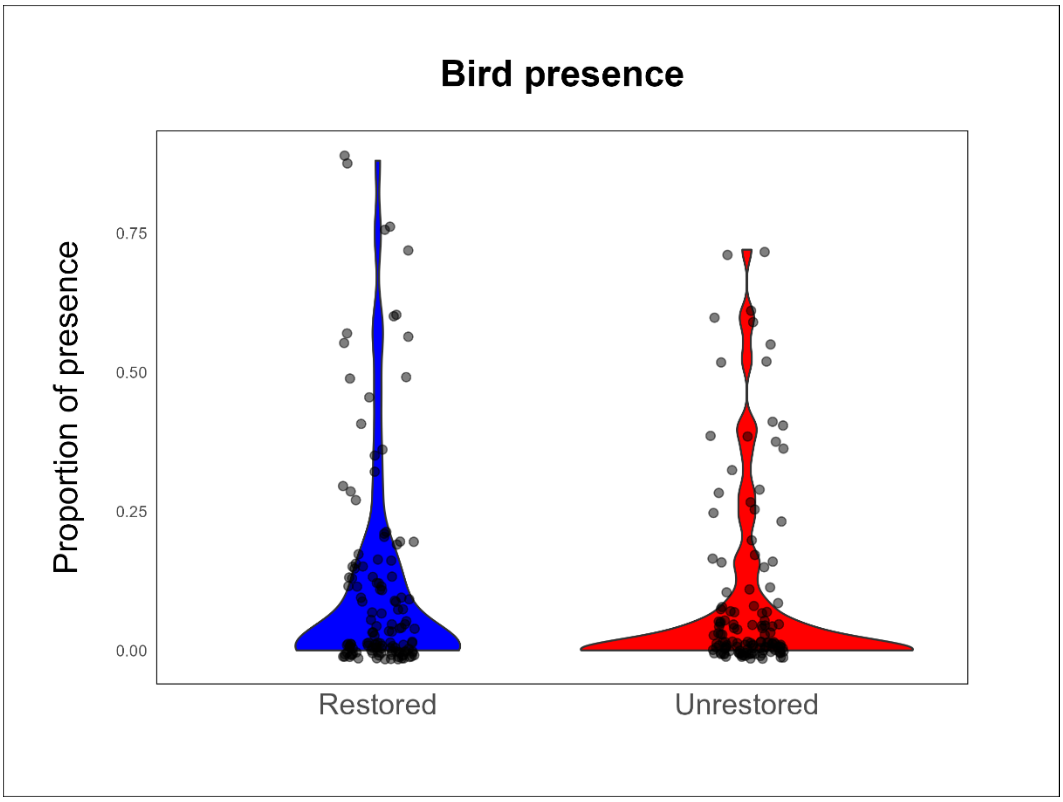
Appendix 6

Appendix 6. *NMDS plot illustrating the spatial arrangement of bird communities across different stands and treatments in the full study, at Färna Ecopark. The plot highlights the 25 most strongly correlated bird species, illustrating their association with different stands.*



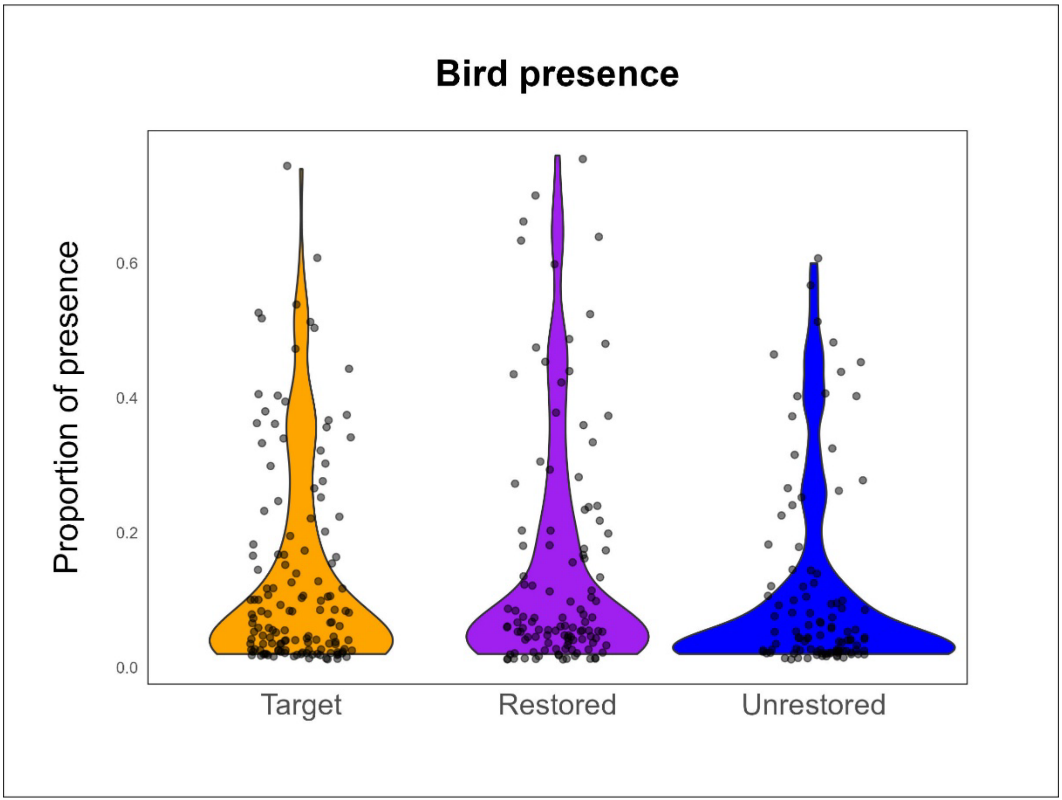
Appendix 7

Appendix 7. *The figure illustrates bird activity in restored and unrestored forest stands in the pilot study at Färna Ecopark. Each dot represents the proportion of recordings in which a specific bird species was detected within a given stand.*



Appendix 8

Appendix 8. *The figure illustrates bird activity in target, restored and unrestored forest stands in the full study at Färna Ecopark. Each dot represents the proportion of recordings in which a specific bird species was detected within a given stand.*



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