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Analysis of the influence of the presence of Black woodpecker (*Dryocopus martius*) cavities and the dendrometric characteristics of the stand on bird communities.


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I. Introduction

Forests are one of the most important habitats for biodiversity. These habitats represent 31% of the world's surface area and are home to 60% of all plant species, 68% of all mammals, 75% of all birds, and 80% of amphibians, highlighting their crucial role for all terrestrial groups (FOA, 2022). They provide protection, resources such as food or nesting opportunities and diverse ecological niches to many specialist species.

In France, forests cover 31% of the total surface area, with 75% of these forests privately owned and many managed for timber production (IGN, 2022). Although forest cover is increasing across Europe, this change is primarily due to agricultural abandonment since the 1940s and earlier regulations established to rationalize forest use, dating back to policies implemented by Colbert. Despite this increase, European forests are becoming less diverse (Langridge *et al.*, 2023). One proposed solution to counteract this biodiversity loss is the implementation of sustainable forest management (Miina *et al.*, 2020).

Measuring forest biodiversity and health involves characterizing the forest structure (Spies, 1998). Diversity in forest structure has been shown to increase overall forest biodiversity (Bouvet *et al.*, 2016; Myllymäki *et al.*, 2024). Various metrics and habitats are used to assess forest maturity and health, including the amount of dead wood, tree age and size, tree species composition (Myllymäki *et al.*, 2024), and the vertical and horizontal variations in canopy density (Spies, 1998). These traditional measurements, historically focused on wood production, often fall short in explaining the full distribution of biodiversity within forests. An essential additional metric is the number of microhabitats on trees (Vuidot *et al.*, 2011; Yoan Paillet *et al.*, 2018), which include diverse features such as tree crown skeletons, crown deadwood, fungal conks, cavities, cracks, and specific bark characteristics (Larrieu *et al.*, 2018). Microhabitats are not only easier and cheaper for forest managers to characterize but also more representative of animal diversity than standard structural measurements (Paillet *et al.,* 2018). Both microhabitat and traditional structural measurements are used to characterize forest stands as structural forest indicators.

To achieve sustainable forest management, it is crucial to develop and use biodiversity indicators alongside structural forest indicators. These indicators address challenges such as limited time, workforce, and expertise while providing traceability and robustness in management practices (Oettel and Lapin, 2021). Biodiversity indicators are metrics or measurements that are indicative of how biodiverse an area is, how many and which species are present or even if the community is healthy (Oettel and Lapin, 2021). Many forest-specific indicators are currently employed such as species persistence, ecosystem area or ecosystem health (Rowland *et al.*, 2020). Each of these indicators can be calculated from measurements or observations made over time but large-scale indicators are not the only ones used in the field. In animal biodiversity assessment, an indicator will often be a chosen species that is relatively common, easy to identify or track and sensitive to environmental variation (Oettel and Lapin, 2021).

In forests, one of the most common taxonomic groups used as indicators of bird diversity and mature forest habitats are woodpeckers (Grzegorz Mikusiński *et al.*, 2001; Drever *et al.*, 2008; Oettel and Lapin, 2021; Basile *et al.*, 2022). Woodpecker species (*Picidae*) are often considered umbrella species for forest dwelling bird conservation as they require large relatively unmanaged forested areas as well as sufficient volumes of dead wood (Garmendia, Cárcamo and Schwendtner, 2006; Bell *et al.*, 2015; Basile *et al.*, 2022) but also provide cavities for other species (Cockle, Martin and Wiebe, 2008; Colmant, 2016; Puverel *et al.*, 2019). Different species are considered indicators of different habitats. For instance, the white-backed woodpecker (*Dencocopos leucotos*) is often referred to as an indicator of mature forests with high levels of both standing and lying dead wood (Garmendia, Cárcamo and Schwendtner, 2006; Bell *et al.*, 2015). The presence of woodpeckers does not only concern dead wood volume, woodpeckers act as ecosystem engineers - due to their ability to modify their environment - as the cavities excavated by woodpeckers provide many other species such as fungi, other birds and mammals with access to the heart of trees as well as shelter (Cockle, Martin and Wesołowski, 2011; Colmant, 2016; Zahner, Bauer and Kaphegyi, 2017; Edworthy *et al.*, 2018; Puverel *et al.*, 2019; Trzcinski *et al.*, 2022).

There are 10 woodpecker species in Europe (Gorman, 2015), the largest of which is the Black woodpecker (*Dryocopus martius*). Though Black woodpeckers are forest specialists, they are also considered one of the more generalist woodpecker species as they do not rely solely on dead wood to excavate or feed (Pirovano and Zecca, 2014) and their range is ever expanding from Scandinavia to southern Europe and even the Middle-East (Rolstad, Majewski and Rolstad, 1998; Olano *et al.*, 2015; Karimi *et al.*, 2018; Fernández-García, 2022)(Figure 1).

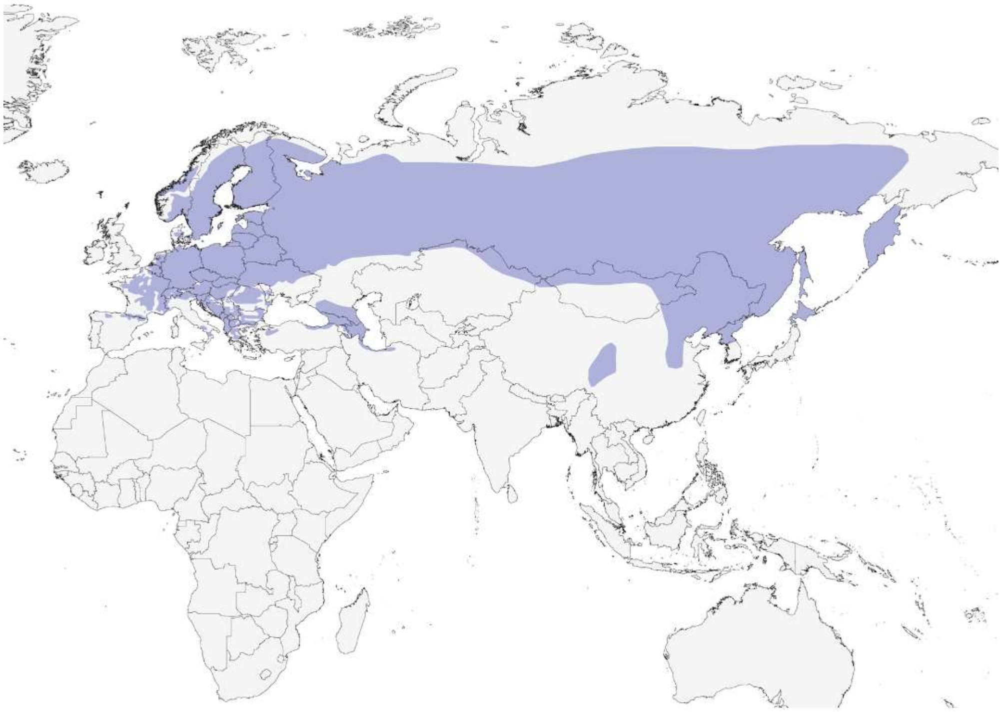


Figure 1: Black woodpecker (*Dryocopus martius*) distribution (source: Lynx Edicions/ Birdlife International).

The cavities of Black woodpeckers are of particular importance due to their size. These cavities can range from 20 to 25 cm in width and 40 to 55 cm in depth (Puverel *et al.,* 2019 ; Cusin, 1967) (Figure 2).

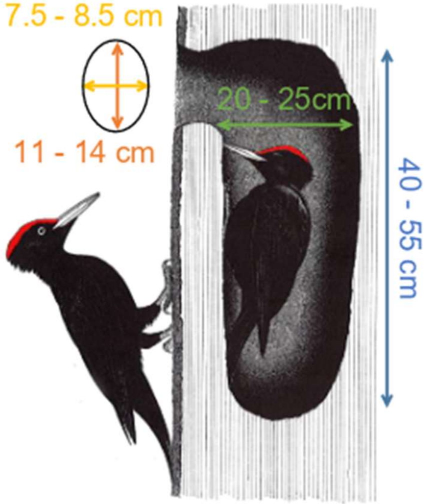


Figure 2: Edited Black woodpecker cavity representation indicating the average size of a cavity entrance (in yellow and orange), the cavity's width (in green) and its depth (in blue).

Black woodpecker cavities are excavated in living trees (Garmendia, Cárcamo and Schwendtner, 2006; Khanaposhtani *et al.*, 2012; Pirovano and Zecca, 2014) with a strong preference, in Western Europe, for trees over 25 cm in diameter within Beech tree stands (Pirovano and Zecca, 2014; Olano *et al.*, 2015; Zahner, Bauer and Kaphegyi, 2017). The excavated cavities are not only nesting holes but can also simply be roosting sites (Bocca, Carisio and Rolando, 2007; Pirovano and Zecca, 2014; Olano *et al.*, 2015). Excavation can accelerate the decomposition rate of the tree by providing access to the heart wood for fungi as well as saproxylic insects (Jusino *et al.*, 2016; Hebda and Błoszyk, 2024). With ever increasing forest management practices and the reduction of mature and old forest patches across the landscape (Miina *et al.*, 2020; Oettel and Lapin, 2021), these cavities can be especially important to large forest cavity nesters that cannot create their own cavities such as the Boreal Owl (*Aegolius funereus*), Pygmy Owl (*Glaucidium passerinum*), Stock doves (*Columba oenas*) and even some mammals such as the Pine martin (*Martes martes*) or Red squirrels (*Sciurus vulgaris*) (Brambilla *et al.*, 2013; Pirovano and Zecca, 2014; Colmant, 2016; Zahner, Bauer and Kaphegyi, 2017). Therefore, the size of both the cavities and home ranges of Black woodpeckers make it an important species to consider in European forestry and biodiversity retention. In this case, the cavity, acting as a structural forest indicator, could also be used as an indirect biodiversity indicator due to the presumed role of the Black Woodpecker in forest communities.

How we monitor avian indicator species is evolving. Bird point counts are still in effect in many studies but the rapid technological progress made in recent years has led to the increased use of passive monitoring devices in scientific studies (Budka, Kułaga and Osiejuk, 2021; Sandbrook *et al.*, 2021; Symes *et al.*, 2022). When monitoring specific bird species or a community, the most adapted passive monitoring devices are acoustic recorders. The use of autonomous sound recorders is comparable to human-led point count surveys with studies achieving statistically similar results using either method (Darras *et al.*, 2018; Blake, 2021). Some of the advantages of recordings are the standardisation of data collection and that these technologies allow for sampling in difficult conditions. Passive recorders can be set in the field to record at pre-determined times and do so automatically for long periods of time given the appropriate battery life.

Growing with the use of passive recording devices is the development of Artificial Intelligence software (AI) capable of identifying species. One of the most prominent AIs used for bird identification is BirdNet (https://github.com/kahst/BirdNET), a convolutional neural network created and maintained by the Cornell Lab of Ornithology (Kahl *et al.*, 2021; Pérez-Granados, 2023; Ware *et al.*, 2023). Convolutional neural networks are capable of learning from ever increasing datasets thanks to citizen science programs and imputed data to enable large amounts of data to be processed automatically with automated species identification (Clark *et al.*, 2023).

Acoustic recordings do not only allow for the identification of animals on a species level. The field of ecoacoustics has developed around the use of passive recordings in research (Sueur and Farina, 2015). Acoustic recordings enable the isolation and study of the soundscape, the totality of sounds occurring at a location (Pijanowski *et al.*, 2011; Gasc *et al.*, 2017), of a given environment. One of the most important means of communication in natural soundscapes is through the production of sound by individuals, most especially in complex bird communities. Representing species diversity, anthropogenic noise or even the complexity of soundscapes from a recording requires acoustic indices. These acoustic indices are metrics calculated from the amplitude, frequency and duration of sounds in a recorded environment (Barbaro *et al.*, 2022).

With the increasing use of technology in research, acoustic indices and convolutional neural networks can be used to study the communities around vocal indicator species such as the Black woodpecker.

This study is part of the wider TRAMETES project (https://trametes.hub.inrae.fr/le-projet-trametes) with a focus on recorded bird communities around Black woodpecker cavities in five forest habitats across France. We are considering the Black woodpecker as an ecosystem engineer that, through the excavation of large cavities, could act as an indicator species in mature forest habitats.

Therefore, we first hypothesised that the presence of Black woodpecker cavities at a given site would increase the number of bird species detected then in the absence of a cavity. Since the response of species may depend on different ecological traits this hypothesis was tested on four levels: the whole bird community, cavity nesting species, then forest specialist species and finally on an individual species level. Cavity nesting species are expected to increase in numbers in cavity plots and rely more on the presence of a cavity. Forest specialists and overall species numbers are also expected to increase in cavity plots as they include many cavity nesting species.

Due to the environmental preferences of *Dryocopus martius*, we also hypothesised that the composition of a community would change between cavity nesting individuals and non-forest specialists depending on the type, with or without a cavity, of the plot with more mature forest specialist species preferring cavity prone areas.

Then, we wanted to investigate whether it is the presence of the cavity itself or the influence of the surrounding environment that could impact any species distributions. We included environmental variables that represent the cavity excavation site preferences of Black woodpeckers to evaluate how higher forest maturity could lead to an increase of species (Bouvet *et al.*, 2016), as opposed to just the presence of a cavity.

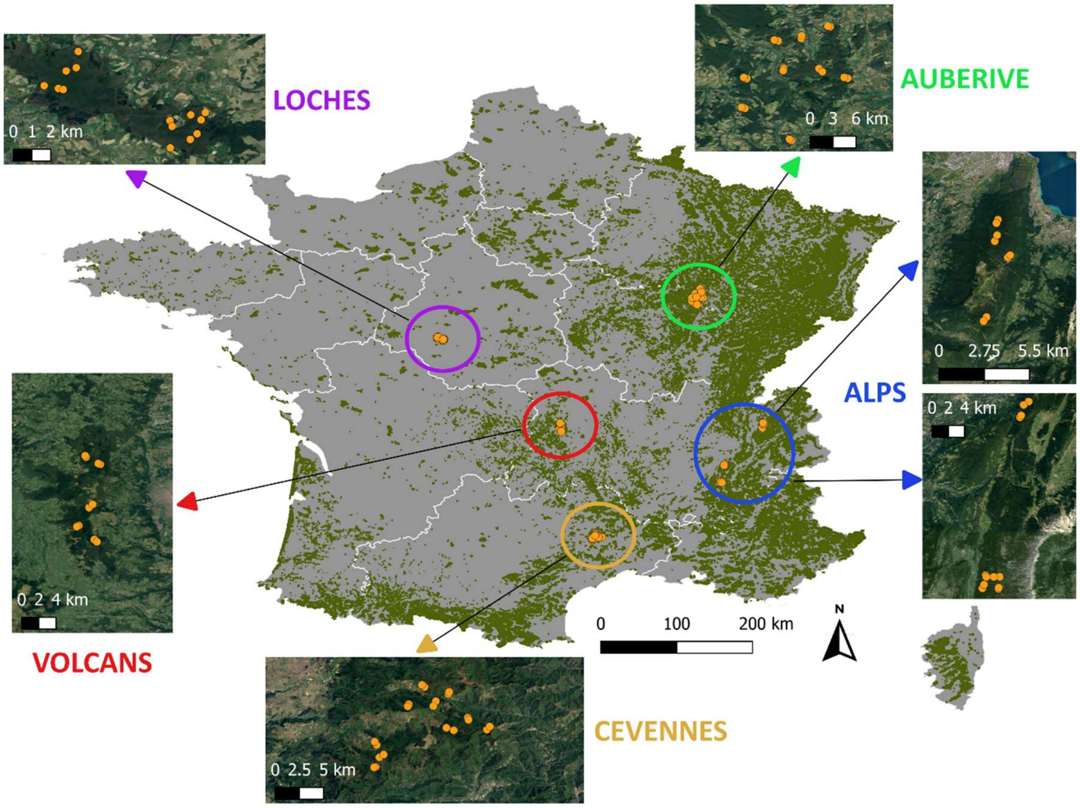
Finally, as recordings were used for this study, we investigated two ecoacoustic hypotheses. First of all, we hypothesised that anthropogenic noise would be reduced in cavity plots as an anthropogenic avoidance tactic of the black woodpecker when excavating the cavity. We also hypothesised that the soundscape in cavity plots would be more diverse and result in higher acoustic index scores.

The main objective of this study was to demonstrate the relative importance of Black woodpecker cavities, as a structural biodiversity indicator, to forest bird communities. In order to reach this objective as well as utilise the format of our data, the second objective of this study was to use both classic biodiversity indices (species richness calculations) and more novel acoustic indices to represent and study the biodiversity of forest bird communities.

II. Materials and Methods

II.1. Study design

Eighty plots were selected across 5 forest sites in Metropolitan France (Map 1). The plots are paired and half have a Black woodpecker cavity on a beech tree at their centre and the other half are control plots with no cavity on the central tree. Only the cavities on the central trees of plots were confirmed as genuine cavities. Therefore, though other tree cavities were noted, we focused on the central tree and did not retain the total number of potential cavities on a plot in our analyses. The paired plots were selected randomly within an 850m zone around the chosen cavity plot prior to fieldwork so that they are both within the Black Woodpecker’s extended home range. Each pair of plots must also be within a difference of altitude of no more than 100 m, a similar slope (less than 20 % difference) and have the same exposure and forest type. The cavity plots were selected from data collected in the field by forest managers, these sites were randomly selected from this data and the supposed cavities were then confirmed to be genuine cavities using a camera on an extendable pole in the field. Each site contains at least 5 pairs.



Map 1: Map of the 5 forest sites and 80 plots. All French public forests are shown in green on the central map of Metropolitan France.

The sites were distributed across two types of forest: 30 in lowland (Loches and Auberive) and 50 in mountainous (Volcans, Cevennes and Alps) forests. All plots were in locations away from high levels of human activity such as towns, roads and highly used footpaths. All the forests are managed except the Hauts plateaux du Vercors which is an unmanaged strict forest reserve in the Alps (Vercors).

II.2. The dendrometric variables

At every site, dendrometric measurements were taken. Dendrometric measurements are measurements of tree and stand attributes. The Protocole de Suivi Dendrométrique des Réserves Forestières (PSDRF) protocol was used to collect tree measurements in every plot (Appendix 1).

This protocol was created by French forestry organisations (the Office National des Forêts (ONF), INRAE, AgroParisTech and ENGREF (Ecole national du genie rural, des eaux et des forêts, the Réserves Naturelles de France (RNF), CEMAGREF (Centre d'Etudes du Machinisme Agricole, du Génie Rural, des Eaux et Forêts) and the Observatoire des Forêts sentinelles) in order to standardize dentrometric measurements in forest reserves on a national scale, and more specifically to enable consistent data collection on dead wood volume and continuity. The protocol is applied to permanent plots which can be measured originally to represent an initial forest conservation status and then again at a later date to measure any changes in composition or structure over time or after a change in management strategy.

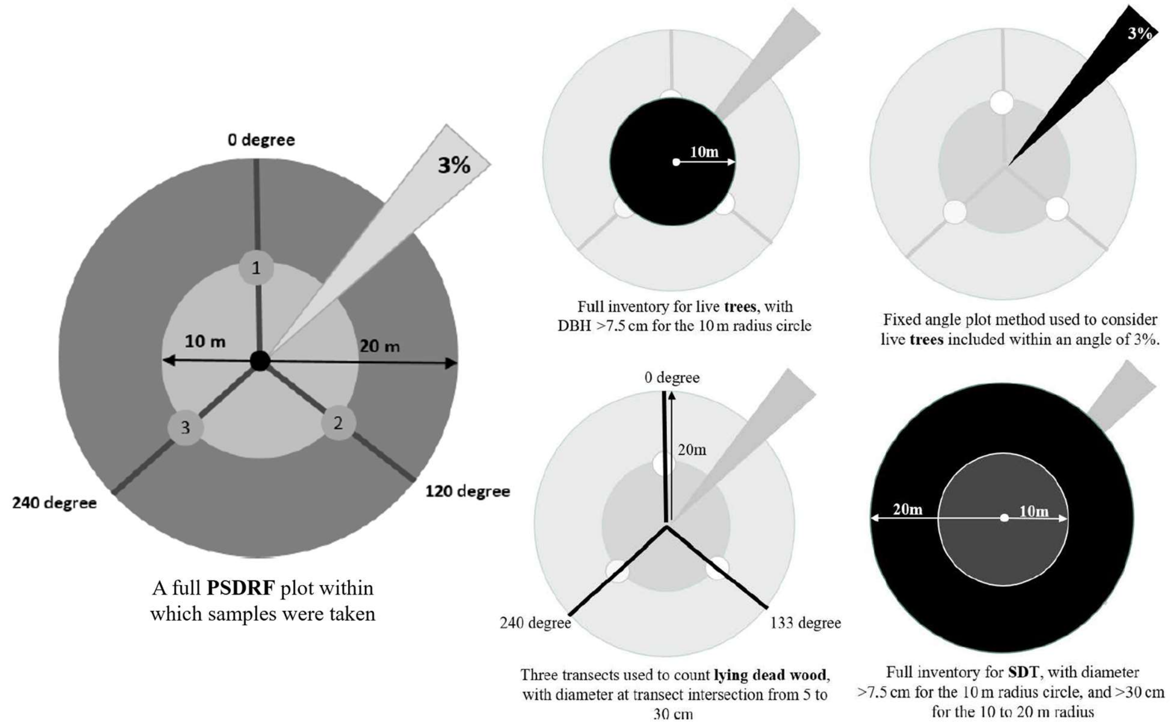
At the centre of each plot is a living tree either with or without a cavity. There are multiple categories of measurements: living trees, dead trees, regeneration in the understory and microhabitat identification. Measurements representing the environmental preferences of Black woodpecker cavity excavation behaviour were retained: mean living tree diameter (mean DBH : measured at breast height (130 cm)), the percentage of Beech trees (Beech %) and the total dead wood volume (V.DW : both standing and lying dead trees).

The mean DBH measurements were recorded in three steps as detailed by Cateau et al. (2024). Any living trees and snags (standing dead trees over 1.30 m) within 7.5 to 30 cm of diameter (DBH) were measured within 10 m of the central tree (314 m^2) (Figure 3).

Living trees with a DBH over 30 cm were recorded using a fixed angle plot method within a relascopic angle of 3 % (Figure 3). The height and DBH of the smallest living trees, with under 7.5 cm DBH, were included within three 1.5 m radius subplots.

Snags with a DBH over 30 cm were recorded within 20 m of the central plot point (Figure 3).

Lying dead wood was included with a DBH between 5 and 30 cm and when it came into contact with one of 3 transects. These 20 m transects started at the centre of the plot and were at 0, 133 and 240 degrees (Figure 3) (Cateau *et al.*, 2024). Lying and standing dead wood values were added together to calculate one total dead wood volume metric.



A full **PSDRF** plot within which samples were taken

Full inventory for live **trees**, with DBH >7.5 cm for the 10 m radius circle

Fixed angle plot method used to consider live **trees** included within an angle of 3%.

Three transects used to count **lying dead wood**, with diameter at transect intersection from 5 to 30 cm

Full inventory for **SDT**, with diameter >7.5 cm for the 10 m radius circle, and >30 cm for the 10 to 20 m radius

Figure 3: Graphical representation of the dendrometric sampling methods performed in each plot. DBH: Diameter at breast height, SDT: Standing dead wood (Cateau *et al.,* 2024).

Volume and basal area were estimated per tree and then added together to calculate a plot wide metric per hectare. Specific beech tree basal area was calculated to be represented per hectare following the equation: $g = (\pi \times DBH1^{2})/(40000)$ x eqn (4) (Cateau *et al.,* 2024).

Volume was determined from four production tables (Cateau *et al.,* 2024). The percentage of Beech trees per plot was determined from the Beech tree basal area in order to best represent Beech tree coverage per hectare.

One pair of plots in Loches had to be removed from the study due to the presence of an undetected cavity on the control plot. A further four pairs, one in the Cevennes, two in Auberive and one in the Alps, were also removed due to the previously recorded cavities in the experimental plots actually being cavity initiations (Appendix 2: Table A).

II.3. The recordings

Over a period of 5 months, between bird migration seasons, one recorder (Figure 4), designed and maintained by fold ecosystemics for this study (https://eco.fold.ai/), was installed at the centre of each cavity and control plot. Two sessions of 30 minutes were recorded at a maximum of 16 kHz with 10 minutes either side up to 110 kHz. One session took place 25 minutes before sunrise and one session 25 minutes before sunset. Over 11 700 hours of recording which equates to 6.6 terabytes of data were collected. Only the morning sessions with recordings up to 16 kHz were retained emulating an extended bird point count each morning.

Figure 4: Photograph of a foldAI ecoacoustic recorder in place on a central tree.

The recording period included spring and summer, excluding most of the bird migratory period. Due to technical difficulties, the number of successful recording days was highly variable with one plot only recording for 5 days whereas other sites recorded over 100 days. Due to devices being stolen or malfunctioning, recordings in Auberive had to be repeated in 2023, as opposed to 2022 when the recordings originally took place. Many sites recorded until early July, however the one in the Volcans recording only started in July. Therefore, in order to best address the unequal number of recorded days over an extended period, the recording period was set from 01-05 to 23-09 in both 2022 and 2023 and 5 days were randomly selected for each plot (Appendix 3). The recordings retained represented a total of two and a half hours of acoustic bird surveys per plot between migration periods.

II.4. Species data preparation

The audio files were downloaded and compiled by foldAI onto a hard drive. This data was then fed into BirdNET where species were automatically detected and identified. This step was undertaken at INRAE Avignon by Thomas Delattre and processed on their servers over a three week period.

Only detections identified with over 95% confidence by BirdNET's AI were retained. The table was reduced by selecting the species name, plot, date and time of day of each BirdNET identification event to generate a table containing the species present in the morning on the pre-selected days for each plot. The dendrometric measurements were then added to this table for analysis. The species data was then split into four categories: the species richness per plot, cavity specialists and forest specialists (calculated with the vegan package (Oksanen *et al.,* 2024)) as well as on an individual species level. When considering occurrence analysis, as in Bouvet *et al.* (2016), the more typical 20-80 % species retention range was expanded to 15 - 85% over the total dataset (Appendix 4). This adjustment was made to exclude species that are either overly common and dominant or very rare, while still retaining species of interest to our study, particularly cavity specialists. In order to assess the influence of each variable on the individual bird species retained, the presence or absence of each species was ascertained for each plot.

During this process, one pair of plots in the Alps was removed from the analysis due to one of the plots not containing any species identifications above the 95% threshold after extraction from BirdNET. Sixty-eight plots were therefore retained for the analysis (Appendix 2 : Table B).

II.5. Acoustic diversity indices

Five acoustic indices were calculated from the left channel (Gasc *et al.*, 2017): Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Bioacoustic Index (BI), Normalised Difference Sound Index (NDSI) and Number of frequency peaks (NP).

Acoustic Complexity Index is a metric used to quantify the diversity and complexity of soundscapes by measuring the variation in sound intensity across different frequency bands and time intervals, reflecting the richness and abundance of acoustic activity such as bird song. ACI values vary from 800 to 2000 in our data and higher values represent higher richness and abundance of acoustic activity (Pieretti, Farina and Morri, 2011; Alcocer *et al.*, 2022). This index is considered one of the less sensitive to anthropogenic noise because it focuses on the variability of sound intensities, which is a characteristic of biotic sounds, while human generated noise (e.g. motors) tend to be more constant.

Acoustic Diversity Index enables the diversity of sound sources to be assessed by quantifying the variety of acoustic signals, analysing the distribution of sound energy across frequency bands and time envelopes. It is based on a derivation of the classical Shannon index. Higher values of ADI reflect greater diversity of sound producing species (Sueur, 2018; Alcocer *et al.*, 2022). ADI values vary between 0 and 2.05 in our data. This index should be interpreted with caution in the presence of dominant background anthropogenic noise, as it may lead to counter-intuitive results.

Bioacoustic Index quantifies the intensity of biophonic activity across specific frequency ranges. Higher values indicate greater biological activity (Boelman *et al.*, 2007; Alcocer *et al.*, 2022). BI scores in our data varied between 0 and 50.

Normalised Difference Sound Index is used to evaluate the balance between sounds of human and natural origin within an environment. Higher values indicate a greater presence of natural sounds relative to anthropophonic sounds (Sueur, 2018; Alcocer *et al.,* 2022). NDSI values are calculated with a score between 0 and 1.

Number of frequency peaks is a metric representing individual or overlapping vocalisations, or sound events, in an environment. High NP values indicate greater acoustic complexity and activity (Sueur, 2018). The NP values in our data varied between 0 and 40. NP is based on the assumption that more species produce more frequency peaks. It is considered insensitive to noise as residual frequency peaks should be automatically discarded. However, it may be sensitive to single species producing intense, noise-like sounds (e.g. Cicadas) which may give higher NP than several species producing pure tones.

In order to homogenise the acoustic and species variables, the same 5-day period was applied to the generation of acoustic indices. These indices were calculated over each 1-minute period of recorded data using the “seewave” package in RStudio (Sueur *et al*., 2008) and subsequently averaged per morning and plot following Barbaro *et al.* (2022).

II.6. Statistical analysis

Generalised mixed models were built using the “glmmTMB” package in RStudio (Brooks *et al*., 2017). We tested a total of 8 biodiversity and acoustic indices as response variables, 3 species richness calculations and 5 acoustic indices. Each of the 20 species retained for our occurrence analysis were also individually tested as response variables.

In order to answer our main hypothesis investigating any influence of the presence of a cavity and the surrounding bird community, the interaction between the three environmental variables and the altitude of each plot with the type of plot were used to build the full model. The three environmental variables retained as explanatory variables in this analysis, mean DBH, percentage beech trees and VDW, were scaled in order to compare the magnitudes between effects as well as to aid model convergence. These variables were chosen as they are considered important to Black woodpecker cavity excavation behaviour and will be used to check whether the environment around cavities is the actual biodiversity driver compared to the presence of a cavity. The variables were tested for any potential correlations (“corrplot” package (Wei and Simko, 2021)). In addition to these 3 response variables, the altitude and type of plot (cavity vs. control) were also included as explanatory variables (lowland vs. mountain). Data exploration revealed a potential interaction between the altitude and the type of plots.

Finally, the forest site and pair to which each plot belongs was set as a random effect to control for the higher resemblance between paired plots within a given site.

However, due to the small size of the datasets and the fact that multiple species are absent from both experimental (cavity) and control (non-cavity) plots when reduced to species specific level, the random effect for the 20 species specific models was set to include only the forest site as the similarity of plots is encapsuled in the similarities of the site too.

Furthermore, the Middle-spotted woodpecker was only detected in lowland sites and so mountainous sites were excluded for this species.

The three measures of species richness were slightly under-dispersed, meaning the variance was less than the mean. To account for this, we modelled them using the Conway-Maxwell Poisson (COM-Poisson) distribution with a log link, as implemented in the "glmmTMB" package. This distribution is flexible and can handle both over-dispersed and under-dispersed count data, making it suitable for our needs.

The NDSI data was continuous but constrained between 0 and 1, suggesting a beta distribution with a logit link. The beta distribution is ideal for modelling proportions and continuous data bounded within the [0, 1] interval, as it can take on a variety of shapes depending on its parameters.

Other bio-acoustic response variables, including the BI, ACI, ADI, and NP, were continuous and positive. These variables were skewed or exhibited high variability and were not confined within the 0 to 1 range. Therefore, we modelled them using the Gamma distribution (with a log link), which is well-suited for positive continuous data that are skewed. The Gamma distribution can effectively handle data with a wide range of variability, providing a flexible fit for our bio-acoustic measurements.

The presence data for each species was binary, indicating whether the species was present or absent. This type of data follows a Bernoulli distribution, which is appropriate for modelling binary outcomes.

Backward elimination, with an AICc 2-point difference, was performed on the remaining models from the full model. After which, when the difference was below 2 AICc points, the model with the lowest number of parameters was retained. The full model tests one of the response variables against the four interactions mentioned previously: the type of plot (cavity or control) interacting with the Altitude of each plot, mean DBH, VDW and the percentage cover of Beech trees for each plot. An example of a full model is written below:

glmmTMB(Plot_Species_Richness ~ Type * Altitude + Type * scale (V.DW) + Type * scale (mean DBH) + Type * scale (Beech %) + (1|Code massif/Pair), data, family = compois (link = "log"))

Due to full model convergence problems, where the full model was overfitted, the low detection rates for the Middle-spotted woodpecker in both experimental and control plots and the low numbers of Green woodpeckers in control plots, all possible model combinations were tested manually and the model with lowest Corrected Akaike Information Criterion (AICc) value by 2 points was selected.

I. Results

III.1. Biodiversity indices

After a Pearson’s correlation test (“Hmisc” package (Harrell, 2024)) with a p-value threshold of 0.05, none of the three variables tested were correlated and could be added as independent fixed effects (Table 1).

Table 1: Correlation matrix of the chosen environmental variables. On the bottom-left, in grey, are the correlation slopes and top-right, in blue, their associated p-values.

	Beech %	DBH	V.DW
Beech %	-	0.62	0.20
DBH	- 0.05	-	0.76
V.DW	- 0.13	0.03	-

The final models for each of the 8 diversity indices studied retained just one explanatory variable each (Table 2).

Table 2: Final generalised linear mixed biodiversity index models after backward elimination. The estimators were standardised with the scaling of numeric values. Standard error values are indicated in brackets. The significance of each effect is indicated by “.”, “*”, “**” and “***”.

	Indices	Intercept	Cavity plot	Lowland	Mean diameter
Species richnesses	**Plot**	**1.88 (0.05)*****	-	-	**0.1 (0.05)***
	Cavity specialists	**1.03 (0.12)*****	-	-	**0.2 (0.06)*****
	Forest specialists	**1.34 (0.09)*****	-	-	**0.17 (0.06)****
Acoustic indices (averaged left)	**BI**	**3.1 (0.06)*****	-	-	-
	ACI	**6.85 (0.04)*****	-	-	-
	ADI	**0.69 (0)*****	-	**-0.01 (0)***	-
	NDSI	**0.61 (0.09)*****	-	**0.53 (0.16)****	-
	NP	**3.04 (0.07)*****	**0.04 (0.02)***	-	-

All three levels of species richness (plot specific, cavity specialists and forest specialists) showed a positive relationship with living tree mean diameter (DBH) only. The larger the trees per plot the more species would be present (Table 2). Cavity and forest specialists were influenced twice as strongly as the overall species count per plot.

The null model was selected for two of the ecoacoustic indices, BI and ACI. ADI was very slightly lower in lowland plots, whereas NDSI was higher in lowland plots. NP was significantly higher in plots with a cavity then control plots (Table 2).

III.1.a. Species richness indices

As the average living tree diameter increases across sites, all three species richness metrics also increase. An increase in 20 cm of mean diameter increases species richness by one species per plot and around one and half species for forest and cavity specialists. The strongest effect by a very small margin was seen for cavity species (Figure 5).

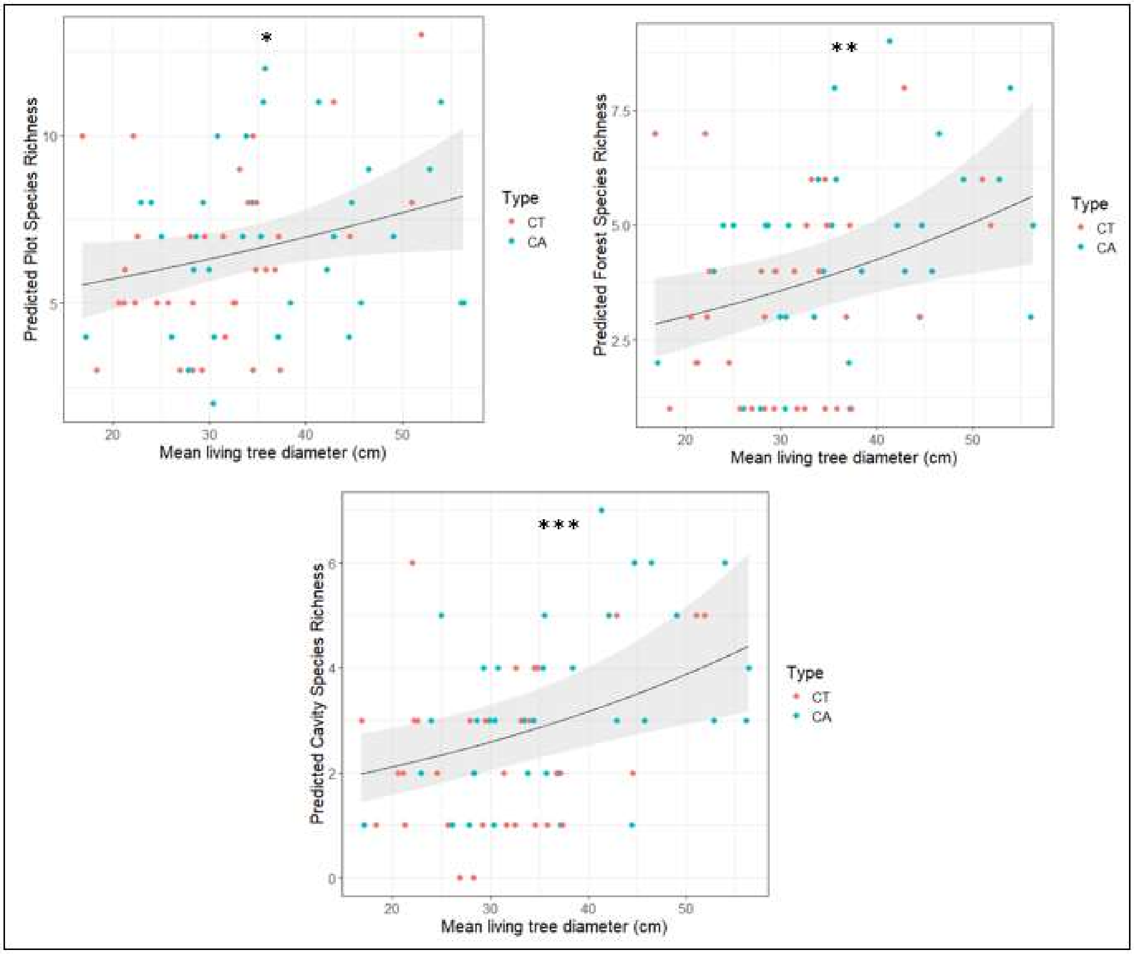


Figure 5: Graphical representations of the predictions generated by each of the species richness final models. Each species richness is plotted against mean DBH. The values for each control (CT, in red) and cavity plot (CA, in blue) are represented on each graph. Plot species richness is on the top left; Forest specialist richness on the top-right and cavity specialist species richness on the bottom. The significance of each effect is indicated by "*", "**" and "***".

III.1.b. Bio-acoustic indices

The bio-acoustic index ADI had a marginally higher range in mountainous areas. The opposite is true for NDSI where lowland plots experience higher levels of NDSI associated sounds (Figure 6).

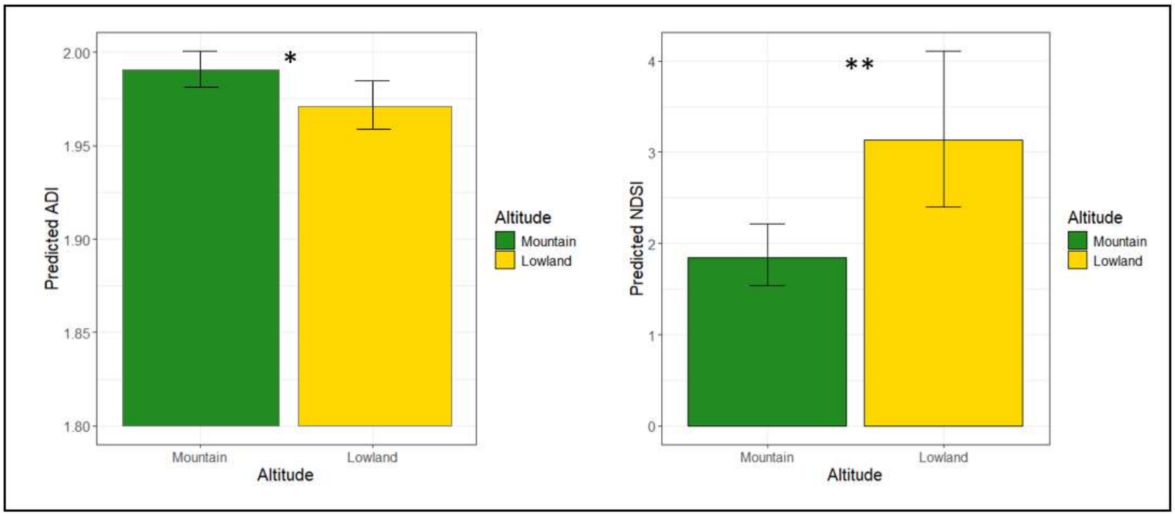


Figure 6: Barplot representing the variation in ADI (left) and NDSI (right) according to the Altitude of the plot. Mountain plots are in green and lowland plots are in yellow. The significance of each effect is indicated by "*" and "**".

The NP index was slightly elevated in cavity plots compared to control sites (Figure 7).

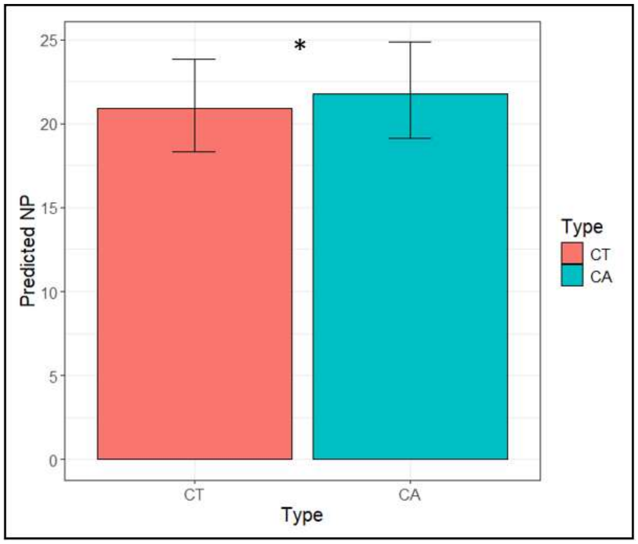
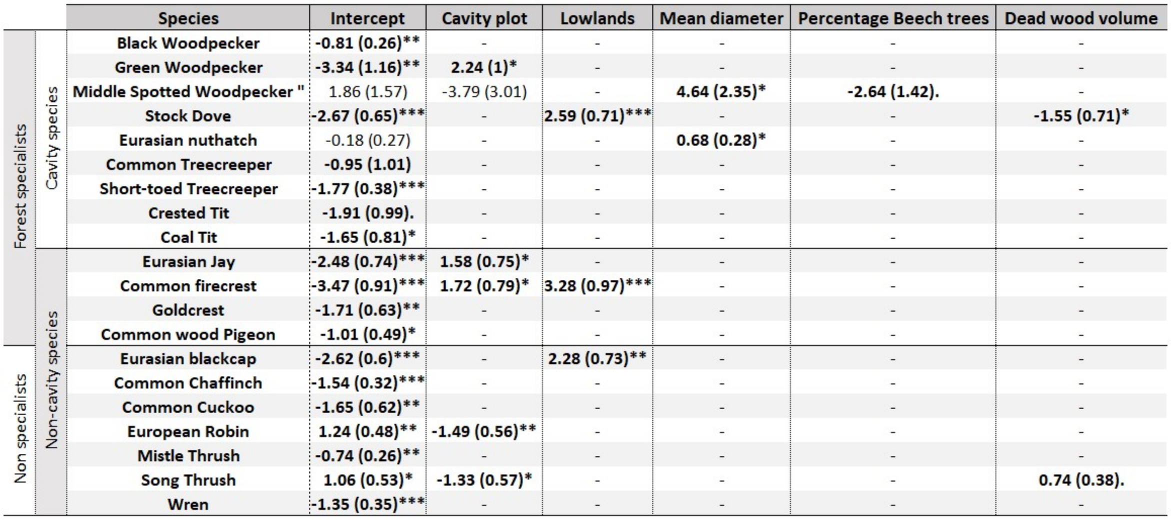


Figure 7: Barplot representing the variation in NP according to the Type of plot. Cavity plots (CA) are in blue and control plots (CT) in red. The significance of the effect is indicated by "*".

III.2. Species specific results

Twenty species were retained in the final presence analysis. Many of the models retained per species were the null model (Table 3).

Table 3: Final generalised linear mixed species models after backward elimination. The Middle-spotted woodpecker was only found in lowland plots (“). The estimators were standardised with the scaling of numeric values. Standard error values are indicated in brackets. The significance of each effect is indicated by “.”, “*”, “**” and “***”.



		Species	Intercept	Cavity plot	Lowlands	Mean diameter	Percentage Beech trees	Dead wood volume
Forest specialists	Cavity species	**Black Woodpecker**	**-0.81 (0.26)****	-	-	-	-	-
		Green Woodpecker	**-3.34 (1.16)****	**2.24 (1)***	-	-	-	-
		Middle Spotted Woodpecker "	1.86 (1.57)	-3.79 (3.01)	-	**4.64 (2.35)***	**-2.64 (1.42).**	-
		Stock Dove	**-2.67 (0.65)*****	-	**2.59 (0.71)*****	-	-	**-1.55 (0.71)***
		Eurasian nuthatch	-0.18 (0.27)	-	-	**0.68 (0.28)***	-	-
		Common Treecreeper	**-0.95 (1.01)**	-	-	-	-	-
		Short-toed Treecreeper	**-1.77 (0.38)*****	-	-	-	-	-
		Crested Tit	**-1.91 (0.99).**	-	-	-	-	-
		Coal Tit	**-1.65 (0.81)***	-	-	-	-	-
	Non-cavity species	**Eurasian Jay**	**-2.48 (0.74)*****	**1.58 (0.75)***	-	-	-	-
		Common firecrest	**-3.47 (0.91)*****	**1.72 (0.79)***	**3.28 (0.97)*****	-	-	-
		Goldcrest	**-1.71 (0.63)****	-	-	-	-	-
		Common wood Pigeon	**-1.01 (0.49)***	-	-	-	-	-
Non specialists		**Eurasian blackcap**	**-2.62 (0.6)*****	-	**2.28 (0.73)****	-	-	-
		Common Chaffinch	**-1.54 (0.32)*****	-	-	-	-	-
		Common Cuckoo	**-1.65 (0.62)****	-	-	-	-	-
		European Robin	**1.24 (0.48)****	**-1.49 (0.56)****	-	-	-	-
		Mistle Thrush	**-0.74 (0.26)****	-	-	-	-	-
		Song Thrush	**1.06 (0.53)***	**-1.33 (0.57)***	-	-	-	**0.74 (0.38).**
		Wren	**-1.35 (0.35)*****	-	-	-	-	-

The presence of the Green woodpecker, Eurasian Jay and European Robin was impacted by the type of plot: cavity or control (Table 3 and Figure 8). Both the Green woodpecker and the Eurasian Jay were predicted to occur more often in plots with a cavity than control plots. The European Robin however is predicted to prefer control plots without cavities (Figure 8).

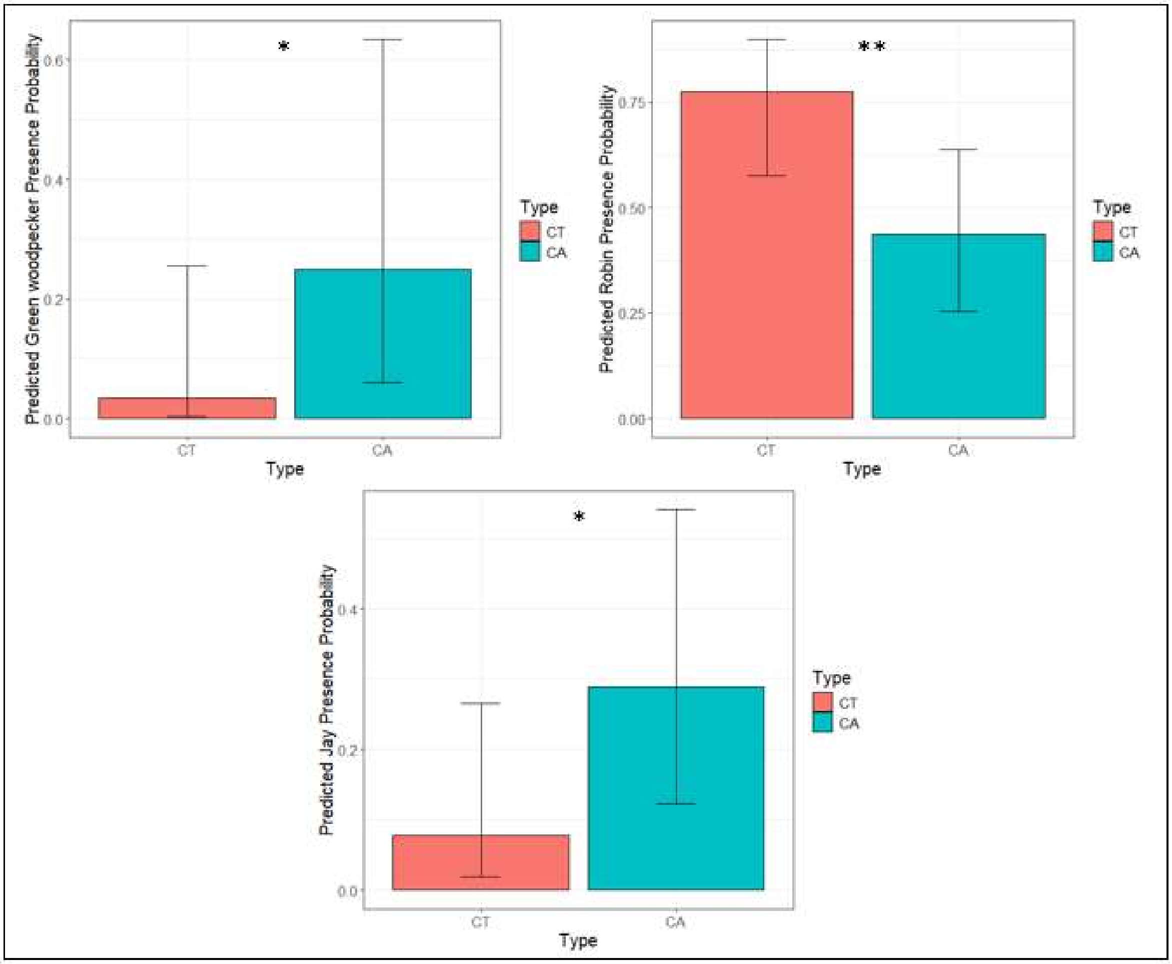


Figure 8: Barplots representing the predicted presence of the Green woodpecker (top left), European Robin (top right) and the Eurasian Jay (bottom) according to whether the plot is a control (CT, in red) or cavity (CA, in blue) plot. The significance of each effect is indicated by "*" and "**".

The Eurasian Blackcap was present more often in lowland plots. Common Firecrest presence increased in lowland plots with a cavity on the central tree (Table 3 and Figure 9).

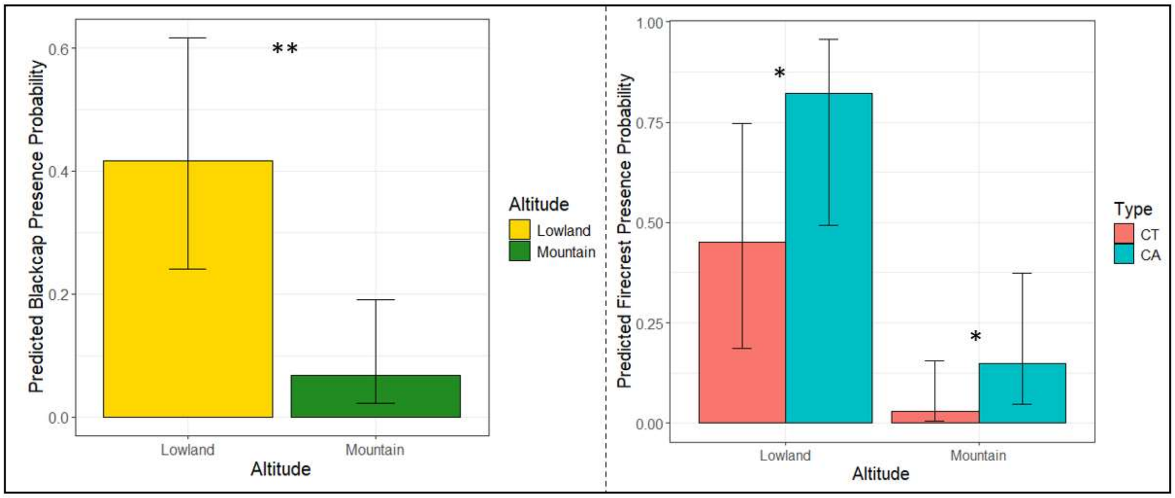


Figure 9: Barplots representing the predicted presence of the Eurasian Blackcap according to the Altitude of the plot (left) and the Firecrest according to both the Altitude (Mountain or Lowland) and Type (cavity or control). Mountain plots are in green and lowland plots in yellow for the Blackcap barplot (left). Cavity plots (CA, in blue) and control plots (CT, in red) are represented by colour in the Firecrest barplots (right). The significance of each effect is indicated by "*" and "**". The altitudinal effect, between lowland and mountain plots, was also strongly significant for the Firecrest (p-value: < 0.001).

However, for the Eurasian Nuthatch it was the increase in mean living tree diameter that increased its presence in plots (Table 3 and Figure 10).

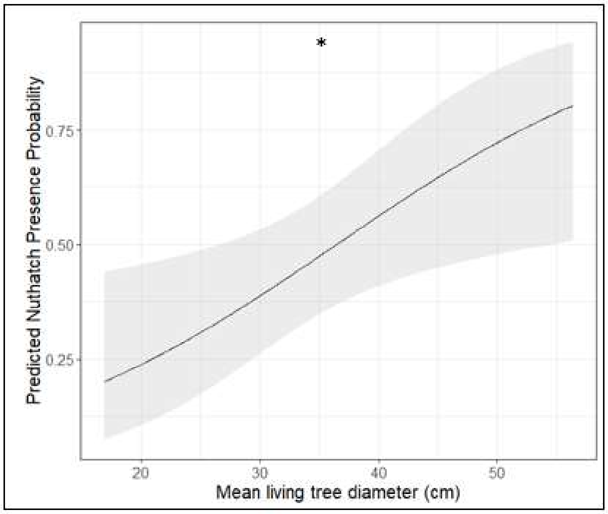


Figure 10: Graphical representation of the predicted presence of the European Nuthatch according to the mean diameter of living trees. The significance of the effect is indicated by "*".

Stock Doves were found more often in lowland plots with lower total volumes of dead wood. Song thrushes were more likely to be in control plots with higher volumes of dead wood (Table 3 and Figure 11).

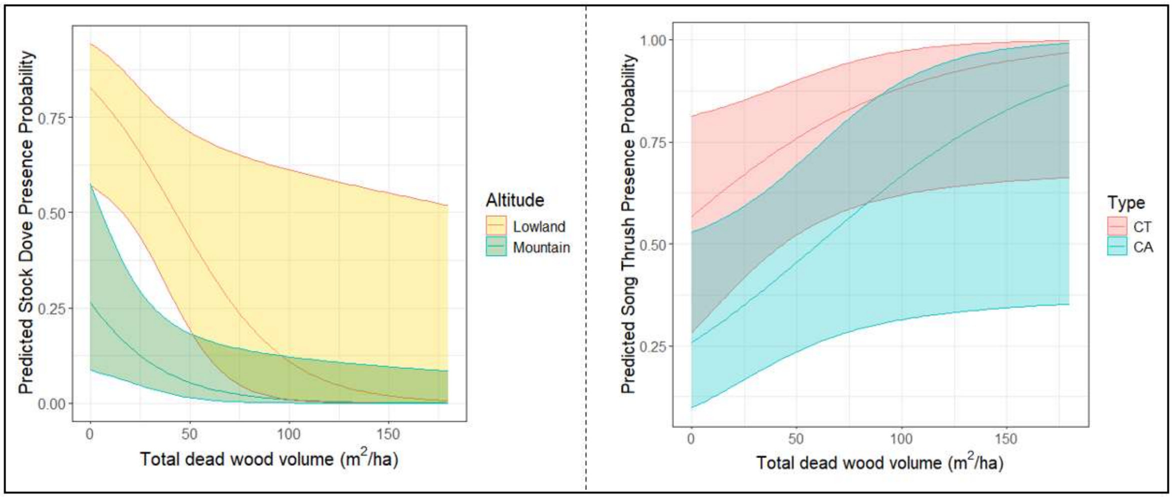


Figure 11: Graphical representations of the predicted presence of Stock Doves according to the total volume of dead wood and the Altitude (Mountain in green, Lowland in yellow) of plots (left); and the predicted presence of Song Thrushes according to the total volume of dead wood and the Type (cavity (CA) in blue and control (CT) in red) of the plot (right). The altitudinal effect, between lowland and mountain plots, was significant for the Stock Dove (p-value: < 0.001). The effect of total dead wood volume was significant for the Stock Dove (p-value: 0.029), and was marginal for the Song Thrush (p-value: 0.052). The effect of Type was significant for the Song Thrush (p-value: 0.02).

Finally, the Middle-spotted woodpecker was present more often in plots with a higher percentage of Beech trees and a higher mean DBH (Table 3). An important comment must be made about the Middle-spotted woodpecker as it was only found in lowland plots and in few numbers. The results are therefore based on a very small dataset and need further investigation.

II. Discussion

The study aimed to assess the impact of Black Woodpecker (*Dryocopus martius*) cavities on forest bird communities, using both species-based and acoustic indices across 68 plots. Contrary to our hypothesis, the presence of these cavities did not significantly affect community-level species richness. However, forest structure (mean diameter at breast height) of trees was positively correlated with species richness across all bird groups: total bird species, cavity-nesting species, and forest specialists. The strongest effect was seen for cavity specialists, then forest specialists and the smallest effect was detected for the total number of species (Table 2 and Figure 5). Acoustic indices showed a more complex soundscape in cavity plots, suggesting some indirect influence of cavities on avian diversity.

The environment a cavity is in appears to be more influential than the presence of the cavity itself. This suggests that mature forests, characterized by larger trees, are inherently more attractive to a higher number of bird species. These results are supported in the literature as mature forests with larger average tree diameters were found to increase species richness (Yoan Paillet *et al.*, 2010; Lelli *et al.*, 2019; Komlós *et al.*, 2024). The presence of large trees, often associated with mature forests, can indirectly promote biodiversity by providing a variety of microhabitats and resources (Vuidot *et al.*, 2011; Regnery, Couvet, *et al.*, 2013; Regnery, Paillet, *et al.*, 2013). The increase of microhabitats in large trees could explain the strength of the effect mean living tree diameter has on cavity species in particular. Cavity species are reliant on either naturally formed or excavated microhabitats (Cockle, Martin and Wiebe, 2008) and so would benefit from larger trees that can provide these niches. Another consideration is that forests also tend to be less dense around large diameter trees creating a more favourable habitat for foliage-gleaners, such as larger crowns to nest and hide in, as well as cavity-nesters (Komlós *et al.*, 2024).

On an individual level, certain species, such as the Middle-spotted woodpecker (*Leiopicus medius*) and Eurasian Nuthatch (*Sitta europaea*), were directly influenced by mean DBH (Table 3 and Figure 10), highlighting its role as a proxy for other ecological factors at larger scales, especially for cavity and forest specialists. It is important to note that the analyses on an individual scale were performed on a reduced number of species and the strength of mean DBH seen at a species richness level could be associated with the most commonly detected species that do not appear in our analysis.

However, further examination of individual retained species responses revealed nuanced interactions with cavity presence (Table 3). Green woodpecker (*Picus viridis*), Eurasian Jay (*Garrulus glandarius*), and Common Firecrest (*Regulus ignicapilla*) showed a preference for cavity plots, while European Robin (*Erithacus rubecula*) and Song Thrush (*Turdus philomelos*), two non-cavity specialists, occurred less in these areas (Figures 8 and 11). This indicates that while some forest specialist species are slightly more attracted to cavity plots (Table 3), the overall effect is not strongly significant (Table 2). Though these results suggest only a small change in community composition between cavity and non-cavity plots, it is important to note that the similarity in species numbers at both types of plots is due to two species avoiding cavities and three species being more present around cavities. This balance results in the difference not being detected in species richness analyses on a plot scale. Some forest specialists favour cavity sites and would be present when non-specialists deterred by cavities are absent. For instance, the Green Woodpecker, a weak excavator, can benefit from living trees weakened by Black Woodpecker cavity excavation. These smaller woodpecker species can more easily access insects hiding behind the bark or even excavate their own cavities once the tree has been initially excavated by a Black Woodpecker. In contrast, the Eurasian Jay, a canopy specialist, may use cavities as rest sites, benefiting from the additional habitat structure. On top of this, some cavity avoidance could be due to species competition or even predation with smaller species, such as the European Robin, avoiding potentially predatory species such as the Eurasian Jay as opposed to the cavity itself (Mallord *et al.*, 2012; Yin *et al.*, 2023).

The composition of forest bird communities was influenced by a variety of factors especially the presence of a cavity but also the location of the site with 4 species, the Middle-spotted woodpecker, Stock Dove, Common Firecrest and Eurasian blackcap favouring lowland plots (Figures 9 and 11).

Interestingly, the Stock Dove (*Columba oenas*), often associated with Black Woodpecker cavities, was negatively influenced by the volume of dead wood, which aligns with an independence of Black Woodpeckers from dead wood when selecting cavity sites (Pirovano and Zecca, 2014).

The exploration of acoustic indices provided additional insights into the soundscape and bird community composition of cavity versus non-cavity plots. The Acoustic Complexity Index (ACI) and Bioacoustic Index (BI) did not show significant differences based on cavity presence, altitude, or total dead wood volume (Table 2). This aligns with previous findings (Barbaro *et al.*, 2022) suggesting ACI may not be well-suited for woodland environments.

However, the average number of frequency peaks (NP) was higher in cavity plots (Figure 7), indicating a more complex soundscape with a variety of bird calls. This could reflect a more diverse avian community at sites with cavities, even if overall species richness metrics did not capture this diversity.

According to the Acoustic Diversity Index (ADI), a slightly higher diversity of species calls was detected in mountain plots (Figure 7) suggesting a more complex community in the Mountains.

Additionally, anthropogenic noise, as measured by the Normalized Difference Soundscape Index (NDSI), was lower in mountainous regions (Figure 6), potentially due to increased human activity such as helicopter or plane traffic.

The combined results of NP, ADI and NDSI suggest that Mountainous cavity plots could contain the most diverse soundscapes with a higher variety of calls produced to combat the higher amount of anthropogenic noise heard at these sites.

While the Black Woodpecker is recognized as an ecosystem engineer and an umbrella species for specific forest birds, such as the Boreal Owl, the presence of its cavity alone does not significantly increase the overall number of species in a forest habitat. However, the presence of a cavity does seem to have a subtle impact on the composition of species present, favouring forest specialists. This effect could be due to factors such as competition, predator avoidance, or niche provisioning (Eggers *et al.*, 2005; Deeming and Reynolds, 2015; Bonaparte and Cockle, 2017; Zahner, Bauer and Kaphegyi, 2017).

When investigating whether the surrounding environment chosen by the Black Woodpecker for cavity excavation more strongly influenced species distributions, we found that forest maturity, indicated by mean DBH, plays a significant role. However, Black Woodpecker cavities are typically excavated in large trees, over 20 cm in diameter (Cusin, 1967; Pirovano and Zecca, 2014; Olano *et al.*, 2015; Zahner, Bauer and Kaphegyi, 2017) and are often situated near areas with dead wood, which the woodpeckers use for feeding (Si *et al.*, 2023). Thus, their presence can still serve as an indicator of mature forests, which are characterized by dead wood and large, older trees (Cusin, 1967; Olano, 2015; Puverel *et al.*, 2019). This finding underscores the importance of preserving mature forests, not only for the presence of cavities but also for the broader ecological benefits they provide.

This study has several limitations that should be acknowledged. The small dataset, comprising only 34 plot pairs and five days of recordings, may not fully capture the variability and complexity of forest bird communities. Fixing and improving the recorders for future studies should enable a longer recording periods as well as improved species detection.

The analysis performed on acoustic indices was exploratory in this study. A meta-analysis by Alcocer et al. (2022) found that acoustic indices were limited concerning their use as proxies for alpha biodiversity and provide more information on smaller scales. In our study, two and a half hours of recordings were sampled per plot, a much larger sample size than a classic bird point count which is no more than two 20-minute sessions (Fuller and Langslow, 1984; Darras *et al.*, 2018). In order to discover in more detail exactly how the soundscape is influenced by the surrounding environment and the presence of a cavity requires more in depth and precise analysis. Studying the acoustic indices over 30-minute periods or even randomly selected 1-minute periods from which the indices are calculated would provide much more in-depth and telling results. It is often by listening to the 1-minute recorded sections that the exact causes of variation or strong index scores can be deduced (Alcocer *et al.*, 2022; Barbaro *et al.*, 2022). However, using only recordings from morning sessions, as we did for this study, is recommended to avoid comparing high detections from active morning sessions with sessions in throughout the day where there are decreasing numbers of detected species (Budka, Kułaga and Osiejuk, 2021). Additionally, future studies should consider beta diversity to better understand the interactions between cavity presence, environmental variables, and bird communities. We did not specifically test for forest specialists against non-forest specialist species in our analysis, investigating the differences between them explicitly could provide us with more concrete results on the community composition differences highlighted above. Studying beta diversity directly between cavity and non-cavity plots, and separately from dendrological data, could provide more nuanced insights. In our study, we chose to eliminate the cavity from our analysis during the backward elimination process and did not individually assess potential impacts of cavities on each index as the cavity was determined to be less influential than the surrounding environment.

Furthermore, integrating more microhabitat data would further enhance our understanding of species-habitat relationships in French forests. Including the presence of bark peeling away from the trunk providing smaller species, such as Treecreepers, shelter, or evidence of woodpecker feeding patches where the heart of deadwood is more exposed enabling a variety of birds to access previously hidden insects could help to explain the distribution of the species retained in our final analyses.

Though the use of convolutional neural networks to identify species in recordings is both efficient and comparable to human point counts (Darras *et al.*, 2018; Blake, 2021), there are still issues being discussed and worked on in BirdNET. BirdNET identifications can be highly reliable when considering a high confidence score and especially when using large recording periods. However, some species are easily mistaken by the software and the performance of BirdNET would be significantly improved by tailoring the minimum confidence scores required by species (Funosas *et al.*, 2024). Thomas Delattre and Raphael Minguet are currently working on gathering which minimal confidence intervals are necessary per target species to increase the accuracy of BirdNET identifications.

III. Conclusion

This study aimed to assess the influence of Black Woodpecker (*Dryocopus martius*) cavities on forest bird communities, employing species-based and acoustic indices across 68 forest plots distributed over 5 sites in France. Contrary to our initial hypothesis, the presence of these cavities did not significantly enhance community-level species richness. However, the mean diameter at breast height of trees emerged as a critical factor, positively correlating with species richness across all bird groups. This finding underscores the importance of forest maturity in supporting diverse avian communities. While the cavities themselves had a subtle impact on the occurrence of species present, favouring forest specialists, it is the broader environmental context, particularly the presence of mature trees, that exerts a stronger influence on bird diversity.

Individual species responses revealed nuanced interactions with cavity presence, highlighting the importance of considering specific habitat preferences and species interactions, such as competition and predation. The study also emphasized the role of acoustic indices in providing additional insights into the soundscape and bird community composition, despite some limitations in their application to woodland environments.

The findings of this research underscore the necessity of preserving mature forests with large trees, which not only support cavity-nesting birds but also offer broader ecological benefits such as tree microhabitats. Though the presence of a cavity on its own is not sufficient to infer higher numbers of bird species, Black woodpecker cavities are still an important mature forest indicator for forest managers and should still be maintained. Future studies should incorporate more detailed microhabitat data, explore beta diversity, and extend recording periods to capture a fuller picture of forest bird communities. Additionally, refining the use of acoustic indices and leveraging advances in species identification technology, such as BirdNET, will enhance our understanding and monitoring of biodiversity in forest ecosystems.

Ultimately, this study highlights the complexity of forest ecosystems and the multifaceted nature of biodiversity conservation. Preserving mature forests with large trees is crucial for maintaining diverse bird communities and ensuring the long-term health and resilience of these habitats. Moving forward, integrating detailed habitat analyses and advanced acoustic monitoring techniques will be essential in developing effective conservation strategies and deepening our understanding of forest biodiversity dynamics.

IV. SWOT analysis

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal origin (attributes of the organization)	S - Previous scientific training and synthesising - Previous experience with most of the statistical analyses performed - Using pre-existing data which allowed a deeper analysis and more time to start discovering bio-acoustics - Worked with researchers in two INRAE centres to best approach both the forestry and the ecoacoustic aspects	W - Results and statistical analysis occurred quite late - Having 8 biodiversity indices and 20 species to build models for is a very long process - Building the main tables from which the analysis was made took the majority of the internship - No direct access to the recordings in order to listen myself (on Avignon servers)
External origin (attributes of the environment)	O - Given access to a shared office within the research buildings - Access to computers and any needed software and papers - Access to relevant previous research and a helpful research team - Opportunity to join field work on microhabitat and bird call identification - Great statistical learning opportunity with help when needed	T - Weren't able to study as many aspects as we wanted to originally due to time constraints - No fieldwork directly related to my subject - Data loss due to the removal of plots and the short time period (5 days) discovered within the last month of the internship

V. Bibliography

Alcocer, I. *et al.* (2022) ‘Acoustic indices as proxies for biodiversity: a meta-analysis’, *Biological Reviews*, 97(6), pp. 2209–2236. Available at: https://doi.org/10.1111/brv.12890.

Barbaro, L. *et al.* (2022) ‘Linking acoustic diversity to compositional and configurational heterogeneity in mosaic landscapes’, *Landscape Ecology*, 37(4), pp. 1125–1143. Available at: https://doi.org/10.1007/s10980-021-01391-8.

Basile, M. *et al.* (2022) ‘Salvage Logging Strongly Affects Woodpecker Abundance and Reproduction: a Meta-analysis’, *Current Forestry Reports*, 9(1), pp. 1–14. Available at: https://doi.org/10.1007/s40725-022-00175-w.

Bell, D. *et al.* (2015) ‘Forest restoration to attract a putative umbrella species, the white-backed woodpecker, benefited saproxylic beetles’, *Ecosphere*, 6(12), pp. 1–14. Available at: https://doi.org/10.1890/ES14-00551.1.

Blake, J.G. (2021) ‘Acoustic monitors and direct observations provide similar but distinct perspectives on bird assemblages in a lowland forest of eastern Ecuador’, *PeerJ*, 9, p. e10565. Available at: https://doi.org/10.7717/peerj.10565.

Bocca, M., Carisio, L. and Rolando, A. (2007) ‘Habitat use, Home Ranges and Census Techniques in the Black Woodpecker *Dryocopus martius* in the Alps’, *Ardea*, 95(1), pp. 17–29. Available at: https://doi.org/10.5253/078.095.0103.

Boelman, N.T. *et al.* (2007) ‘MULTI-TROPHIC INVASION RESISTANCE IN HAWAII: BIOACOUSTICS, FIELD SURVEYS, AND AIRBORNE REMOTE SENSING’, *Ecological Applications*, 17(8), pp. 2137–2144. Available at: https://doi.org/10.1890/07-0004.1.

Bonaparte, E.B. and Cockle, K.L. (2017) ‘Nest niche overlap among the endangered Vinaceous-breasted Parrot (*Amazona vinacea*) and sympatric cavity-using birds, mammals, and social insects in the subtropical Atlantic Forest, Argentina’, *The Condor*, 119(1), pp. 58–72. Available at: https://doi.org/10.1650/CONDOR-16-94.1.

Bouvet, A. *et al.* (2016) ‘Effects of forest structure, management and landscape on bird and bat communities’, *Environmental Conservation*, 43(2), pp. 148–160. Available at: https://doi.org/10.1017/S0376892915000363.

Brambilla, M. *et al.* (2013) ‘Modelling distribution and potential overlap between Boreal Owl *Aegolius funereus* and Black Woodpecker *Dryocopus martius* : implications for management and monitoring plans’, *Bird Conservation International*, 23(4), pp. 502–511. Available at: https://doi.org/10.1017/S0959270913000117.

Budka, M., Kułaga, K. and Osiejuk, T.S. (2021) ‘Evaluation of Accuracy and Precision of the Sound-Recorder-Based Point-Counts Applied in Forests and Open Areas in Two Locations Situated in a Temperate and Tropical Regions’, *Birds*, 2(4), pp. 351–361. Available at: https://doi.org/10.3390/birds2040026.

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017). “glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling.” *The R Journal*, 9(2), 378–400. doi:10.32614/RJ-2017-066.

Cateau, E. *et al.* (2024) ‘Tree inventory data from permanent plots in F rench forest reserves’, *Ecology*, 105(7), p. e4324. Available at: https://doi.org/10.1002/ecy.4324.

Clark, M.L. *et al.* (2023) ‘The effect of soundscape composition on bird vocalization classification in a citizen science biodiversity monitoring project’, *Ecological Informatics*, 75, p. 102065. Available at: https://doi.org/10.1016/j.ecoinf.2023.102065.

Cockle, K., Martin, K. and Wiebe, K. (2008) ‘AVAILABILITY OF CAVITIES FOR NESTING BIRDS IN THE ATLANTIC FOREST, ARGENTINA’, *ORNITOLOGIA NEOTROPICAL*, 19, p. 269_278.

Cockle, K.L., Martin, K. and Wesołowski, T. (2011) ‘Woodpeckers, decay, and the future of cavity-nesting vertebrate communities worldwide’, *Frontiers in Ecology and the Environment*, 9(7), pp. 377–382. Available at: https://doi.org/10.1890/110013.

Colmant, L. (2016) ‘Les loges du Pic noir Dryocopus martius : espèces hôtes et prédation par la martre Martes martes en période de nidification et en automne-hiver’.

Cusin, M. (1967) — Essai d'une monographie du Pic noir (Dryocopus martius L.). L'Oiseau et la Revue française d'Ornithologie.

Darras, K. *et al.* (2018) ‘Comparing the sampling performance of sound recorders versus point counts in bird surveys: A meta-analysis’, *Journal of Applied Ecology*. Edited by S. Willis, 55(6), pp. 2575–2586. Available at: https://doi.org/10.1111/1365-2664.13229.

Deeming, D.C. and Reynolds, S.J. (2015) *Nests, eggs, and incubation: new ideas about avian reproduction*. 1st ed. Oxford (GB): Oxford university press.

Drever, M.C. *et al.* (2008) ‘Woodpeckers as reliable indicators of bird richness, forest health and harvest’, *Biological Conservation*, 141(3), pp. 624–634. Available at: https://doi.org/10.1016/j.biocon.2007.12.004.

Edworthy, A.B. *et al.* (2018) ‘Tree cavity occupancy by nesting vertebrates across cavity age’, *The Journal of Wildlife Management*, 82(3), pp. 639–648. Available at: https://doi.org/10.1002/jwmg.21398.

Eggers, S. *et al.* (2005) ‘Nest predation and habitat change interact to influence Siberian jay numbers’, *Oikos*, 111(1), pp. 150–158. Available at: https://doi.org/10.1111/j.0030-1299.2005.13802.x.

Fernández-García, J.M. (2022) ‘Remarkable range expansion of the black woodpecker *Dryocopus martius* in Spain’, *Oryx*, 56(6), pp. 812–813. Available at: https://doi.org/10.1017/S0030605322001089.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (2022) *LA SITUATION DES FORETS DU MONDE (SOFO) 2022: des solutions forestieres pour une relance verte et... des economies inclusives, resilientes et durables*. S.l.: FOOD & AGRICULTURE ORG. Available at: https://openknowledge.fao.org/handle/20.500.14283/cb9360fr.

Fuller, R.J. and Langslow, D.R. (1984) 'Estimating numbers of birds by point counts: how long should counts last?', *Bird Study*, 31(3), pp. 195–202. Available at: https://doi.org/10.1080/00063658409476841.

Funosas, D. *et al.* (2024) 'Assessing the potential of BirdNET to infer European bird communities from large-scale ecoacoustic data', *Ecological Indicators*, 164, p. 112146. Available at: https://doi.org/10.1016/j.ecolind.2024.112146.

Garmendia, A., Cárcamo, S. and Schwendtner, O. (2006) 'Forest Management Considerations for Conservation of Black Woodpecker Dryocopus martius and White-backed Woodpecker Dendrocopos leucotos Populations in Quinto Real (Spanish Western Pyrenees)', *Biodiversity and Conservation*, 15(4), pp. 1399–1415. Available at: https://doi.org/10.1007/s10531-005-5410-0.

Gasc, A. *et al.* (2017) 'Future directions for soundscape ecology: The importance of ornithological contributions', *The Auk*, 134(1), pp. 215–228. Available at: https://doi.org/10.1642/AUK-16-124.1.

Gorman, G. (2015) 'Foraging signs and cavities of some European woodpeckers (Picidae): Identifying the clues that lead to establishing the presence of species'.

Grzegorz Mikusiński *et al.* (2001) 'Woodpeckers as Indicators of Forest Bird Diversity', *Conservation Biology*, 15(1), pp. 208–217. Available at: https://doi.org/10.1111/j.1523-1739.2001.99236.x.

Harrell Jr F (2024). *Hmisc: Harrell Miscellaneous*. R package version 5.1-3, https://github.com/harrelfe/hmisc.

Hebda, G. and Błoszyk, J. (2024) 'Type of Material, Not Tree Hole Characteristics Shapes Uropodina Mites' Species Composition in Excavated Tree Holes', *Diversity*, 16(2), p. 114. Available at: https://doi.org/10.3390/d16020114.

INSTITUT NATIONAL DE L'INFORMATION GEOGRAPHIQUE ET FORESTIERE (IGN) (2023). INVENTAIRE FORESTIER NATIONAL : Mémento 2023. Mémento édition 2023. Available at : Le mémento - INVENTAIRE FORESTIER (ign.fr) .

Jusino, M.A. *et al.* (2016) 'Experimental evidence of a symbiosis between red-cockaded woodpeckers and fungi', *Proceedings of the Royal Society B: Biological Sciences*, 283(1827), p. 20160106. Available at: https://doi.org/10.1098/rspb.2016.0106.

Kahl, S. *et al.* (2021) 'BirdNET: A deep learning solution for avian diversity monitoring', *Ecological Informatics*, 61, p. 101236. Available at: https://doi.org/10.1016/j.ecoinf.2021.101236.

Karimi, S. *et al.* (2018) ‘Fine-scale habitat use by Black Woodpecker Dryocopus martius: a year-round study in the Hyrcanian forest, Iran’, *NORTH-WESTERN JOURNAL OF ZOOLOGY*, 14(1), pp. 76–84.

Khanaposhtani, M.G. *et al.* (2012) ‘Habitat requirements of the Black Woodpecker, *Dryocopus martius* , in Hyrcanian forests, Iran: (Aves: Picidae)’, *Zoology in the Middle East*, 55(1), pp. 19–25. Available at: https://doi.org/10.1080/09397140.2012.10648913.

Komlós, M. *et al.* (2024) ‘Tall, large-diameter trees and dense shrub layer as key determinants of the abundance and composition of bird communities in oak-dominated forests’, *Journal of Forestry Research*, 35(1), p. 62. Available at: https://doi.org/10.1007/s11676-024-01714-w.

Langridge, J. *et al.* (2023) ‘Biodiversity responses to forest management abandonment in boreal and temperate forest ecosystems: A meta-analysis reveals an interactive effect of time since abandonment and climate’, *Biological Conservation*, 287, p. 110296. Available at: https://doi.org/10.1016/j.biocon.2023.110296.

Larrieu, L. *et al.* (2018) ‘Tree related microhabitats in temperate and Mediterranean European forests: A hierarchical typology for inventory standardization’, *Ecological Indicators*, 84, pp. 194–207. Available at: https://doi.org/10.1016/j.ecolind.2017.08.051.

Lelli, C. *et al.* (2019) ‘Biodiversity response to forest structure and management: Comparing species richness, conservation relevant species and functional diversity as metrics in forest conservation’, *Forest Ecology and Management*, 432, pp. 707–717. Available at: https://doi.org/10.1016/j.foreco.2018.09.057.

Mallord, J.W. *et al.* (2012) ‘Mortality of Wood Warbler *Phylloscopus sibilatrix* nests in Welsh Oakwoods: predation rates and the identification of nest predators using miniature nest cameras’, *Bird Study*, 59(3), pp. 286–295. Available at: https://doi.org/10.1080/00063657.2012.669359.

Miina, J. *et al.* (2020) ‘Modelling Non-timber Forest Products for Forest Management Planning in Europe’, *Current Forestry Reports*, 6(4), pp. 309–322. Available at: https://doi.org/10.1007/s40725-020-00130-7.

Myllymäki, M. *et al.* (2024) ‘The relationship between forest structure and naturalness in the Finnish national forest inventory’, *Forestry: An International Journal of Forest Research*. Edited by H. McKay, 97(3), pp. 339–348. Available at: https://doi.org/10.1093/forestry/cpad053.

Oettel, J. and Lapin, K. (2021) ‘Linking forest management and biodiversity indicators to strengthen sustainable forest management in Europe’, *Ecological Indicators*, 122, p. 107275. Available at: https://doi.org/10.1016/j.ecolind.2020.107275.

Olano, M. *et al.* (2015) ‘Black woodpecker Dryocopus martius (L., 1758) distribution, abundance, habitat use and breeding performance in a recently colonized region in SW Europe’, *Munibe Ciencias Naturales*, 63, pp. 049–071. Available at: https://doi.org/10.21630/mcn.2015.63.03.

Olano, M. (2015) ‘Black woodpecker Dryocopus martius (L., 1758) distribution, abundance, habitat use and breeding performance in a recently colonized region in SW Europe', *Munibe Ciencias Naturales*, 63, pp. 049–071. Available at: https://doi.org/10.21630/mcn.2015.63.03.

Oksanen J, Simpson G, Blanchet F, Kindt R, Legendre P, Minchin P, O'Hara R, Solymos P, Stevens M, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Carvalho G, Chirico M, De Caceres M, Durand S, Evangelista H, FitzJohn R, Friendly M, Furneaux B, Hannigan G, Hill M, Lahti L, McGlinn D, Ouellette M, Ribeiro Cunha E, Smith T, Stier A, Ter Braak C, Weedon J (2024). *vegan: Community Ecology Package*. R package version 2.6-7, https://github.com/vegandevs/vegan, https://vegandevs.github.io/vegan/.

Paillet, Y. *et al.* (2010) 'Biodiversity Differences between Managed and Unmanaged Forests: Meta-Analysis of Species Richness in Europe', *Conservation Biology*, 24(1), pp. 101–112. Available at: https://doi.org/10.1111/j.1523-1739.2009.01399.x.

Paillet, Y. *et al.* (2018) 'The indicator side of tree microhabitats: A multi-taxon approach based on bats, birds and saproxylic beetles', *Journal of Applied Ecology*, 55(5), pp. 2147–2159. Available at: https://doi.org/10.1111/1365-2664.13181.

Pérez-Granados, C. (2023) 'BIRDNET : applications, performance, pitfalls and future opportunities', *Ibis*, 165(3), pp. 1068–1075. Available at: https://doi.org/10.1111/ibi.13193.

Pieretti, N., Farina, A. and Morri, D. (2011) 'A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI)', *Ecological Indicators*, 11(3), pp. 868–873. Available at: https://doi.org/10.1016/j.ecolind.2010.11.005.

Pijanowski, B.C. *et al.* (2011) 'What is soundscape ecology? An introduction and overview of an emerging new science', *Landscape Ecology*, 26(9), pp. 1213–1232. Available at: https://doi.org/10.1007/s10980-011-9600-8.

Pirovano, A.R. and Zecca, G. (2014) 'Black Woodpecker *Dryocopus martius* habitat selection in the Italian Alps: implications for conservation in Natura 2000 network', *Bird Conservation International*, 24(3), pp. 299–315. Available at: https://doi.org/10.1017/S0959270913000439.

Puverel, C. *et al.* (2019) 'This is my spot: What are the characteristics of the trees excavated by the Black Woodpecker? A case study in two managed French forests', *Forest Ecology and Management*, 453, p. 117621. Available at: https://doi.org/10.1016/j.foreco.2019.117621.

Regnery, B., Couvet, D., *et al.* (2013) 'Tree microhabitats as indicators of bird and bat communities in Mediterranean forests', *Ecological Indicators*, 34, pp. 221–230. Available at: https://doi.org/10.1016/j.ecolind.2013.05.003.

Regnery, B., Paillet, Y., *et al.* (2013) 'Which factors influence the occurrence and density of tree microhabitats in Mediterranean oak forests?', *Forest Ecology and Management*, 295, pp. 118–125. Available at: https://doi.org/10.1016/j.foreco.2013.01.009.

Rolstad, J., Majewski, P. and Rolstad, E. (1998) 'Black Woodpecker Use of Habitats and Feeding Substrates in a Managed Scandinavian Forest', *The Journal of Wildlife Management*, 62(1), p. 11. Available at: https://doi.org/10.2307/3802260.

Rowland, J.A. *et al.* (2020) ‘Testing the performance of ecosystem indices for biodiversity monitoring’, *Ecological Indicators*, 116, p. 106453. Available at: https://doi.org/10.1016/j.ecolind.2020.106453.

Sandbrook, C. *et al.* (2021) ‘Principles for the socially responsible use of conservation monitoring technology and data’, *Conservation Science and Practice*, 3(5), p. e374. Available at: https://doi.org/10.1111/csp2.374.

Si, Y. *et al.* (2023) ‘Foraging Niche Differentiation of Five Woodpecker Species in the Primitive Broadleaved Korean Pine Forests of Northeast China’, *Forests*, 14(11), p. 2166. Available at: https://doi.org/10.3390/f14112166.

Spies, T.A. (1998). Forest structure: a key to the ecosystem. Northwest Sci., 72 , pp. 34-39.

Sueur, J., Aubin, T. and Simonis, C. (2008). “Seewave: a free modular tool for sound analysis and synthesis.” *Bioacoustics*, 18, 213-226

Sueur, J. (2018) *Sound Analysis and Synthesis with R*. Cham: Springer International Publishing (Use R!). Available at: https://doi.org/10.1007/978-3-319-77647-7.

Sueur, J. and Farina, A. (2015) ‘Ecoacoustics: the Ecological Investigation and Interpretation of Environmental Sound’, *Biosemiotics*, 8(3), pp. 493–502. Available at: https://doi.org/10.1007/s12304-015-9248-x.

Symes, L.B. *et al.* (2022) ‘Analytical approaches for evaluating passive acoustic monitoring data: A case study of avian vocalizations’, *Ecology and Evolution*, 12(4), p. e8797. Available at: https://doi.org/10.1002/ece3.8797.

Trzcinski, M.K. *et al.* (2022) ‘Woodpeckers and other excavators maintain the diversity of cavity-nesting vertebrates’, *Journal of Animal Ecology*, 91(6), pp. 1251–1265. Available at: https://doi.org/10.1111/1365-2656.13626.

Vuidot, A. *et al.* (2011) ‘Influence of tree characteristics and forest management on tree microhabitats’, *Biological Conservation*, 144(1), pp. 441–450. Available at: https://doi.org/10.1016/j.biocon.2010.09.030.

Ware, L. *et al.* (2023) ‘Artificial intelligence (BirdNET) supplements manual methods to maximize bird species richness from acoustic data sets generated from regional monitoring’, *Canadian Journal of Zoology*, 101(12), pp. 1031–1051. Available at: https://doi.org/10.1139/cjz-2023-0044.

Wei T, Simko V (2021). *R package 'corrplot': Visualization of a Correlation Matrix*. (Version 0.92), https://github.com/taiyun/corrplot

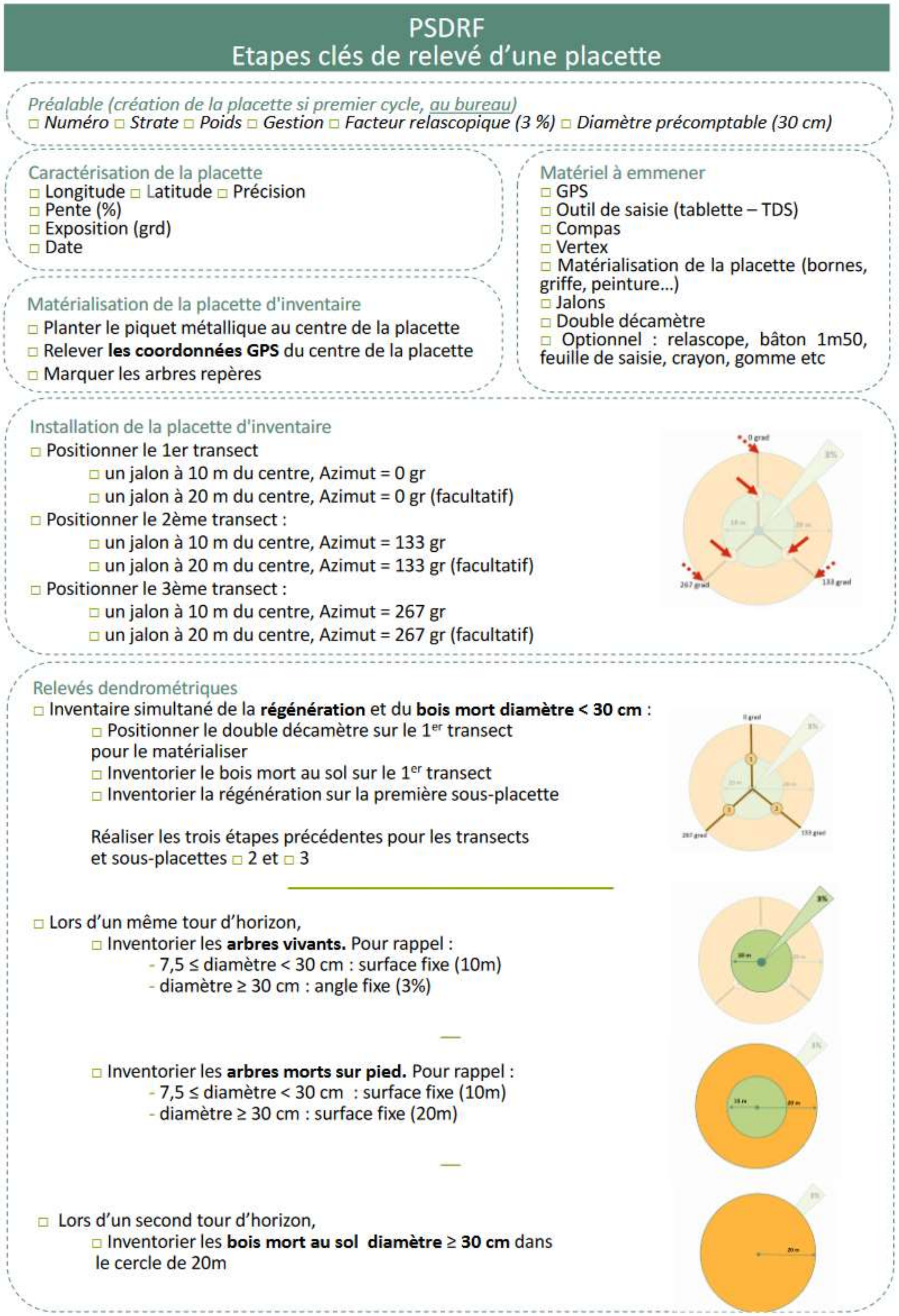
Yin, D. *et al.* (2023) ‘A case report of an Eurasian jay (*Garrulus glandarius*) attacking an incubating adult and depredating the eggs of the Japanese tit (*Parus minor*)’, *Ecology and Evolution*, 13(3), p. e9931. Available at: https://doi.org/10.1002/ece3.9931.

Zahner, V., Bauer, R. and Kaphegyi, T.A.M. (2017) ‘Are Black Woodpecker (Dryocopus martius) tree cavities in temperate Beech (Fagus sylvatica) forests an answer to depredation risk?’, *Journal of Ornithology*, 158(4), pp. 1073–1079. Available at: https://doi.org/10.1007/s10336-017-1467-2.

VI. Appendices

Appendix 1:

Figure A: Graphical representations and field aid for dendrometric measurements adapted from the PSDRF protocol.



PSDRF
Etapes clés de relevé d'une placette

Préalable (création de la placette si premier cycle, au bureau)
☐ Numéro ☐ Strate ☐ Poids ☐ Gestion ☐ Facteur relascopique (3 %) ☐ Diamètre précomptable (30 cm)

Caractérisation de la placette
☐ Longitude ☐ Latitude ☐ Précision
☐ Pente (%)
☐ Exposition (grd)
☐ Date

Matérialisation de la placette d'inventaire
☐ Planter le piquet métallique au centre de la placette
☐ Relever **les coordonnées GPS** du centre de la placette
☐ Marquer les arbres repères

Matériel à emmener
☐ GPS
☐ Outil de saisie (tablette – TDS)
☐ Compas
☐ Vertex
☐ Matérialisation de la placette (bornes, griffe, peinture…)
☐ Jalons
☐ Double décamètre
☐ Optionnel : relascope, bâton 1m50, feuille de saisie, crayon, gomme etc

Installation de la placette d'inventaire
☐ Positionner le 1er transect
    ☐ un jalon à 10 m du centre, Azimut = 0 gr
    ☐ un jalon à 20 m du centre, Azimut = 0 gr (facultatif)
☐ Positionner le 2ème transect :
    ☐ un jalon à 10 m du centre, Azimut = 133 gr
    ☐ un jalon à 20 m du centre, Azimut = 133 gr (facultatif)
☐ Positionner le 3ème transect :
    ☐ un jalon à 10 m du centre, Azimut = 267 gr
    ☐ un jalon à 20 m du centre, Azimut = 267 gr (facultatif)

Relevés dendrométriques
☐ Inventaire simultané de la **régénération** et du **bois mort diamètre < 30 cm** :
    ☐ Positionner le double décamètre sur le 1er transect pour le matérialiser
    ☐ Inventorier le bois mort au sol sur le 1er transect
    ☐ Inventorier la régénération sur la première sous-placette

    Réaliser les trois étapes précédentes pour les transects et sous-placettes ☐ 2 et ☐ 3

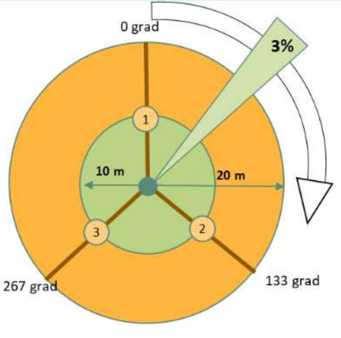
☐ Lors d'un même tour d'horizon,
    ☐ Inventorier les **arbres vivants.** Pour rappel :
        - 7,5 ≤ diamètre < 30 cm : surface fixe (10m)
        - diamètre ≥ 30 cm : angle fixe (3%)

    ☐ Inventorier les **arbres morts sur pied.** Pour rappel :
        - 7,5 ≤ diamètre < 30 cm : surface fixe (10m)
        - diamètre ≥ 30 cm : surface fixe (20m)

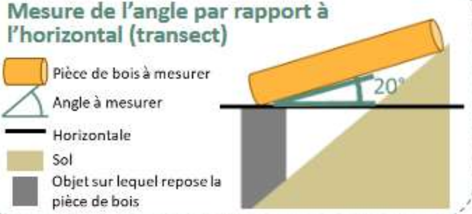
☐ Lors d'un second tour d'horizon,
    ☐ Inventorier les **bois mort au sol diamètre ≥ 30 cm** dans le cercle de 20m

AIDE MÉMOIRE

- Arbre vivant
  - D < 7,5 cm → 3 sous placettes, de rayon 1,5m
  - 7,5 cm ≤ D < 30 cm → Cercle de 10 m
  - 30 cm ≤ D → Angle relascopique
- Arbre mort
  - Debout
    - 7,5 cm ≤ D < 30 cm → Cercle de 10 m
    - 30 cm ≤ D → Cercle de 20 m
  - Au sol
    - 5 cm ≤ D < 30 cm → 3 transects
    - 30 cm ≤ D → Cercle de 20 m



Mesure de l’angle par rapport à l’horizontal (transect)



Angle relascopique (exemple)

Un arbre d’un diamètre de	Est pris en compte jusqu’à
60 cm	20 m
90 cm	30 m
120 cm	40 m

Stade D et stade E

Écorce (stade E):

1. Présente sur tout le billon
2. Présente sur plus de 50% de la surface
3. Présente sur moins de 50% de la surface
4. Absente du billon

Pourriture du bois (Stade D) :

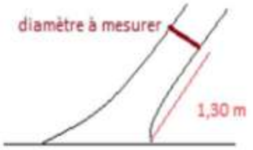
1. Dur ou non altéré
2. Pourriture <1/4 du diamètre
3. Pourriture entre 1/4 et 1/2 du diamètre
4. Pourriture entre 1/2 et 3/4 du diamètre
5. Pourriture supérieure à 3/4.

Type de bois mort

1 (arbre) : conserve les parties importantes du squelette

2 (volis, chandelle): > 1m30 ayant perdu une part importante de leur squelette

3 (souche): < 1m30



Classes de régénération

Classe 1 : 0,5 < H < 1,5 m

Classe 2 : H ≥ 1,5 m et D ≤ 2,5 cm

Classe 3 : 2,5 cm < D < 7,5 cm

Semis : ≤ 50 cm noté en recouvrement (%).

Mesure de bois mort au sol supérieur à 30 cm

A et B: prise de mesures

A : Longueur < 5m. 1 diamètre mesuré

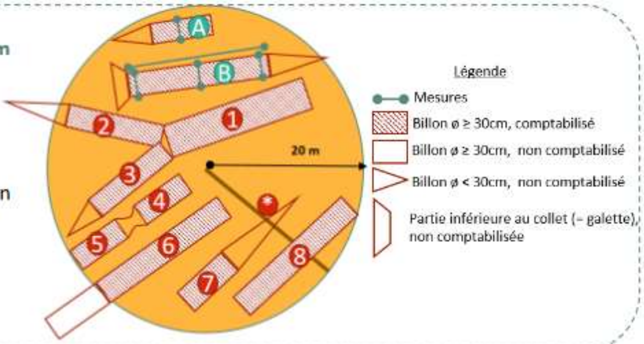
B : Longueur ≥ 5m. 3 diamètre mesurés

1 à 8 : cas particulier/questions fréquentes :

Seules les parties hachurées sont comptabilisées et chaque numéro est un billon différent

* : Comptabilisé dans les bois mort au sol inférieur à 30 cm

Voir protocole pour plus de détail



Aide à la remesure

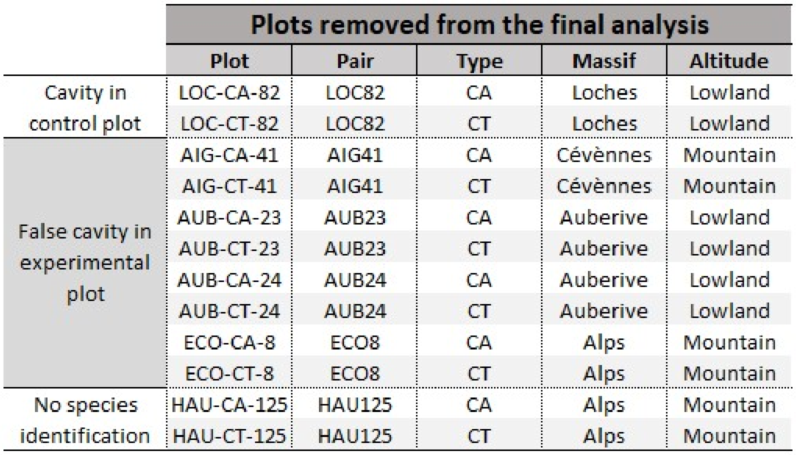
- Si diamètre < diamètre du cycle précédent : Noter le diamètre mesuré lors du relevé

- Si vous observez des différences d’azimut et/ou de distance et que vous êtes **certain** qu’il s’agit bien du même arbre (!!!!), corrigez les azimut et distance du (des) cycles(s) précédent(s).

- Lorsqu’un arbre est tombé au sol ou a été exploité, depuis le cycle précédent, modifier la donnée du cycle précédent et cochez « chablis/exploité »

Appendix 2:

Table A: Table listing the plots that were removed from our analysis and the reasons for their removal. The Mountain range (Massif), Altitude and Type of each plot is stated. CA stands for cavity plots, CT stands for control plots and the pair indicates which plots are paired together as a cavity and control duo.



	Plots removed from the final analysis				
	Plot	**Pair**	**Type**	**Massif**	**Altitude**
Cavity in control plot	LOC-CA-82	LOC82	CA	Loches	Lowland
	LOC-CT-82	LOC82	CT	Loches	Lowland
False cavity in experimental plot	AIG-CA-41	AIG41	CA	Cévènnes	Mountain
	AIG-CT-41	AIG41	CT	Cévènnes	Mountain
	AUB-CA-23	AUB23	CA	Auberive	Lowland
	AUB-CT-23	AUB23	CT	Auberive	Lowland
	AUB-CA-24	AUB24	CA	Auberive	Lowland
	AUB-CT-24	AUB24	CT	Auberive	Lowland
	ECO-CA-8	ECO8	CA	Alps	Mountain
	ECO-CT-8	ECO8	CT	Alps	Mountain
No species identification	HAU-CA-125	HAU125	CA	Alps	Mountain
	HAU-CT-125	HAU125	CT	Alps	Mountain

Table B: Table listing all 68 plots retained in the final analysis along with their Mountain range (Massif), Altitude and Type. CA stands for cavity plots, CT stands for control plots and the pair indicates which plots are paired together as a cavity and control duo.

Plots retained in the final analysis									
Plot	**Pair**	**Type**	**Massif**	**Altitude**	**Plot**	**Pair**	**Type**	**Massif**	**Altitude**
AIG-CA-1	AIG1	CA	Cévènnes	Mountain	AUB-CA-10	AUB10	CA	Auberive	Lowland
AIG-CT-1	AIG1	CT	Cévènnes	Mountain	AUB-CT-10	AUB10	CT	Auberive	Lowland
AIG-CA-114	AIG114	CA	Cévènnes	Mountain	AUB-CA-14	AUB14	CA	Auberive	Lowland
AIG-CT-114	AIG114	CT	Cévènnes	Mountain	AUB-CT-14	AUB14	CT	Auberive	Lowland
AIG-CA-116	AIG116	CA	Cévènnes	Mountain	AUB-CA-16	AUB16	CA	Auberive	Lowland
AIG-CT-116	AIG116	CT	Cévènnes	Mountain	AUB-CT-16	AUB16	CT	Auberive	Lowland
AIG-CA-137	AIG137	CA	Cévènnes	Mountain	AUB-CA-2	AUB2	CA	Auberive	Lowland
AIG-CT-137	AIG137	CT	Cévènnes	Mountain	AUB-CT-2	AUB2	CT	Auberive	Lowland
AIG-CA-17	AIG17	CA	Cévènnes	Mountain	AUB-CA-21	AUB21	CA	Auberive	Lowland
AIG-CT-17	AIG17	CT	Cévènnes	Mountain	AUB-CT-21	AUB21	CT	Auberive	Lowland
AIG-CA-45	AIG45	CA	Cévènnes	Mountain	AUB-CA-4	AUB4	CA	Auberive	Lowland
AIG-CT-45	AIG45	CT	Cévènnes	Mountain	AUB-CT-4	AUB4	CT	Auberive	Lowland
AIG-CA-52	AIG52	CA	Cévènnes	Mountain	AUB-CA-5	AUB5	CA	Auberive	Lowland
AIG-CT-52	AIG52	CT	Cévènnes	Mountain	AUB-CT-5	AUB5	CT	Auberive	Lowland
AIG-CA-63	AIG63	CA	Cévènnes	Mountain	AUB-CA-56	AUB56	CA	Auberive	Lowland
AIG-CT-63	AIG63	CT	Cévènnes	Mountain	AUB-CT-56	AUB56	CT	Auberive	Lowland
AIG-CA-85	AIG85	CA	Cévènnes	Mountain	LOC-CA-16	LOC16	CA	Loches	Lowland
AIG-CT-85	AIG85	CT	Cévènnes	Mountain	LOC-CT-16	LOC16	CT	Loches	Lowland
ECO-CA-136	ECO136	CA	Alps	Mountain	LOC-CA-27	LOC27	CA	Loches	Lowland
ECO-CT-136	ECO136	CT	Alps	Mountain	LOC-CT-27	LOC27	CT	Loches	Lowland
HAU-CA-109	HAU109	CA	Alps	Mountain	LOC-CA-42	LOC42	CA	Loches	Lowland
HAU-CT-109	HAU109	CT	Alps	Mountain	LOC-CT-42	LOC42	CT	Loches	Lowland
HAU-CA-33	HAU33	CA	Alps	Mountain	LOC-CA-77	LOC77	CA	Loches	Lowland
HAU-CT-33	HAU33	CT	Alps	Mountain	LOC-CT-77	LOC77	CT	Loches	Lowland
HAU-CA-85	HAU85	CA	Alps	Mountain	VOL-CA-19	VOL19	CA	Volcans	Mountain
HAU-CT-85	HAU85	CT	Alps	Mountain	VOL-CT-19	VOL19	CT	Volcans	Mountain
SEM-CA-28	SEM28	CA	Alps	Mountain	VOL-CA-22	VOL22	CA	Volcans	Mountain
SEM-CT-28	SEM28	CT	Alps	Mountain	VOL-CT-22	VOL22	CT	Volcans	Mountain
SEM-CA-31	SEM31	CA	Alps	Mountain	VOL-CA-247	VOL247	CA	Volcans	Mountain
SEM-CT-31	SEM31	CT	Alps	Mountain	VOL-CT-247	VOL247	CT	Volcans	Mountain
SEM-CA-32	SEM32	CA	Alps	Mountain	VOL-CA-4	VOL4	CA	Volcans	Mountain
SEM-CT-32	SEM32	CT	Alps	Mountain	VOL-CT-4	VOL4	CT	Volcans	Mountain
SEM-CA-34	SEM34	CA	Alps	Mountain	VOL-CA-54	VOL54	CA	Volcans	Mountain
SEM-CT-34	SEM34	CT	Alps	Mountain	VOL-CT-54	VOL54	CT	Volcans	Mountain

Appendix 3:

Figure B: Graphical representation of the 5 randomly selected days per plot sampled in 2022. Each site is represented by an individual colour: Aigual (AIG) in blue, Ecouges (ECO) in orange, the Haut plateaux (HAU) in purple and the Semnoz (SEM) in pink.

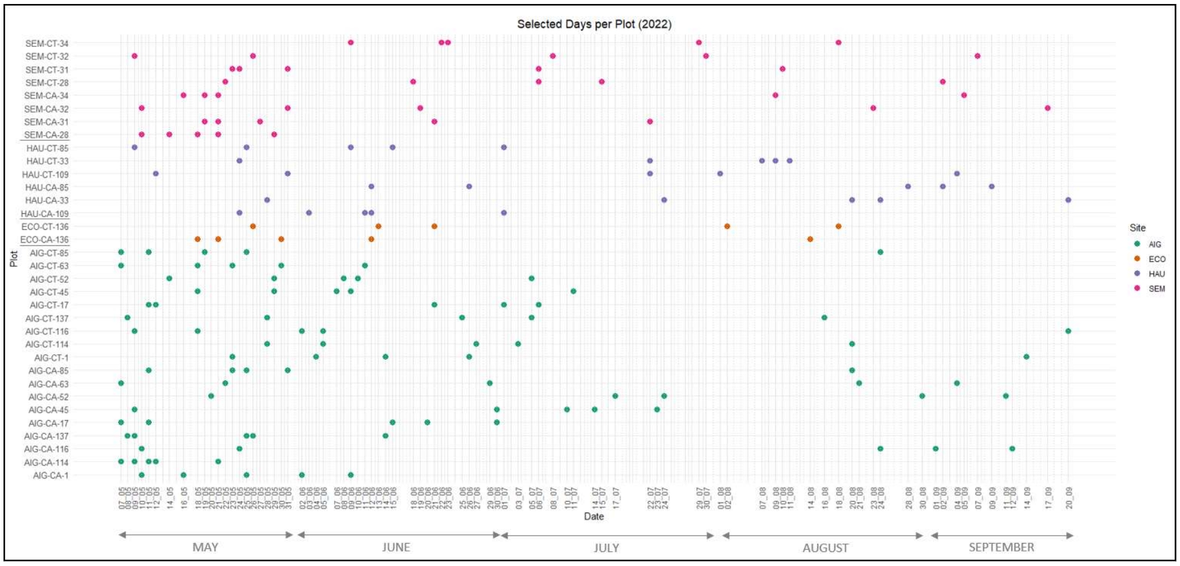
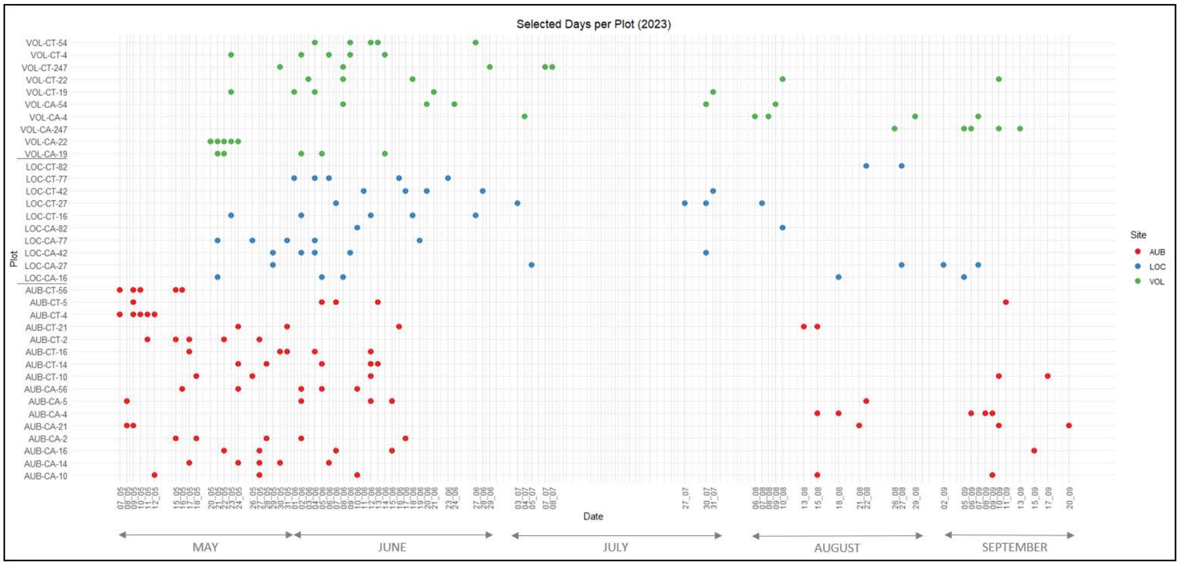


Figure C: Graphical representation of the 5 randomly selected days per plot sampled in 2023.

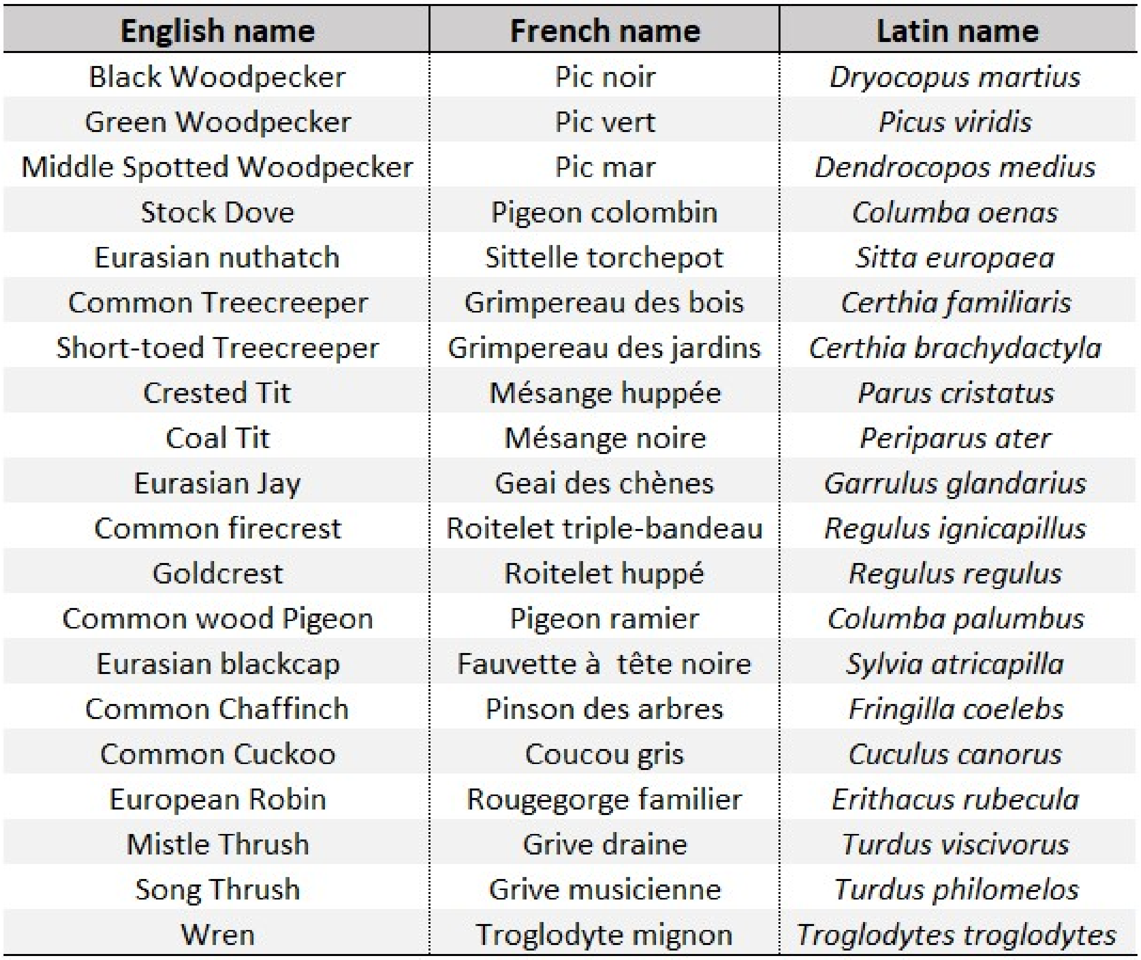
Each site is represented by one colour for all the plots of that site: Auberive (AUB) in red,

Loches (LOC) in dark blue and Volcans (VOL) in green.



Appendix 4:

Table C: Table listing the 20 bird species retained in the final analysis.



English name	French name	Latin name
Black Woodpecker	Pic noir	*Dryocopus martius*
Green Woodpecker	Pic vert	*Picus viridis*
Middle Spotted Woodpecker	Pic mar	*Dendrocopos medius*
Stock Dove	Pigeon colombin	*Columba oenas*
Eurasian nuthatch	Sittelle torchepot	*Sitta europaea*
Common Treecreeper	Grimpereau des bois	*Certhia familiaris*
Short-toed Treecreeper	Grimpereau des jardins	*Certhia brachydactyla*
Crested Tit	Mésange huppée	*Parus cristatus*
Coal Tit	Mésange noire	*Periparus ater*
Eurasian Jay	Geai des chènes	*Garrulus glandarius*
Common firecrest	Roitelet triple-bandeau	*Regulus ignicapillus*
Goldcrest	Roitelet huppé	*Regulus regulus*
Common wood Pigeon	Pigeon ramier	*Columba palumbus*
Eurasian blackcap	Fauvette à tête noire	*Sylvia atricapilla*
Common Chaffinch	Pinson des arbres	*Fringilla coelebs*
Common Cuckoo	Coucou gris	*Cuculus canorus*
European Robin	Rougegorge familier	*Erithacus rubecula*
Mistle Thrush	Grive draine	*Turdus viscivorus*
Song Thrush	Grive musicienne	*Turdus philomelos*
Wren	Troglodyte mignon	*Troglodytes troglodytes*

VII. Back cover

VIII.1. English Abstract

This study assesses the impact of Black Woodpecker (*Dryocopus martius*) cavities on forest bird communities in French temperate forests across 68 plots. Generalised linear mixed models tested eight indices (species richness and acoustic) against four environmental variables (cavity presence, altitude, total dead wood volume and mean tree diameter). Contrary to our main hypothesis, cavity presence did not significantly enhance overall species richness. Instead, forest structure, particularly mean diameter at breast height of trees (mean DBH), explained species distribution across plots. As mean DBH increased so did species richness across all bird groups: total bird species, cavity-nesting species, and forest specialists. Acoustic indices suggested increased complex soundscape in cavity plots, indicating indirect influence of cavities on avian diversity. Individual species analyses revealed nuanced interactions, with species including Green Woodpecker and Eurasian Jay favouring cavity plots, while the European Robin and Song Thrush preferred control plots. Bio-acoustic indices indicated higher acoustic diversity in mountainous regions. Altitudinal distribution has an effect on both plots' soundscapes and species distributions and must be considered in French studies. These findings highlight the importance of mature forests with large trees in supporting diverse bird communities, suggesting that broader environmental context is more influential than cavity presence alone. Preserving mature forests is crucial for maintaining bird diversity and ecological resilience. These results do not indicate that cavity trees should no longer be preserved by forest managers, only that the presence of a cavity on its own is not sufficient to infer higher numbers of bird species.

Keywords: Black Woodpecker, forest bird communities, species richness, forest structure, acoustic indices.

VIII.2. Résumé français

Cette étude évalue l'impact des cavités de pic noir sur les communautés d'oiseaux dans 68 parcelles de forêts tempérées françaises. Huit indices (richesse et acoustique) ont été testés avec des modèles linéaires mixtes généralisés selon quatre variables environnementales. Contrairement à notre hypothèse, la présence de cavités n'a pas amélioré la richesse en espèces. La structure forestière, notamment le diamètre moyen des arbres (mean DBH), explique mieux la distribution des espèces. Une augmentation du mean DBH entraîne une plus grande richesse en espèces pour : l'ensemble des oiseaux, les espèces nichant dans les cavités et les spécialistes de la forêt. Les indices acoustiques suggèrent un paysage sonore plus complexe dans les parcelles à cavités, indiquant une influence indirecte sur la diversité aviaire. Les analyses des espèces individuelles montrent des interactions nuancées : le pic vert et le geai d'Europe favorisent les parcelles à cavités, tandis que le merle et la grive musicienne préfèrent les parcelles sans cavités. Les indices bioacoustiques montrent une plus grande diversité acoustique en montagne. La distribution altitudinale influence les paysages sonores et la distribution des espèces, et doit être considérée dans les études françaises. Ces résultats soulignent l'importance des forêts matures avec de grands arbres pour soutenir des communautés d'oiseaux diversifiées, suggérant que le contexte global est plus influent que les cavités seules. La préservation des forêts matures est essentielle pour maintenir la diversité des oiseaux. Les gestionnaires doivent préserver les arbres à cavités, mais comprendre que leur présence seule n'augmente pas nécessairement le nombre d'espèces d'oiseaux.

Mots-clés : Pic noir, communautés d'oiseaux forestiers, richesse en espèces, structure forestière, indices acoustiques.