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# Reduced vocal activity of resident birds following clearcutting reflects a decline in a few species at highly impacted sites in boreal forests

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ABSTRACT

Intensive forestry management, particularly clearcutting, threatens boreal biodiversity by reducing critical habitat for specialist species such as resident forest birds. Research on clearcutting often emphasizes the breeding season, primarily reflecting migratory birds, while year-round resident birds—more exposed to local disturbances—remain understudied. Moreover, cross-sectional studies dominate, limiting our ability to detect the clearcutting's true impact. Using a Before-After Control-Impact (BACI) design coupled with Passive Acoustic Monitoring (PAM), we investigated how clearcutting affects 12 resident forest birds in Southwest Finland. Acoustic data were collected before (2020) and after (2024) clearcutting across 60 sites: 30 control (uncut) and 30 impact (clearcut) sites. Impact sites were further categorized into low-impact (6.45–<33.87%) and high-impact (>33.87–100%) areas based on the proportion of forest removed within a 100-meter radius. Total vocal activity declined significantly at high-impact sites, whereas species richness showed no clear response. Species-specific analyses revealed negative responses for Crested Tit, Eurasian Treecreeper, and Goldcrest, with Eurasian Treecreeper particularly sensitive, declining at even low-impact sites. In contrast, the Black Woodpecker vocal activity increased at high-impact sites. Our results demonstrate that observed changes stemmed from clearcutting rather than natural variation. Our findings highlight that intensive clearcutting substantially reduces resident bird activity in boreal forests, emphasizing the need for sustainable forest management practices, including tree retention strategies, selective harvesting, and species-specific conservation measures. The present study represents one of the first applications of BACI design with PAM for assessing the clearcutting impacts on resident forest birds, providing valuable insights for evidence-based forest management and biodiversity conservation.

## 1. Introduction

Rising anthropogenic pressures exert tremendous strain on natural ecosystems, leading to habitat loss, species extinctions, and increased human-wildlife conflict (Ceballos et al., 2015; Inskip and Zimmermann, 2009). At present, logging (clearcuts) is the most aggravated form of disturbance affecting boreal biodiversity (Girona et al., 2023; Seedre et al., 2018; Venier et al., 2014), with nearly two-thirds of boreal forests managed for timber production (Gauthier et al., 2015). These practices have resulted in the reduction of old-growth forests, deadwood availability, and habitat heterogeneity, which are crucial elements to safeguard biodiversity across this region (Gauthier et al., 2015; Hellberg et al., 2009; Kuuluvainen, 2009; Mönkkönen et al., 2022). Habitat specialists dependent on old-growth and natural forests are particularly affected (Eide et al., 2020; Eyvindson et al., 2021; Hyvärinen et al., 2019; Kayes and Mallik, 2020). In Finland, 12% of species are classified as threatened according to IUCN criteria, with 31% of these species being forest-dependent (Hyvärinen et al., 2019). Similarly, in Sweden, 1400 of 2000 forest-associated species are red-listed (Eide et al., 2020). Birds of boreal forests face a multitude of threats from forestry activities, including reduced breeding success (Betts et al., 2022; Winiarski et al., 2017), decreased food availability (Hollander et al., 2015; Pettersson

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et al., 1995), disruption of movement (Bélisle et al., 2001; Ferraz et al., 2007), increased predation and brood parasitism (Cavitt and Martin, 2002; Gannon, 2005; Manolis et al., 2002; Thompson et al., 2008), and edge effects (Brazaitis and Angelstam, 2004; Hanski et al., 1996; Manolis et al., 2002). Together, all these factors can have compounding effects on birds, potentially leading to reduced fitness and, ultimately, local extirpations. For example, Betts et al. (2022) documented a loss of 66% of breeding habitat for 54 common species in eastern Canada between 1985 and 2020, solely due to clearcutting practices. Additionally, the forest bird index, a multispecies indicator used in the European Union to monitor ecosystem health and the effectiveness of some conservation actions, declined by 4.5% between 1990 and 2023, with no possible recovery by 2030 (European Environment Agency, 2025).

Although the impacts of clearcuts on boreal forest birds have been well-documented over the years, significant gaps remain in our understanding. For instance, existing research is largely concentrated on breeding birds during spring, often dominated by migratory species (long-distance migrants—wintering in tropics; short-distance migrants—wintering in temperate areas). Permanent residents make up only 5–15% of the breeding bird species in this region (Helle and Niemi, 1996). A decline in migrants does not necessarily reflect local forest management but rather conditions along their migration routes and wintering grounds (e.g., Laaksonen and Lehikoinen, 2013) since the majority of their annual cycle includes non-breeding grounds (La Sorte et al., 2017). In contrast, resident birds remain in these forests year-round and thus are directly affected only by local habitat conditions. In addition, many resident bird species prefer old, contiguous forests and therefore are particularly vulnerable to forestry activities. However, resident bird species have received less attention and are often limited to short-term studies or a narrow range of indicator species. Moreover, most forestry studies are cross-sectional rather than longitudinal designs, which often fail to disentangle the effect of forestry on the avian community from natural temporal variations.

Passive acoustic monitoring (PAM) has become a powerful tool to monitor biodiversity given its robustness, efficiency, non-invasiveness, and cost-effectiveness while enabling long-term data collection over broad spatial and temporal scales (Gibb et al., 2019; Hoefer et al., 2023; Sugai et al., 2019). PAM uses automated recording units (ARUs) that record soundscapes, which are valuable for describing biophony, geophony, and anthropophony (Ross et al., 2023). Furthermore, animal vocalizations provide essential information about their behavior and ecology (Bradbury and Vehrencamp, 1998; Kershenbaum et al., 2014), which is necessary for effective management and conservation. The applications of PAM include assessing species diversity and composition (Alquezar and Machado, 2015; De Araújo et al., 2024), studying population dynamics (Bezerra et al., 2019; Hutschenreiter et al., 2024; Pérez-Granados and Traba, 2021), measuring anthropogenic impacts (Astaras et al., 2017; Braulik et al., 2017; Pirotta et al., 2015; Proppe et al., 2013), mapping species distributions (Inoue et al., 2025), monitoring habitat use (Baroni et al., 2023), and detecting rare species (Jaramillo-Legorreta et al., 2016). Despite these advantages, PAM has several limitations. It is confined to vocalizing animals, such as bats, birds, cetaceans, and anurans. Additionally, while PAM can provide information on species presence at a given time and location, determining true absence can be challenging when the species is present but silent and hence remains undetected. PAM also faces difficulties in estimating abundance as species differ in their propensity to vocalize, and because it is difficult to identify individuals based on audio data alone in most taxa. Finally, several behavioral aspects are hard to disentangle. For instance, detecting a bird's call only confirms its presence but not its behavior, such as whether it was commuting, foraging, interacting, mate-searching, nesting, or breeding. Nevertheless, PAM's omnidirectional sampling offers broad detection ranges and the ability to capture entire communities (Gibb et al., 2019; Wrege et al., 2017).

The Before-After Control-Impact (BACI) design is a powerful tool in Environmental Impact Assessment (EIA) studies, as it helps distinguish changes in impact sites from natural variability, particularly when treatment sites cannot be chosen randomly (Smith, 2002). The objective of a BACI design is to compare environmental variables in an affected (impact) and an unaffected (control) area before and after perturbations (natural or human-mediated) (Stewart-Oaten et al., 1986). Unlike most descriptive studies, which fail to distinguish between temporal and spatial effects, the BACI design incorporates the interaction of both time (before vs. after) and treatment (impact vs. control) to mitigate the unknown covariates influencing the observed effects (McDonald et al., 2000; Smith, 2002). The application of the BACI approach has been applied to study diverse forestry impacts on birds, including thinning, clearcutting, selective logging, reduced impact logging, and many more (Battisti and Marini, 2018; Hache et al., 2013; Kellner et al., 2016; Klein et al., 2022). Most studies focused on short-term responses, while studies examining long-term recovery are often limited. Furthermore, while BACI studies have proven to be effective for assessing ecological consequences of various disturbances, they are still rarely used, with most studies conducted in North America (USA, Canada) and Australia, and with emerging applications in South America.

In this study, we employ BACI design combined with PAM to investigate the effects of clearcutting practices on resident boreal birds in Southwest Finland. We focus on 12 bird species included in the European Forest Bird Index that are residents in the study area. Baseline data were collected in early spring 2020, and the sampling was replicated in 2024 at sites where the forest was either clearcut (impact; variable proportion of the area cut) or uncut (control) within 100 m of the ARU between these sampling periods. Particularly, we aim to (1) quantify the changes in species richness and total vocal activity before and after the formation of clearcuts; (2) identify species that are most affected by clearcutting practices. By integrating spatially and temporally replicated acoustic data with a robust semi-experimental design, our study addresses a key knowledge gap in understanding forestry-related biodiversity declines while providing actionable insights for sustainable forest management.

## 2. Materials and methods

### 2.1. Study area

The study area was approximately 370 km$^2$ (60°34' - 60°49' N & 22°01' - 22°26' E), located in the Boreal biogeographic region of Southwest Finland (Fig. 1). The landscape is predominantly a mosaic of forest and agricultural tracts. These forests are dominated by the monoculture of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). Other important tree species in this region include deciduous trees such as Silver Birch (*Betula pendula*), Downy Birch (*Betula pubescens*), and European aspen (*Populus tremula*). The majority of these forests are privately owned and managed for commercial purposes, experiencing significant forestry activity in the form of timber logging. Only a small portion of the study area (~3%) enjoys legal protection (SYKE, 2021) through established protected area networks for conservation purposes.

### 2.2. Study design

A BACI study was conducted to assess the impact of clearcutting on the activity of resident forest birds in Southwest Finland. In 2020, the study area comprised a network of 292 grid cells, each measuring 1 km$^2$. Each grid cell was equipped with an AudioMoth recorder (Open Acoustic Devices, version 1.1) placed within a 100-meter radius from the centroid, based on the availability of suitable habitat, namely, forest. The majority of these sampling locations were situated in the mid-aged forests (>15 and <80 years). The forest patch size varied across sites, and because the prevailing landscape was a mosaic of forest and agricultural tracts, the 100-meter buffers around some sampling locations included agricultural land in addition to forest. To minimize the spatial

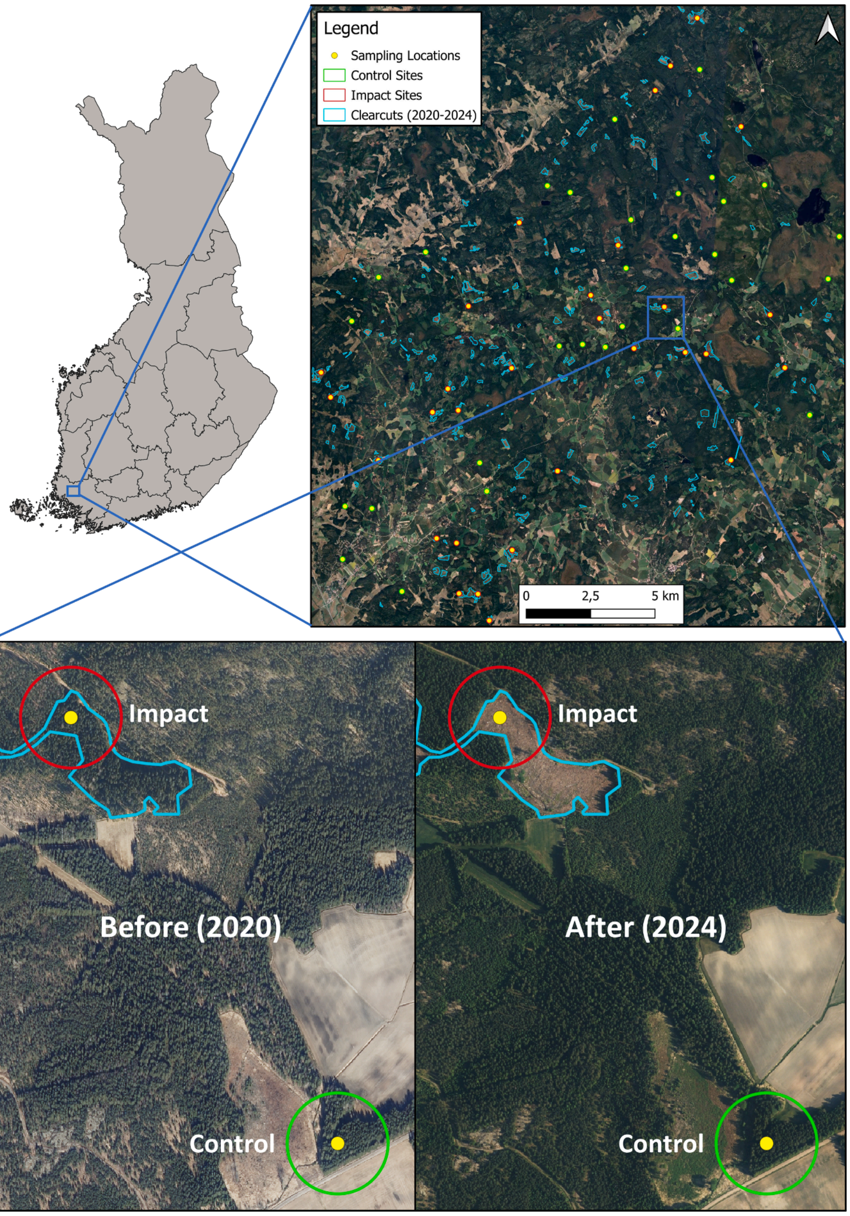


**Fig. 1.** Study area map showing 60 acoustic sampling locations across ~370 km$^2$ of mixed forest and agricultural landscape in Southwest Finland. Yellow dots indicate AudioMoth recorder placement locations; green circles delineate control sites and red circles delineate impact sites, with both circles representing 100-meter buffers around sampling points. Cyan polygons depict clearcuts harvested between 2020 and 2024. The lower panels provide detailed before (2020) and after (2024) comparisons of representative impact and control sites, illustrating the forest change within the study period.

autocorrelation, recorders were spaced approximately 1 km apart. Recorders were strapped to a tree trunk, branch, or pole at approximately 2 m above the ground and programmed to record the birds' activities daily between 03:00–10:00 and 19:00–23:00 (GMT+3) for a week during early spring (March 16 to April 25). In 2024, sampling was repeated across 60 of these 292 sites, which were selected to consist of 30 clearcut (impact) sites and 30 uncut (control) sites (see below for explanation of the selection procedure), for a week (April 4 to May 8). For this study, hence, we considered acoustic data across these 60 sites, comprising 30 control and 30 impact sites, during the periods before (2020) and after (2024) the formation of clearcuts (Fig. 1).

### 2.2.1. *Impact site selection*

A 100-meter buffer was created around 292 sampling points from 2020. Orthophotos from the National Land Survey of Finland (https://www.maanmittauslaitos.fi) taken between May 2020 and July 2023 were manually observed and marked for clearcuts. Additionally, the Finnish Forest Declaration (https://www.metsakeskus.fi) data were used to cross-validate and further check for clearcuts between August 2023 and April 2024. Sites with clearcuts comprising ≥ 5% of the total area (3.14 ha) inside the 100-meter buffer were classified as 'impact' sites. In total, 30 impact sites were identified, representing 10.3% of the original study area. Among these sites, the percentage coverage of clearcut ranged from 6.45% to 100%, with a median of 33.87%. To better understand the effects of clearcutting on resident birds, these sites were further categorized based on the median clearcut percentage (33.87%) into low-impact (6.45 – <33.87% clearcut) and high-impact (>33.87 – 100% clearcut) sites.

### 2.2.2. *Control site selection*

To identify the control sites matching the habitat characteristics of impact sites, 111 candidate sites were selected. These candidate sites had no clearcuts within a 400-meter radius of the original sampling points for four years (until April 2024). Principal Component Analysis (PCA) was performed on 30 impact sites and 111 candidate sites using 2020 habitat data. Habitat variables included foliage biomass of pine, spruce, and deciduous trees, as well as the area of peatland, rock forest, and wet forest, obtained from the National Resources Institute of Finland. Agricultural land area was derived from the CORINE Land Cover dataset. Clearcuts and young stands (<15 years), mid-aged forest (>15 and <80 years), and mature forest (>80) were mapped using aerial photographs and Google satellite imagery. The proportion of each habitat type per sampling unit was computed. Distance from nearest road and inhabited house to the recorders was also measured (See Baroni et al., 2023 for details). From the PCA, the first five principal components (PC1-PC5) with eigenvalues of $> 1$ and a cumulative variance of ~77% were retained, and the Euclidean distances between these components were calculated to find the nearest-neighbor values. These values correspond to sites with the most similar habitat characteristics to the impact sites. This process resulted in the selection of 30 'control' sites, and each control site was paired with a corresponding impact site.

### 2.3. Automated species identification

The bird species were automatically identified from the audio data using a deep learning-based bird classification model introduced in the *Finnish Muuttolintujen Kevät* project (see Nokelainen et al., 2024, and Lauha et al., 2025). The model has been trained to classify 263 Finnish bird species. The audio recordings were split into 3-second chunks with a 1-second overlap between consecutive chunks. Each chunk was analyzed separately, producing confidence scores between 0% and 100% for each bird species for each chunk, where 0% indicates that the model is certain of the absence of the species and 100% indicates that the model is certain of the presence of the species. The classification model adjusts the predictions based on location and time of the year by decreasing the confidence of unlikely detections. Only detections with a confidence level $\geq$ 90% were retained. Additionally, manual identification was performed on selected species by an experienced ornithologist (PC), who reviewed sonograms and listened to recordings to eliminate any false detections.

A total of 12 species (Table S1) were selected for the present study: Black Woodpecker (*Dryocopus martius*), Coal Tit (*Periparus ater*), Crested Tit (*Lophophanes cristatus*), Eurasian Bullfinch (*Pyrrhula pyrrhula*), Eurasian Jay (*Garrulus glandarius*), Eurasian Treecreeper (*Certhia familiaris*), Goldcrest (*Regulus regulus*), Grey-headed Woodpecker (*Picus canus*), Great Spotted Woodpecker (*Dendrocopos major*), Hazel Grouse (*Tetrastes bonasia*), Red Crossbill (*Loxia curvirostra*), and Willow Tit (*Poecile montanus*). These species were selected because they are included in the European forest bird index and are considered residents, based on the categorizations of Laaksonen and Lehikoinen (2013), a Finnish bird indicator called Luonnontila (https://luonnontila.fi/en/indicators-by-major-environment-type/forests/forest-winter-birds/), and the PanEuropean Common Bird Monitoring Scheme (https://www.ebcc.info/).

### 2.4. Statistical analysis

Since estimating bird abundance from acoustic data is not feasible, we quantified vocal activity instead as a proxy for habitat use. Detections of the same species within a 10-minute interval were considered a single encounter, and the sum of such encounters was used as a measure of vocal activity. From this data, we derived (1) total vocal activity (the pooled vocal activity of 12 species) and (2) species richness (the number of species detected). Furthermore, to evaluate the sampling adequacy, we plotted species accumulation curves. Species accumulation curves were plotted using the cumulative number of species detected against the number of sampling sites. The curves reached an asymptote (plateau), indicating that sufficient sampling was achieved to detect changes in resident birds (Fig. S1).

We used BACI design within a generalized linear mixed model (GLMM) framework to assess the effects of clearcutting on total vocal activity, species richness, and species-specific vocal activity. The analyses contrasted periods before (2020) and after (2024) clearcutting, treatments (control, impact-low, and impact-high), and their interaction. GLMMs offer a robust approach for analyzing non-normal data, such as counts or proportions, while accounting for random effects (Bolker et al., 2009). The fixed effects were hence BA (Before-After, corresponding to the years 2020 and 2024), CI (Control-Impact, categorized as control, impact-low, and impact-high), and their interaction (BA $\times$ CI). The CI sites were paired (30), with each pair consisting of one control and one impact site matched by similar habitat characteristics (see Section 2.2). In a BACI design, the main interest is whether the interaction shows statistical significance, as this interaction indicates whether the temporal change in the impacted sites differed from the change in the control sites. Lastly, we included site-specific sampling effort (total recording minutes per site/10-minute interval) as a covariate. The site and the pair were considered random effects.

To determine the most suitable distribution, we compared three candidate GLMMs with different error distributions: (1) the Poisson model, (2) the negative binomial model with a linear variance, and (3) the negative binomial model with quadratic variance. All these models were fitted using the R package glmmTMB (version 1.1.10; Brooks et al., 2017), and if necessary, an optimizer was employed to enhance model convergence. Model selection was done through Akaike's Information Criterion (AIC), and the model with the lowest AIC was considered the most probable model for inference. The statistical significance was assessed using a Type II Wald chi-square test. All analyses were performed in the statistical program R (version 4.4.1; R Core Team, 2024).

## 3. Results

Following the initial sampling in 2020, the recorders in 2024 were deployed during the same timeframe to ensure temporal compatibility. However, due to cold weather, several AudioMoths failed and had to be replaced, preventing us from matching the original duration. Sampling lasted for approximately 5.9 $\pm$ 2.0 days in 2020 and 8.7 $\pm$ 2.2 days in 2024. Since most recorders in 2024 collected data for five days, we adjusted sampling effort by selecting the first five consecutive days of recordings from each deployment. Any additional days were excluded to ensure consistent sampling effort across years. Total sampling effort amounted to 15,112 and 15,861 10-minute recording events in 2020 and 2024, respectively. Both total vocal activity and species richness varied between the periods before and after clearcutting (Table 1).

To assess the impact of clearcutting on the resident birds (12 species), we ran BACI analyses on both total vocal activity and species

**Table 1**
Changes in total vocal activity and species richness before (year 2020) and after (year 2024) the formation of clearcuts in control, low-impact, and high-impact sites. The last columns show the proportional change between 2020 and 2024 (i.e., before and after the clearcuts occurred in the impact sites) against the control sites.

| Response variables | Treatment | Before (2020) | After (2024) | Change (%) | BACI difference (%) |
|---|---|---|---|---|---|
| Total bird activity | Control | 656 | 637 | -2.90 | - |
| | Impact-low | 395 | 319 | -19.24 | -16.34 |
| | Impact-high | 419 | 281 | -32.94 | -30.04 |
| Species richness | Control | 8.17 ± 0.24 | 7.57 ± 0.37 | -7.34 | - |
| | Impact-low | 8.47 ± 0.49 | 7.60 ± 0.36 | -10.27 | -2.93 |
| | Impact-high | 9.47 ± 0.27 | 7.07 ± 0.55 | -25.34 | -18.00 |

richness. Statistical evaluation revealed that the interaction between before-after and control-impact (BA × CI) was only significant for total vocal activity at high-impact sites (Fig. 2a), but not for species richness (Fig. 2b) (Table 2). For total vocal activity, the BA × CI interaction was negative at high-impact sites, suggesting that bird vocal activity declined with increasing clearcut proportion, with the most pronounced effects observed at sites with > 33.87% clearcut area. Sampling effort also had a strong positive effect, as expected, on total vocal activity (Table 2), indicating that longer recording periods captured higher levels of bird activity.

The species-specific BACI analyses revealed varied responses among species (Fig. 3). A significant before-after and control-impact (BA × CI) interaction was observed for the Black Woodpecker ($\chi^2 = 9.09$, $p = 0.01$), Crested Tit ($\chi^2 = 6.09$, $p = 0.05$), Eurasian Treecreeper ($\chi^2 = 13.38$, $p = 0.001$), and Goldcrest ($\chi^2 = 7.25$, $p = 0.03$). For most species, the interaction was negative, implying reduced activity after clearcutting, whereas the Black Woodpecker showed a positive association, suggesting increased activity at impacted sites following clearcutting. All these interactions were observed at high-impact sites, except for Eurasian Treecreeper, which also showed significance at low-impact sites (Fig. 3). Sampling effort positively influenced the vocal activity of several species (Table S2).

## 4. Discussion

We used a BACI design to study the impact of low and high levels of clearcutting on 12 resident forest bird species in Southwest Finland. We considered a four-year period and employed PAM to detect species at sites before (2020) and after (2024) clearcutting. Impact intensity (low vs high) was determined based on the area coverage of clearcuts observed (via aerial photographs) around recording sites during the study period. We found evidence that resident forest birds underwent changes following clearcutting. Total vocal activity declined sharply at high-impact sites, whereas low-impact sites showed minimal effects that did not differ significantly from controls. Furthermore, species richness was not impacted by clearcuts. The most likely reason for the fairly weak overall evidence of an impact of clearcuts on resident avian species was that we found species-specific responses to clearcut intensity. Many species showed no response, whereas others responded negatively to both low- and high-impact clearcuts; however, one species showed increased activity after clearcutting. Overall, the observed reductions in total bird activity are consistent with past studies that have documented sharp declines in forest-dependent species after intensive logging (Betts et al., 2022; Virkkala, 2004, 2016). Such changes are expected, given the habitat alterations caused by clearcutting. Clearcutting reduces structural complexity and diminishes key resources—old-growth forests, deadwood trees, and microhabitats—that are crucial for specialist species' survival (Kuuluvainen, 2009; Kuuluvainen and Gauthier, 2018; Mönkkönen et al., 2022).

Our BACI analysis demonstrated that total vocal activity declined during the study period. This difference could reflect broader environmental and demographic stochasticity (temperature, precipitation, and natural disturbances), which create temporal fluctuations in populations and communities (Desharnais et al., 2006; Shoemaker et al., 2020). We found that PAM at impacted sites recorded a higher total call rate prior to clearcutting. This occurred despite impact sites being paired with control sites based on similar habitat characteristics. We therefore expected control and impact sites to be similar. It has been argued that selecting appropriate controls is difficult as species patterns vary spatially (Underwood, 1994). This finding likely indicates that sites selected for clearcutting initially possessed more favorable conditions for resident species compared to control sites. In this study, the decision on which forests were harvested was made outside the research team's control. As a result, impact sites may consist of higher-quality forests with distinct micro-climatic conditions (e.g., temperature and precipitation), and greater microhabitat complexity, all of which support higher species abundance and richness. Importantly, our results indicate that cross-sectional comparisons of avian communities at sites with and without clearcuts are likely to underestimate the true effect of clearcutting. This is because our findings underline that differences in bird activity are minimal when only contrasting post-clearcuts with control sites. This demonstrates the value of a BACI design to gain a more comprehensive understanding of the biodiversity consequences of forestry activity.

Following clearcutting, the overall effect of clearcuts (i.e., combining low- and high-impact sites) on avian species was not pronounced; however, we observed a significant reduction in total vocal activity at high-impact sites. This indicates that despite initially favorable conditions, intensive forestry activity negatively affects resident forest birds. This pattern is consistent with previous studies, which have shown that forest-dependent bird communities are severely affected by intensive clearcutting practices (Betts et al., 2022; Virkkala et al., 2023). Our findings indicate that high-intensity clearcuts primarily reduced habitat use, as the total vocal activity declined rather than species richness. Critical habitat features associated with forests, such as vertical and horizontal diversity, old-growth and deadwood trees, canopy cover, and a diverse array of microhabitat conditions that provide foraging opportunities, are likely reduced after clearcutting.

A likely reason for the lack of a strong overall effect of clearcutting on avian activity is that of the 12 species included, only four species showed significant responses. Vocal activity of Crested Tit, Eurasian Treecreeper, and Goldcrest significantly declined after clearcutting, particularly at the high-impact sites. These species are typically associated with mature and structurally complex forests. The Eurasian Treecreeper,

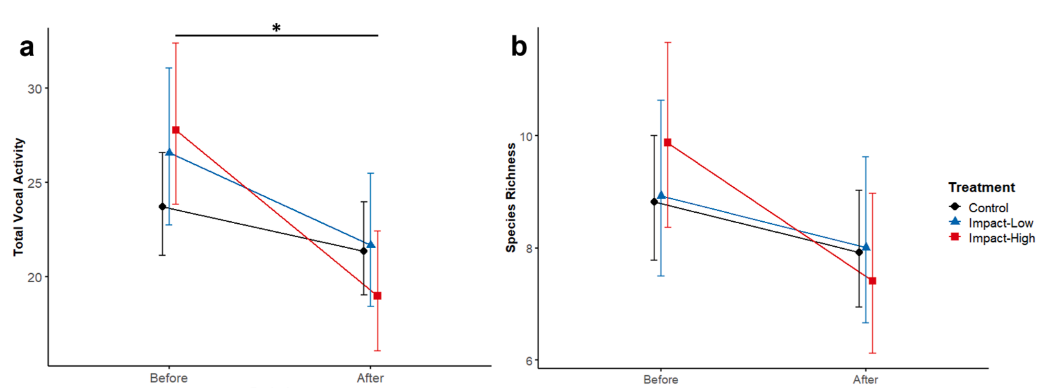


**Fig. 2.** Predicted BACI interaction for a) total vocal activity and b) species richness for resident forest birds (12 species) across time (before and after) and treatment (control, impact-low, and impact-high). Predictions were made from GLMM-TMB models using maximum likelihood estimation. Error bars suggest 95% confidence intervals. Statistical significance is indicated as:. $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

**Table 2**
Statistical summary of generalized linear mixed models (GLMM) evaluating the impact of clearcutting on resident forest birds using a BACI design. The response variables are total vocal activity and species richness. Fixed effects include before-after (BA) the clearcutting, control-impact (CI: control, impact-low, impact-high), their interaction (BA × CI-Low, BA × CI-High), and recording effort (minutes). Estimates are presented with standard errors (SE) and test statistics; contrasts for main effects are shown in parentheses. Overall significance was evaluated using the Type-II Wald ($\chi^2$) test. For the interaction, contrast represents the difference between before and after clearcuts in the low- and high-impact sites relative to the controls. Bold values indicate statistical significance at $p < 0.05$.

| Response | Term | Estimate | SE | z value | *p*-value | $\chi^2$ *(Wald)* | *df* | *p*-value |
|---|---|---|---|---|---|---|---|---|
| ***Total bird activity (negative binomial model with quadratic variance)*** | Intercept | 1.93 | 0.22 | 8.98 | **< 0.001** | - | - | - |
| | BA (Before vs After) | -0.10 | 0.08 | -1.27 | 0.20 | 12.41 | 1 | **< 0.001** |
| | CI (Impact-Low vs Control) | 0.11 | 0.10 | 1.16 | 0.25 | 0.79 | 2 | 0.67 |
| | CI (Impact-High vs Control) | 0.16 | 0.10 | 1.62 | 0.11 | | | |
| | BA × CI-Low | -0.10 | 0.14 | -0.72 | 0.47 | 3.94 | 2 | 0.14 |
| | BA × CI-High | -0.28 | 0.14 | -1.99 | **0.05** | | | |
| | Effort | 0.005 | 0.0008 | 5.53 | **< 0.001** | 30.53 | 1 | **< 0.001** |
| ***Species richness (Poisson model)*** | Intercept | 1.75 | 0.21 | 8.52 | **< 0.001** | - | - | - |
| | BA (Before vs After) | -0.11 | 0.09 | -1.16 | 0.25 | 5.63 | 1 | **0.02** |
| | CI (Impact-Low vs Control) | 0.01 | 0.11 | 0.11 | 0.91 | 0.18 | 2 | 0.91 |
| | CI (Impact-High vs Control) | 0.11 | 0.11 | 1.06 | 0.29 | | | |
| | BA × CI-Low | -0.001 | 0.16 | -0.01 | 0.99 | 1.43 | 2 | 0.49 |
| | BA × CI-High | -0.18 | 0.16 | -1.13 | 0.26 | | | |
| | Effort | 0.001 | 0.0008 | 1.83 | 0.07 | 3.34 | 1 | 0.07 |

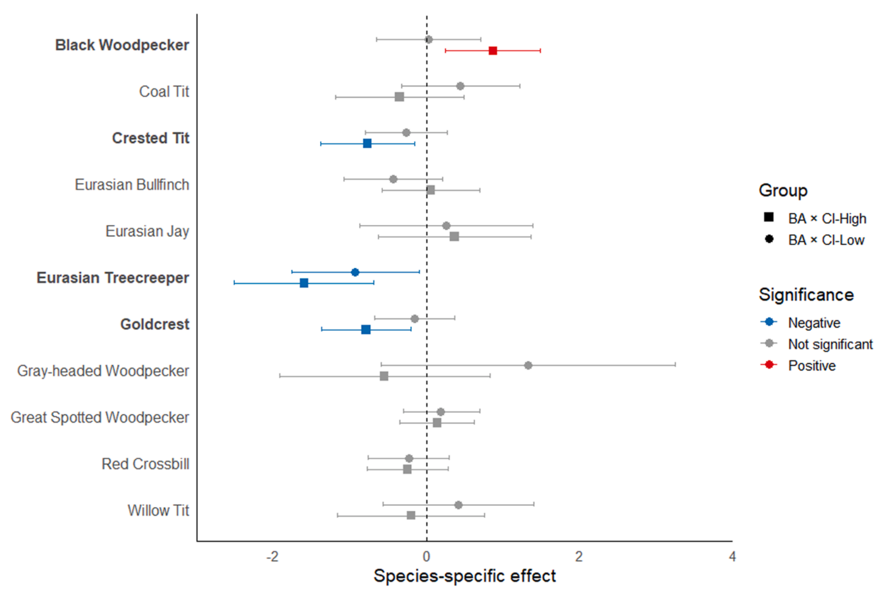


**Fig. 3.** The figure shows species-specific effect (BACI interaction estimates with ± 95% confidence intervals) from the BACI analysis. Circles show the BA × CI-Low estimates, whereas squares show the BA × CI-High estimates. The horizontal lines represent 95% confidence intervals around the estimated effect size. The vertical dashed line at the zero denotes no effect. Estimates on either side of the dashed line, represented in color, indicate statistically significant effects (See Table S2 for details). Note: estimates for Hazel Grouse were excluded due to overestimation, likely resulting from the low number of detections.

an obligate old-growth species feeding on trunk-dwelling arthropods (Cramp and Perrins, 1993; Virkkala et al., 1994), showed sensitivity to both high- and low-impact sites, consistent with its documented absence from clearcuts and the young stands (Suorsa et al., 2005). The Crested Tit's decline likely reflects the immediate loss of mature conifer canopies where it forages for insects and spiders (Cramp and Perrins, 1993), a pattern confirmed in both long-term and short-term Finnish studies (Virkkala, 2004; Virkkala et al., 2020). Similarly, Goldcrest's exclusive arthropod diet (Cramp, 1992) and preference for spruce-dominated interiors (Tiainen et al., 1983) can explain the observed reductions. Moreover, these small passerines have relatively small home ranges (<12 ha; Hagemeijer and Blair, 1997; Suorsa et al., 2005), making them particularly vulnerable to habitat alteration. Additionally, their specific habitat requirements (i.e., mature forests) and narrow-range resource exploitation (i.e., insects) classify them as habitat specialists; loss of such habitat would explain the observed declines.

Conversely, the Black Woodpecker showed increased activity post-clearcutting. This was unexpected as obligate cavity nesters are particularly vulnerable to intensive forestry practices given their preference for old-growth forests and deadwood trees (Gorman, 2004; Mikusiński and Angelstam, 1997). We speculate this increased activity can be due to: (1) the retention of standing deadwood, providing both foraging and nesting opportunities (Cramp, 1985; Zawadzki and Sławski, 2023); (2) temporary foraging grounds by facilitating higher conspicuousness of prey species, particularly ant mounds; (3) the species' large home ranges, which often include open areas such as clearcuts (Gorman, 2011; Olano et al., 2015; Rolstad and Rolstad, 2000); and (4) finally, the open areas created by the removal of trees may have reduced call attenuation, facilitated easier detection.

Whilst PAM effectively captured the species' presence, careful consideration should be made while interpreting such data. We recorded the acoustic activity in the early spring, which coincides with most species' breeding period. However, we were unable to infer what specific activities birds were involved in, such as mate attraction, territory defense, or nest building. Due to these reasons, we considered vocal activity as a measure of habitat use. Consequently, the reductions in activity at impacted sites not only reflect reduced habitat utilization but also behavioral avoidance of recently clearcut areas, where key resources such as nesting sites and foraging substrates are diminished. Such habitat loss is widely recognized as the main driver of biodiversity declines across the globe (Banks-Leite et al., 2020; Fahrig, 1997). Habitat loss and fragmentation can affect key biological processes by reducing resource availability, limiting dispersal, and decreasing breeding success (Bregman et al., 2014). These factors ultimately affect the overall fitness of species, potentially leading to their local extirpation or extinction.

Dawn chorus is a daily period of high song output in birds during the breeding season prior to sunrise (Staicer et al., 1996). The dawn chorus is influenced by both intrinsic (e.g., reproductive stage, eye size) and environmental factors, including ambient light, temperature, weather conditions, and seasonal timing, which can strongly influence the vocalizations (Bruni et al., 2014). The formation of clearcuts can alter these local environmental conditions by increasing the light penetration and, consequently, ground and air temperature (Carlson and Groot, 1997). Such changes have the potential to influence the dawn chorus. For instance, it has been shown that birds' vocalizations are negatively associated with higher temperatures (Diepstraten and Willie, 2021). Furthermore, optimal light conditions are known to evoke dawn chorus, but increased light penetration in open areas such as clearcuts might hinder the vocal activity, potentially due to increased risk of predation. Although our study did not directly measure these environmental variables, which represents a limitation, future studies incorporating these factors would help clarify their relative contributions to the dawn chorus in disturbed versus intact forests.

In our species-specific analyses, we tested 12 species independently without accounting for corrections for multiple comparisons, which increases the risk of false positives (Type I errors). At a significance level of $\alpha = 0.05$, we would expect approximately 0.6 ($0.05 \times 12$) false positives by chance alone. While most of our findings showed relatively strong statistical significance ($p \leq 0.01$; Table S2), which could evade correction, we acknowledge that some of the marginally significant results ($p \approx 0.05$) should be interpreted with caution. We present our species-specific findings as exploratory analyses necessitating further research rather than definitive conclusions about the species.

Despite Finland being the most forested country in Europe (75% of its total land area), the majority of these forests are privately owned, and only 12.6% of forested expanse is protected (Ministry of Agriculture and Forestry). These private forests (20 million hectares) are subjected to various forestry practices, including clearcutting (Virkkala and Toivonen, 1999). In recent years, clearcutting has increased by 15% from 2016 to 2019, compared to the period from 2011 to 2015 (Natural Resources Institute Finland). This trend is expected to increase in the coming years, as population growth necessitates greater timber and paper pulp production to meet demand, ultimately affecting forest-dependent species. As evidenced by our results, it becomes highly imperative to protect the resident boreal birds from clearcutting practices, which are often considered indicator species, reflecting a healthy biodiversity. Our results demonstrate that both total vocal activity and individual vocal activity of species like the Crested Tit, Eurasian Treecreeper, and Goldcrest declined, particularly at high-intensity clearcuts. Although our study did not evaluate the alternative forestry practices, several approaches suggested in the literature may help reduce the biodiversity losses associated with intensive harvesting. The most widely accepted approach is tree retention, which helps preserve the key biotopes of conservation value (Gustafsson et al., 2010). It is advised to retain a tree volume of at least 10% compared to the pre-harvest level (Virkkala, 2004). Other strategies include uneven-aged forestry (selective felling), which maintains habitat heterogeneity and species assemblages (Versluijs et al., 2020); deadwood tree retention, which could act as a refuge for cavity nesters and insects; and longer rotation periods between clearcuts (Nirhamo et al., 2025). Lastly, species-specific mitigation measures should be implemented. For example, our results also indicated that the Eurasian Treecreeper was affected by low-intensity clearcuts; such effects could be mitigated by retaining undisturbed buffers around the clearcuts.

## 5. Conclusion

To our knowledge, this is one of the first studies to evaluate the impact of clearcutting on resident birds in boreal forests using a state-of-the-art BACI design coupled with PAM. Our study provides evidence that the bird activity declined at post-intervention clearcuts, particularly at high-impact sites. The findings underscore the ecological consequences of intensive forestry, necessitating the need for sustainable forest management to offset the impacts. Our results also highlight the usefulness of PAM and the robustness of the BACI design for assessing the anthropogenic disturbances. This research provides growing evidence on the impacts of forestry and offers insights into sustainable management practices that help reconcile conservation and development in boreal forests. We urge policymakers, landowners, and conservation practitioners to adopt evidence-based management to safeguard the biodiversity in boreal forests.

## CRediT authorship contribution statement

**Pavan Chikkanarayanaswamy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Toni Laaksonen:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Patrik Lauha:** Writing – review & editing, Methodology. **Daniele Baroni:** Writing – review & editing, Methodology. **Jon E Brommer:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.


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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2026.123770.

## Data availability

Data will be made available on request.

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