



# How Does the Presence of Natural Habitat Patches in a Large-Scale Coconut Plantation in Ivory Coast Influence Pest Control?

A study using soundscape analysis and artificial prey

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Swedish University of Agricultural Sciences, SLU

Faculty of Natural Resources and Agricultural Sciences

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## Abstract

This study investigates the impact of natural habitat patches on pest control efficacy within a large-scale coconut plantation in Ivory Coast.

Using soundscape analysis and artificial prey methods, the research evaluates how biodiversity within natural habitat patches can influence predation rates. The findings indicate that the presence of natural habitats may play a role in enhancing pest control services by increasing predator diversity and activity in intensively managed monocultures.

The research was conducted on a 900-hectare coconut plantation. By using AudioMoths to gather soundscape data and placing dummy caterpillars as artificial prey across various distances from the natural habitat patches, the study measured predation rates and acoustic complexity to draw correlations between biodiversity and pest control potential.

Key results indicate that natural habitat patches, comprising of remnant forests, fallow land, and single large trees, may serve as refuge for pest predators and enhance biological control in adjacent coconut crops. Trends observed showed increased predation activity nearer to the natural habitat patches. Soundscape indices were explored as potential indicators of biodiversity. The acoustic complexity index displayed significant results when correlated to predation events.

The findings are particularly relevant for large-scale monocultures in the Global South, where the importance of balancing agricultural productivity with ecological sustainability is increasingly being recognised. Future studies should continue to explore these dynamics with extended monitoring periods to further expand upon these observations.

**Keywords:** Acoustic monitoring, Biodiversity, Dummy caterpillars, Ecosystem services, Predation rate, Soundscape analysis, Tropical agriculture

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# Abbreviations

ACI	Acoustic Complexity Index
ADI	Acoustic Diversity Index
AEI	Acoustic Evenness Index
AI	Agricultural Intensification
ARUs	Autonomous Recording Units
$\beta$	Slope
BI	Bioacoustic Index
DCs	Dummy Caterpillars
GLM	Generalised Linear Model
H	Temporal Entropy
HP	Habitat Patch
IC	Ivory Coast
GIS	Geographical Information System
GPS	Global Positioning System
NDSI	Normalised Difference Soundscape Index
NH	Natural Habitat
NHP	Natural Habitat Patch
NHPs	Natural Habitat Patches
P	Predation
PMCI	Plantations Modernes de Côte d'Ivoire
PRate	Predation Rate
$R^2$	Coefficient of Determination
SD	Standard Deviation
SE $\beta$	Standard Error of the Slope
SLU	Swedish University of Agricultural Sciences
UHOH	University of Hohenheim
USB	Universal Serial Bus

## Introduction

The number of natural forests in developing countries continues to decline, with Africa having the largest annual net loss of forests since 1990, and the past decade (2010-2020), being particularly critical, with a loss of 3.9 million hectares (FAO 2020). Agricultural intensification (AI) has led to the simplification of farmed landscapes resulting in the loss of landscape diversity (Frey-Ehrenbold et al. 2013; Emmerson et al. 2016; Tal 2018). In essence, agricultural intensification aims at increasing the productivity and rentability of farmland through high-yield monocultures, which most often involves the use of agricultural inputs. In the Ivory Coast (IC), more than 80% of original forests have been destroyed through traditional swidden agriculture, illegal logging, and large-scale land conversion for cash crop cultivation (Amani et al. 2021; Doua-Bi et al. 2021), such as palm oil, cocoa, and coconut. This alteration in the natural landscape in such a short period of time, has led to the loss of biodiversity and destruction of natural ecosystems (Gray & Lewis 2014; Emmerson et al. 2016; Kouadio & Singh 2021). Biodiversity is not only important as such, but it is directly linked to the function, maintenance, and resilience of ecosystems (Hooper et al. 2005; Pennekamp et al. 2018; Martini et al. 2024). It is thus important to investigate further the role of biodiversity in the form of natural habitat patches within agricultural landscapes.

The importance of including natural habitats (NH) within agricultural landscapes and the role ecosystem services play in maintaining various habitats is increasingly being recognised and promoted in the agricultural world (Howe et al. 2009; Smukler et al. 2012; Gray & Lewis 2014; Tschardtke et al. 2021). Habitat patches, comprising remnant natural forested areas, land left fallow, and large trees, not only provide a refuge for biodiversity but may also confer several ecosystem services (Emmerson et al. 2016). For example, natural habitat patches may support higher levels of pest predators and pollinators, thereby increasing biological control and pollination in the adjacent crops (Howe et al. 2009). However, it is important to note that ecosystem disservices may also occur (Decocq et al. 2016). For instance, crops next to natural habitat may have reduced yields due to resource competition and habitats may increase pest numbers. Agricultural landscapes nurture a range of ecological networks from arable and nonarable habitats (Gabriel et al. 2013; Emmerson et al. 2016). However, agricultural habitats and natural habitats within agricultural landscapes vary in terms of species composition and ecosystem functions, where the later usually harbours more beneficial ecosystem services, due to its higher biodiversity (Kremen & Miles 2012).

Acoustic monitoring has emerged as a practical and low-cost method for assessing biodiversity (Lapp et al. 2023). Autonomous recording units (ARUs) are used to collect and analyse soundscape data offering insights into species diversity and acoustic complexity in a cost-effective and practical manner (Alcocer et al. 2022; Martini et al. 2024). Predation is one of the central factors that can assist in determining the abundance of insect communities and predatory activity for birds (Gray & Lewis 2014; Sam et al. 2015). Through the use of ARUs coupled with artificial prey methods, predation rates across a study site can thus be assessed (Schwab et al. 2021).

## Context

The following study took place on a ~900-hectare coconut plantation in the Ivory Coast. Coconut plants, in most growing regions of the world, are attacked by numerous pests all year round, including both vertebrates and invertebrates (Rajan et al. 2009; Kumara et al. 2015). In such a large-scale monoculture, the integration of natural habitat and the benefits that it might yield across the plantation are of particular interest. Moreover, the plantation wishes to obtain the Bio Suisse certification which includes a mandatory 7% natural habitat as a standard. Given that the certification is organic, there is a need to assess the quality of the natural habitat patches on the plantation and the pest control benefits that they may bring about.

Birds and bats are often indicator species for habitat quality and ecosystem services (Russo et al. 2021; Fill et al. 2022). Additionally in tropical climates, the use of insects as bioindicators is frequently used as they are often associated with increased plant diversity (Lövei & Ferrante 2017; Sajjad 2020; Lima et al. 2021; Chowdhury et al. 2023). When areas surrounding crop lands contain more natural habitat, predation pressure can increase or decrease following natural habitat fragmentation (Langellotto & Denno 2004; Maas et al. 2013; Haan et al. 2020; Schwab et al. 2021). The natural habitat in this study consists of well-developed tree stands, in part remnant natural forested areas on slopes too steep for farming, and in other parts land left fallow to restore patches of biodiverse land on the property.

## Research gaps

Many studies have highlighted the benefits of integrating patches of natural habitat within agricultural landscapes (Howe et al. 2009; Kremen & Miles 2012; Gray & Lewis 2014; Decocq et al. 2016; Emmerson et al. 2016; Tschardtke et al. 2021), as well as establishing links between biodiversity and ecosystem functions (Hooper et al. 2005; Pennekamp et al. 2018; Haan et al. 2020; Martini et al. 2024). However, there is a scarcity of research focusing on the specific integration of natural habitats in large-scale monocultures, such as coconut plantations in tropical regions.

Furthermore, the Bio Suisse certification is more commonly applied in Europe, so transferring the standard to West Africa and other parts of the tropics is a novel challenge, especially given that the natural habitat in this context is well developed tree stands rather than natural grasslands and flower patches. Thus, more detailed studies are needed to emphasise and quantify the contributions of birds, bats, and predatory insects to ecosystem services in farmed lands in the Global South.

Addressing these research gaps will enhance our understanding of how to effectively integrate natural habitats within agricultural landscapes to promote biodiversity and ecosystem services, especially in the context of developing countries and large-scale monocultures.

## Research Questions and Hypotheses

### Aims

This research aims to assess and formulate a deeper understanding of the following questions:

- a. How does the presence of natural habitat patches within a large-scale coconut plantation in Ivory Coast influence pest control?
- b. Do the larger natural habitat patches display more predatory activity observed in the surrounding coconut fields?
- c. Does the distance away from the natural habitat patches influence the amount of predation observed?
- d. How do soundscape indices relate to pest control?

### Hypotheses

From the aforementioned research questions the following hypotheses were generated:

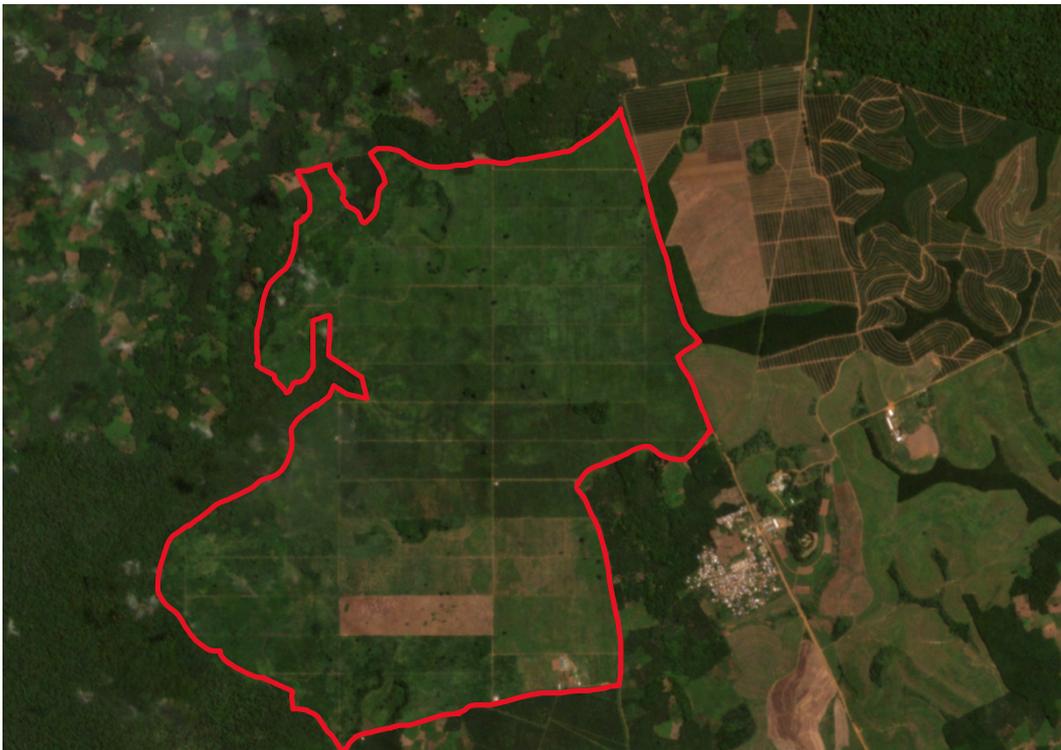
- a.1 The acoustic indices will correlate with the predation rate of the dummy caterpillars. The acoustic complexity index (ACI) and the acoustic entropy (H) will increase with the level of activity of birds, bats, and predatory insects.
- b.1 The rate of attenuation of acoustic signals is dependent on the natural habitat patch size. Larger patches provide more resources to support greater populations of natural enemies of pests, as indicated or represented by the presence of predation events.

- c.1 Acoustic complexity and predation activity observed will decrease with increasing distance from the habitat patch. Birds, bats, and insect predators may exhibit higher levels of activity closer to the habitat patch, as they benefit from resources and shelter provided by the patch.
- d.1 Acoustic complexity will increase with higher recorded predation rates.

## Materials and Methods

### Study site

The study was conducted in April 2024 on a nine-hundred-hectare coconut (*Cocos nucifera*) plantation two hours Northeast of Abidjan in the Ivory Coast, West Africa (5°24'16.38" N, 3°35'35.40" W) (Figure 1). There are two distinct seasons each year: dry from June until October and wet from November until May (*World Bank Climate Change Knowledge Portal* 2021), with mean annual temperatures and rainfall of 24-28°C and 1299.33 mm (1991-2020). To successfully gather the necessary acoustic and temporal field data, it was preferable to go during the dry season for ease of movement and acoustic monitoring, as torrential downfall experienced in the tropics during the wet season would hinder the recordings.



*Figure 1. A satellite image of the plantation dating from April 2024, matching the sampling period of the study. In red the theoretical border of the plantation. Within the red border, the vertical and horizontal straight lines are tracks, separating the coconut plots, and the darker, more irregular shapes correspond to the natural habitat patches. In the bottom left-hand corner of the image, a*

*natural forest. All other elements that can be seen are mixed agricultural lands. (Image source: Planet Labs Inc., 2024).*

## Planting design and Management of the plantation

The coconut trees on the plantation are planted 8 meters by 12 meters apart and are aged from zero to five years old.

The management methods, which are usually relatively modest in coconut plantations (Plucknett 2019), involve the addition of calcium carbonate to the acidic, sandy, soil, and the use of nitrogen-fixing tropical Kudzu (*Pueraria phaseoloides*) throughout the plantation as a cover crop.

## QField

In preparation for this systematic survey, a mapping exercise was undertaken using QField by members of the plantation research team to determine the size of natural habitat patches. QField is a mobile GIS application, for geospatial data collection and analysis, allowing the operator to view and manage a GIS project created with QGIS on a smartphone in the field (Montagnetti & Guarino 2021). This enabled the clear delineation of the plantation's geographical limits as well as mapping the patches of natural habitat. In this study, the natural habitats mapped consisted of the existing natural habitat patches, which are in part remnant natural forested areas, too steep for farming, and in other parts land left fallow to regain biodiverse land on the property, as well as large remnant trees, which are also important components of habitat (Zwartz et al., 2019) (Figure 2).



*Figure 2. An example of a natural habitat patch (NHP) found in the plantation, where an area of remnant forest can be seen in the background, and rows of planted coconut trees in the foreground. (Photo by F.M.M. Jamme, 2024).*

The app was also used as a GPS to facilitate the orientation in the large study area and the creation of points at each sampling site. Post-fieldwork, the collected data from QField was exported to QGIS, for integration with the other relevant GIS layers and datasets.

## AudioMoths

Large-scale monitoring of such species may bring about several limitations, such as the costs and impracticality of the data collection (Hill et al. 2019). In recent years, there have been significant improvements in the technologies available for biodiversity monitoring in the field (Lapp et al. 2023). With acoustic monitoring becoming an increasingly widespread technique for surveying populations of sound-producing species (Laiolo 2010; Marques et al. 2013; Sugai et al. 2019; Rhinehart et al. 2020; Lapp et al. 2023). Collected sound files can be analysed to estimate the number of species heard in the audio files, and derive indices of acoustic complexity, which in turn may give indications of species diversity (Alcocer et al. 2022; Martini et al. 2024).

Open Acoustic Devices released the first version of the AudioMoth in 2017 (Hill et al. 2019), and it has quickly become one of the most widely used autonomous recording units (ARUs) (Lapp et al. 2023). AudioMoths are a low-cost, open-source acoustic logger, for monitoring and analysing environmental sounds (Hill et al. 2019; AudioMoth | Open Acoustic Devices 2023) (Figure 3). A total of thirty AudioMoths version 1.2 were used in this study to collect acoustic data, in the form of audio recordings of bird, bat, and insect vocalisations across the plantation. Acoustic surveying of 14 NHPs and 168 sampling points within the ~900-hectare coconut plantation was achieved with and through the following materials and methods.



Figure 3. The AudioMoth device, in an IPX7 Waterproof case open (left) and closed (right). (Image source: AudioMoth | Open Acoustic Devices 2023).

Materials used to build an audio recording station include: AudioMoth devices, MicroSD cards (for data storage), AudioMoth IPX7 Waterproof Cases, AA lithium batteries, bamboo sticks, a hand-digging trowel, cable ties, the AudioMoth Configuration App version 1.10.2, a USB to Micro B cable, a MicroSD card reader to USB, a Computer with R and R-Studio installed, and a GPS device, for precise location logging, in this case the QField app was used.

The AudioMoths were attached using the Velcro band present on the weatherproof casings, on trees within and on the edge points of the habitat patches. In the transects, no trees, apart from the coconut trees, were present. Thus, bamboo sticks of approximately three metres in height were used to securely attach the AudioMoths using cable ties (Figure 4).



*Figure 4. AudioMoths in the field. From left to right; in the middle of a natural HP fixed on a tree, at the border of a natural HP fixed on a tree, and at a sample point on a transect fixed on a bamboo stick. (Photos by F.M.M. Jamme, 2024).*

The recording schedule was set 30 minutes before both, dawn (05:45-08:45 UTC) and dusk (17:45-20:45 UTC) to coincide with peak biophony (Rhinehart et al. 2020). *AudioMoth-config* was used to configure the desired settings. These included the sample rate, which determines the maximum sound frequency able to be recorded (Rhinehart et al. 2020). It was set to 250kHz to capture both audible (birds and insects) and ultrasonic (bats) sounds. The recording duration of the sound files was set to 1 minute every 2 minutes, to facilitate the processing of the data, and to avoid having large quantities of unusable sound files due to unforeseen external events (rain/wind). Lastly, the gain, which depends on the environment in which

the AudioMoths are deployed (*AudioMoth* | *Open Acoustic Devices* 2023), was set to 'medium' (Appendix 1).

Within each natural HP, one recorder was set up in the middle of the patch (-50m), and two edge points (0m), selected at random each time, from which two transects perpendicular to each other were conducted out from the patch with increasing distance, each point having one recorder (Figure 5). Thus 12 recorders for each habitat patch, recorded for two nights and two mornings before being moved to new sites. One transect had sampling points of 25m, 50m, 100m, 200m, and 400m from the edge of the habitat patch, whilst the other transect going perpendicularly to the previous one, had distances of 75m, 150m, 250m, and 300m from the other edge point of the habitat patch. For ease of analysis the distance of the point in the NHP was approximated to “-50m” and the two edge points to “0m”.

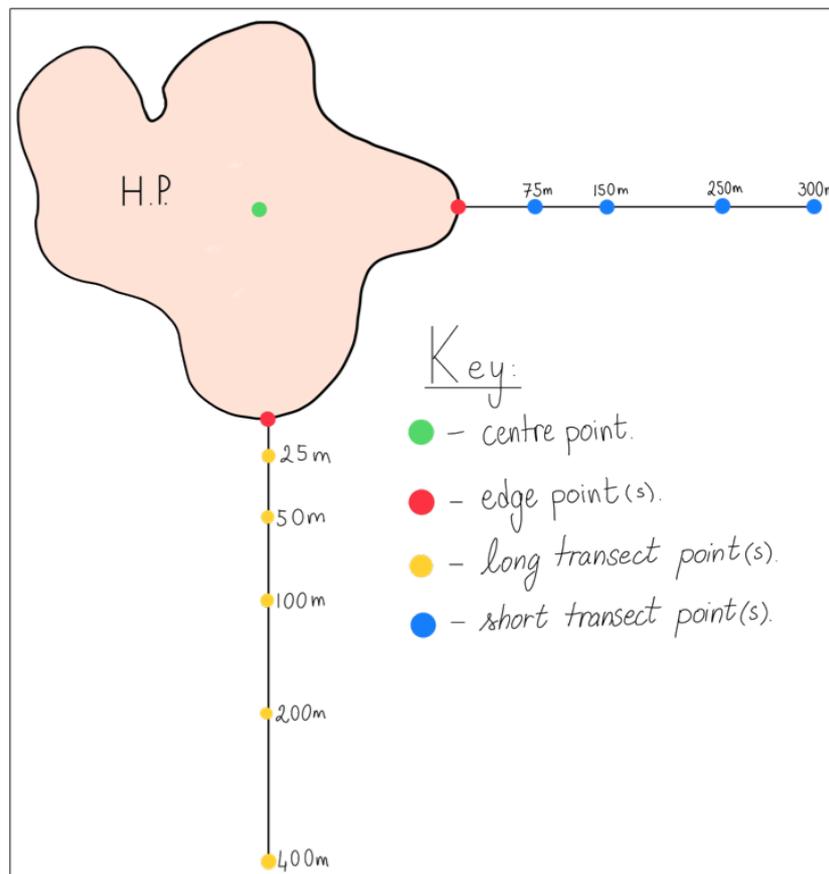


Figure 5. Graphical depiction of the sample design for the placement of the AudioMoths and dummy caterpillars in the subsequent transects from the natural habitat patches. (Illustration by F.M.M. Jamme, 2024).

ARUs can pick up a significant amount of background noise, both natural and anthropogenic. Additionally, their detection range is somewhat limited as a single

AudioMoth can monitor an area of  $\sim 0.8\text{km}^2$  (Hill et al. 2018), leading to distant sound sources being missed, potentially creating an incomplete data set. The orientation of the AudioMoths was designed to maximise the efficiency and effectiveness of the acoustic data collection, thus they were placed facing away from the natural HP at the edge points and facing towards the natural HP at all the transect points.

Each single site was sampled only once, unless rain occurred during one of the four 3-hour recording periods, in which case, the site was repeated. After each 48-hour data collection period, the AudioMoths were retrieved. The microSD cards were removed and connected to a computer using the microSD to USB connector to transfer the audio files to an external hard drive. A backup of all the recordings was also maintained. The microSD cards were then erased, returned to the devices, and the AudioMoths reconfigured to be placed at a new site.

## Soundscape analysis

The soundscape analysis was performed using a specific R package entitled ‘soundecology’, to calculate acoustic indices from the recorded sound files gathered in the field using the AudioMoths (Villanueva-Rivera et al. 2011; Bradfer-Lawrence et al. 2024). The mean and standard deviation of the acoustic indices were used in this study, as shown to uncover hidden patterns of variability and to be the most useful variables for differentiating habitats (Fuller et al. 2015; Pieretti et al. 2015; Bradfer-Lawrence et al. 2024).

The following indices were calculated:

Acoustic Complexity Index (ACI) produces a direct quantification of the complexity of the soundscape by evaluating the variability in sound intensity over time and frequency bands (Pieretti et al. 2011; Martini et al. 2024). Different habitats generate unique soundscapes due to the varying presence and activities of species (Frommolt & Tauchert 2014). High ACI values typically indicate a complex soundscape, which can be correlated to habitat diversity, and are often indicative of rich biological activity which can serve to infer on biodiversity (Alcocer et al. 2022).

Temporal Entropy (H) assesses the temporal variability of the soundscape, indicating the predictability or randomness of sound events over time, which enables the understanding of acoustic activity patterns, such as diel or seasonal variations (Sueur et al. 2008; Alcocer et al. 2022). High H values ( $> 0.5 - 1$ ) typically indicate areas with high species diversity which often show complex temporal patterns of acoustic activity (Sueur et al. 2008; Martini et al. 2024). Predictable patterns might indicate regular activities such as feeding or mating calls,

while randomness might indicate sporadic or diverse species interactions (Sueur et al. 2008).

The Bioacoustic Index (BI) quantifies the intensity of biological sounds in a soundscape, typically in a frequency range where most biological sounds occur, and is used to monitor biological activity changes over time (Boelman et al. 2007; Alcocer et al. 2022). High BI values ( $> 2$ ) suggest that many different species are present and contribute to the diversity of the sound frequencies (Boelman et al. 2007). However, Alcocer et al. (2022), reports that BI is weakly connected to biodiversity.

The Acoustic Evenness Index (AEI) measures the evenness of sound energy distribution across frequency bands. Typically, values close to zero indicate uneven distribution and values close to one, even distribution which can be related to habitat quality and species diversity (Villanueva-Rivera et al. 2011; Martini et al. 2024). Alcocer et al. (2022) reports an “almost perfect” correlation between AEI and species richness.

The Acoustic Diversity Index (ADI) quantifies the diversity of sound sources in the environment by examining the distribution of acoustic energy across different frequency bands (Villanueva-Rivera et al. 2011; Alcocer et al. 2022; Martini et al. 2024). It is used to assess the presence and diversity of species, with values above 0.7 indicating rich biodiversity (Villanueva-Rivera et al. 2011; Alcocer et al. 2022; Martini et al. 2024). Alcocer et al. (2022), reports ADI values being specifically associated with bird species richness.

Acoustic indices are valuable tools for non-invasively monitoring biodiversity. By analysing acoustic data, one can infer habitat quality, species presence, and ecosystem health (Alcocer et al. 2022). However, some limitations are to be considered when using acoustic indices to infer on biodiversity richness and ecosystem health.

Anthropogenic noise can interfere with the recordings, theoretically masking biophonic sounds and affecting the resulting indices. However, the Normalised Difference Soundscape Index (NDSI), which focuses on distinguishing the balance between biological and anthropogenic sounds in an environment can be used (Kasten et al. 2012; Alcocer et al. 2022). In this study, NDSI was not calculated as it was not relevant with the area being so remote. Moreover, the recording schedule was set outside of working hours for the plantation staff, thereby reducing the possibility of anthropogenic noise.

Dense vegetation, complex terrain, and natural environmental sounds (wind/rain) can attenuate the sounds recorded by the ARUs, hindering the detection of certain species. Moreover, not all species are vocal and/or not during the specific recording time periods, leading to an underrepresentation in which rare species may not be accounted for. A long-term monitoring is thus required to accurately capture acoustic biodiversity. Additionally, acoustic monitoring should be used in conjunction with other biodiversity assessment methods to provide a more comprehensive understanding of the ecosystem under study (Alcocer et al. 2022). Several of the above-mentioned limitations can be circumvented through the use of artificial prey (Howe et al. 2009).

The indices were calculated with the default settings. Each site had 360 1-minute files, and each file was analysed individually to get a score for each index. This was then used to calculate the mean and standard deviation (SD) of all the indices.

### Dummy caterpillars

Using artificial prey is a simple method which allows the observer to monitor the rate of attack or disappearance, thereby obtaining quantitative data on predation pressure (Howe et al. 2009).



*Figure 6. Left, a live caterpillar (Hippotion esson), after which the artificial caterpillars in this study were modelled. Right, a dummy caterpillar upon placement. (Photos by F.M.M. Jamme, 2024).*

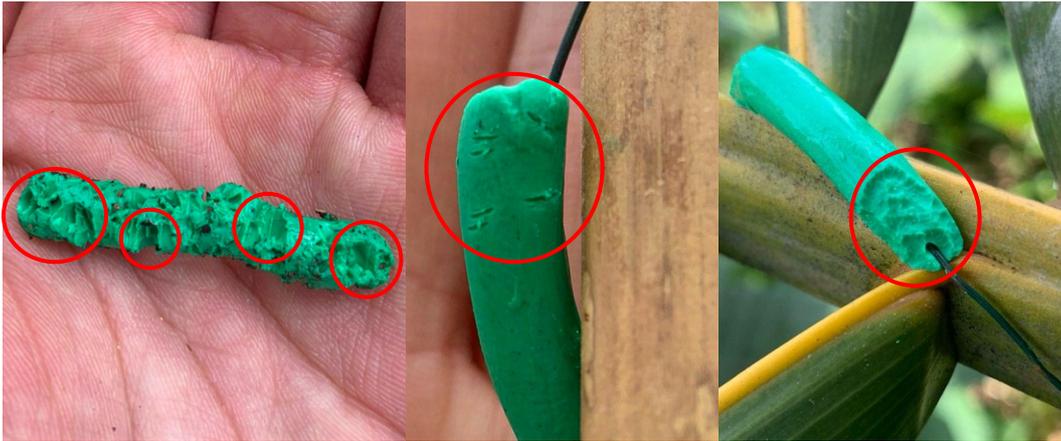
The technique relies on the malleability and non-hardening quality of the modelling clay which can then be shaped into regular 3.5cm long and 0.5cm wide cylindrical shape of a caterpillar, using a T-handle reamer and insertion tool. As far as it is known, this clay is suitable for children and thus poses no health/welfare issues. Furthermore, the green colour seems to be perceived as more palatable by predators (Howe et al. 2009). These artificial caterpillars can be perforated and attached to any substrate (plant leaf, stem, or soil) using wire. Care should be taken to minimise

the amount of handling as this may give unwanted chemical signals to predators, as well as spoiling of samples through accidental markings (Howe et al. 2009).



Figure 7. Tools and materials used to make dummy caterpillars following the standards by Howe et al. (2009) green plasticine modelling clay, a T-handle reamer and insertion tool, a spool of thin, flexible, green wire, and a pair of wire cutters to fix them onto the desired surface. (Photos by F.M.M. Jamme, 2024).

Three dummy caterpillars were used per audio sampling site. The distribution of the DCs at each sampling site consisted of three locations, one on the floor, one on a nearby coconut tree/plant, and one on the bamboo used to support the AudioMoth. They were categorised for ease of use as; “floor”, “coconut”, and “bamboo”.



*Figure 8. A selection of three DCs in the field, photographed, labelled, and recorded showing signs of predation, circled in red. From left to right, a floor DC with multiple rodent bite marks, a DC on a bamboo stick with large ant mandibular bite marks, a DC on a nearby coconut tree with ant bite marks. (Photos by F.M.M. Jamme, 2024).*

A total of 504 artificial caterpillars, placed at 168 sampling sites, were used in the field data collection period. After being exposed for two nights and two mornings, roughly 48 hours, the DCs were inspected in situ, recorded, and documented using a phone camera and labelling on each picture. They were then removed and discarded. It is often best not to remove the dummy caterpillar from the surface on which it was fixed, but rather to take a detailed and focused photograph of the predation marks. The plasticity of the clay allows one to observe marks caused by predator's mandibles, teeth, beak, or ovipositor. Signs of predation were later examined and recorded by comparing each of the pictures taken, to a standard "bite-guide" (Howe et al. 2009; Low et al. 2014; Sam et al. 2015; Molleman et al. 2016) (Figure 9).



*Figure 9. An example of a predation event on two different DCs. Circled in red, clear triangular-shaped beak marks, typical of bird predation, can be observed on the DCs. (Photos by F.M.M. Jamme, 2024).*

The record of predation/parasitism on the artificial caterpillars, was then reorganised to streamline its input into RStudio for statistical analysis, to determine levels and types of predations. The following categories were used for the dependent variables, Predation (P), and Predation Rate (PRate).

## Data analysis

The predation rates [%] were calculated as the ratio of the number of predated dummy caterpillars to the total number of deployed DCs. If the DC displayed bite marks, it was counted as predated. If two distinct bite marks on a DC were identified, two separate predation events were recorded. DCs that were no longer at the sample site were assumed to have been preyed upon.

The Pearson correlation coefficients between predation (P) and predation rate (PRate) and all the explanatory variables, distance from the natural habitat patch (D), natural habitat patch size (NHPsize), acoustic complexity index (ACIMean and ACIsd), temporal entropy (HMean and Hsd), bioacoustic index (BIMean and BIsd), acoustic evenness index (AEIMean and AEIsd), acoustic diversity index (ADIMean and ADIsd), were calculated in RStudio using the ‘pearson’ method. This method measures the strength and direction of the linear relationship between two variables, where ‘1’ indicates a perfect positive linear correlation, ‘-1’ a perfect negative correlation, and ‘0’ no linear correlation.

Furthermore, a linear regression was fitted to model the relationship between the dependent variables (P and PRate) and the explanatory variables. The coefficient of determination ( $R^2$ ) was extracted to assess the goodness of fit of the models. This statistical measure explains the proportion of the variance in P and PRate that is predictable from the explanatory variables it is modelled against.

To test the potential relationship between the acoustic indices and predation and predation rate, generalised linear models (GLMs) were used, using the ‘ggplot2’ package in RStudio. GLMs are a flexible extension of ordinary linear regression that allows for the dependent variables (P and PRate) to have a distribution other than a normal distribution. The key advantages of using ‘ggplot2’ include its capacity to generate intricate, multi-layered graphics with extensive customization options and its user-friendly syntax.

The ‘binomial’ family was used for GLMs of P and PRate in RStudio. This family is used for modelling binary or proportional data. However, an important issue of this family is **overdispersion**. This occurs when the observed variability in the data is greater than what the model expects under the assumed distribution. Thus, when fitting the GLMs of PRate with the binomial family, overdispersion was checked. This was done by comparing the residual deviance to the degrees of freedom. If the

residual deviance significantly exceeded the degrees of freedom, overdispersion was likely present. When overdispersion was detected, the ‘quasibinomial’ family was used. This adjustment provides more accurate estimates of the standard errors and improves the reliability of the statistical inferences obtained.

One model was run for each explanatory variable, thus 24 models in total. In each model, P and PRate were the response variables, and each acoustic index as well as D and NHPsize, were the explanatory variables.

For PRate as a response variable, a two-column matrix with the number of attacked DCs (eaten) and the number of undamaged DCs (remaining) per sampling site was generated, using the function ‘cbind’ in RStudio.

A correlation matrix of all the explanatory variables was created to **detect for multicollinearity, inform variable selection and identify redundant variables.**

The data was analysed using R-Studio version 4.4.1 for all analyses (R Core Team 2024), and  $\alpha < 0.05$  was used as a significance threshold for all hypothesis tests.

## Literature review

A review of published scientific literature was conducted to investigate on the current research involving acoustic surveying and dummy caterpillar methods, and ecosystem services within agricultural landscapes. Furthermore, other studies using soundscape analyses were explored to better compare with the findings in this study.

The following keywords were researched on Google Scholar (Google 2024), ScienceDirect (Elsevier B.V. 2024), and ResearchGate (ResearchGate GmbH 2024), ‘(“ecosystem services” AND “agricultural landscapes”)', ‘(“ecosystem services” AND “habitat patches” AND “tropical agriculture”)', ‘(“natural habitat” AND “acoustic recordings”)', ‘(“dummy caterpillars”)', among others.

## Critiques and limitations

### *Study site*

While the choice of the dry season was made to ease movement and recording, having only one month of data limited the accuracy of the representation of the yearly activity of the species present on the plantation. Thus, a more representative data collection across various seasons in the year may yield more significant results.

### *AudioMoths*

The 30 AudioMoths, while numerous, may still provide incomplete coverage of the ~900-hectare plantation. Should this study be replicated, a greater number of

AudioMoths and more manpower should be considered to enhance the findings by increasing the amount of audio data collected per transect and throughout the study site.

#### *Dummy caterpillars*

The interpretation of predation rates using dummy caterpillars can be challenging. Marks on the caterpillars may not always be clear or distinguishable, leading to potential misidentification of predation events. Additionally, the 48-hour exposure period may not be sufficient to capture the full range of predation pressures.

#### *Data analysis*

The use of generalised linear models (GLMs) might oversimplify the complex interactions within the ecosystem. More sophisticated models could be used to provide a deeper insight.

## Results

### Dummy caterpillars

Overall, of the 504 DCs placed at the 168 sampling sites, across the 14 different NHP sites on the plantation, a total of 149 individual predation events were counted. A resulting total mean predation rate of 29.3% was obtained.

All NHP sites sampled displayed some level of predation. Mean predation rates within NHP sites ranged from 19.25% to 49.67%.

Predation frequencies observed on the DCs were identified as conducted by insects (44.44%), birds (43.79%), and rodents (11.76%).

Table 1. Coefficient of determination ( $R^2$ ), probability value ( $p$ ), slope ( $\beta$ ), and standard error of the slope ( $SE\beta$ ) of the different interactions of the explanatory variables (D, NHP, ACIMean, ACIsd, HMean, Hsd, BIMean, BIsd, AEIMean, AEIsd, ADIMean, ADIsd) and the Predation (P) and Predation Rate (PRate). Significant results are indicated in bold. Marginally significant results are indicated by an asterisk (\*).

		$R^2$	$p$	$\beta$	$SE\beta$
D	P	0.0036	0.438	-0.0009	0.0012
	PRate	0.0017	0.599	-0.0004	0.0008
NHP	P	0.0048	0.374	-1.078e-05	8.087e-06
	PRate	0.0214*	0.058*	-7.226e-06*	5.667e-06*
ACIMean	P	<b>0.0251</b>	<b>0.032</b>	<b>0.0147</b>	<b>0.0070</b>
	PRate	0.0073	0.248	0.0047	0.0041
ACIsd	P	<b>0.0335</b>	<b>0.013</b>	<b>0.0079</b>	<b>0.0033</b>
	PRate	0.0181*	0.068*	0.0031*	0.0017*
HMean	P	0.0001	0.911	-0.3879	3.4476
	PRate	0.0078	0.530	1.4740	2.3420
Hsd	P	0.0021	0.233	10.3741	8.7009
	PRate	0.0003	0.821	1.3278	5.8622
BIMean	P	0.0011	0.648	0.7814	1.7019
	PRate	0.0002	0.842	-0.2317	1.1584
BIsd	P	0.0049	0.344	3.3254	3.5250
	PRate	0.0004	0.780	0.6748	2.4099
AEIMean	P	0.0012	0.638	1.0491	2.2152
	PRate	0.0007	0.721	-0.5380	1.5056
AEIsd	P	0.0062	0.289	3.9697	3.7440
	PRate	0.0037	0.423	2.1224	2.5878
ADIMean	P	0.0006	0.733	-0.9526	2.7730
	PRate	0.0006	0.742	0.6231	1.8874
ADIsd	P	0.0043	0.375	2.4444	2.7456
	PRate	0.0028	0.474	1.3290	1.8550

## Distance

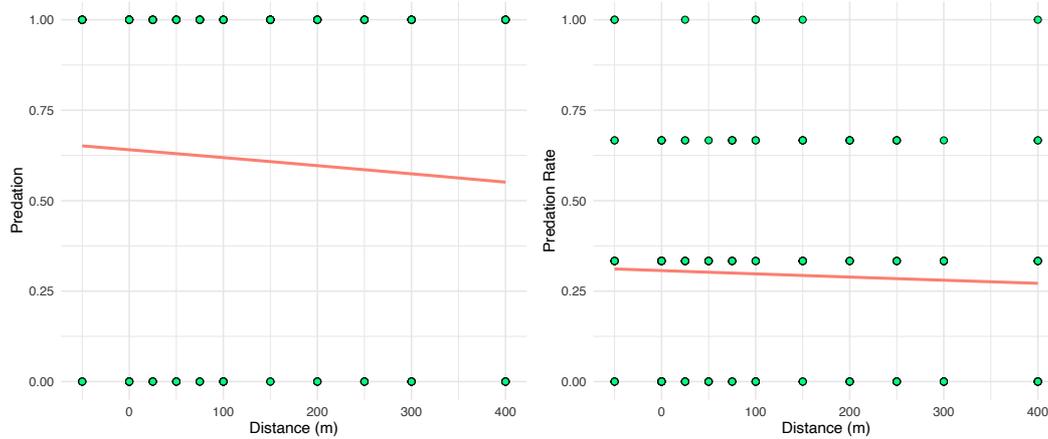


Figure 10. Left, predation events (1 = predation, 0 = no predation) versus distance (m) away from the natural habitat patches correlation scatter plot. Right predation rate (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site) versus distance (m) away from the natural habitat patches correlation scatter plot.

## Predation

A non-significant tendency between the frequency of predation (P) and distance (D) was found, that declined with increasing distance from the NHPs (Figure 10). Distance explained a limited amount of the variation in predation ( $R^2=0.0036$ ) and was non-significant ( $p=0.438$ ) (Table 1).

## Predation rate

A non-significant tendency between the predation rate (PRate) and distance (D) was found, that declined with increasing distance from the NHPs (Figure 10). Distance explained a limited amount of the variation in predation rate ( $R^2=0.0017$ ) and was non-significant ( $p=0.599$ ) (Table 1).

## Natural habitat patch size

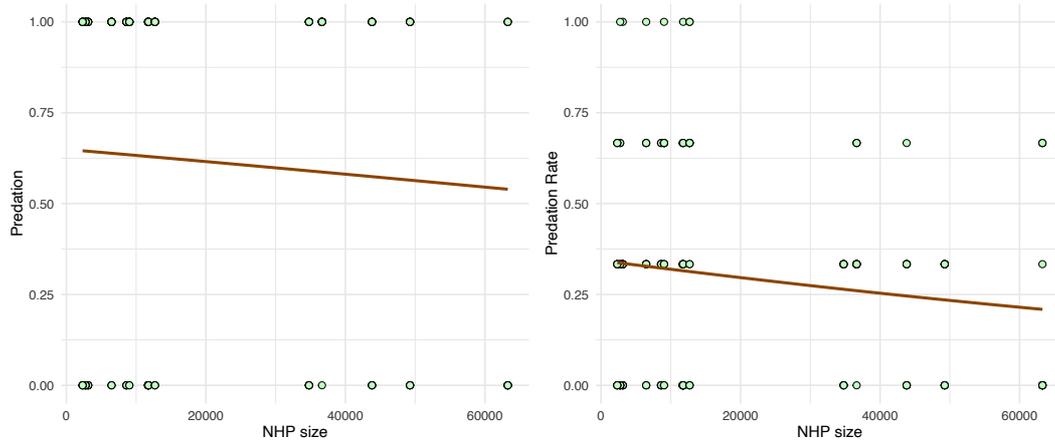


Figure 11. Left, predation events (1 = predation, 0 = no predation) versus natural habitat patch size ( $m^2$ ) correlation scatter plot. Right predation rate (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site) versus natural habitat patch size ( $m^2$ ) correlation scatter plot.

### Predation

A non-significant tendency between the frequency of predation (P) and the natural habitat patch size (NHPsize) was found, that declined with increasing NHPsize (Figure 11).

Natural habitat patch size explained a limited amount of the variation in predation ( $R^2=0.0048$ ) and was non-significant ( $p=0.374$ ) (Table 1).

### Predation rate

A marginally significant tendency between the predation rate (PRate) and the natural habitat patch size (NHPsize) was found, that declined with increasing NHPsize (Figure 11).

Natural habitat patch size explained a limited amount of the variation in predation rate ( $R^2=0.0214$ ) and was marginally significant ( $p=0.058$ ) (Table 1).

## Acoustic complexity index

### Predation

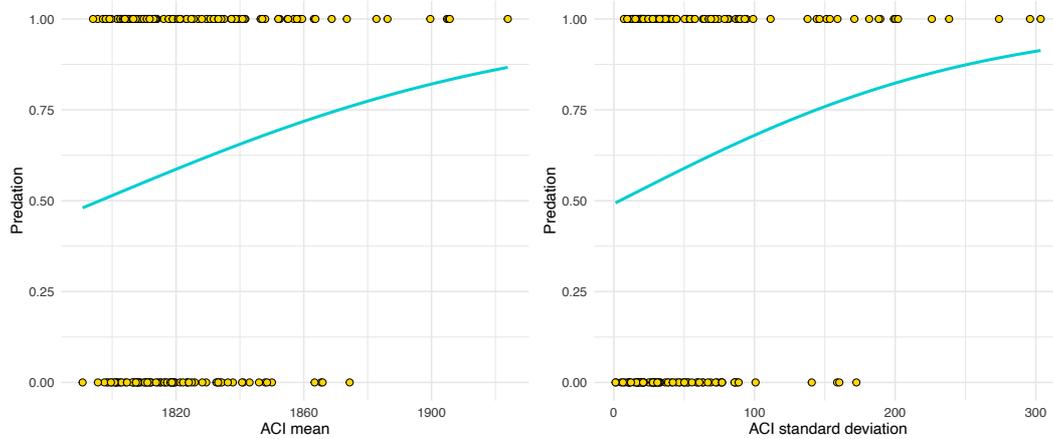


Figure 12. Left, predation events versus ACIMean correlation scatter plot. Right predation events versus ACIsd correlation scatter plot. (1 = predation, 0 = no predation).

#### *Acoustic Complexity Index Mean*

A significant tendency between the frequency of predation (P) and the Acoustic Complexity Index Mean (ACIMean) was found (Figure 12).

ACIMean explained a limited amount of the variation in predation ( $R^2=0.0251$ ) and was significant ( $p=0.032$ ) (Table 1).

#### *Acoustic Complexity Index Standard Deviation*

A significant tendency between the frequency of predation (P) and the Acoustic Complexity Index Standard Deviation (ACIsd) was found (Figure 12).

ACIsd explained a limited amount of the variation in predation ( $R^2=0.0335$ ) and was significant ( $p=0.013$ ) (Table 1).

## Predation rate

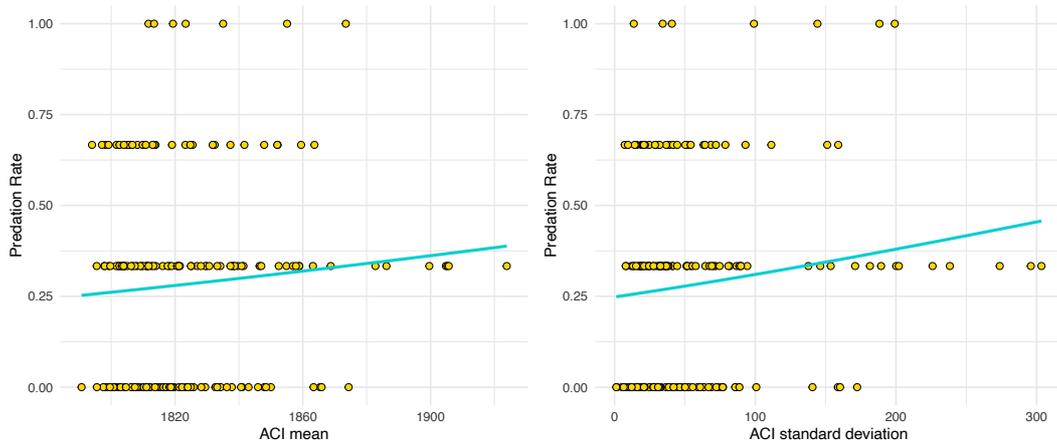


Figure 13. Left, predation rate versus ACIMean correlation scatter plot. Right predation rate versus ACIsd correlation scatter plot. (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site).

### Acoustic Complexity Index Mean

A non-significant tendency between the predation rate (PRate) and the Acoustic Complexity Index Mean (ACIMean), was found (Figure 13).

ACIMean explained a limited amount of the variation in predation rate ( $R^2=0.0073$ ) and was non-significant ( $p=0.248$ ) (Table 1).

### Acoustic Complexity Index Standard Deviation

A marginally significant tendency between the predation rate (PRate) and the Acoustic Complexity Index Standard Deviation (ACIsd) was found (Figure 13).

ACIsd explained a limited amount of the variation in predation rate ( $R^2=0.0181$ ) and was marginally significant ( $p=0.0685$ ) (Table 1).

## Temporal entropy

### Predation

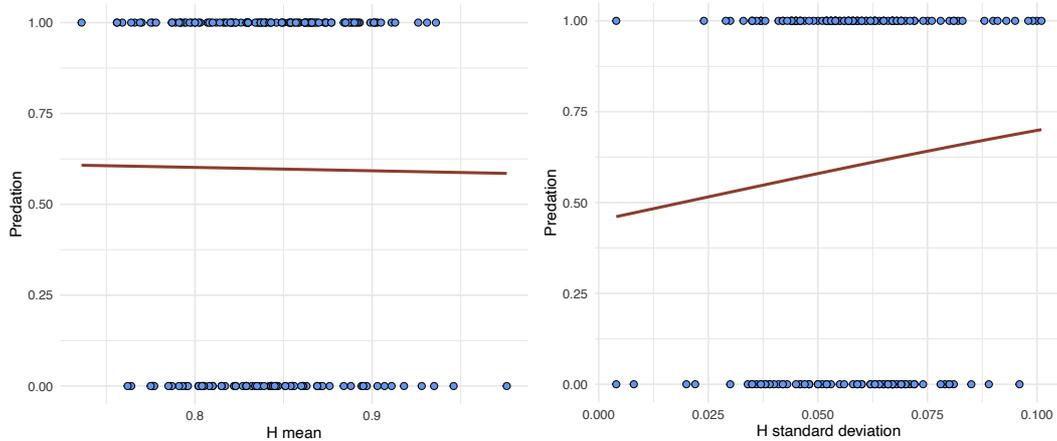


Figure 14. Left, predation events versus HMean correlation scatter plot. Right predation events versus Hsd correlation scatter plot. (1 = predation, 0 = no predation).

### *Temporal Entropy Mean*

No tendency between the frequency of predation (P) and the Temporal Entropy Mean (HMean) was found (Figure 14).

HMean explained a limited amount of the variation in predation ( $R^2=0.0001$ ) and was non-significant ( $p=0.911$ ) (Table 1).

### *Temporal Entropy Standard Deviation*

A non-significant tendency between the frequency of predation (P) and the Temporal Entropy Standard Deviation (Hsd) was found (Figure 14).

Hsd explained a limited amount of the variation in predation ( $R^2=0.0078$ ) and was non-significant ( $p=0.233$ ) (Table 1).

## Predation rate

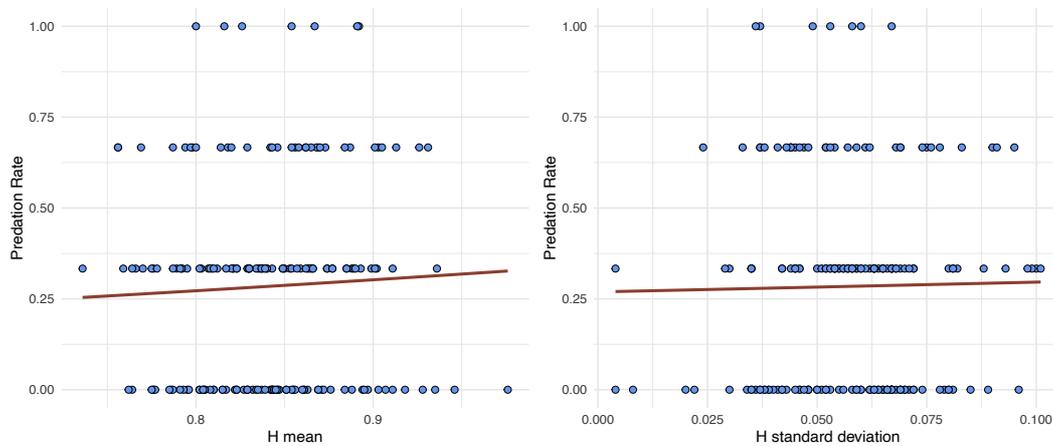


Figure 15. Left, predation rate versus HMean correlation scatter plot. Right predation rate versus Hsd correlation scatter plot. (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site).

### *Temporal Entropy Mean*

A non-significant tendency between the predation rate (PRate) and the Temporal Entropy Mean (HMean) was found (Figure 15).

HMean explained a limited amount of the variation in predation rate ( $R^2=0.0022$ ) and was non-significant ( $p=0.530$ ) (Table 1).

### *Temporal Entropy Standard Deviation*

No tendency between the predation rate (PRate) and the Temporal Entropy Standard Deviation (Hsd) was found (Figure 15).

Hsd explained a limited amount of the variation in predation rate ( $R^2=0.0003$ ) and was non-significant ( $p=0.821$ ) (Table 1).

# Bioacoustic index

## Predation

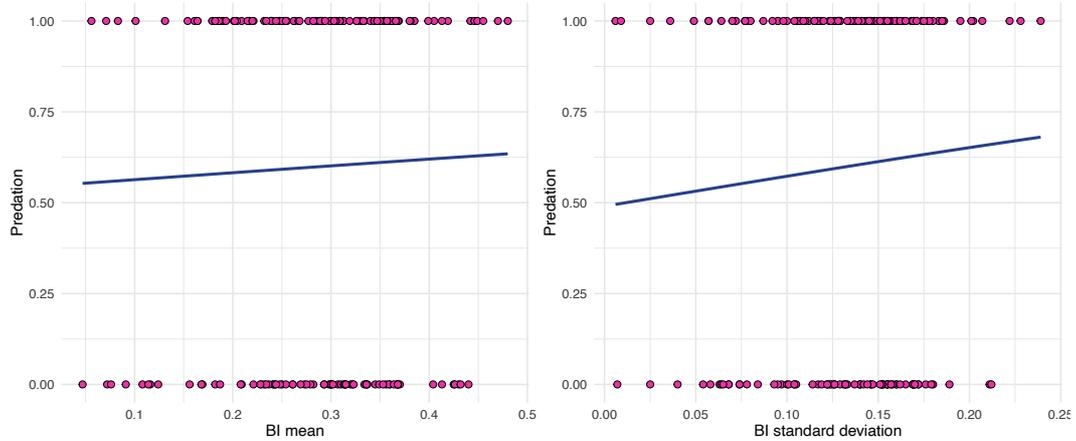


Figure 16. Left, predation events versus BIMean correlation scatter plot. Right predation events versus BIstd correlation scatter plot. (1 = predation, 0 = no predation).

### Bioacoustic Index Mean

A non-significant tendency between the frequency of predation (P) and the Bioacoustic Index Mean (BIMean) was found (Figure 16).

BIMean explained a limited amount of the variation in predation ( $R^2=0.0011$ ) and was non-significant ( $p=0.648$ ) (Table 1).

### Bioacoustic Index Standard Deviation

A non-significant tendency between the frequency of predation (P) and Bioacoustic Index Standard Deviation (BIstd) was found (Figure 16).

BIstd explained a limited amount of the variation in predation ( $R^2=0.0049$ ) and was non-significant ( $p=0.347$ ) (Table 1).

## Predation rate

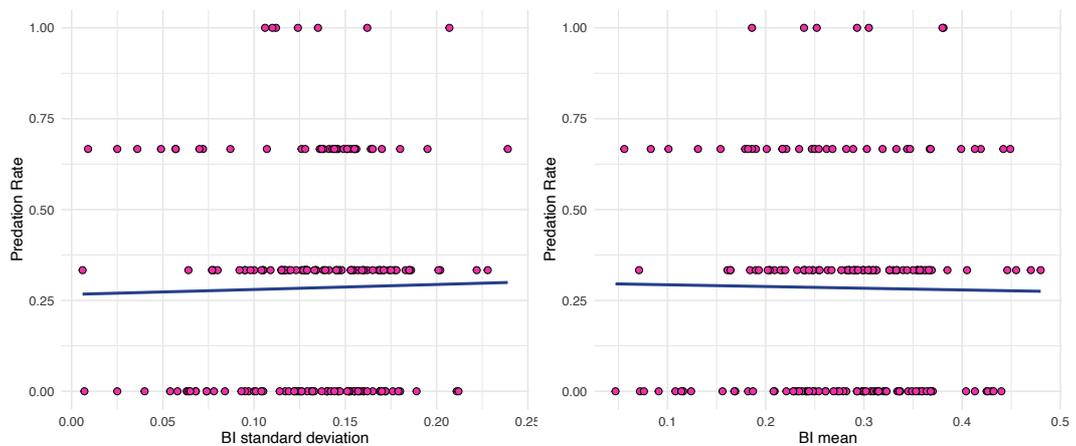


Figure 17. Left, predation rate versus BIMean correlation scatter plot. Right predation rate versus BIstd correlation scatter plot. (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site).

### Bioacoustic Index Mean

A non-significant tendency between the predation rate (PRate) and the Bioacoustic Index Mean (BIMean) was found (Figure 17).

BIMean explained a limited amount of the variation in predation rate ( $R^2=0.0002$ ) and was non-significant ( $p=0.842$ ) (Table 1).

### Bioacoustic Index Standard Deviation

A non-significant tendency between the predation rate (PRate) and the Bioacoustic Index Standard Deviation (BIsd) was found (Figure 17).

BIsd explained a limited amount of the variation in predation rate ( $R^2=0.0004$ ) and was non-significant ( $p=0.780$ ) (Table 1).

## Acoustic evenness index

### Predation

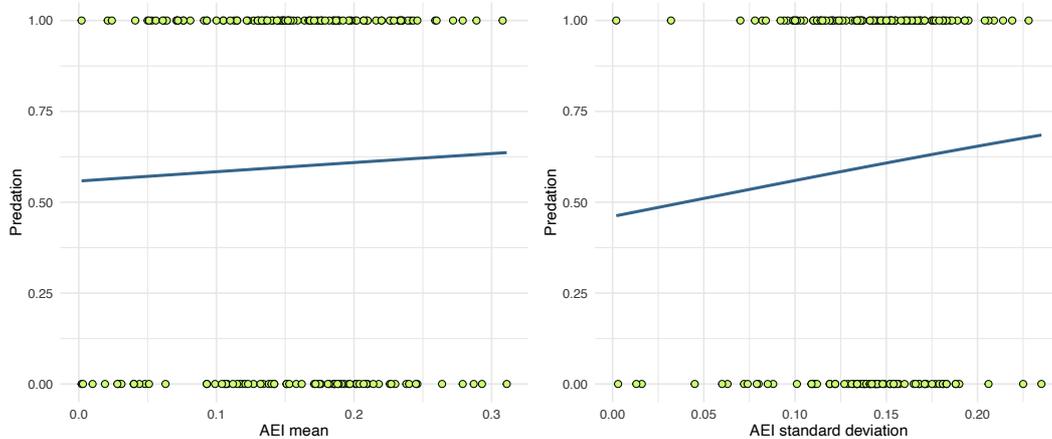


Figure 18. Left, predation events versus AEIMean correlation scatter plot. Right predation events versus AEIsd correlation scatter plot. (1 = predation, 0 = no predation).

### Acoustic Evenness Index Mean

A non-significant tendency between the frequency of predation (P) and the Acoustic Evenness Index Mean (AEIMean) was found (Figure 18).

AEIMean explained a limited amount of the variation in predation ( $R^2=0.0012$ ) and was non-significant ( $p=0.638$ ) (Table 1).

### Acoustic Evenness Index Standard Deviation

A non-significant between the frequency of predation (P) and the Acoustic Evenness Index Standard Deviation (AEIsd) was found (Figure 18).

AEIsd explained a limited amount of the variation in predation ( $R^2=0.0062$ ) and was non-significant ( $p=0.289$ ) (Table 1).

## Predation rate

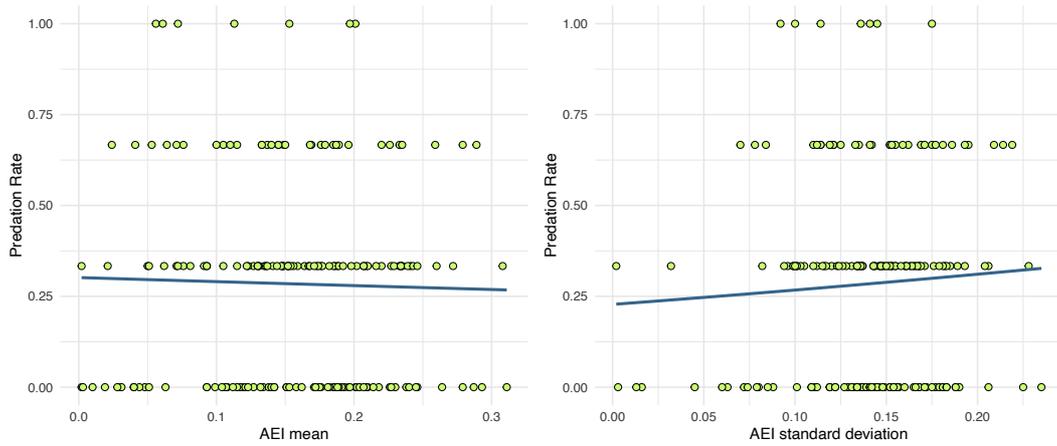


Figure 19. Left, predation rate versus AEIMean correlation scatter plot. Right predation rate versus AEIsd correlation scatter plot. (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site).

### Acoustic Evenness Index Mean

A non-significant tendency between the predation rate (PRate) and the Acoustic Evenness Index Mean (AEIMean) was found (Figure 19).

AEIMean explained a limited amount of the variation in predation rate ( $R^2=0.0007$ ) and was non-significant ( $p=0.721$ ) (Table 1).

### Acoustic Evenness Index Standard Deviation

A non-significant tendency between the predation rate (PRate) and the Acoustic Evenness Index Standard Deviation (AEIsd) was found (Figure 19).

AEIsd explained a limited amount of the variation in predation rate ( $R^2=0.0037$ ) and was non-significant ( $p=0.412$ ) (Table 1).

## Acoustic diversity index

### Predation

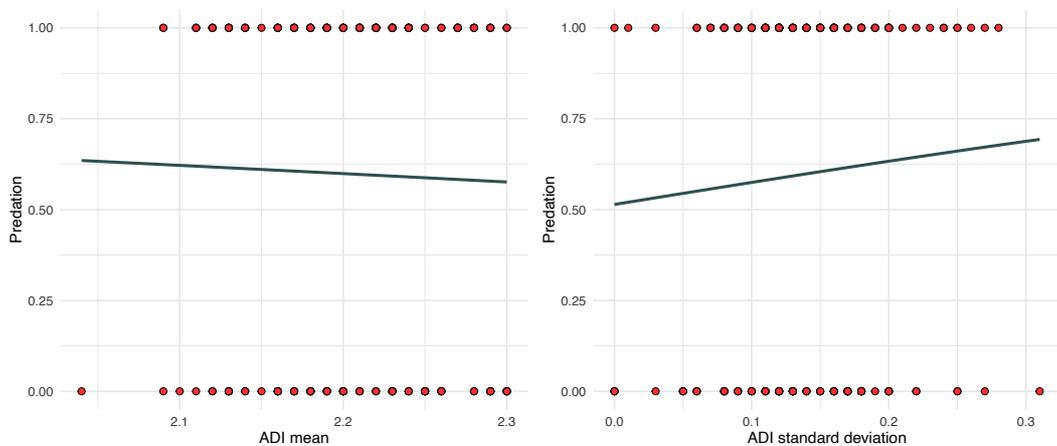


Figure 20. Left, predation events versus ADIMean correlation scatter plot. Right predation events versus ADIsd correlation scatter plot. (1 = predation, 0 = no predation).

### *Acoustic Diversity Index Mean*

A non-significant tendency between the frequency of predation (P) and the Acoustic Diversity Index Mean (ADIMean) was found (Figure 20).

ADIMean explained a limited amount of the variation in predation ( $R^2=0.0006$ ) and was non-significant ( $p=0.733$ ) (Table 1).

### *Acoustic Diversity Index Standard Deviation*

A non-significant tendency between the frequency of predation (P) and the Acoustic Diversity Index Standard Deviation (ADIsd) was found (Figure 20).

ADIsd explained a limited amount of the variation in predation ( $R^2=0.0043$ ) and was non-significant ( $p=0.375$ ) (Table 1).

## Predation rate

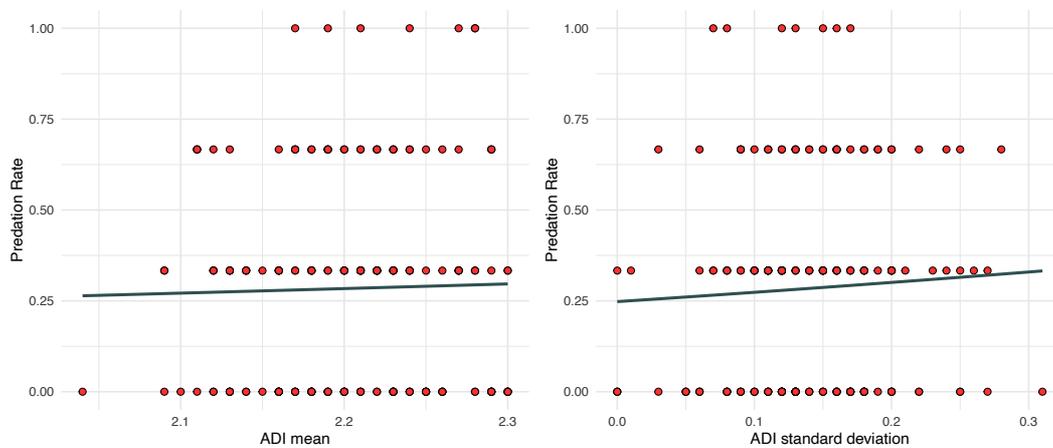


Figure 21. Left, predation rate versus ADIMean correlation scatter plot. Right predation rate versus ADIsd correlation scatter plot. (0, 0.33, 0.66, 1 = 0, 1, 2, 3 DCs 'attacked' per sampling site).

### *Acoustic Diversity Index Mean*

A non-significant tendency between the predation rate (PRate) and the Acoustic Diversity Index Mean (ADIMean) was found (Figure 21).

ADIMean explained a limited amount of the variation in predation rate ( $R^2=0.0006$ ) and was non-significant ( $p=0.742$ ) (Table 1).

### *Acoustic Diversity Index Standard Deviation*

A non-significant tendency between the predation rate (PRate) and the Acoustic Diversity Index Standard Deviation (ADIsd) was found (Figure 21).

ADIsd explained a limited amount of the variation in predation rate ( $R^2=0.0028$ ) and was non-significant ( $p=0.474$ ) (Table 1).

## Explanatory variables

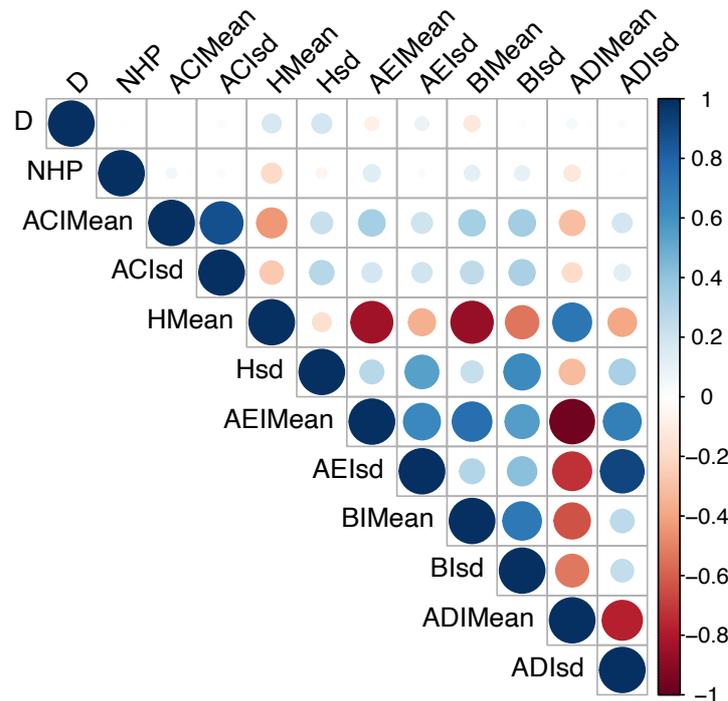


Figure 22. The correlation matrix of all the explanatory variables; D, NHP, ACIMean, ACIsd, HMean, Hsd, AEIMean, AEIsd, BIMean, Blsd, ADIMean, and ADIsd.

A correlation matrix of all the explanatory variables was created to **detect for multicollinearity, inform variable selection, and identify redundant variables.**

Correlations were found between variables H, AEI, and BI. Many of the correlations found between the explanatory variables were very weak or negligible (Figure 22).

Notable correlations were found between AEIsd and ADIsd (0.9157), and AEIMean and ADIMean (-0.9614).

Furthermore, strong correlations were found between ACIMean and ACIsd (0.8748), BIMean and AEIMean (0.7511), HMean and ADIMean (0.7216), BIMean and Blsd (0.7160), HMean and AEIMean (-0.8430), HMean and BIMean (-0.8601), AEIsd and ADIMean (-0.7270), ADIMean and ADIsd (-0.7749).

# Discussion

## Interpretations and implications

This study aimed to understand the influence of natural habitat patches (NHPs) within a large-scale coconut plantation, on pest control, through acoustic and artificial prey monitoring.

The total mean predation rate recorded on the plantation (29.3%) was relatively high. While the values from other studies are not directly comparable to these findings, as experiments vary in many aspects, such as land use and exposure time (Lövei & Ferrante 2017), it is worth noting that the following studies reported mean predation rates of 25.8% (Lövei & Ferrante 2017), 32.4% (Schwab et al. 2021), 10.4% (Moreno & Ferro 2012), 14% (Martini et al. 2024), and 20.9% (Leles et al. 2017). Paralleled to the values reported from other experiments conducted in similar climatic conditions the predation rate results presented here seems to be akin, with a tendency towards the upper limit, even though the exposure time of the DCs in this study was lower (Moreno & Ferro 2012; Leles et al. 2017; Lövei & Ferrante 2017; Schwab et al. 2021).

Though mostly non-significant, the tendencies observed showed some interesting existing relationships between predation (P) and the distance away from the natural habitat patches (D), decreasing as D increased (Figure 10). With the hypothesis of NHPs harbouring more biodiversity due to their species variation and undisturbed habitats, it was expected that the predation rate would decrease, the further away from the NHPs in the plantation, however, these effects were only partially detected, and predation events did not significantly increase closer to the natural habitat patches.

The lack of statistically significant results might be attributed to the plantation's environment. The organic management methods foster a rich and diverse undergrowth, which in turn enhances the overall biodiversity observed across the plantation. The main crop cover in the plantation is tropical Kudzu (*Pueraria phaseoloides*), a vigorous winding and climbing perennial legume, commonly used in this type of tree-crop plantations in humid regions (Nair et al. 2021). The omnipresence of this cover crop may have contributed to the results obtained in this study which partially agree with previous published literature, where most of acoustic indices are reported to be good reflections of biological activity and showing strong relationships with predation rates (Alcocer et al. 2022; Martini et al. 2024).

The correlation between PRate and NHPsize was found to be marginally significant, indicating a tendency for both P and PRate to decrease with increasing natural HP size (Figure 11). These findings go against the hypothesis that the rate of attenuation of acoustic signals is dependent on the natural habitat patch size (b.1) and lead to infer that the NHPsize does not necessarily play an important role in the amount of predatory activity observed in the plantation. This again may be due to the nature of the study site, having a relatively overgrown understory where the coconuts are planted.

Both the ACI mean and standard deviation showed statistically significant positive correlations with predation (Figure 12). It is inferred from these results that high ACI- and P- values could indicate a higher level of biodiversity. This further contributes to the results of Sueur et al. (2008) and Alcocer et al. (2022), confirming ACI as one of the reference indices as indicator of biodiversity.

PRate and ACIsd showed marginally significant results (Figure 13). However, no other significant tendencies between PRate and ACIMean, HMean, and Hsd were found (Figure 13 and Figure 15), which might have indicated predictable activity patterns (Sueur et al. 2008). This lack of significant result can potentially be attributed to the lack of long-term data which could have included seasonal variations (Sueur et al. 2008; Alcocer et al. 2022).

No significant relationships were noted between both BIMean and BIsd with P and PRate. However, it is interesting to note the slight positive tendency that may indicate that predation events increased with an increasing intensity of sounds recorded. The value might display more statistically significant results if the AudioMoths were left in the field over long-term time period, as prolonged exposure would potentially monitor more biological activity changes over time (Boelman et al. 2007; Alcocer et al. 2022).

AEI displays no significant results. Yet, a slight positive tendency can be remarked between P and AEIsd which could indicate the start of a trend implying that increased predation events correlate with species richness (Alcocer et al. 2022). The lack of a significant result may be due once again to the nature of the study area. Furthermore, these results could be the consequence of the AudioMoths' range not being large enough for this context, where the vegetation is so dense.

ADI results were non-significant, still a slight positive tendency between P and ADIsd can be seen. These results could be explained by the variation in predatory species present in the sampled plantation (i.e.: insects (44.44%), birds (43.79%),

and rodents (11.76%). ADI may not accurately represent the level of predation but could infer on the level of bird species richness (Alcocer et al. 2022).

Many of the correlations found between the explanatory variables were very weak or negligible, an indication that their results were complementary to each other in the context of this study.

Notable correlations were found between AEI<sub>sd</sub> and ADI<sub>sd</sub> (0.9157), and AEI<sub>Mean</sub> and ADI<sub>Mean</sub> (-0.9614). This may indicate that a soundscape analysis may be more aimed towards bird sound detection and that AEI and ADI may be redundant to each other. Additionally, in the study, many predation events were caused by various insects (44.44%), therefore, these two indices may not be an accurate representation of all the predatory species available on the plantation as they mostly relate to bird species richness (Alcocer et al. 2022).

It is useful to note that ACI and H are known to show inconsistent relationships with biodiversity among studies, inferring that their performance may be area specific (Mammides et al. 2017; Eldridge et al. 2018; Martini et al. 2024). Furthermore, BI, AEI, and ADI, have all been reported as weakly correlated to biodiversity (Alcocer et al. 2022; Martini et al. 2024).

In this context, the soundscape indices obtained are not good indicators of potential predation and pest control. The dense vegetation found in the understory of the study sites was relatively ubiquitous and may have influenced the results by potentially promoting insect activity, irrespective of the presence of the NHPs. Previous studies revealed that Kudzu coverage had a significant negative impact on avian diversity and species richness (Hudson 2013; Profetto & Howard 2021). Therefore, given that the NHPs may be relatively unimportant in this study, in a more intensively managed agricultural system with minimal to no ground cover, a different outcome may be seen.

Overall, this analysis highlights the complexity of ecological interactions in agricultural landscapes. The findings suggest that while natural habitat patches contribute to biodiversity and potentially offer pest control benefits, the relationship is not straightforward and is likely influenced by a multitude of other factors not captured in this study.

## Limitations

This study presents several limitations that need to be considered.

Firstly, some of the acoustic and predation data were not collected concurrently, resulting in a temporal mismatch. This occurred only on a few occasions, where

technical issues with the AudioMoths were encountered. Therefore, acoustic data collection at these sites was repeated, but new DCs were not deployed due to lack of time.

Secondly, DC damage is caused by many different species; birds (43.79%), rodents (11.76%), and insects (44.44%), where most insect orders do not produce sounds (Greenfield 2016; Martini et al. 2024), implying that part of the recorded predation data was produced by species that were not necessarily captured by the AudioMoths.

Thirdly, the quantity of DCs deployed at each sampling site (3) was relatively small. Additionally, the data collected per sampling site consisted of 12 hours of audio recordings and 48 hours of DC exposure, which may have led to missing certain rare species. Therefore, had time and manual labour not been a limiting factor in this study, more DCs at each subsite could have been placed. Additionally, repeated sampling at the same points could have been made to capture variability over time. Moreover, extra data-collection points along each of the NHP transects could have been sampled, to increase the surface area of the plantation covered in this study.

Furthermore, extreme weather, for example torrential rain and very warm temperatures (35 - 40°C) experienced in tropical climates such as the one in Ivory Coast, can cause technical as well as structural problems to the fake prey due to dislodging and/or melting of the caterpillars (Howe et al. 2009). These intense meteorological conditions were experienced on only a few days during the data collection period and did not show to significantly alter the quality of the DCs. However, it must be mentioned that these phenomena could have resulted in non-representative predation rates on the days following heavy rain.

As previously mentioned, although this study contained a good sample size, additional time per site would have maybe ensured more concrete results. It was not expected to provide definitive findings, but rather to further demonstrate the potential of NHPs and the benefits they might provide within a large-scale coconut monoculture.

## Future research

Future research should aim to address these limitations by expanding the temporal scope of data collection and increasing the spatial coverage with more recording units and artificial prey. This could be done by including longer transects with more sampling points where possible, and/or collecting data from the same sample sites over an extended period of time.

Furthermore, this study examined the effects of natural habitat patches in a coconut (*Cocos nucifera*) monoculture. While this is one of the most important crops grown in this region, it is far from being the only one. Therefore, interesting follow up studies could replicate this analysis in an oil palm (*Elaeis guineensis*) plantation, and/or in non-tree crops farmland, and/or in a plantation with limited understory development.

Lastly, a comparative study across different types of monocultures in these geographical regions could help generalise the findings and provide more robust results about the potential ecosystem benefits that the integration of natural habitats patches in agricultural systems may bring.

## Conclusions

In conclusion, this study aimed to gain a better understanding of the potential role of natural habitat patches in providing niches for the enhancement of biodiversity thereby providing ecosystem services within a large-scale coconut plantation in Ivory Coast.

The effects of natural habitat patches within tropical monocultures cannot be significantly demonstrated in this study, however trends in correlation can be seen highlighting the general importance of NHPs with regards to biodiversity density and ecosystem services through predation. Natural habitat patches may bring about certain advantages to a large-scale plantation, such as pollinators and potential pest predators, however no significant results were found in this study that proved that those ecosystem services emerged solely due to the presence of the NHPs.

Even though statistically not significant, the tendencies that emerged in this study were notable, considering that the plantation is relatively bio-friendly-managed. Thus, the results obtained are mostly due to the lack of time/workforce and thus, repetitions.

For the plantation managers, these findings imply that while maintaining natural habitat patches is beneficial for biodiversity, relying solely on these patches for effective pest control may be insufficient. Thus, understanding the complex interplay of factors influencing predation can help in designing a more resilient agricultural system and sustainable practices.

Overall, I believe that this is a field of research that has the potential to develop and increase our understanding of the effects ecosystem services that natural habitat patches may provide in simplified farmed lands.

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## Popular science summary

Agricultural intensification, particularly in developing countries, has led to significant loss of natural forests and a decrease in biodiversity. In the Ivory Coast, the conversion of natural landscapes into agricultural land for cash crop cultivation has been a major contributor to these issues. However, amidst these extensive monocultures, patches of natural habitat may provide certain benefits such as pollination and a natural pest control method. This study explores how these natural areas can contribute to managing pests in a large-scale coconut plantation.

The analysis reveals that these natural habitat patches may play a crucial role in controlling pests in agricultural landscapes. Using devices that capture the sounds emitted by birds, bats and predatory insects present in the plantation, as well as placing artificial caterpillars in different areas, revealed that these natural patches attract a variety of predators.

Even though the results obtained were mostly statistically not significant, the trends observed support the hypothesis that the natural habitat patches within the plantation harbour more biodiversity. This means that by maintaining and integrating areas of natural habitat within large-scale agricultural landscapes, farmers could reduce the need for chemical pest control, benefiting both the environment and agricultural productivity.

In summary, this research highlights the role of natural habitats in agricultural landscapes and provides valuable insights for farmers and policymakers aiming to promote reasonable farming practices. By embracing biodiversity, large-scale plantations can improve their ecological health and resilience, ensuring long-term productivity and environmental sustainability.

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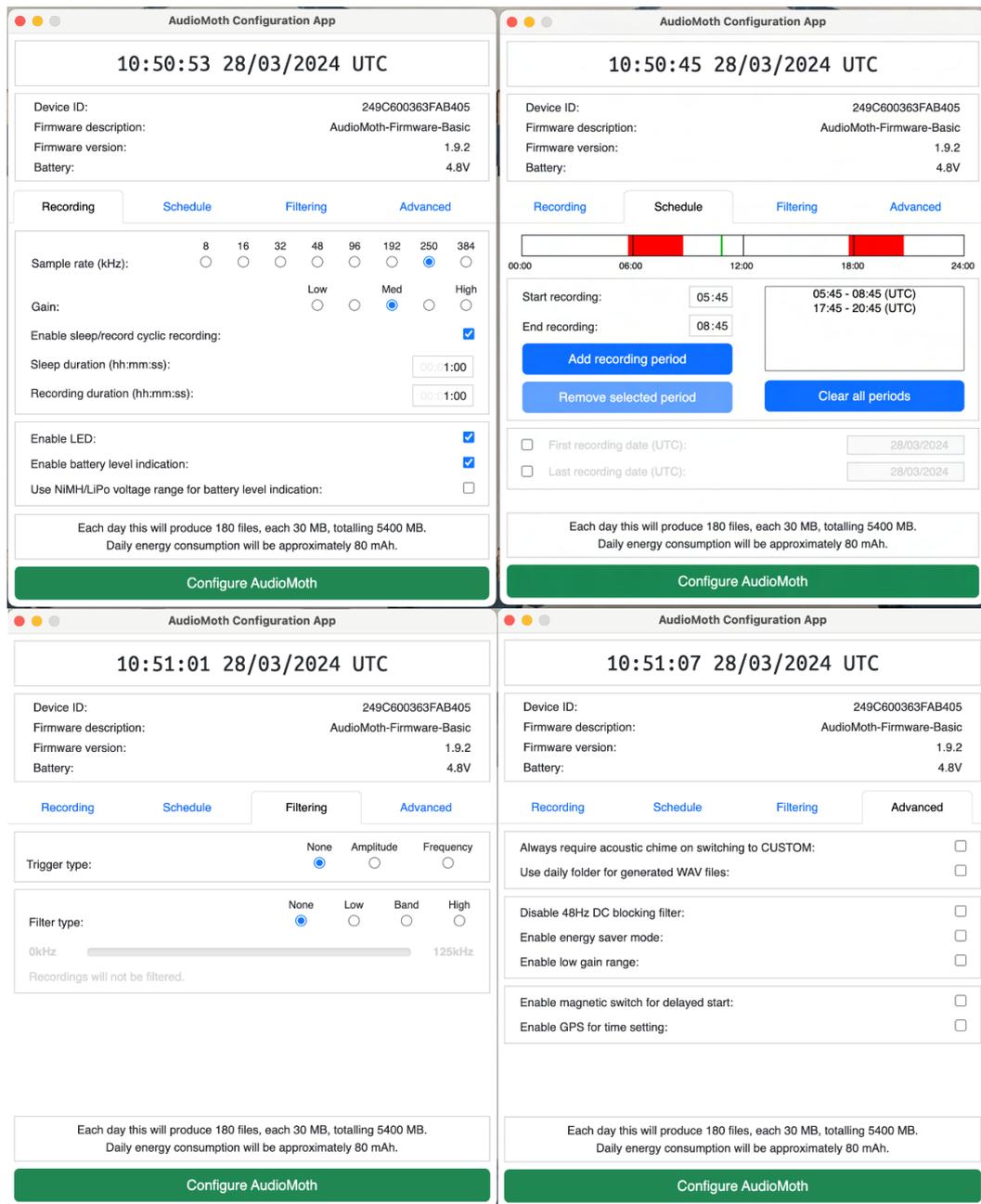
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# Appendix 1

Screenshots of the exact configuration settings used in this study, for the configuration of the AudioMoths.



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