UNIVERSITÄT FÜR BODENKULTUR WIEN
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# Master's Thesis

## Bird diversity in relation to forest management in the Wienerwald Biosphere Reserve

submitted by

Eva-Teresa Raphaela SZEKERES, BSc

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Supervisor

Priv.-Doz. Dr. Swen Renner

Institute of Forest Ecology
Department of Forest- and Soil Sciences

# Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 17.01.2024 Eva-Teresa Szekeres (manu propria)

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# Abstract

Forest management practices have a long history in Central Europe resulting in altered forest ecosystems. Intensive forestry processes can cause severe changes in the composition and age structure of forests and forest bird diversity. By contrast, sustainable silvicultural practices can preserve forests in a nature near state and thereby support forest birds. This study was conducted in 116 to 161-year-old forest stands in the unmanaged core zone as well as in the managed parts of the Wienerwald Biosphere Reserve, Central Europe's largest deciduous beech forest known for its rich biodiversity. The core zone areas are formerly managed forests taken out of use at least since 2003. The non-core zone areas are very sustainably managed without clear cuts, a natural tree species composition, steppingstones and standing old living or dead trees. In this study, I compared the impact of the different forestry management on numerical and functional bird diversity between the core and non-core zone. The bird diversity was assessed with point counts in the morning hours from mid-March to mid-June. I found a significant relation between a higher avian species richness and a denser canopy and a wider range of canopy cover values. Steeper slopes were associated with a significantly lower abundance. The forest age and the mean DBH showed a significant impact of on the avian species composition. However, I could not find a significant difference between the species richness, abundance, Shannon Diversity Index and community composition between the core and non-core zone, although I found significantly higher canopy cover values and on average 10 years younger forest stands in the core zone. My findings suggest that the core and non-core zone both are very natural like and may be still too similar to ascertain differences in species richness, abundance and Shannon Diversity Index and that the silvicultural practices in the non-core zone support a very nature near forests.

# Kurzfassung

In Mitteleuropa hat die Waldbewirtschaftung eine lange Geschichte. Intensive Waldbewirtschaftung bewirkt schwerwiegende Veränderungen in der Artenzusammensetzung und Altersstruktur der Wälder und in weiterer Folge der Waldvogeldiversität. Im Gegensatz dazu können nachhaltige Waldbaupraktiken einen naturnahen Wald erhalten und Waldvögel fördern. Diese Studie wurde in der Kern- und der nicht-Kernzone des für seinen Artenreichtum bekannten, größten Buchenlaubwald Mitteleuropas, dem Biosphärenpark Wienerwald durchgeführt. Die Kernzonenflächen sind seit spätestens 2003 außer Betrieb genommene, ehemals bewirtschaftete Wälder. Die Nicht-Kernzonenflächen werden sehr nachhaltig bewirtschaftet, ohne Kahlschläge, mit natürlicher Baumartenzusammensetzung, Trittsteinen und stehenden alten Bäumen. Ich habe den Einfluss der Waldbewirtschaftung auf numerische und funktionelle Vogelvielfalt zwischen Kern- und Nicht-Kernzone verglichen. Die Vogelvielfalt wurde durch morgendliche Punktzählungen von Mitte März bis Mitte Juni erfasst. Ich fand signifikante Einflüsse zwischen einem höheren Vogelartenreichtum und einer höheren dichte und größeren Streuung der Kronendachbedeckung. Weiters fand ich einen signifikanten Zusammenhang zwischen Hangneigung und Abundanz. Das Waldalter und der BHD zeigten einen signifikanten Einfluss auf die Zusammensetzung der Vogelarten. Jedoch konnte ich trotz signifikant höherer Kronendachbedeckung und jüngerer Baumbestände in der Kernzone keinen signifikanten Unterschied zwischen Artenreichtum, Abundanz, Shannon Diversitätsindex und Artengemeinschaft zwischen Kern- und Nicht-Kernzone feststellen. Meine Ergebnisse deuten auf eine sehr naturnahe Kern- als auch Nicht-Kernzone hin, die sich in Bezug auf Artenreichtum, Abundanz, Shannon Diversitätsindex und Vogelartenzusammensetzung noch sehr stark ähneln, und dass die Waldbewirtschaftung in der Nicht-Kernzone einen sehr naturnahen Wald mit vielen Lebensräumen für natürlicherweise vorkommende Waldvögel ermöglicht.

# .1 Introduction

The avifauna is often used as an indicator of forest ecosystems as birds are easy to perceive and have various ecological functions in ecosystems (Roberge and Angelstam 2006; C. H. Sekercioglu 2006; Larsen, Sorace, and Mancini 2010; Gregory and Strien 2010). The seed dispersal of frugivores, the pest control of predators that feed on invertebrates and vertebrates, the carcass and waste disposal of scavengers, and the ecosystem engineering of burrow and cavity breeders are some of the most important avian ecosystem services in northern temperate forests (C. H. Sekercioglu 2006). Predatory forest birds contribute to a stabilisation of predator-prey dynamics end therefore are an essential part of forest ecosystems (Herrera 1984; C. H. Sekercioglu 2006). For example, a reduced number of insect feeding birds like woodpeckers can reduce their impact in controlling pest species and thereby lead to an increased number of bark beetles (Fayt, Machmer, and Steeger 2005). Many insectivorous birds are very specialised and sensitive to changes in environmental conditions, as they rely on insects as food source (Şekercioğlu, Daily, and Ehrlich 2004; Sherry 1984; C. Sekercioglu 2006). This is because insects are also often specialised to certain environmental conditions like for example dead and decaying wood, that serves them as food and habitat and the emergence of insects is bound to seasons. (Şekercioğlu, Daily, and Ehrlich 2004; Sherry 1984). Frugivore bird species disperse seeds and thereby genetic plant material from one site to another, what maintains forest plant diversity and helps forests to spread in a natural way (Stiles 1985; Daily, Ehrlich, and Haddad 1993). Cavity nesters like woodpeckers act as ecosystem engineers and keystone species, as they construct nesting sites that are used by many other cavity-nesting animals like other birds, but also mammals and insects (Pakkala et al. 2019). Due to the lack of old trees and standing deadwood in many managed forests, tree holes constructed by woodpeckers are of even greater importance in these forest types than in primeval forests (C. H. Sekercioglu 2006).

In temperate forests, many bird species are dependent on the availability of tree cavities as they use them as nesting or sleeping site (Gibbons & Lindenmayer, 2002, as cited in Redolfi DeZan et al. 2016). Dead and decaying wood, which can often be found in unmanaged forests or forests with low management intensity, provides habitat and food resources for many different organisms and thus promotes biodiversity (Bobiec 2005). Forest specialists in general need a highly structured forest with large mature trees and a high diversity of deadwood, as younger trees offer fewer possibilities for nesting (Brazaitis and Angelstam, 2004; Gil-Tena, Saura, and Brotons 2007; Ghadiri Khanaposhtani et al. 2013; Czeszczewik et al. 2015; Redolfi DeZan et al. 2016; Perry et al. 2018). For example, Woodpeckers build their own cavity in large living trees and standing deadwood, which is more often to find in unmanaged and natural-like forests. Other species such as European nuthatches (Sitta europaea), tits (e.g. Parus major, Cyanistes caeruleus, Periparus ater), treecreepers (Certhia sp.), flycatchers (Ficedula sp.), European starling (Sturnus vulgaris), field sparrow (Passer montanus), stock dove (Columba oenas), or tawny owl (Strix aluco) are dependent on natural holes or holes excavated by woodpeckers (Bobiec 2005; Aitken and Martin 2007; Blanc and Walters 2008; Wesołowski and Rowiński 2012).

Forest management practices have a long history in Central Europe resulting in altered forests. Timber harvesting practices can cause a severe change in the composition and age structure of forests and, consequently, a change in forest bird diversity (Kosenko and Kaigorodova 2001; Brazaitis and Angelstam, 2004; Tozer et al. 2010; Czeszczewik et al. 2015). Cavity-nesting birds, for example, are particularly sensitive to changes in forest management practices, because forestry measures often cause habitat fragmentation, habitat loss and isolation of single populations (Kosenko and Kaigorodova 2001; Brazaitis and Angelstam, 2004; Czeszczewik et al. 2015). Intensive forestry processes like clearcutting, removal of deadwood and tree planting can have a negative influence on the habitat quality for various bird species (Czeszczewik et al. 2015). However, sustainable forest management practices like selective logging and retention forestry can preserve the forest in a more natural state or increase biodiversity by creating more heterogeneous habitats (Vanderwel, Malcolm, and Mills 2007; Schall et al. 2018; Schulze et al. 2019).

According to the intermediate disturbance hypothesis, in natural forests, clearings or gaps caused by natural disturbance processes like riverbuilding or treefall, lead to a dynamic mosaic of canopy openings (Bongers et al. 2009; Shea, Roxburgh, and Rauschert 2004; Roxburgh, Shea, and Wilson 2004; Johns 1997). These gaps can lead to an increase in biodiversity by slightly changing the environmental factors so that a wider range of species like climax species, that favour late successional forest states and pioneer species that favour open habitats can coexist (Bongers et al. 2009; Shea, Roxburgh, and Rauschert 2004; Roxburgh, Shea, and Wilson 2004; Hill 1999). However, lower or higher grades of disturbance often lead to a minor level of biodiversity (Connell 1978). More severe disturbance like happening in intensively managed forests have a negative influence on many species and specialised forest species are the first ones to be lost (Hill 1999; Shea, Roxburgh, and Rauschert 2004; Czeszczewik et al. 2015). This applies for example to forest specialist birds or insects that depend on closed old-growth forest (Thiollay 1997; Czeszczewik et al. 2015; Perry et al. 2018; Hill 1999).

Insect diversity and abundance is influenced by different environmental factors, like the amount of dead and decaying wood and the quantity of light available under the canopy, that determines the vegetation and thereby the food sources of insects and the forest microclimate. (Steffan-Dewenter and Tscharntke 1997; Hamer et al. 2003; Bobiec 2005). An extensive canopy opening bigger than natural gaps can lead to a change in the natural food supply and a changed, dryer microclimate what may affect forest specialist insects that are sensitive to a reduced humidity (Hill 1999; Steffan-Dewenter and Tscharntke 1997). Dead and decaying wood are an important food source and habitat for many forest specialist insects (Bobiec 2005). The amount of dead and decaying wood, forest specific microclimate and vegetation determines the diversity and abundance of insects what makes insectivore birds the most vulnerable feeding guild, as omnivores, granivores or carnivores can find alternatively find sources more easily in the cultural landscape (Hill 1999; Steffan-Dewenter and Tscharntke 1997; Bobiec 2005; Thiollay 1997; Ç. H. Sekercioglu et al. 2002).

Mature forests are characterised through taller and older trees, which lead to an increased supply of nesting sites and food resources (Gustafsson et al. 2012; Fedrowitz et al. 2014). Putting forests out of use and sustainable forest management methods retain large, mature trees, deadwood and a forest typical microclimate and thereby provide enough food, habitats and nesting sites not only for generalists but also forest specialist birds (Gustafsson et al. 2012; Fedrowitz et al. 2014). In retention forestry the type and quantity of the maintained forest structures are important as the goal is the preservation of functioning ecosystems between forest generations (Gustafsson et al. 2012). In contrast to intensive forestry processes, retention forestry provides a more diverse forest ecosystem and thus, is able to support forest species (Gustafsson et al. 2012; Fedrowitz et al. 2014). Maintained forest structures like mature trees are possibly conserving specialist species, which are often rare and have decreasing populations (Gustafsson et al. 2012; Fedrowitz et al. 2014).

Another sustainable forestry management method to keep the forest very nature near is realised in the managed Parts of the Wienerwald Biosphere Reserve. In the non-core zone of the Wienerwald Biosphere Reserve they avoid damaging large areas of the forest floor, no clear cuts are made and, only a part of the mature trees are removed and a natural tree species composition through natural regeneration is promoted (Österreichische Bundesforste 2023a; Biosphärenpark Wienerwald Management GMBH 2023). Old trees with structures such as wide crowns, broken branches, tree cavities and ruptures in the trunk or standing deadwood are often left standing if procurable without a safety risk so that many important habitat features for many forest birds never completely disappear (Österreichische Bundesforste 2023a; Biosphärenpark Wienerwald Management GMBH 2023). Furthermore, trees or tree parts of inferior quality are left in the forest as dead wood (Biosphärenpark Wienerwald Management GMBH 2023). Stepping stones like hedges of native plant species between and dead wood islands connect the managed parts of the Wienerwald Biosphere reserve with the core zone and other protected areas (Biosphärenpark Wienerwald Management GMBH 2023; Österreichische Bundesforste 2023b).

This study took place in the Wienerwald Biosphere Reserve, Central Europe's largest deciduous beech forest that is known for its rich biodiversity (Köck, Koch, and Diry 2009). More than 60% of the whole Wienerwald Biosphere Reserve are forests (Biosphärenpark Wienerwald Management GmbH 2021b; 2021a). The study was carried out in the core zone and the managed parts of the Wienerwald Biosphere Reserve. In the buffer zone, ecologically sustainable activities and land use are allowed whereas the development zone serves as settlement and recuperation area (Köck, Koch, and Diry 2009). The buffer and the settlement zone form the non-core zone of the Wienerwald Biosphere Reserve where a very sustainable silvicultural practice is applied. (Köck, Koch, and Diry 2009). An area of approximately 5400 ha is declared as core zone, in which no forestry practices are carried out, human intervention is extremely limited and habitats are held as nature near as possible (Biosphärenpark Wienerwald Management GmbH 2021b; Köck, Koch, and Diry 2009). The core zone areas in the Vienna Woods Biosphere Reserve are formerly managed forests in which no management has taken place since 2003 at the latest, so that only a few forest stands in the core zone areas have already reached the climax succession stage (Brenner 2014). Trees in the core zone are left to themselves, thus they can live for several hundred years and can remain in the natural cycle as dead and decaying wood. Natural forests often show a higher amount of dead and decaying wood, older and larger trees and more trees with a large diameter compared to managed forests and therefore often contain a higher number of species (Böhm et al. 2013; Paillet et al. 2010; Økland et al. 2003). Those impacts are stronger, the more time has passed since the abandonment of the forestry management (Paillet et al. 2010).

In this study, I compared the influence of the different forest management methods in the Wienerwald Biosphere Reserve on numerical and functional bird diversity between the unmanaged core zone and the managed forest stands in the non-core zone. I hypothesize that avian species richness, abundance and Shannon Diversity Index is higher in the unmanaged core zone than in the managed parts of the Wienerwald Biosphere Reserve. Furthermore, I hypothesize that a distinct avian community and a difference in the proportion of the different functional groups in the core zone and the non-core zone.

# 2 Material and Methods

## 2.1 Study area

This study was conducted in 116 to 161-year-old forest stands in 25 research plots in the unmanaged core zone as well as in 25 research plots in the managed parts of the Wienerwald Biosphere Reserve in the northeast of Vienna (Figure 1).

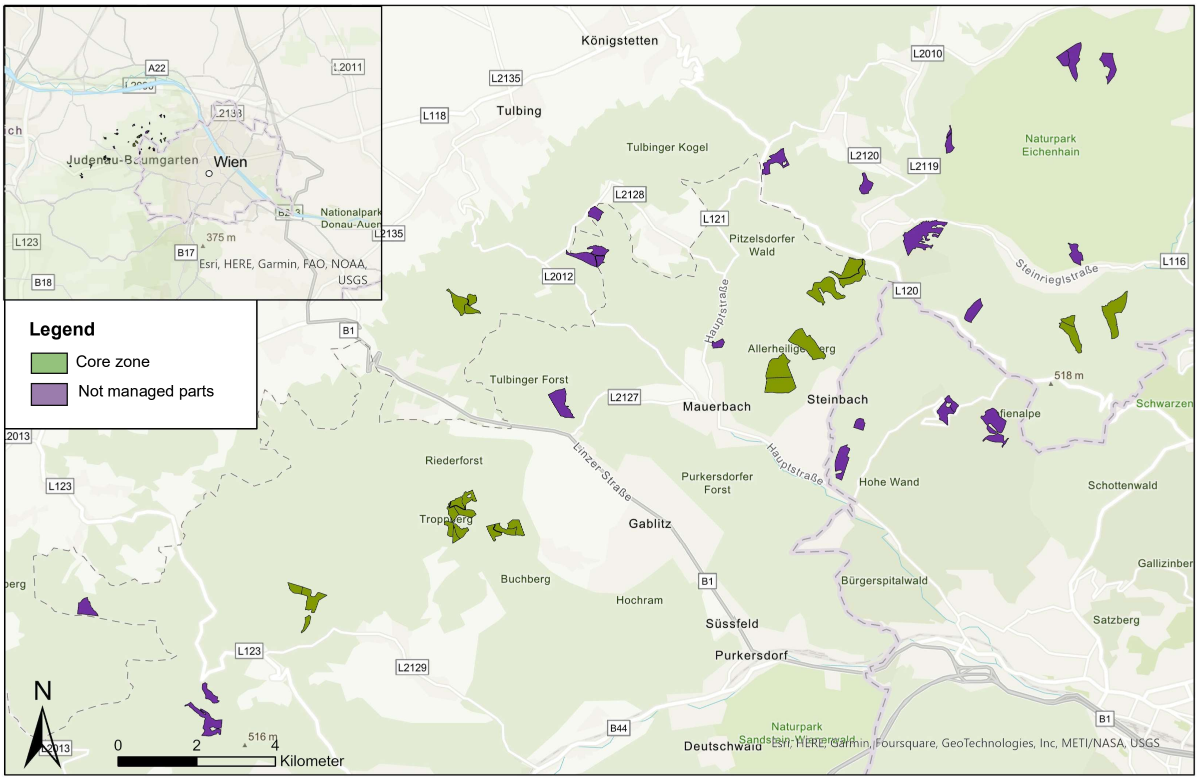


Figure 1: Location of the 25 research plots in the core zone (green) and in the managed parts (purple) of the Wienerwald Biosphere Reserve, respectively.

The Wienerwald Biosphere Reserve is shaped by different geological and climatic conditions and climatic zones and a long history of human impacts through land use (Berger and Ehrendorfer 2011). The geology ranges from flysch, carbonate and old sea basins with sediment deposits and the altitude ranges from approximately 160 m to nearly 900 m above sea level (Köck, Koch, and Diry 2009; Berger and Ehrendorfer 2011). Due to these varieties of conditions various distinctive plant communities have emerged (Köck, Koch, and Diry 2009). The most common plant community in the Wienerwald Biosphere Reserve are beech forests as they can grow on both flysch and carbonate (Berger and Ehrendorfer 2011). In addition to being a Biosphere Reserve, large parts of the Wienerwald Biosphere Reserve are protected by the Natura 2000 network of nature protection areas (Köck, Koch, and Diry 2009). The Wienerwald Biosphere Reserve consists of a core, a buffer and a development zone (Köck, Koch, and Diry 2009). In the buffer zone, ecologically sustainable activities and land use are allowed whereas the development zone serves as settlement and recuperation area (Köck, Koch, and Diry 2009). The buffer and the settlement zone form the non-core zone of the Wienerwald Biosphere Reserve. In the core zone human intervention is extremely limited and it is held as nature near as possible (Köck, Koch, and Diry 2009).

The non-core zone is managed with a sustainable forestry management method to keep the forest nature-near. A natural and site typical tree species composition and natural regeneration through the germination of seeds from the old stand and thus the emergence of young growth is specifically promoted (Österreichische Bundesforste 2023a). The harvesting machines only move on precisely defined tramlines in order to avoid damaging large areas of the forest floor

(Österreichische Bundesforste 2023a). Only as much wood is taken from the forest as can grow back, so during thinning, no clear cuts are made, but only a part of the old trees are removed (Österreichische Bundesforste 2023a). In this way, the seedlings of the old trees can grow under an existing canopy and the remaining old trees are only removed when the new forest generation has reached a sufficient growth height (Österreichische Bundesforste 2023a). During timber harvesting, parts of the crown, branches and trunks or trees of inferior quality usually are left in the forest (Biosphärenpark Wienerwald Management GMBH 2023). If procurable, old trees with structures such as wide crowns, broken branches, tree cavities and ruptures in the trunk or standing deadwood that does not pose a safety risk for visitors or a breeding ground for pests remain in the forest in the function of ecologically valuable biotope trees (Biosphärenpark Wienerwald Management GMBH 2023). Another important approach in the nature near forestry management are stepping stones like hedges of native plant species between forest stands or small-scale dead-wood islands for deadwood-dependent species (Österreichische Bundesforste 2023b). These stepping stone elements connect the managed parts of the Wienerwald Biosphere reserve with the core zone and other protected areas (Biosphärenpark Wienerwald Management GMBH 2023; Österreichische Bundesforste 2023b).

An area of approximately 5400 ha is declared as core zone, in which no forestry practices are carried out, human intervention is extremely limited and habitats are held as nature near as possible (Biosphärenpark Wienerwald Management GmbH 2021b; Köck, Koch, and Diry 2009). The core zone areas in the Vienna Woods Biosphere Reserve are formerly managed forests in which no management has taken place since 2003 at the latest, so that only a few forest stands in the core zone areas have already reached the climax succession stage (Brenner 2014). Trees in the core zone are left to themselves, thus they can live for several hundred years and can remain in the natural cycle as dead and decaying wood. In the managed forest stands of the Vienna Woods Biosphere Reserve, the average standing deadwood amounts to 8.92 $m^3$/ha compared to the unmanaged core zone areas with 8.07 $m^3$/ha (Brenner 2014). One explanation for on average less standing deadwood per hectare in the core zone areas than in managed forest stands could be that the last core zone areas have only been put out of use since the moratorium in 2003 (Brenner 2014). However, natural forests often show a higher amount of dead and decaying wood, older and larger trees and more trees with a large diameter compared to managed forests (Böhm et al. 2013; Paillet et al. 2010). Those impacts are stronger, the more time has passed since the abandonment of forestry management (Paillet et al. 2010).

## 2.2 Field methods and data collection

I conducted the study together with Michaela Maislinger. In the managed and the unmanaged parts of the Wienerwald Biosphere Reserve we visited 25 research plots, respectively. Every research plot consisted of 3 survey points in a distance of 100 m from each other and 100 m from the edge of the research plots. In total that made 50 research plots with 150 survey points. The order of the plot visits varied in every sampling round. The plots were sampled in three sampling rounds, so every plot was visited three times. To assess the bird diversity in the study area point counts were used (Sutherland 2006). At each survey point, the abundance of bird species heard or seen in a radius of 50m were assessed for five minutes simultaneously by two observers. Both observers each covered a semicircle, taking care not to count any individuals twice. For the acoustical assessment method, the birds were identified in the field. Additionally, the bird sounds were recorded to identify birds in a radius of 50m, that could not be determined during the fieldwork. With the visual method, the birds were spotted and identified with the naked eye or binoculars. For every spotted bird, the respective species, sex and further information like overflying bird was noted. The field surveys were conducted between sunrise and 10:00 am (CEST), when most bird activity occurs. For optimal recording conditions it was necessary that it didn't rain stronger than drizzle and that the wind speed did not exceed 15 km/h, because higher wind speed impedes the acoustical perception of bird sounds too strongly. The period of data collection was from mid-March to mid-June, the period of pronounced song activity and visibility of breeding birds. The GPS-Coordinates were recorded with a smartphone with the application Locus Map Pro (Asamm Software r. o. 2021) and the exact location of the survey points were marked with coloured ribbons.

In addition to data on bird diversity, habitat parameters were recorded. In order to control for possible influences of weather on the collected data on the local bird-diversity, daily temperature, wind and precipitation at nine o'clock from www.meteostat.net were used. For the study plots in Pressbaum, Mauerbach and Gablitz the weather station Tulln was used (Meteostat 2022a). For the study plots in Weidlingbach, Kierling, Klosterneuburg and Wien the weather station Wien Hohe Warte was used (Meteostat 2022b). In mid-June, when the canopy was fully formed, the percentage of canopy cover and at each survey point was determined. To assess the percentage of canopy cover, one measurement was taken in each cardinal direction with a spherical densiometer. The percentage of the cover of the herb and shrub layers at every survey point was estimated visually. The diameter at breast height (DBH) of fife representative trees per survey point was measured with a tape measure. The mean and the median of the DBH, the canopy cover, the shrub cover and the herb cover per survey point was calculated, as well as the standard deviation (SD) of the DBH and the canopy cover.

## 2.3 Statistical analysis

Statistics were performed using R version 4.2.2 (R Core Team 2022) and the packages vegan (Oksanen et al. 2019), glmmTMB (Brooks et al. 2017) and DHARMa (Hartig 2022). For the auditive and visual sampling method, the same statistical analyses were done separately. In this study, I consider a significance level below the threshold of p-values from 0.05 as indicative of statistical significance. P-values ranging from 0.05 to 0.1 are treated as trends, that indicate a noticeable tendency for values to vary in a particular direction. However, to confirm this, further analyses, a larger sample size or monitoring the development of the core and the non-core zone, respectively, would be necessary.

To illustrate the collection success, species accumulation curves for the three runs, the survey points and the dietary, migratory and nesting guild were created. The species richness, abundance and Shannon Diversity Index were calculated. The species richness was calculated as the total number of detected species and the abundance as the total number of detected individuals for each forestry type per survey point for the core zone and the non-core zone. To analyse if the assessed data were normal distributed, a Shapiro-Wilk test was used. The auditive data were normal distributed whereas the visual data showed a binomial distribution, and a transformation of the data did not lead to a normal distribution. Correlation tests between the standard deviation of the canopy cover, and the mean of shrub and herb cover were conducted. The herb cover correlated with the shrub cover and the standard deviation of canopy cover, so it was excluded in the further analysis.

To prove whether the vegetation structure explains the two forest types a generalised linear model (GLM) for the auditive and the visual data together was created. The a priori GLM had the dependent variable forest management and the mean, median, and standard deviation of DBH and canopy cover, median of herb and shrub cover, forest age, proportion of beech, slope and area in ha as independent variables and the survey point ID as random effect. A stepwise AIC in direction backwards and family binomial was conducted to select the best model. The best fitted GLM selected for included habitat parameters in the following order: mean of DBH and canopy cover, standard deviation of canopy cover, mean of shrub cover, forest age, proportion of beech and slope.

With the auditive data a linear mixed-effects model was created because of a normal distribution and a generalized linear mixed model (GLMM) for the visual data because of a negative binomial distribution. Diagnostic plots were used to check if the models fit. The linear mixed-effects model and GLMM had species richness, abundance and the Shannon Diversity Index per survey point in each case as dependent variables and the mean and the standard deviation of the DBH and canopy cover, the mean shrub cover, the forest age, the proportion of beech, the slope and the forest management as independent variables.

With a PERMANOVA the impacts of forestry management, the mean of canopy cover, DBH and shrub cover and the standard deviation of the mean canopy cover and the mean DBH on the bird community was tested. An ANOVA of the distance to group centroid based on a Bray-Curtis dissimilarity matrix, calculated with the R function “betadisper” (R package vegan) was conducted. To visualise the Bray Curtis dissimilarity matrix, non-metric multidimensional scaling (NMDS) plot was used.

For the analysis of the functional diversity, the observed bird species were classified in the functional groups diet, migratory behaviour, and nesting site. The dietary groups were classified in omnivores, granivores, insectivores and carnivores considering their main food group in the breeding season (Renner and Hoesel 2017; Svensson 2018; Schweizerische Vogelwarte Sempach 2023). The migratory groups were classified in non-migratory bird species that remain in the breeding area during the winter, in short-distance migrating bird species that only migrate short distances in winter or only a part of the population migrates and in long-distance migrating bird species that migrate across the Mediterranean or the Sahara in winter (Khil 2018; Schweizerische Vogelwarte Sempach 2023). The nesting site groups were classified according to their nesting sites on the ground, in trees or shrubs, in tree-cavities, in earth-cavities and in brood parasites (Svensson 2018; Schweizerische Vogelwarte Sempach 2023).

After the classification of the functional groups, I summarized the data per run and forestry management type for the auditive and visual dataset separately and calculated the Shannon Diversity Index. A Shapiro-Wilk test revealed a non-normal distribution of both datasets.

The auditive and visual dataset for the functional diversity did not show a normal distribution, therefore GLMMs were created for the dietary, nesting site, and migratory groups for the two datasets separately for the analysis of the functional diversity. The dependent variables for the GLMMs were the abundance and the Shannon Diversity Index. The independent variables were the mean and the SD of the DBH and the canopy cover, the forest age, the proportion of beech, the slope and the forestry management. As random factor I used and the functional group. Subsequently, a likelihood ratio test was performed to ascertain whether the estimated variance for the effect of different dietary groups was significantly different from zero. This test compared the full model, which included the random factor, with a reduced model that omitted this effect. Q-Q plot residual values and residual versus predicted values from the diagnostic plot package DHARMa (Hartig 2022) were not following ethical patterns for the GLMMs for the auditive and visual dataset. Consequently, I consider the models as not converged and not robust and I disregard the models. In further consequence, a different type of model would be needed for a further evaluation of the data, what was not performed in this study.

# 3 Results

## 3.1 Impact of the forestry management on the vegetation structure

The herb cover correlated with the shrub cover (r=0.27, p=<2.2e-16) and the SD of canopy cover (r=-0.15, p=4.572e-10), therefore it was excluded in the further analysis. The chosen research plots in the core zone and the non-core zone of the Wienerwald Biosphere Reserve differed significantly in the mean canopy cover and the mean shrub cover, the forest age, the proportion of beech and the slope. I found a significantly denser canopy cover in the core zone but a significantly denser shrub cover in the non-core zone. Furthermore, the analysis revealed significantly steeper slopes in the core zone, a significantly higher proportion of beech and significantly older forest stands in the non-core zone. In the non-core zone the mean forest age on the selected study sites was 141 years. The tree age ranged between 116 and 161 years. On the selected study sites in the core zone , the mean forest age was 131 years, with a tree age range between 106 and 161 years. The mean DBH and the mean SD of the canopy cover did not show a significant difference between the two forest management zones, but a trend (Table 1, Figure 2).

Table 1: Results of the GLM testing the impact of the habitat parameters in the forest management method with significant dependencies highlighted in bold.

| **Response variable** | **Explanatory variable** | **Estimate** | **SE** | **z-value** | | **p-value** | |
|---|---|---|---|---|---|---|---|
| **AIC selected Model** | | | | | | | |
| Forest management | DBH mean | 0.036 | 0.021 | 1.669 | | 0.095 | . |
| | Canopy cover mean | -0.388 | 0.148 | -2.613 | **<** | **0.009** | ** |
| | Canopy cover SD | -0.390 | 0.234 | -1.667 | | 0.096 | . |
| | Shrub cover mean | 0.024 | 0.009 | 2.763 | **<** | **0.006** | ** |
| | Forest age | 0.094 | 0.022 | 4.347 | **<** | **0.001** | *** |
| | Beech proportion | 0.159 | 0.044 | 3.360 | **<** | **0.001** | *** |
| | Slope | 0.120 | 0.036 | -3.360 | **<** | **0.001** | *** |
| **Full Model** | | | | | | | |
| Forest management | DBH mean | 0.032 | 0.024 | 1.331 | | 0.183 | |
| | DBH SD | 0.004 | 0.038 | 0.117 | | 0.907 | |
| | Canopy Cover mean | -0.393 | 0.147 | -2.680 | | **0.007** | ** |
| | Canopy cover SD | 0.421 | 0.240 | -1.753 | | 0.080 | . |
| | Shrub Cover mean | 0.025 | 0.010 | 2.540 | | **0.011** | * |
| | Herb cover mean | 0.006 | 0.010 | 0.646 | | 0.518 | |
| | Forest age | 0.093 | 0.022 | 4.248 | **<** | **0.001** | *** |
| | Beech proportion | 0.154 | 0.044 | 3.490 | **<** | **0.001** | *** |
| | Slope | 0.111 | 0.038 | -2.939 | | **0.003** | ** |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = p < 0.1

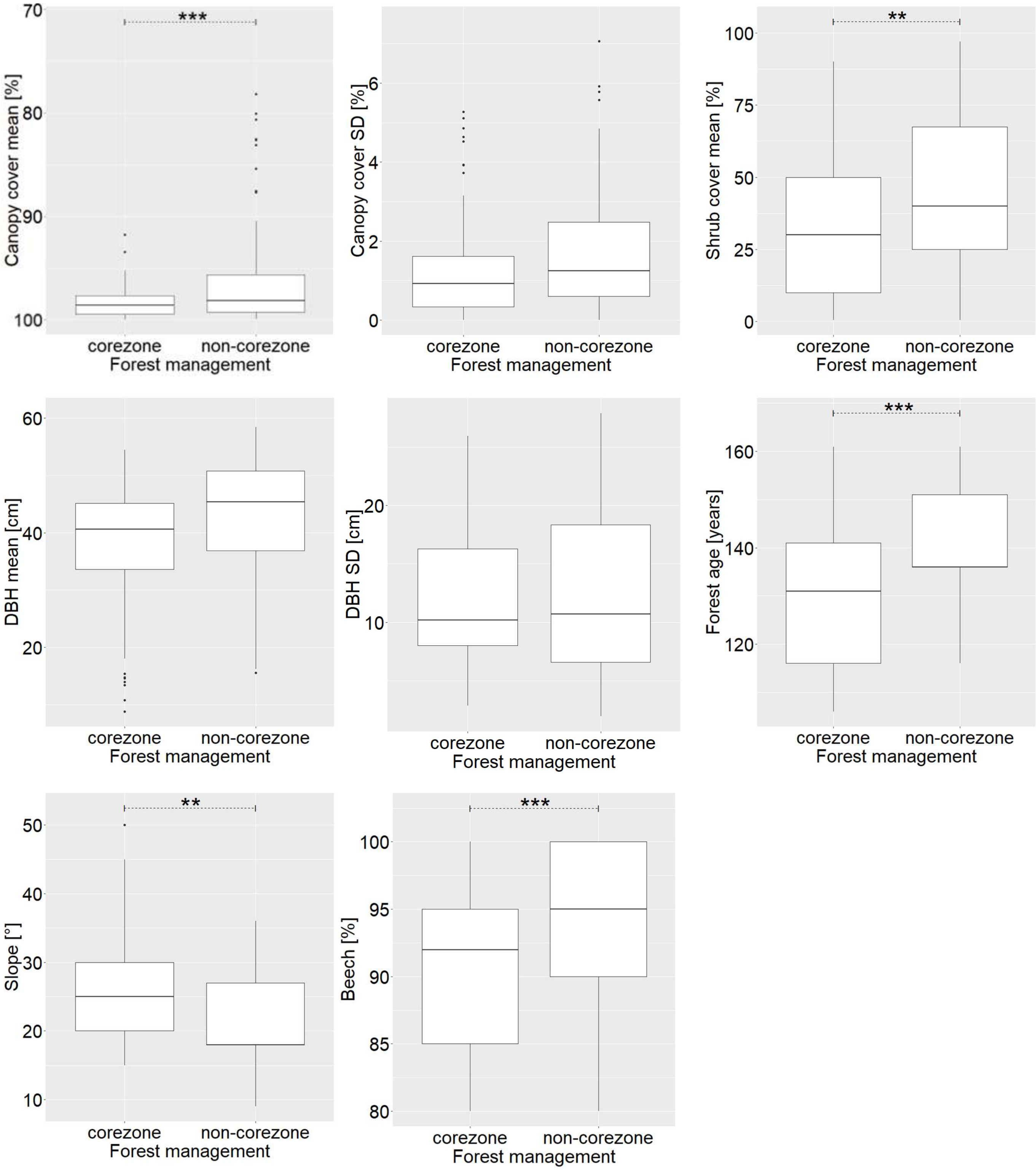


Figure 2: Boxplots showing the impacts of the forest management on the vegetation structure. The core zone and the non-core zone of the Wienerwald Biosphere Reserve differed significantly in the mean of the canopy and the shrub cover, the forest age, the proportion of beech and the slope. The mean DBH and the mean SD of the canopy cover showed a trend between the two forest management zones.

## 3.2 Observed species and species accumulation curves

Altogether, I observed 4885 birds in 55 species with both sampling methods. With the auditive method I observed 4384 birds, what makes 90% of the data, and with the visual method 501 birds, what represents 10% of the data. I found 7 species, that were only detected auditive or visual, respectively. I also found 7 species, that were only found in the core zone or the non-core zone, respectively (Figure 2).

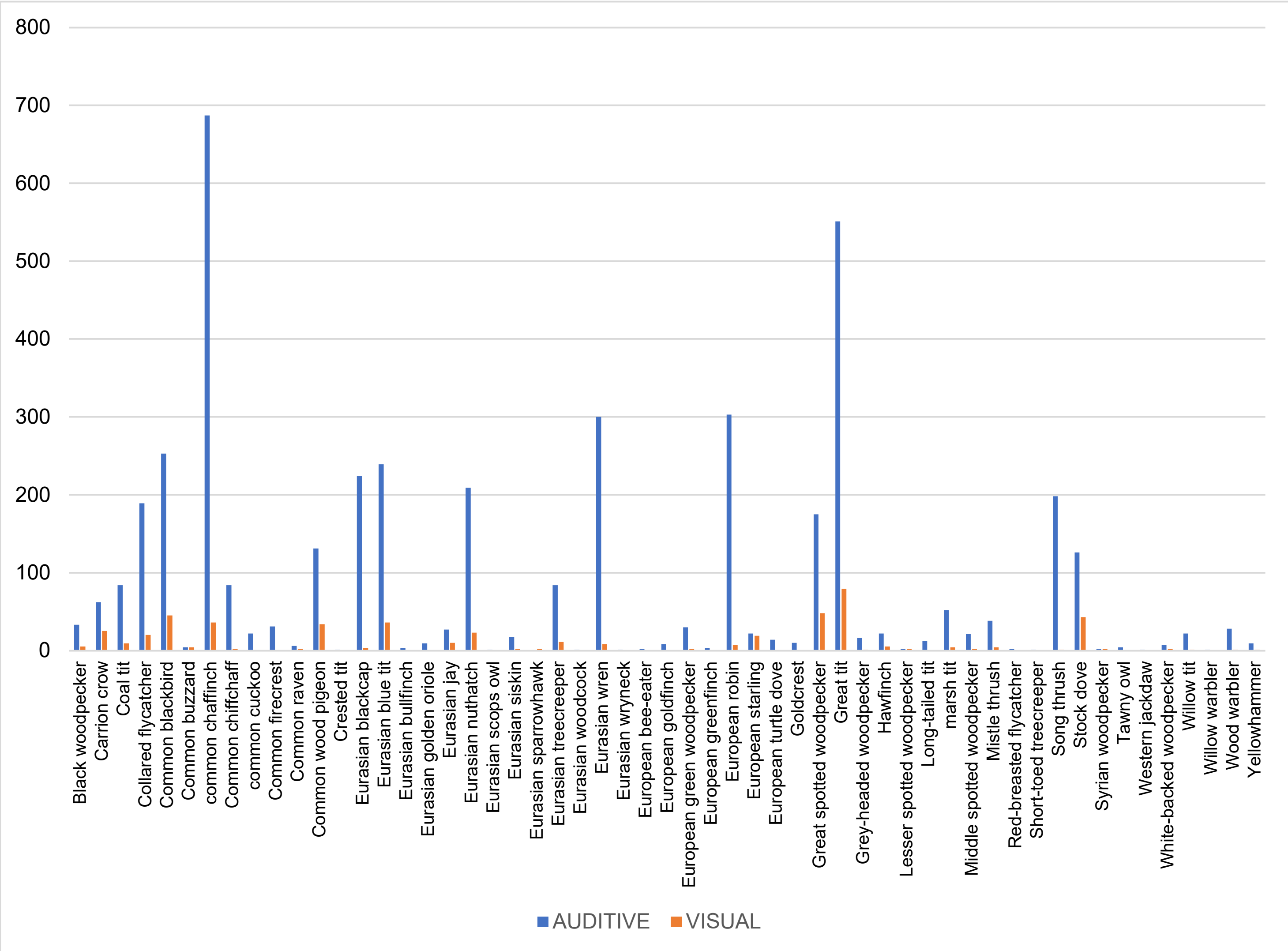


Figure 2: With the auditive and visual method together I observed 4885 birds of 55 species. The auditive method made 90% and the visual 10% of the data. With both methods I found 7 species, that were only found with one of both methods, respectively.

Seven species were only found either in the core or non-core zone, respectively. Of the seven species exclusively found in the core zone, one species was categorized as endangered, two as near threatened and four as least concern, whereas in the non-core zone, one species was classified as vulnerable, three as near threatened and three as least concern, according to the red list of endangered birds of Austria (Umweltbundesamt 2023) (Figure 3). Further details can be found in Table A1 in the appendix.

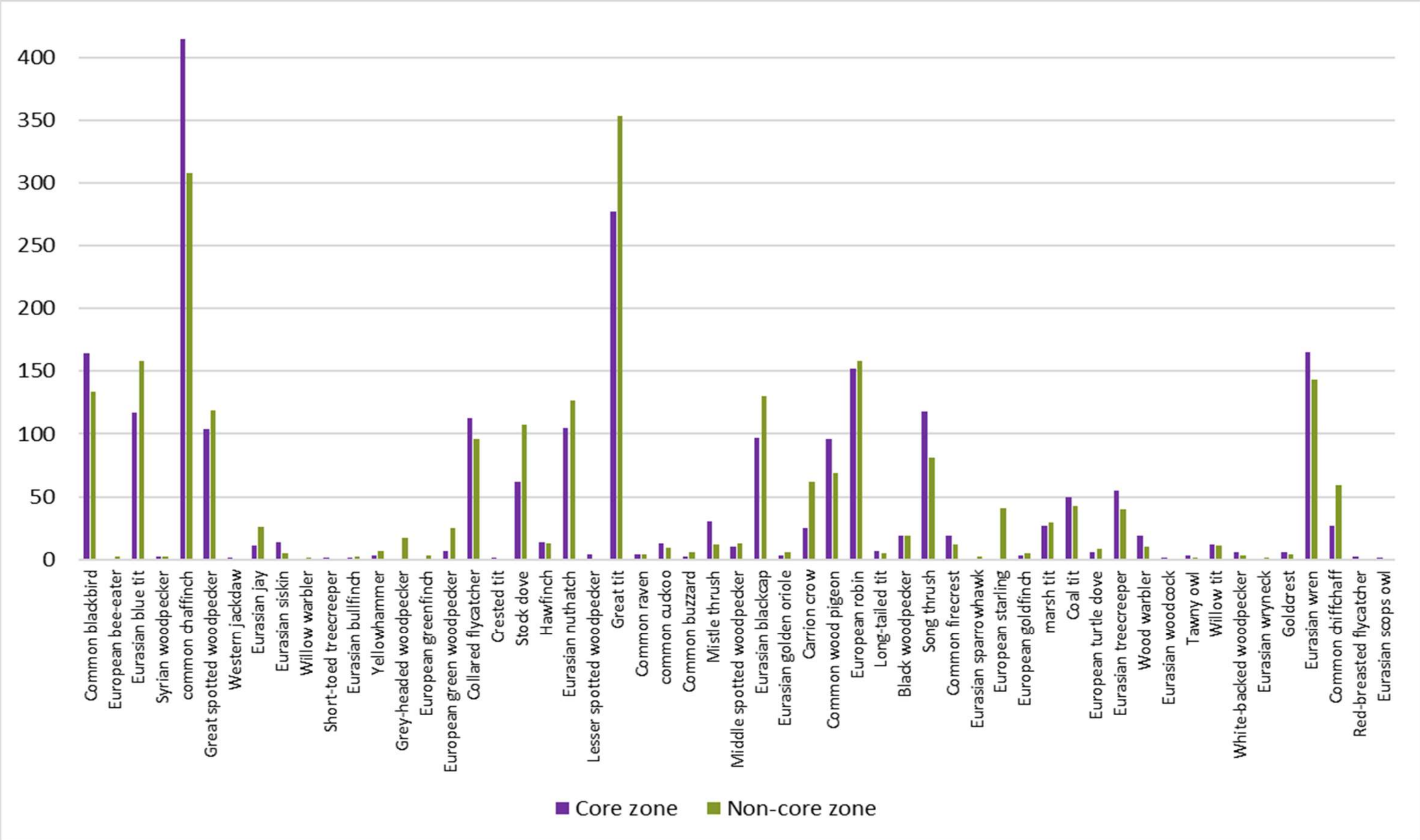


Figure 3: Abundance of all species in the core zone and the non-core zone. Seven species were only found either in the core or non-core zone, respectively.

The species accumulation curves for the three runs and the number of study points visited show, that the plateau of the curve was nearly reached with the auditive method, whereas the visual method was less successful. (Figure 4).

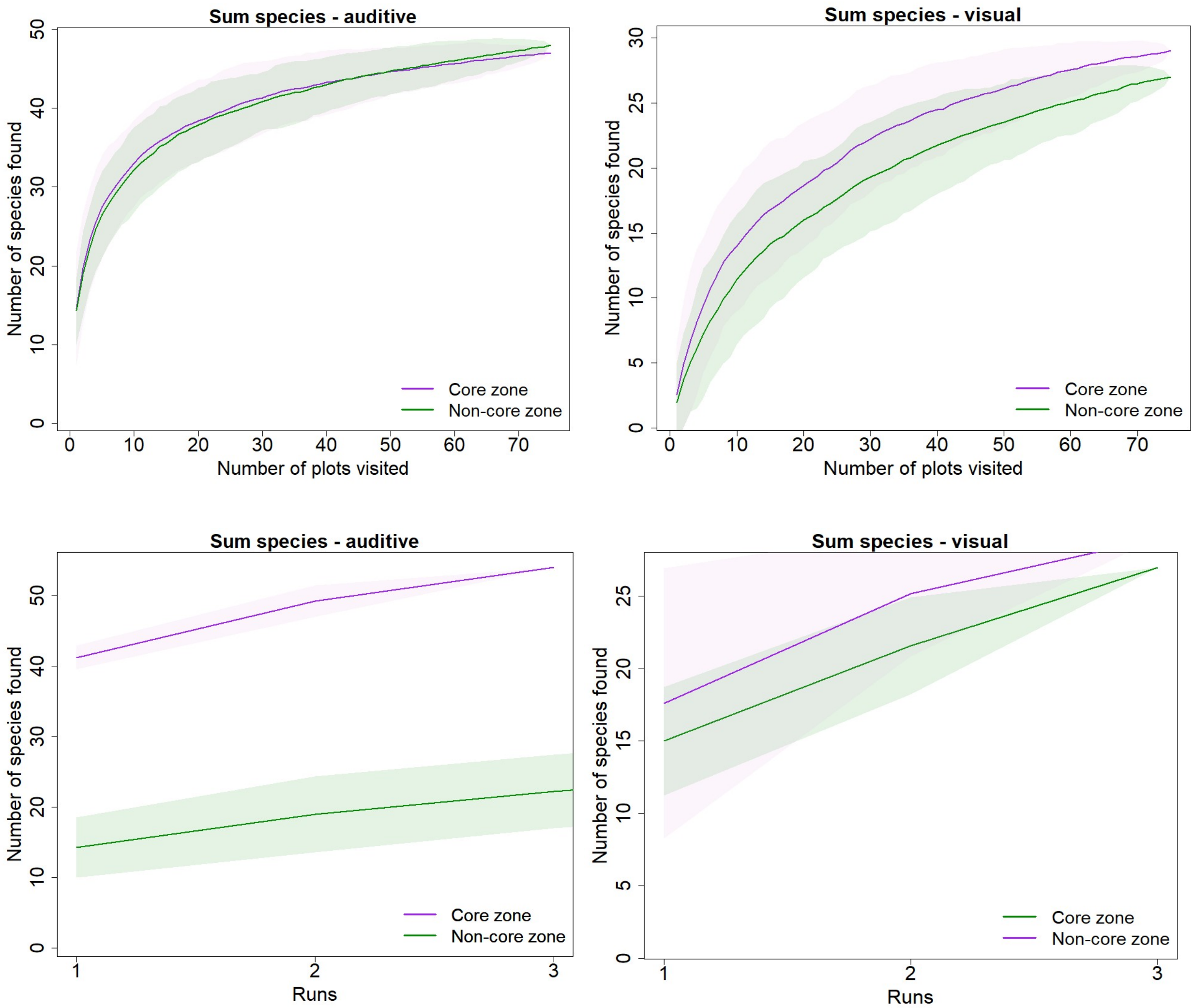


Figure 4: Species accumulation curves comparing the collection success of all species of the auditive and the visual method. With the auditive method, the plateau of the curve was nearly reached, whereas the visual method was less successful.

## 3.3 Species richness, abundance and Shannon Diversity Index

The species richness, the abundance and the Shannon Diversity Index for the auditive data showed a normal distribution, for the visual data it showed a negative binomial distribution.

A GLMM with the visual data showed a trend of the mean shrub cover on the abundance ($t_{1,141}$ = 1.653, p = 0.0984). Further details can be found in Table A2 in the appendix.

With a linear mixed-effects model for the auditive data, I found a statistically significant impact of the mean canopy cover ($t_{1,141}$ = -2.1669, p = 0.0319, $R^2$ = 0.0060) and the SD of the canopy cover ($t_{1,141}$ = 2.2131, p = 0.0285, $R^2$ = 0.0048) on the species richness. This suggests that a denser canopy cover and a wider range of canopy cover values were significantly related to a higher species richness. Additionally, a steeper slope (in the range from 9° to 50°) was associated with a significantly lower abundance of birds ($t_{1,141}$ = -2.1177, p = 0.0360, $R^2$ = 0.0256). Trends were also observed for the mean canopy cover ($t_{1,141}$ = -1.8531, p = 0.0660) and the SD of the canopy cover ($t_{1,141}$ = 2.6692, p = 0.0085), indicating potential effects on bird abundance. Furthermore, trends were found for the mean canopy cover ($t_{1,141}$ = 1.9733, p = 0.0509) and the SD of the canopy cover ($t_{1,141}$ = 1.9733, p = 0.0504) on the Shannon Diversity Index. However, I could not find a significant difference between the species richness, abundance, and Shannon Diversity Index between the core and the non-core zone. However, I observed significantly higher canopy cover values in the core zone compared to the non-core zone (Estimate = -0.393, SE = 0.147, z-value = -2.680, p = 0.007). Additionally, there was a trend in the SD of the canopy cover (Estimate = 0.421, SE = 0.240, z-value = -1.753, p = 0.080) between the core and non-core zone (Figure 5). Further details can be found in Table A3 in the appendix.

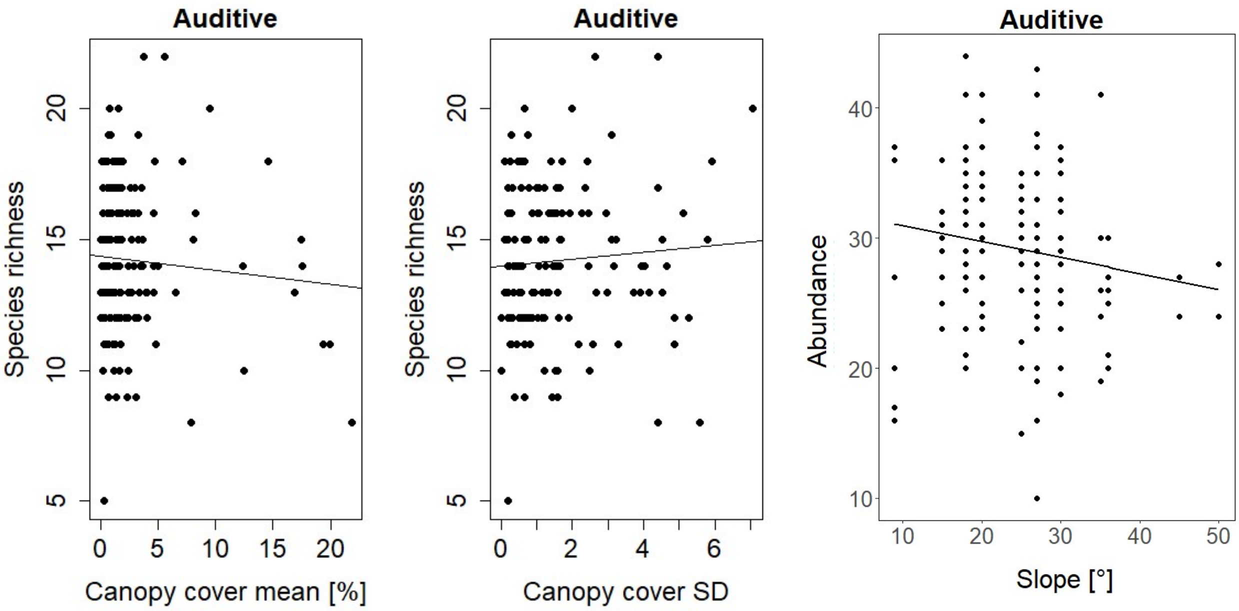


Figure 5: Significant impact of the linear mixed-effects models for the auditive data testing for the impact of forestry management and the habitat parameters in the core zone on the abundance.

## 3.4 Impact of the forestry management on the bird communities

With the visual data I found a significant impact of the mean DBH on the species composition (PERMANOVA, $F(1, 323) = 4.8853$, $p = 0.018$) and no difference in the dispersion of the species composition between the core and non-core zone (ANOVA, betadisper, $F1, 202 = 2.3599$, $p = 0.1261$). However, with the auditive data, I found a significant impact of the forest age on the species composition (PERMANOVA, $F1, 802 = 4.6461$, $p = 0.028$) and a trend in the dispersion of the two communities (ANOVA, betadisper, $F11, 733 = 1.7549$, $p = 0.0581$) (Figure 6). Further details can be found in Table A4 in the appendix.

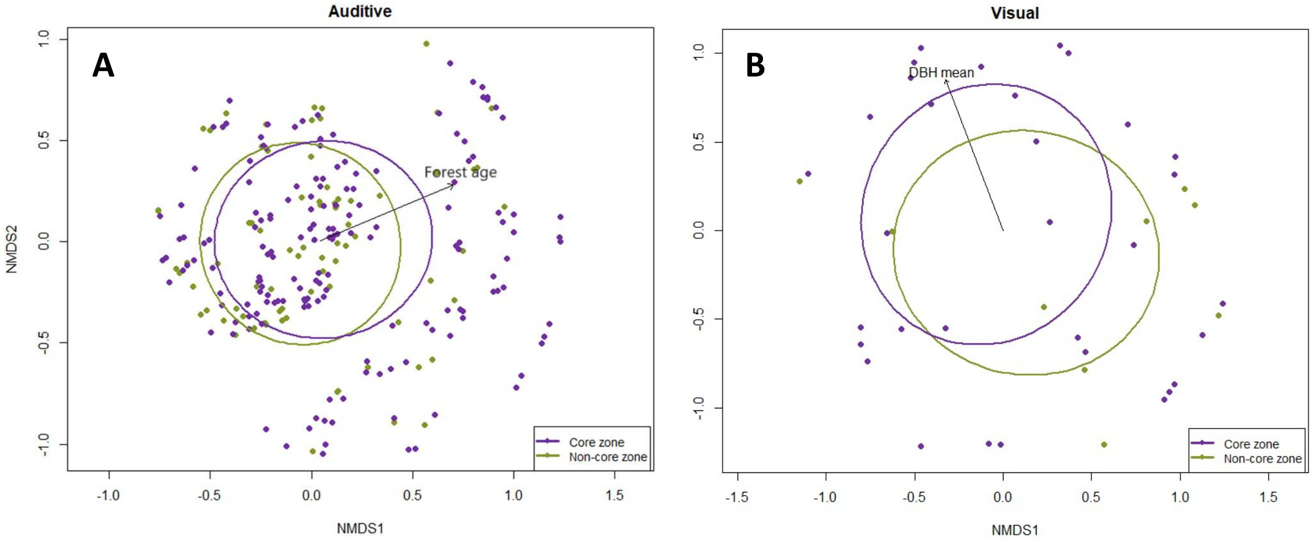


Figure 6: NMDS Plot visualising the Bray Curtis dissimilarity matrix, showing the communities in the core zone and the non-core zone. A shows a significant impact of the mean DBH on the community with the auditive data. B shows a significant effect of the mean DBH with the visual data on the community.

## 3.5 Functional Diversity

### Feeding groups

80% of the 4885 observed birds were insectivores, 18% grain eaters, 1.9% omnivores and under 0.1% were carnivores. With the auditive method, the plateau of the species collection curve was nearly reached for the insectivores in the diet group. For the granivores, omnivores and carnivores the plateau was reached or nearly reached with both methods (Figure 7).

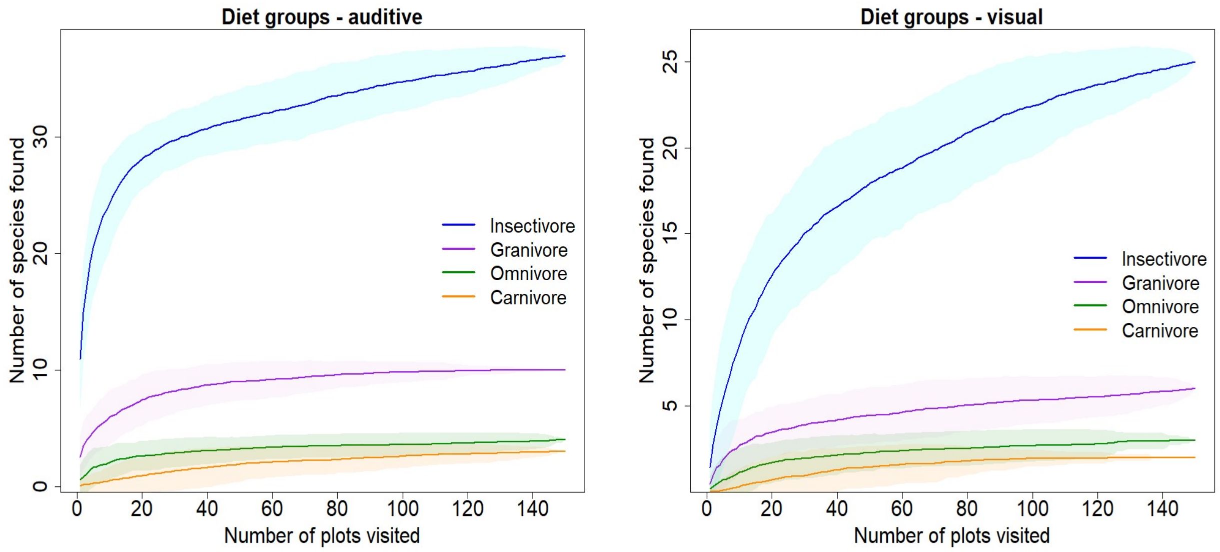


Figure 7: Species accumulation curves for the diet groups showing the species collection success. For the insectivores observed acoustically, the plateau of the curve was nearly reached. For the insectivores perceived visually and the granivores, omnivores and carnivores the plateau was reached or nearly reached with both methods.

The Likelihood Ratio Test results reveal a significant difference between the full model GLMM for the auditive data (DF=10) with the feeding groups as random effect and the reduced model GLMM (DF=11) without the random effect in respect to the bird abundance (p=< 2.2e-16). This suggests that there is a significant variability in bird abundance associated with different dietary preferences. However, the same does not apply to the abundance for the visual data (p=0.9998) and the Shannon Diversity Index (p=0.2769) for the auditive data. Nevertheless, as I consider the models as not converged and not robust I disregard the models and rate the associated results as not trustworthy. I could not conduct the analysis of the variability for the Shannon Diversity Index because the models did not converge due to insufficient data. Further details can be found in the Tables A5, A6 and A10 in the appendix.

## Migratory status

74% of the observed birds were non-migratory birds, 22% were short distance migratory birds and 4% were long distance migratory birds. The short distance migratory birds nearly reached the plateau of the species accumulation curve with the auditive method, which was not the case with the other groups using both methods (Figure 8).

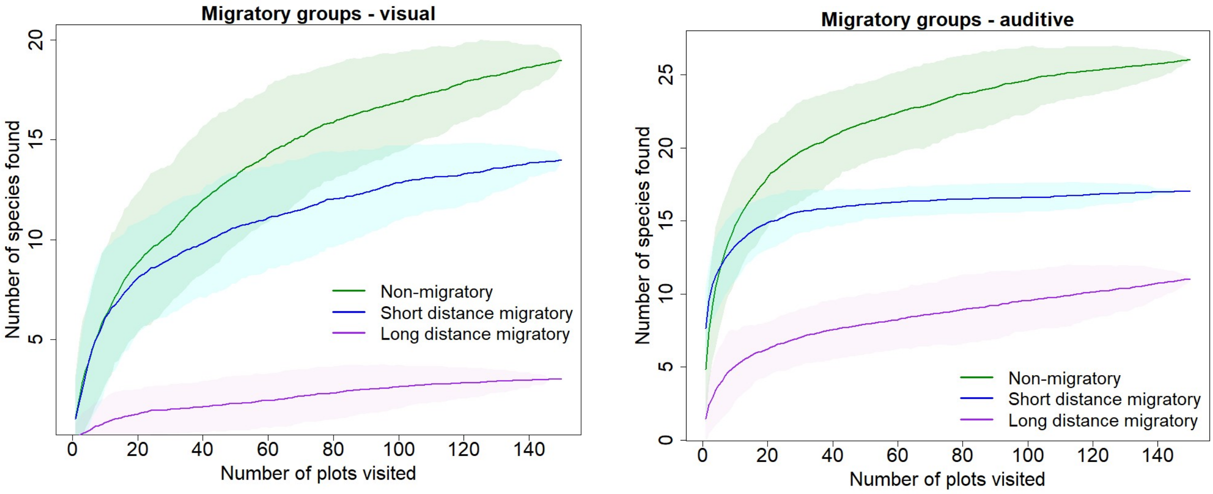


Figure 8: Species accumulation curves for the migratory groups showing the species collection success. The short distance migratory birds perceived acoustically nearly reached the plateau, whereas the short and long-distance migratory birds did not reach the plateau with both observing methods.

The Likelihood Ratio Test results reveal a significant difference between the full model GLMM for the auditive data (DF=10) with the migratory status groups as random effect and the reduced model GLMM (DF=11) without the random effect in respect to the variation of the bird abundance (p=0.02674) and the Shannon Diversity Index (p=0.01072). This suggests that there is a significant variability in the bird abundance and the Shannon Diversity Index associated with different migratory status groups. However, the same does not apply to the abundance for the visual data for the bird abundance (p=0.9998). Nevertheless, as I consider the models as not converged and not robust I disregard the models and rate the associated results as not trustworthy. I could not conduct the analysis of the variability for the Shannon Diversity Index because the models did not converge due to insufficient data. Further details can be found in the Tables A7, A8 and A11 in the appendix.

### Nesting site groups

The nesting sites of 65% of the observed birds were in tree holes, 28% in trees, 6% on the ground, 1% were parasitic breeders. With the auditive method, the plateau of the curve was nearly reached, whereas the visual method was less successful (Figure 9).

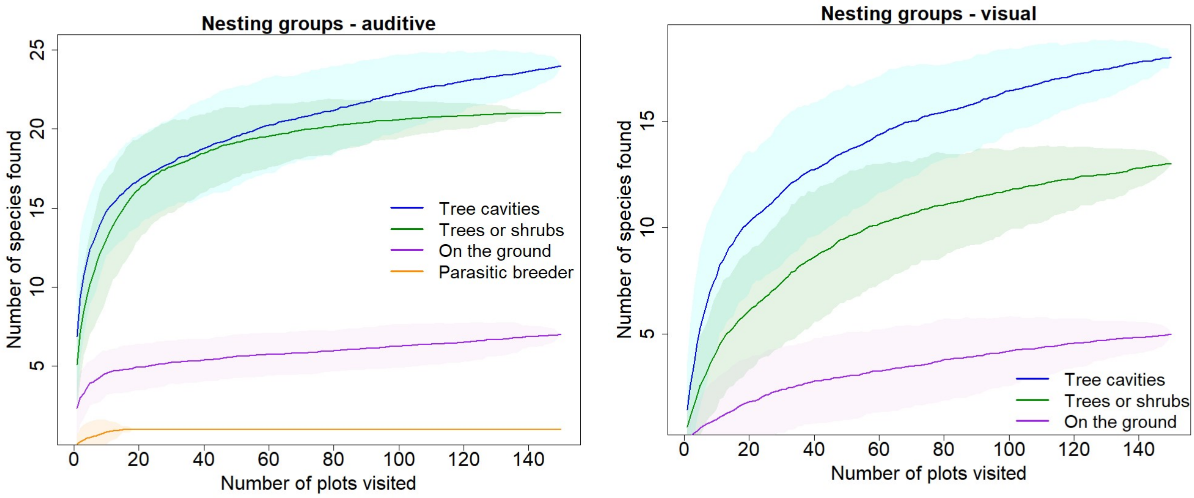


Figure 9: Species accumulation curves for the nesting groups showing the species collection. With the auditive method, the plateau of the curve was nearly reached, whereas the visual method was less successful.

The Likelihood Ratio Test results reveal a significant difference between the full model GLMM for the visual data (DF=10) with the nesting site groups as random effect and the reduced model GLMM (DF=11) without the random effect in respect to the variation of the bird abundance (p=0.003374). For the auditive data I only found a trend (p=0.06646) referring to the variation of the bird abundance. This suggests that there is a significant variability in the bird abundance associated with different nesting site preferences. Nevertheless, as I consider the models as not converged and not robust I disregard the models and rate the associated results as not trustworthy. I could not conduct the analysis of the variability for the Shannon Diversity Index because the models did not converge due to insufficient data. Further details can be found in the Tables A9 and A12 in the appendix.

# 4 Discussion

The chosen research plots in the core zone and the non-core zone differed significantly in the mean canopy and shrub cover, the forest age, the proportion of beech and the slope. I found that a denser canopy cover and a wider range of canopy cover values were significantly related to a higher species richness. Additionally, a steeper slope (in the range from 9° to 50°) was associated with a significantly lower abundance of birds. Furthermore, I found a significant impact of the forest age and the mean DBH on the species composition. Nevertheless, I could not ascertain a significant difference between the species richness, abundance, Shannon Diversity Index and the communities between the core zone and the non-core zone.

## 4.1 Impacts of the forestry management on species richness, abundance and Shannon Diversity Index

My first hypothesis was a higher avian species richness, abundance and Shannon Diversity Index in the core zone compared with the non-core zone. I could not confirm this hypothesis although the core and the non-core zone differed significantly in several vegetational characteristics. However, avian species composition is linked with environmental characteristics like the proportion of canopy cover or the slope (Basnet et al. 2016). In further consequence, those environmental characteristics influence the habitat quality, for example in the form of the availability of shelter and food resources (Basnet et al. 2016).

**Canopy cover**

Coinciding to other studies, I found a significant impact of the canopy cover on avian species richness and abundance (Moning and Müller 2008). In high montane forests in Central Europe, Moning and Müller 2008 consider the percentage of canopy cover the most important factor influencing the occurrence of bird species. In my study a denser canopy cover and a wider range of canopy cover values were significantly related to a higher species richness. This is contrary to the findings of many other studies, which show that canopy openings often lead to an increased bird diversity (Muscolo et al. 2014; Roxburgh, Shea, and Wilson 2004). In natural forests, clearings or gaps caused by natural processes like riverbuilding or treefall can increase the biodiversity by slightly changing the environmental factors so that a wider range of species like climax species, that favour late successional forest states and pioneer species that favour open habitats can coexist (Bongers et al. 2009; Shea, Roxburgh, and Rauschert 2004; Roxburgh, Shea, and Wilson 2004; Hill 1999; Johns 1997). With 106-161 years, both the core zone and the non-core zone are in the optimal phase, characterized by an almost fully closed canopy (Scherzinger 1991; Moning and Müller 2008). The optimal phase is followed by the plenter phase, which begins around 250-400 years, when falling deadwood increasingly creates gaps in the canopy (Scherzinger 1991). This fits the findings of Schieck, Nietfeid, and Stelfox 1995, who found the lowest canopy heterogeneity in young forest stands, an intermediate heterogeneity in older forest stands and the highest heterogeneity in mature forest stands. I could not find a significant difference between the SD of the canopy cover between the core and non-core zone, only a trend. This also indicates that the core and non-core zone are still both in a similar succession stage. In my study, the forest age and the measured canopy cover span with a canopy cover of 90% or higher in 87% of the survey points and a measured canopy cover range of 78-100% fit the optimal phase. It could be that the canopy cover measured was too dense and canopy cover span too narrow for gaps and forest edges to impact the avifauna in the form described in other studies. The forest age influences the canopy cover and Moning and Müller 2008 consider it to be the second most important factor influencing the avifauna. Therefore, they suggest a range of canopy openness from 5% to 70% in forest areas to cover the needs of not only generalists and edge species, but also more specialised forest birds.

## 4.2 Impacts of the forestry management on the avian community and functional diversity

My second hypothesis was to find a distinct avian community and a difference in the proportion of the different functional groups in the core zone and the non-core zone. I could partly confirm this hypothesis.

**DBH and forest age**

With the mean DBH, that differed with a trend between the core and non-core zone, I found a significant impact on the species composition. A bigger DBH indicates older trees which in further consequence can have a positive impact on bird communities, as mature large trees offer more habitats and nesting sites for birds as younger trees (Czeszczewik et al. 2015). The forest stands chosen for this study in the non-core zone areas were significantly older than those in the core zone areas. In Moning and Müller 2008 the forest age was the second most important factor influencing the bird community. I also found a significant impact of the forest age on the species composition and a trend in the dispersion of the communities. The mean age of the forest stands in the core zone was 131 years, whereas the forest stands in the non-core zone were on average 10 years older. The difference of 10 years in the forest age is only one factor influencing the forest bird diversity. Nevertheless, this difference and the decommission of the core zone areas only since at least 2003 could have weakened the impact of the differing forest management practices on the bird community composition. Nonwithstanding, the core zone and the non-core zone may still not be sufficiently different to ascertain differences in the bird community composition. This may be because of the sustainable forestry management method in the non-core zone of the Wienerwald Biosphere Reserve on the one hand and the putting out of use of the last core zone areas only since 2003 on the other hand. This resembles the findings of Czeszczewik et al. 2015 in the Bialowieza Forest in Poland, who compared natural forests in the Bialowieza National Park, sustainable managed forest stands with very moderate management impacts and intensively managed forest stands. They found that the richness, abundance and diversity of the sustainable managed forest stands did not differ significantly from those in the natural forests in the Bialowieza National Park, but from the intensively managed forest stands (Czeszczewik et al. 2015). Therefore, the chosen forest stands may have not been sufficiently representative in respect to the forest age and succession stage. However, unfortunately the selection of the research plots was limited due to logistical, time and equipment restrictions. In further studies, I would recommend taking this aspect more into account when selecting the study areas.

**Functional diversity**

The Q-Q plot residual values and residual versus predicted values for the GLMMs for the analysis of the functional diversity were not following ethical patterns. Consequently, I consider the models as not converged and not robust and the results as not reliable. A different type of model would be needed for a further evaluation of the data. Due to time restrictions, this was not possible in this study. Therefore, the functional diversity could not be evaluated further in this study.

## 4.3 Conclusion

It could be that the managed and not managed parts of the Wienerwald Biosphere Reserve both are in very a similar nature near state and offer very good habitats for many forest bird species so that I could not find significant differences in species richness, abundance, Shannon Diversity Index and bird communities between the core and non-core zone yet. In further studies, when more of the core zone areas of the Wienerwald Biosphere Reserve have reached the climax state, there may be a bigger difference between the species richness, the abundance, the Shannon Diversity Index and the bird communities between the core and non-core zone. Therefore, I recommend a further investigation of the core and non-core zone over the course of time to monitor the changes taking place.

# References

Aitken, Kathryn E. H., and Kathy Martin. 2007. 'The Importance of Excavators in Hole-Nesting Communities: Availability and Use of Natural Tree Holes in Old Mixed Forests of Western Canada'. Journal of Ornithology 148 (2): 425–34. https://doi.org/10.1007/s10336-007-0166-9.

Asamm Software r. o. 2021. 'Locus Map Pro'.

Basnet, Tej B., Maan B. Rokaya, Bishnu P. Bhattarai, and Zuzana Münzbergová. 2016. 'Heterogeneous Landscapes on Steep Slopes at Low Altitudes as Hotspots of Bird Diversity in a Hilly Region of Nepal in the Central Himalayas'. Edited by Andy J Green. PLOS ONE 11 (3): e0150498. https://doi.org/10.1371/journal.pone.0150498.

Berger, Roland, and Friedrich Ehrendorfer, eds. 2011. Ökosystem Wien: Die Naturgeschichte Einer Stadt. Reihe 'Wiener Umweltstudien', Band 2. Wien: Böhlau Verlag. https://www.researchgate.net/publication/318421364_Der_Wienerwald_-_Natur_fast_pur_am_Rande_der_Stadt.

Biosphärenpark Wienerwald Management GmbH. 2021a. 'Kernzonen'. Biosphärenpark Wienerwald. 2021. https://www.bpww.at/de/artikel/kernzonen.

———. 2021b. 'Wälder'. Biosphärenpark Wienerwald. 2021. https://www.bpww.at/de/artikel/waelder.

Biosphärenpark Wienerwald Management GMBH. 2023. 'Die Wiege Des Waldes - Über Die Bedeutung von Totholz Für Biodiversität Und Ökosystemleistungen'. https://www.bpww.at/sites/default/files/download_files/DW-410517-20220330-Wiege-des-Waldes.pdf.

Blanc, Lori A., and Jeffrey R. Walters. 2008. 'Cavity Excavation and Enlargement as Mechanisms for Indirect Interactions in an Avian Community'. Ecology 89 (2): 506–14. https://doi.org/10.1890/07-0219.1.

Bobiec, Andrzej, ed. 2005. The Afterlife of a Tree. Warszawa: WWF Poland.

Böhm, Monika, Ben Collen, Jonathan E.M. Baillie, Philip Bowles, Janice Chanson, Neil Cox, Geoffrey Hammerson, et al. 2013. 'The Conservation Status of the World's Reptiles'. Biological Conservation 157 (January): 372–85. https://doi.org/10.1016/j.biocon.2012.07.015.

Bongers, Frans, Lourens Poorter, William D. Hawthorne, and Douglas Sheil. 2009. 'The Intermediate Disturbance Hypothesis Applies to Tropical Forests, but Disturbance Contributes Little to Tree Diversity'. Ecology Letters 12 (8): 798–805. https://doi.org/10.1111/j.1461-0248.2009.01329.x.

Brazaitis, Gediminas, and Per Angelstam,. 2004. 'Influence of Edges between Old Deciduous Forest and Clearcuts on the Abundance of Passerine Hole-Nesting Birds in Lithuania'. Ecological Bulletins 51: 209–2017. https://doi.org/10.2307/20113309.

Brenner, Harald. 2014. 'Totholz in Kernzonen Und Bewirtschafteten Wäldern Des Biosphärenparks Wienerwald'. Wissenschaftliche Mitteilungen Niederösterreichisches Landesmuseum, no. 25: 137–56.

Brooks, Mollie, E., Kasper Kristensen, Koen Benthem J.,van, Arni Magnusson, Casper Berg W., Anders Nielsen, Hans Skaug J., Martin Mächler, and Benjamin Bolker M. 2017. 'glmmTMB Balances Speed and Flexibility Among Packages for Zero-Inflated Generalized Linear Mixed Modeling'. The R Journal 9 (2): 378. https://doi.org/10.32614/RJ-2017-066.

Czeszczewik, D, K Zub, T Stanski, M Sahel, A Kapusta, and W Walankiewicz. 2015. 'Effects of Forest Management on Bird Assemblages in the Bialowieza Forest, Poland'. iForest - Biogeosciences and Forestry 8 (3): 377–85. https://doi.org/10.3832/ifor1212-007.

Daily, G C, P R Ehrlich, and N M Haddad. 1993. ‘Double Keystone Bird in a Keystone Species Complex.’ Proceedings of the National Academy of Sciences 90 (2): 592–94. https://doi.org/10.1073/pnas.90.2.592.

Fayt, Philippe, Marlene M. Machmer, and Christoph Steeger. 2005. ‘Regulation of Spruce Bark Beetles by Woodpeckers—a Literature Review’. Forest Ecology and Management 206 (1–3): 1–14. https://doi.org/10.1016/j.foreco.2004.10.054.

Fedrowitz, Katja, Julia Koricheva, Susan C. Baker, David B. Lindenmayer, Brian Palik, Raul Rosenvald, William Beese, et al. 2014. ‘REVIEW: Can Retention Forestry Help Conserve Biodiversity? A Meta-Analysis’. Journal of Applied Ecology 51 (6): 1669–79. https://doi.org/10.1111/1365-2664.12289.

Ghadiri Khanaposhtani, Maryam, Mohammad Kaboli, Mahmoud Karami, Vahid Etemad, and Saeedeh Baniasadi. 2013. ‘Effects of Logged and Unlogged Forest Patches on Avifaunal Diversity’. Environmental Management 51 (3): 750–58. https://doi.org/10.1007/s00267-012-9979-2.

Gil-Tena, A, S Saura, and L Brotons. 2007. ‘Effects of Forest Composition and Structure on Bird Species Richness in a Mediterranean Context: Implications for Forest Ecosystem Management’. FOREST ECOLOGY AND MANAGEMENT 242 (2–3): 470–76. https://doi.org/10.1016/j.foreco.2007.01.080.

Gregory, Richard D., and Arco van Strien. 2010. ‘Wild Bird Indicators: Using Composite Population Trends of Birds as Measures of Environmental Health’. Ornithological Science 9 (1): 3–22. https://doi.org/10.2326/osj.9.3.

Gustafsson, Lena, Susan C. Baker, Jürgen Bauhus, William J. Beese, Angus Brodie, Jari Kouki, David B. Lindenmayer, et al. 2012. ‘Retention Forestry to Maintain Multifunctional Forests: A World Perspective’. BioScience 62 (7): 633–45. https://doi.org/10.1525/bio.2012.62.7.6.

Hamer, K. C., J. K. Hill, S. Benedick, N. Mustaffa, T. N. Sherratt, M. Maryati, and Chey V. K. 2003. ‘Ecology of Butterflies in Natural and Selectively Logged Forests of Northern Borneo: The Importance of Habitat Heterogeneity: Bornean Forest Butterflies’. Journal of Applied Ecology 40 (1): 150–62. https://doi.org/10.1046/j.1365-2664.2003.00783.x.

Hartig, F. 2022. ‘DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed)’. https://CRAN.R-project.org/package=DHARMa.

Herrera, Carlos M. 1984. ‘A Study of Avian Frugivores, Bird-Dispersed Plants, and Their Interaction in Mediterranean Scrublands’. Ecological Monographs 54 (1): 1–23. https://doi.org/10.2307/1942454.

Hill, Jane K. 1999. ‘Butterfly Spatial Distribution and Habitat Requirements in a Tropical Forest: Impacts of Selective Logging’, 9.

Johns, Andrew Grieser. 1997. Timber Production and Biodiversity Conservation in Tropical Rain Forests. Cambridge Studies in Applied Ecology and Resource Management. Cambridge ; New York: Cambridge University Press.

Khil, Leander. 2018. Vögel Österreichs. 1st ed. Stuttgart: Frankh-Kosmos Verlags-GbmH & Co. KG.

Köck, Günter, Gerfried Koch, and Christian Diry. 2009. ‘The UNESCO Biosphere Reserve “Biospharenpark Wienerwald” (Vienna Woods) - a Long History of Conservation’. Eco.Mont 1 (June): 51–56. https://doi.org/10.1553/eco.mont1s51.

Kosenko, S.M., and E.Yu Kaigorodova. 2001. ‘Effect of Habitat Fragmentation on Distribution, Density and Breeding Performance of the Middle Spotted Woodpecker Dendrocopos Medius (Alves, Picidae) in Nerussa-Desna Polesye’. Zool. Zhurnal 80 (January): 71–78.

Larsen, Stefano, Alberto Sorace, and Laura Mancini. 2010. ‘Riparian Bird Communities as Indicators of Human Impacts Along Mediterranean Streams’. Environmental Management 45 (2): 261–73. https://doi.org/10.1007/s00267-009-9419-0.

Meteostat. 2022a. weather station ‘Tulln’, coordinates 48.3167, 16.1167. https://meteostat.net/de/station/11030?t=2023-01-11/2023-01-18.

———. 2022b. weather station ‘Hohe Warte’, coordinates 48.25, 16.3667. https://meteostat.net/de/station/11035?t=2023-01-11/2023-01-18.

Moning, Christoph, and Jörg Müller. 2008. ‘Environmental Key Factors and Their Thresholds for the Avifauna of Temperate Montane Forests’. Forest Ecology and Management 256 (5): 1198–1208. https://doi.org/10.1016/j.foreco.2008.06.018.

Muscolo, Adele, Silvio Bagnato, Maria Sidari, and Roberto Mercurio. 2014. ‘A Review of the Roles of Forest Canopy Gaps’. Journal of Forestry Research 25 (4): 725–36. https://doi.org/10.1007/s11676-014-0521-7.

Økland, Tonje, Knut Rydgren, Rune Halvorsen Økland, Ken Olaf Storaunet, and Jørund Rolstad. 2003. ‘Variation in Environmental Conditions, Understorey Species Number, Abundance and Composition among Natural and Managed Picea Abies Forest Stands’. Forest Ecology and Management 177 (1–3): 17–37. https://doi.org/10.1016/S0378-1127(02)00331-6.

Oksanen, Jari, F. Guillaume Blanchet, Michael Friendly, Roeland Kindt, Pierre Legendre, Dan McGlinn, Peter R. Minchin, et al. 2019. ‘Vegan: Community Ecology Package’. https://CRAN.R-project.org/package=vegan.

Österreichische Bundesforste. 2023a. ‘Forstbetrieb Wienerwald’. In . https://www.bundesforste.at/wienerwald/der-forstbetrieb.html.

———. 2023b. ‘Trittsteine Im Biosphärenpark Wienerwald’. In . https://www.bundesforste.at/natur-erleben/biosphaerenpark-wienerwald/projekte/trittsteine.html.

Paillet, Yoan, Laurent Bergès, Joakim Hjältén, Péter Ódor, Catherine Avon, Markus Bernhardt-Römermann, Rienk-Jan Bijlsma, et al. 2010. ‘Biodiversity Differences between Managed and Unmanaged Forests: Meta-Analysis of Species Richness in Europe’. Conservation Biology 24 (1): 101–12. https://doi.org/10.1111/j.1523-1739.2009.01399.x.

Pakkala, Timo, Juha Tiainen, Markus Piha, and Jari Kouki. 2019. ‘Hole Life: Survival Patterns and Reuse of Cavities Made by the Lesser Spotted Woodpecker Dendrocopos Minor’. Ardea 107 (2): 173. https://doi.org/10.5253/arde.v107i2.a4.

Perry, Roger W., Julianna M. A. Jenkins, Ronald E. Thill, and Frank R. Thompson. 2018. ‘Long-Term Effects of Different Forest Regeneration Methods on Mature Forest Birds’. Forest Ecology and Management 408 (January): 183–94. https://doi.org/10.1016/j.foreco.2017.10.051.

Redolfi DeZan, Lara, Sarah Rossi de Gasperis, Luigi Fiore, Corrado Battisti, and Giuseppe Maria Carpaneto. 2016. ‘The Importance of Dead Wood for Hole-Nesting Birds: A Two Years Study in Three Beech Forests of Central Italy’. Israel Journal of Ecology & Evolution, August, 1–9. https://doi.org/10.1080/15659801.2016.1191168.

Renner, Swen C., and Willem van Hoesel. 2017. ‘Ecological and Functional Traits in 99 Bird Species over a Large-Scale Gradient in Germany’. Data 2 (2): 12. https://doi.org/10.3390/data2020012.

Roberge, Jean-Michel, and Per Angelstam. 2006. ‘Indicator Species among Resident Forest Birds – A Cross-Regional Evaluation in Northern Europe’. Biological Conservation 130 (1): 134–47. https://doi.org/10.1016/j.biocon.2005.12.008.

Roxburgh, Stephen H., Katriona Shea, and J. Bastow Wilson. 2004. ‘The Intermediate Disturbance Hypothesis: Patch Dynamics and Mechanisms of Species Coexistence’. Ecology 85 (2): 359–71. https://doi.org/10.1890/03-0266.

Schall, Peter, Martin M. Gossner, Steffi Heinrichs, Markus Fischer, Steffen Boch, Daniel Prati, Kirsten Jung, et al. 2018. 'The Impact of Even-Aged and Uneven-Aged Forest Management on Regional Biodiversity of Multiple Taxa in European Beech Forests'. Journal of Applied Ecology 55 (1): 267–78. https://doi.org/10.1111/1365-2664.12950.

Scherzinger, Wolfgang. 1991. 'Das Mosaik-Zyklus-Konzept Aus Der Sicht Des Zoologischen Artenschutzes'. Akademie Für Naturschutz Und Landschaftspflege, Laufener Seminarbeiträge, no. 5: 30–42.

Schieck, Jim, Marie Nietfeid, and J. Brad Stelfox. 1995. 'Differences in Bird Species Richness and Abundance among Three Successional Stages of Aspen-Dominated Boreal Forests'. Canadian Journal of Zoology 73 (8): 1417–31. https://doi.org/10.1139/z95-167.

Schulze, ED, D Craven, A Durso, J Reif, M Guderle, F Kroiher, P Hennig, et al. 2019. 'Positive Association between Forest Management, Environmental Change, and Forest Bird Abundance'. FOREST ECOSYSTEMS 6 (January). https://doi.org/10.1186/s40663-019-0160-8.

Schweizerische Vogelwarte Sempach. 2023. 'Vogelwarte Sempach'. Vogelwarte Sempach. 2023. https://www.vogelwarte.ch/de/home.

Sekercioglu, Cagan H. 2006. 'Increasing Awareness of Avian Ecological Function'. Trends in Ecology & Evolution 21 (8): 464–71. https://doi.org/10.1016/j.tree.2006.05.007.

Sekercioglu, Çağan H., Paul R. Ehrlich, Gretchen C. Daily, Deniz Aygen, David Goehring, and Randi F. Sandí. 2002. 'Disappearance of Insectivorous Birds from Tropical Forest Fragments'. Proceedings of the National Academy of Sciences 99 (1): 263–67. https://doi.org/10.1073/pnas.012616199.

Shea, Katriona, Stephen H. Roxburgh, and Emily S. J. Rauschert. 2004. 'Moving from Pattern to Process: Coexistence Mechanisms under Intermediate Disturbance Regimes'. Ecology Letters 7 (6): 491–508. https://doi.org/10.1111/j.1461-0248.2004.00600.x.

Steffan-Dewenter, I., and Teja Tscharntke. 1997. 'Early Succession of Butterfly and Plant Communities on Set-aside Fields'. Oecologia 109 (2): 294–302. https://doi.org/10.1007/s004420050087.

Stiles, Gary F. 1985. 'Stiles, F. GARY. "On the Role of Birds in the Dynamics of Neotropical Forests'. Conservation of Tropical Forest Birds, 1985.

Sutherland, William J., ed. 2006. Ecological Census Techniques: A Handbook. 2nd ed. Cambridge ; New York: Cambridge University Press.

Svensson, Lars. 2018. Der Kosmos Vogelführer. 2nd ed. Stuttgart: Frankh-Kosmos Verlags-GbmH & Co. KG.

Thiollay, JM. 1997. 'Disturbance, Selective Logging and Bird Diversity: A Neotropical Forest Study'. BIODIVERSITY AND CONSERVATION 6 (8): 1155–73. https://doi.org/10.1023/A:1018388202698.

Tozer, Douglas C., Dawn M. Burke, Erica Nol, and Ken A. Elliott. 2010. 'Short-Term Effects of Group-Selection Harvesting on Breeding Birds in a Northern Hardwood Forest'. Forest Ecology and Management 259 (8): 1522–29. https://doi.org/10.1016/j.foreco.2010.01.028.

Umweltbundesamt. 2023. Rote Liste Vögel Österreich. Spittelauer Lände 5, 1090 Wien. https://www.umweltbundesamt.at/umweltthemen/naturschutz/rotelisten/downloads-rl-tiere.

Vanderwel, Mark C., Jay R. Malcolm, and Stephen C. Mills. 2007. 'A Meta-Analysis of Bird Responses to Uniform Partial Harvesting across North America'. Conservation Biology: The Journal of the Society for Conservation Biology 21 (5): 1230–40. https://doi.org/10.1111/j.1523-1739.2007.00756.x.

Wesołowski, Tomasz, and Patryk Rowiński. 2012. 'The Breeding Performance of Blue Tits Cyanistes Caeruleus in Relation to the Attributes of Natural Holes in a Primeval Forest'. Bird Study 59 (4): 437–48. https://doi.org/10.1080/00063657.2012.722189.

# List of abbreviations

This table gives an overview and explanation of the abbreviations used in this study. The page number indicates the page where the abbreviation was first used.

| **Abbreviation** | **Meaning** | **Page** |
|---|---|---|
| BHD | Brusthöhendurchmesser | 5 |
| CEST | Central European Summertime | 10 |
| SD | Standard deviation | 11 |
| DBH | Diameter at breast height | 11 |
| AIC | Akaike information criterion | 11 |
| GLM | Generalised linear model | 11 |
| GLMM | Generalised linear mixed model | 11 |
| ANOVA | Analysis of variance | 12 |
| PERMANOVA | Permutational multivariate analysis of variance | 12 |
| NMDS | Non-metric multidimensional scaling | 12 |
| SE | Standard error | 13 |
| DF | Degrees of freedom | 20 |
| Sum of Sq | Sum of squares | 34 |

# Appendix

Table A1: Conservation status of the seven species only found either in the core or non-core zone, respectively, according to the red list of endangered birds of Austria.

| Exclusively found in | English name | Latin name | Conservation status |
|---|---|---|---|
| Core zone | Eurasian scops owl | Otus scops | endangered |
| | Eurasian woodcock | Scolopax rusticola | Near threatened |
| | Red-breasted flycatcher | Ficedula parva | Near threatened |
| | Short-toed treecreeper | Certhia brachydactyla | Least concern |
| | Crested tit | Lophophanes cristatus | Least concern |
| | Western jackdaw | Corvus monedula | Least concern |
| | Lesser spotted woodpecker | Dryobates minor | Least concern |
| Non-core zone | Eurasian wryneck | Jynx torquilla | vulnerable |
| | Willow warbler | Phylloscopus trochilus | Near threatened |
| | European bee-eater | Merops apiaster | Near threatened |
| | Grey-headed woodpecker | Picus canus | Near threatened |
| | Eurasian sparrowhawk | Accipiter nisus | Least concern |
| | European greenfinch | Chloris chloris | Least concern |
| | European starling | Sturnus vulgaris | Least concern |

Table A2: Summary of all results of the GLMMs for the visual data testing for the impact of the habitat parameters and the forestry management on the species richness, abundance and the Shannon Diversity Index. Significant impacts are marked in bold and with stars, trends are marked with points.

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value | |
|---|---|---|---|---|---|---|
| Species richness | DBH mean | 0.0088549 | 0.0069539 | 1.273 | 0.203 | |
| Species richness | DBH SD | -0.0016758 | 0.0115985 | -0.144 | 0.885 | |
| Species richness | Canopy cover mean | 0.0033026 | 0.0217755 | 0.152 | 0.879 | |
| Species richness | Canopy cover SD | 0.0754766 | 0.0576336 | 1.310 | 0.190 | |
| Species richness | Shrub cover mean | 0.0036481 | 0.0026488 | 1.377 | 0.168 | |
| Species richness | Forest age | 0.0011495 | 0.0052682 | 0.218 | 0.827 | |
| Species richness | Beech proportion | 0.0004913 | 0.0102347 | 0.048 | 0.962 | |
| Species richness | Slope | -0.0033340 | 0.0089107 | -0.374 | 0.708 | |
| Species richness | DBH mean | 0.2092214 | 0.1591005 | 1.315 | 0.189 | |
| Abundance | DBH mean | 0.010128 | 0.007869 | 1.287 | 0.1981 | |
| Abundance | DBH SD | -0.006812 | 0.013313 | -0.512 | 0.6089 | |
| Abundance | Canopy cover mean | -0.003251 | 0.024851 | -0.131 | 0.8959 | |
| Abundance | Canopy cover SD | 0.049490 | 0.065650 | 0.754 | 0.4509 | |
| **Abundance** | **Shrub cover mean** | **0.004848** | **0.002934** | **1.653** | **0.0984** | . |
| Abundance | Forest age | -0.000104 | 0.006126 | -0.017 | 0.9865 | |
| Abundance | Beech proportion | -0.004793 | 0.011397 | -0.420 | 0.6741 | |
| Abundance | Slope | -0.004453 | 0.010092 | -0.441 | 0.6590 | |
| Abundance | DBH mean | 0.341335 | 0.186074 | 1.834 | 0.0666 | |
| Shannon | DBH mean | 0.009117 | 0.011709 | 0.779 | 0.436 | |
| Shannon | DBH SD | -0.003629 | 0.019295 | -0.188 | 0.851 | |
| Shannon | Canopy cover mean | 0.001902 | 0.035228 | 0.054 | 0.957 | |
| Shannon | Canopy cover SD | 0.076018 | 0.093588 | 0.812 | 0.417 | |
| Shannon | Shrub cover mean | 0.003471 | 0.004391 | 0.790 | 0.429 | |
| Shannon | Forest age | 0.001298 | 0.008746 | 0.148 | 0.882 | |
| Shannon | Beech proportion | 0.000456 | 0.017005 | 0.027 | 0.979 | |
| Shannon | Slope | -0.003295 | 0.014849 | -0.222 | 0.824 | |
| Shannon | DBH mean | 0.227514 | 0.267803 | 0.850 | 0.396 | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = p < 0.1

Table A3: Summary of all results of the linear mixed-effects models for the auditive data testing for the impacts of the habitat parameters and the forestry management on the species richness, abundance and the Shannon Diversity Index. Significant impacts are marked in bold and with stars, trends are marked with points.

| Dependent variable | Independent variable | Value | SE | DF | t-value | p-value | |
|---|---|---|---|---|---|---|---|
| Species richness | DBH mean | -0.005931 | 0.024166 | 141 | -0.245442 | 0.8065 | |
| Species richness | DBH SD | 0.021901 | 0.042685 | 141 | 0.513083 | 0.6087 | |
| **Species richness** | **Canopy cover mean** | **-0.188010** | **0.086765** | **141** | **-2.166889** | **0.0319** | * |
| **Species richness** | **Canopy cover SD** | **0.508000** | **0.229540** | **141** | **2.213127** | **0.0285** | * |
| Species richness | Shrub cover mean | -0.003232 | 0.009643 | 141 | -0.335179 | 0.7380 | |
| Species richness | Forest age | 0.005048 | 0.016969 | 141 | 0.297457 | 0.7666 | |
| Species richness | Beech proportion | -0.024626 | 0.034823 | 141 | -0.707183 | 0.4806 | |
| Species richness | Slope | -0.040458 | 0.030575 | 141 | -1.323202 | 0.1879 | |
| Abundance | DBH mean | -0.04489 | 0.051343 | 141 | 0.874334 | 0.3834 | |
| Abundance | DBH SD | 0.01007 | 0.090689 | 141 | 0.111055 | 0.9117 | |
| **Abundance** | **Canopy cover mean** | **-0.34160** | **-0.34160** | **141** | **-1.853106** | **0.0660** | . |
| **Abundance** | **Canopy cover SD** | **1.30173** | **1.30173** | **141** | **2.669227** | **0.0085** | . |
| Abundance | Shrub cover mean | 0.01330 | 0.020488 | 141 | 0.649070 | 0.5173 | |
| Abundance | Forest age | 0.00212 | 0.036053 | 141 | 0.058756 | 0.9532 | |
| Abundance | Beech proportion | -0.08934 | 0.073986 | 141 | -1.207518 | 0.2293 | |
| **Abundance** | **Slope** | **-0.13757** | **-0.13757** | **141** | **-2.117719** | **0.0360** | * |
| Shannon | DBH mean | -0.0002577 | 0.001842 | 141 | -0.139952 | 0.8889 | |
| Shannon | DBH SD | 0.0019619 | 0.003253 | 141 | 0.603180 | 0.5474 | |
| **Shannon** | **Canopy cover mean** | **-0.0130178** | **0.006612** | **141** | **1.973282** | **0.0509** | . |
| **Shannon** | **Canopy cover SD** | **0.0345152** | **0.017491** | **141** | **1.973282** | **0.0504** | . |
| Shannon | Shrub cover mean | -0.0002801 | 0.000735 | 141 | -0.381142 | 0.7037 | |
| Shannon | Forest age | 0.0001340 | 0.001293 | 141 | 0.103607 | 0.9176 | |
| Shannon | Beech proportion | 0.0010690 | 0.002654 | 141 | 0.402858 | 0.6877 | |
| Shannon | Slope | -0.0017012 | 0.002330 | 141 | -0.73016 | 0.4665 | |

Significance codes: * = p < 0.05 |** = p < 0.01 |*** = p < 0.001 | Trend = p < 0.1

Table A4: Results from the PERMANOVA to test the species composition between the communities in the core zone and the non-core zone with the data from the auditive and the visual method. Significant impacts are marked in bold and with a star.

| Method | Independent Variable | DF | Sum of Sq | $R^2$ | F-value | p-value | |
|---|---|---|---|---|---|---|---|
| Auditive | DBH mean | 1 | 0.055 | 0.00107 | 0.8729 | 0.373 | |
| | DBH SD | 1 | 0.002 | 0.00004 | 0.0286 | 0.963 | |
| | Canopy cover mean | 1 | 0.027 | 0.00054 | 0.4345 | 0.517 | |
| | Canopy cover SD | 1 | 0.003 | 0.00006 | 0.0480 | 0.930 | |
| | Shrub cover mean | 1 | 0.016 | 0.00032 | 0.2606 | 0.704 | |
| | **Forest age** | **1** | **0.293** | **0.00572** | **4.6461** | **0.028** | * |
| | Beech proportion | 1 | 0.032 | 0.00063 | 0.5110 | 0.517 | |
| | Slope | 1 | 0.059 | 0.00115 | 0.9332 | 0.336 | |
| | Forestry management | 1 | 0.149 | 0.00290 | 2.3533 | 0.125 | |
| | Residual | 802 | 50.649 | 0.98758 | | | |
| | Total | 811 | 51.286 | 1.00000 | | | |
| Visual | **DBH mean** | **1** | **0.0818** | **0.01465** | **4.8853** | **0.018** | * |
| | DBH SD | 1 | 0.0022 | 0.00040 | 0.1337 | 0.774 | |
| | Canopy cover mean | 1 | 0.0083 | 0.00148 | 0.4940 | 0.496 | |
| | Canopy cover SD | 1 | 0.0002 | 0.00003 | 0.0114 | 0.965 | |
| | Shrub cover mean | 1 | 0.0169 | 0.00303 | 1.0116 | 0.317 | |
| | Forest age | 1 | 0.0055 | 0.00098 | 0.3278 | 0.578 | |
| | Beech prop | 1 | 0.0101 | 0.00181 | 0.6040 | 0.450 | |
| | Slope | 1 | 0.0052 | 0.00092 | 0.3074 | 0.626 | |
| | Forestry management | 1 | 0.0433 | 0.00775 | 2.5825 | 0.110 | |
| | Residual | 323 | 5.4110 | 0.96893 | | | |
| | Total | 332 | 5.5845 | 1.00000 | | | |

Significance codes: * = $p$ < 0.05 |** = $p$ < 0.01 |*** = $p$ < 0.001 | Trend = p < 0.1

Table A5: Results of the trait analysis for the feeding group with the auditive data. This table shows the relation of the feeding group and the bird abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

| Method: Auditive | | | | | | |
|---|---|---|---|---|---|---|
| **Random effect** | **Variance** | **Std. Dev** | | | | |
| **Feeding group** | 2.398e-09 | 4.897e-05 | | | | |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value | |
|---|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-2.129255** | **0.739207** | **-2.880** | **0.00397** | ** |
| Abundance | DBH mean | 0.006183 | 0.008530 | 0.725 | 0.46854 | |
| Abundance | DBH SD | 0.002033 | 0.016031 | 0.127 | 0.89906 | |
| Abundance | Canopycover mean | -0.031897 | 0.038821 | -0.822 | 0.41129 | |
| Abundance | Canopycover SD | 0.047085 | 0.101716 | 0.463 | 0.64343 | |
| **Abundance** | **Forest age** | **0.013810** | **0.005809** | **2.377** | **0.01744** | * |
| **Abundance** | **Beech proportion** | **0.036318** | **0.009252** | **3.925** | **8.66e-05** | *** |
| Abundance | Slope | -0.005897 | 0.013846 | -0.426 | 0.67016 | |
| **Abundance** | **Forestry management** | **-0.337498** | **0.159549** | **-2.115** | **0.03440** | * |

| Likelihood Ratio Test | DF | Log likelihood value | Chi2 | p-value | |
|---|---|---|---|---|---|
| Full model | 10 | 1462.61 | **1207.8** | **< 2.2e-16** | *** |
| Reduced model | 11 | 858.69 | | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$

Table A6: Results of the trait analysis for the feeding group with the auditive data. This table shows the relation of the feeding group and the Shannon Diversity Index. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

| Method: Auditive | | | | | |
|---|---|---|---|---|---|
| **Random effect** | **Variance** | **Std. Dev** | | | |
| **Feeding group** | 0.005818 | 0.07628 | | | |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value |
|---|---|---|---|---|---|
| Shannon Diversity Index | Intercept | 0.686701 | 0.904301 | 0.759 | 0.448 |
| Shannon Diversity Index | DBH mean | -0.002053 | 0.005151 | -0.398 | 0.690 |
| Shannon Diversity Index | DBH SD | 0.005523 | 0.009477 | 0.583 | 0.560 |
| Shannon Diversity Index | Canopycover mean | 0.011939 | 0.023091 | 0.517 | 0.605 |
| Shannon Diversity Index | Canopycover SD | -0.012758 | 0.058918 | -0.216 | 0.829 |
| Shannon Diversity Index | Forest age | -0.002160 | 0.004086 | -0.529 | 0.597 |
| Shannon Diversity Index | Beech proportion | -0.005924 | 0.007924 | -0.748 | 0.455 |
| Shannon Diversity Index | Slope | 0.002294 | 0.008247 | 0.278 | 0.781 |
| Shannon Diversity Index | Forestry management | 0.109993 | 0.098836 | 1.113 | 0.266 |

| Likelihood Ratio Test | DF | Log likelihood value | Chi2 | p-value |
|---|---|---|---|---|
| Full model | 10 | -111.72 | 1.1823 | 0.2769 |
| Reduced model | 11 | -111.12 | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$

Table A7: Results of the trait analysis for the feeding group with the auditive data. This table shows the relation of the nesting site group and the abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

| Method: Auditive | | |
|---|---|---|
| **Random effect** | **Variance** | **Std. Dev** |
| **Migratory behaviour** | 0.03638 | 0.1907 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value | |
|---|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-2.195658** | **0.744888** | **-2.948** | **0.0032** | ** |
| Abundance | DBH mean | 0.006043 | 0.008392 | 0.720 | 0.4714 | |
| Abundance | DBH SD | 0.002501 | 0.016028 | 0.156 | 0.8760 | |
| Abundance | Canopycover mean | -0.030864 | 0.038682 | -0.798 | 0.4249 | |
| Abundance | Canopycover SD | 0.017006 | 0.106055 | 0.160 | 0.8726 | |
| **Abundance** | **Forest age** | **0.013989** | **0.005753** | **2.432** | **0.0150** | * |
| **Abundance** | **Beech proportion** | **0.037444** | **0.009308** | **4.023** | **5.75e-05** | *** |
| Abundance | Slope | -0.008032 | 0.013422 | -0.598 | 0.5496 | |
| **Abundance** | **Forestry management** | **-0.339865** | **0.158381** | **-2.146** | **0.0319** | * |

| Likelihood Ratio Test | DF | Log likelihood value | Chi² | p-value | |
|---|---|---|---|---|---|
| Full model | 10 | -858.69 | 4.9073 | 0.02674 | * |
| Reduced model | 11 | -856.24 | | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = p < 0.1

Table A8: Results of the trait analysis for the feeding group with the auditive data. This table shows the relation of the nesting site group and the Shannon Diversity Index. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

| Method: Auditive | | |
|---|---|---|
| **Random effect** | **Variance** | **Std. Dev** |
| **Migratory behaviour** | 0.008852 | 0.09409 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value |
|---|---|---|---|---|---|
| Shannon Diversity Index | Intercept | 0.6858563 | 0.8874235 | 0.773 | 0.440 |
| Shannon Diversity Index | dbh_mean | -0.0008229 | 0.0050575 | -0.163 | 0.871 |
| Shannon Diversity Index | dbh_sd | 0.0046810 | 0.0092762 | 0.505 | 0.614 |
| Shannon Diversity Index | canopycover_mean | 0.0050327 | 0.0221787 | 0.227 | 0.820 |
| Shannon Diversity Index | canopycover_sd | -0.0039407 | 0.0581137 | -0.068 | 0.946 |
| Shannon Diversity Index | forest_age | -0.0017613 | 0.0039904 | -0.441 | 0.659 |
| Shannon Diversity Index | beech_prop | -0.0070059 | 0.0077822 | -0.900 | 0.368 |
| Shannon Diversity Index | slope | 0.0034164 | 0.0081146 | 0.421 | 0.674 |
| Shannon Diversity Index | Forestry_mgmt | 0.1125620 | 0.0969150 | 1.161 | 0.245 |

| Likelihood Ratio Test | DF | Log likelihood value | Chi² | p-value | |
|---|---|---|---|---|---|
| Full | 10 | -111.72 | 6.5109 | 0.01072 | * |
| Reduced | 11 | -108.46 | | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = p < 0.1

Table A9: Results of the trait analysis for the feeding group with the auditive data. This table shows the relation of the nesting site group and the bird abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

**Method: Auditive**

| Random effect | Variance | Std. Dev |
|---|---|---|
| **Nesting site** | 0.04606 | 0.2146 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value | |
|---|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-2.045352** | **0.713567** | **-2.866** | **0.00415** | ** |
| Abundance | DBH mean | 0.004683 | 0.008629 | 0.543 | 0.58732 | |
| Abundance | DBH SD | 0.006008 | 0.016409 | 0.366 | 0.71427 | |
| Abundance | Canopycover mean | -0.029450 | 0.039003 | -0.755 | 0.45021 | |
| Abundance | Canopycover SD | 0.046481 | 0.102635 | 0.453 | 0.65064 | |
| **Abundance** | **Forest age** | **0.013124** | **0.005860** | **2.240** | **0.02510** | * |
| **Abundance** | **Beech proportion** | **0.036551** | **0.009220** | **3.964** | **7.37e-05** | *** |
| Abundance | Slope | -0.006494 | 0.013820 | -0.470 | 0.63840 | |
| **Abundance** | **Forestry management** | **-0.324968** | **0.159229** | **-2.041** | **0.04126** | * |

| Likelihood Ratio Test | DF | Log likelihood value | $Chi^2$ | p-value |
|---|---|---|---|---|
| Full model | 10 | -858.69 | 3.3683 | 0.06646 . |
| Reduced model | 11 | -857.01 | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$

Table A10: Results of the trait analysis for the feeding group with the visual data. This table shows the relation of the feeding group and the bird abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

**Method: Visual**

| Random effect | Variance | Std. Dev |
|---|---|---|
| **Feeding group** | 6.626e-10 | 2.574e-05 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value | |
|---|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-3.857753** | **0.864836** | **-4.461** | **8.17e-06** | *** |
| Abundance | DBH mean | 0.019475 | 0.011213 | 1.737 | 0.082423 | . |
| Abundance | DBH SD | -0.003545 | 0.017645 | -0.201 | 0.840768 | |
| Abundance | Canopycover mean | -0.033861 | 0.036253 | -0.934 | 0.350299 | |
| Abundance | Canopycover SD | -0.068913 | 0.106308 | -0.648 | 0.516828 | |
| Abundance | Forest age | 0.003316 | 0.008110 | 0.409 | 0.682630 | |
| **Abundance** | **Beech proportion** | **0.038124** | **0.011512** | **3.312** | **0.000927** | *** |
| Abundance | Slope | 0.034163 | 0.017692 | 1.931 | 0.053492 | . |
| Abundance | Forestry management | 0.312006 | 0.207042 | 1.507 | 0.131820 | |

| Likelihood Ratio Test | DF | Log likelihood value | $Chi^2$ | p-value |
|---|---|---|---|---|
| Full model | 10 | -268.63 | 0 | 0.9998 |
| Reduced model | 11 | -268.63 | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$

Table A11: Results of the trait analysis for the migratory behaviour group with the visual data. This table shows the relation of the migratory behaviour group and the bird abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

**Method: Visual**

| Random effect | Variance | Std. Dev |
|---|---|---|
| **Migratory behaviour** | 1.461e-08 | 0.0001209 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value |
|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-3.857753** | **0.864837** | **-4.461** | **8.17e-06** *** |
| Abundance | DBH mean | 0.019475 | 0.011213 | 1.737 | 0.082423. |
| Abundance | DBH SD | -0.003545 | 0.017645 | -0.201 | 0.840768 |
| Abundance | Canopycover mean | -0.033861 | 0.036253 | -0.934 | 0.350300 |
| Abundance | Canopycover SD | -0.068913 | 0.106308 | -0.648 | 0.516828 |
| Abundance | Forest age | 0.003316 | 0.008110 | 0.409 | 0.682632 |
| **Abundance** | **Beech proportion** | **0.038124** | **0.011512** | **3.312** | **0.000927*** ** |
| Abundance | Slope | 0.034163 | 0.017692 | 1.931 | 0.053493. |
| Abundance | Forestry management | 0.312006 | 0.207043 | 1.507 | 0.131820 |

| Likelihood Ratio Test | DF | Log likelihood value | $Chi^2$ | p-value |
|---|---|---|---|---|
| Full model | 10 | 268.63 | 0 | 0.9998 |
| Reduced model | 11 | 268.63 | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$

Table A12: Results of the trait analysis for the nesting site group with the visual data. This table shows the relation of the nesting site group and the bird abundance. Significant impacts are marked in bold and with a star. However, I do not consider the models as robust and trustworthy and disregard the results.

**Method: Visual**

| Random effect | Variance | Std. Dev |
|---|---|---|
| **Nesting site** | 0.1511 | 0.3887 |

| Dependent variable | Independent variable | Estimate | SE | z-value | p-value |
|---|---|---|---|---|---|
| **Abundance** | **Intercept** | **-3.725957** | **0.837538** | **-4.449** | **8.64e-06** *** |
| Abundance | DBH mean | 0.014122 | 0.011445 | 1.234 | 0.21725 |
| Abundance | DBH SD | -0.008235 | 0.017738 | -0.464 | 0.64247 |
| Abundance | Canopycover mean | -0.017931 | 0.038345 | -0.468 | 0.64006 |
| Abundance | Canopycover SD | -0.051986 | 0.107438 | -0.484 | 0.62848 |
| Abundance | Forest age | 0.006772 | 0.008245 | 0.821 | 0.41147 |
| **Abundance** | **Beech proportion** | **0.035559** | **0.011531** | **3.084** | **0.00204** ** |
| Abundance | Slope | 0.027254 | 0.017665 | 1.543 | 0.12287 |
| Abundance | Forestry management | 0.177028 | 0.203631 | 0.869 | 0.38465 |

| Likelihood Ratio Test | DF | Log likelihood value | $Chi^2$ | p-value |
|---|---|---|---|---|
| Full model | 10 | 268.63 | 8.5935 | 0.003374** |
| Reduced model | 11 | 264.34 | | |

Significance codes: * = $p < 0.05$ |** = $p < 0.01$ |*** = $p < 0.001$ | Trend = $p < 0.1$