Bird diversity benefits from large and diverse tree islands but not mechanical weeding within an oil palm landscape in Sumatra.

Die Vogelvielfalt profitiert von großen und vielfältigen Bauminseln, aber nicht von mechanischem Jäten in einer Ölpalmenlandschaft auf Sumatra.

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Master's thesis at the Faculty for Forest Science and Forest Ecology

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December 9, 2019

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Abstract

Oil palm plantations are a profitable crop worldwide. However, their establishment usually can produce negative outcomes for tropical biodiversity and ecosystem services. To buffer its impacts, several management practices have been proposed, such as a reduction in the use of herbicides, apply mechanical weeding, increase the number of trees species as well as the area planted. Nevertheless, few is known about their relative benefits for biodiversity, and especially if their combined implementation has a positive effect. Using data of birds' assemblages obtained of two experiments conducted in an oil palm landscape in the province of Jambi; Sumatra, Indonesia, I explored the effects of these management practices on bird diversity. The aim of my study, was to explore whether mechanical weeding benefits birds compared to herbicide use, and whether a combination of increase the number of trees species with the area planted, can increase bird diversity. Using generalized linear and negative binomial models, I found that mechanical weeding and herbicide (glyphosate) treatments were no significantly affecting bird richness, abundance and activity, suggesting that landscape factors can have a stronger effect than the local conditions imposed by the treatments. This same set of models suggested that high tree richness (> 6 species) and large plot size (> 1600 m^2) had a highly significant positive effect on bird diversity, suggesting that there is a minimum threshold value in area and tree richness above which, tropical birds can benefit. My study provides evidence that invest in establish large and diverse areas with trees (tree islands) within oil palm plantations can help to maintain bird biodiversity.

Abstrakt

Ölpalmenplantagen sind weltweit eine rentable Kulturpflanze. Ihre Einrichtung kann jedoch in der Regel negative Auswirkungen auf die tropische Biodiversität und die Ökosystemleistungen haben. Um die Auswirkungen abzufedern, wurden mehrere Bewirtschaftungspraktiken vorgeschlagen, wie z.B. eine Verringerung des Einsatzes von Herbiziden, die Anwendung von mechanischem Jäten, die Erhöhung der Anzahl der Baumarten sowie der gepflanzten Fläche. Dennoch sind nur wenige über ihren relativen Nutzen für die Biodiversität bekannt, insbesondere wenn ihre gemeinsame Umsetzung einen positiven Effekt hat. Anhand von Daten aus zwei Experimenten, die in einer Ölpalmenlandschaft in der Provinz Jambi, Sumatra, Indonesien, durchgeführt wurden, untersuchte ich die Auswirkungen dieser Managementpraktiken auf die Vogelvielfalt. Das Ziel meiner Studie war es, zu untersuchen, ob die mechanische Unkrautbekämpfung den Vögeln im Vergleich zum Herbizideinsatz zugute kommt und ob eine Kombination aus der Erhöhung der Anzahl der Baumarten mit der gepflanzten Fläche die Vogelvielfalt erhöhen kann. Unter Verwendung verallgemeinerter linearer und negativer Binomialmodelle fand ich heraus, dass mechanische Jäte- und Herbizidbehandlungen (Glyphosat) den Vogelreichtum, die Häufigkeit und die Aktivität der Vögel nicht signifikant beeinflussten, was darauf hindeutet, dass Landschaftsfaktoren eine stärkere Wirkung haben können als die lokalen Bedingungen, die durch die Behandlungen vorgegeben sind. Dieselbe Modellreihe deutete darauf hin, dass ein hoher Baumbestand (> 6 Arten) und eine große Grundstücksgröße (> 1600 m²) einen sehr signifikanten positiven Einfluss auf die Vogelvielfalt haben, was darauf hindeutet, dass es einen Mindestschwellenwert für die Fläche und den Baumbestand gibt, ab dem tropische Vögel profitieren können. Meine Studie liefert den Nachweis, dass Investitionen in große und vielfältige Flächen mit Bäumen (Bauminseln) innerhalb von Ölpalmenplantagen helfen können, die Biodiversität der Vögel zu erhalten.

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1. Introduction

Oil palm plantations

Oil palm is the most profitable and rapidly expanding vegetable oil crop in tropical regions, due to a combination of high productivity and extensive longevity (Vijay, Pimm, Jenkins, & Smith, 2016; Woittiez, van Wijk, Slingerland, van Noordwijk, & Giller, 2017). Oil palm (*Elaeis guineensis* Jacq) is native from tropical western Africa and their plantations have expanded during the past century (Woittiez et al., 2017). Palms are early successional species; no domesticated populations show preference in their native range for swamps and riverine habitats associated with high light and water availability. This trait is one of the reasons for its fast growth and production (Woittiez et al., 2017). Palm oil has been considered as the most important vegetable oil on the planet (Foster et al., 2011; Vijay et al., 2016), and its importance will undoubtedly increase in the future (Shevade & Loboda, 2019). For example, growth of biofuel production is predicted to be 170 % in 2020 (Fargione, Plevin, & Hill, 2010), and demand for oil palm products should double by 2050 (Corley, 2009). The total area allocated for producing oil palm fruits in 2017 was estimated at 21.4 million *ha*, with a yield of 5.4 million *hg/ha* (FAO, 2019).

Oil palm plantations and biodiversity loss

Oil palm plantation establishment is a driver of tropical biodiversity loss (Fitzherbert et al., 2008, Danielsen et al., 2009, Foster et al., 2011; Gibson et al., 2011; William F. Laurance, Sayer, & Cassman, 2014; Vijay et al., 2016). In almost all taxonomic groups of plants and animals there is a decline in species richness and abundance, when conversion from forest to monocultures occurs (Gibson et al., 2011), as well as other biodiversity dimensions like functional and phylogenetic diversity (Chapman, Tobias, Edwards, & Davies, 2018). Declines of species richness and abundance are stronger in forest species, and usually habitat generalists increase in abundance (Edwards et al., 2010). Moreover, land use transitions such as those from forest to monoculture considerably change species composition, which can modify ecosystem stability and functioning (Barlow et al., 2018). Furthermore, forest conversion to oil palm plantations, can produce changes in ecosystem functioning such as a reduction of energy flows with losses around 51% (Barnes et al., 2014).

There are several reasons why oil palm plantations reduce biodiversity (Foster et al., 2011). First, the establishment of the plantations simplifies habitat (Foster et al., 2011): tree diversity decrease and vertical heterogeneity decrease, with a concomitant loss of resources

and microhabitats (MacArthur & MacArthur, 1961, Suarez-Rubio & Thomlinson, 2009, Sam, Koane, Bardos, Jeppy, & Novotny, 2019). Second, oil palm plantations reduce biodiversity because of their limited lifespan, making them ephemeral habitats for some groups of long-lived animals and plants compared to forest, which can remain for millennia and even millions of years (Fitzherbert et al., 2008; Gasparatos, Stromberg, & Takeuchi, 2011).

Bird biodiversity on oil palm plantations

A great deal of research has been conducted on the effects of forest conversion to oil palm plantations on bird diversity, indicating that forest species, including several of conservation concern, are the first to confront local extinctions within the plantations (Lian Pin Koh & Wilcove, 2008,.Danielsen et al., 2009; Edwards et al., 2010, Lees, Moura, de Almeida, & Vieira, 2015, Prabowo et al., 2016, Srinivas & Koh, 2016). However, we do not know in detail how the diversity of birds changes within the plantations (Lees et al., 2015). For example, (Lees et al., 2015), found differences in species richness between young and old oil palm transects and evidence of change in species composition with oil palm age, while (Koh, 2008), detected that species richness is significantly related with epiphyte prevalence and leguminous crops, highlighting small-scale undetected variation of bird diversity in oil palm plantations. The majority of studies on biodiversity of oil palm plantations has focused on making diversity comparisons (mainly species richness) with other habitat types such as forests (reviewed by Fitzherbert et al., 2008,.Danielsen et al., 2009, Foster et al., 2011); but see (Azhar et al., 2011, 2013, Clough et al., 2016, Dislich et al., 2017). Nevertheless, little is known about how specifically bird diversity changes with local attributes within the oil palm plantation ecosystem (Koh, 2008), particularly, whether species richness and composition change at small spatial scales due to variation in critical resources such as vegetation cover and food abundance. Moreover, there is limited knowledge of spatial and temporal species turnover (beta diversity) within the oil palm landscape (Foster et al., 2011), and how biodiversity will spatially respond to current and future stressors within oil palm plantations, implying that a better understanding of bird diversity in oil palm plantations is needed.

Management practices and bird diversity on oil palm plantations

Management practices can benefit bird biodiversity in agricultural landscapes such as those dominated by oil palm plantations (Azhar et al., 2011, 2013, Foster et al., 2011, Teuscher et

al., 2016, Darras et al., 2019;). Some of these practices include creating agroforestry systems (Y. Clough, Putra, Pitopang, & Tscharntke, 2009), increasing the number of species of trees (tree enrichment) (Azhar et al., 2013, Teuscher et al., 2016, Zemp et al., 2019), creating tree islands (groups of trees planted) (Teuscher et al., 2016), maintaining ground layer vegetation, opening the oil palm canopy (Azhar et al., 2013), and limiting the use of herbicides (Darras et al., 2019). Agroforestry systems can play a role in conserving bird diversity within the plantations. In a similar way, tree islands can benefit birds in agricultural landscapes (Zahawi & Augspurger, 2006,.Fink, Lindell, Morrison, Zahawi, & Holl, 2009, Morrison, Lindell, Holl, & Zahawi, 2010, Teuscher et al., 2016), and in oil palm plantations, they can enhance bird diversity compared to oil palm plantations without islands (Teuscher et al., 2016). Reducing the use of herbicides could also benefit bird diversity, but recent evidence failed to show a positive effect (Darras et al., 2019). Nevertheless, these studies have been conducted only in some tropical landscapes, only with some species groups and the myriad of effects on ecological interactions are just beginning to be explored. Furthermore, the mechanisms behind how these management practices can support bird diversity in oil palm landscapes are also not well known. Previous research has shown that herbicide use can indirectly influence bird-breeding success, via effects on prey abundance and plants cover (Cimadom et al., 2019). Evidence in other agricultural crops such as rice showed that waterbird species richness was positively associated with an increase in the proportion of organic rice fields, which do not use herbicides (Katayama et al., 2019). However, this study did not explore directly the effect of herbicides on bird richness and abundance.

However, some have argued that these proposed management practices are ineffective for supporting populations of forest-dwelling birds, but the empirical support to draw general conclusions is limited (Edwards et al., 2010; Wilcove, Giam, Edwards, Fisher, & Koh, 2013).In summary, in oil palm plantations as well as in other crops, it is still not clear how factors directly influencing bird populations can change with cascading effects on plants for the use of herbicides, or an increase in the number of trees (tree richness) and the size of the tree islands. This lack of knowledge can hamper efforts to increase the conservation value of oil palm plantations, and do not show the necessity for policy makers and companies, to implement these management practices.

Research problem, knowledge gaps and proposed hypothesis

Indonesia has been the epicenter of massive deforestation associated with oil palm plantation expansion (Margono, Potapov, Turubanova, Stolle, & Hansen, 2014, Austin et al., 2017). Oil palm development in Indonesia has led to the conversion of 383 518 *ha* of peat swamp forest and 289 406 *ha* of lowland forest during the period from 2000 to 2010 (Lee et al., 2014). This drastic forest loss has raised the concern for a generalized biodiversity crisis in South-east Asia (Sodhi, Koh, Brook, & Ng, 2004; Wilcove et al., 2013, Coleman et al., 2019). This is particularly true in Indonesia, where deforestation is caused by the expansion of oil palm plantations (Vijay et al., 2016). Within this context, it is necessary to try to find win-win situations in agricultural landscapes, to understand the drivers of biodiversity loss within them and especially assess how management practices can support biodiversity (Coleman et al., 2019). Importantly, it is not well established whether bird diversity is indirectly influenced by different management practices within oil palm plantations such as herbicide use versus mechanical weeding. For example, Darras et al., 2019, found that there were no significant effects of mechanical weeding and herbicide on bird richness, and that plants had a negative effect on bird richness and arthropods' a negative effect on bird activity. However, these authors proposed more analysis to understand what species are generating these relationships. Moreover, is still an open question whether increasing tree richness, or expand the size of planted area with trees had positive effects on local bird diversity. For instance, Teuscher et al., 2016, found a positive effect of the size of tree planting (tree islands) on bird richness; however, these authors proposed an assessment of the fauna for more years, to evaluate the effectiveness of these management practices. Nevertheless, critical questions still to be answered are whether it is better to have few large tree islands or many small tree islands and whether few or many tree species are important for birds in an oil palm plantation. Furthermore, there is a limited knowledge of spatial and temporal turnover of diversity (beta diversity) within the oil palm landscape, (Foster et al., 2011), particularly the degree of dissimilarity in species composition within the oil palm ecosystem. Despite these knowledge gaps, there has not been a direct test in an experimental context of the effects of these management practices on bird diversity in oil palm plantations, and particularly how these management practices interact to benefit bird diversity in an oil palm ecosystem. Getting a better picture of how management practices impact bird diversity in oil palm plantations will inform policy and management and allow to explore how birds

will adapt and persist in human modified landscapes as oil palm states, where a large proportion of tropical biodiversity will be forced to survive (Gardner et al., 2009).

I will investigate how bird diversity and community composition change in two oil palm experiments conducted in the province of Jambi, Sumatra, Indonesia during 2017. Specifically, I will test whether bird species richness, abundance, and vocalising activity are higher under mechanical weeding compared to herbicide wedding. Furthermore, I will test the hypothesis that species richness, abundance and vocalizing activity increase with more tree species and with an increase in the area with planted trees (tree islands). Because richness only shows one facet of diversity (Shahid Naeem, Duffy, & Zavaleta, 2012, Naeem et al., 2016), I will explore whether bird diversity (richness and evenness) changes between the herbicide and mechanical weeding treatments. Moreover, I will explore the degree of dissimilarity in species composition of the assemblages of the herbicide and mechanical weeding treatments, and whether dissimilarity in species composition of the bird assemblages increases with tree island size and tree richness. The objective of my study is to assess whether these management practices enhance bird diversity in an oil palm plantation landscape and whether the interaction of some of them (tree island size and richness) produces a positive effect. Furthermore, I will assess which number of tree species and what size of tree islands can benefit bird diversity. These empirical data will inform decision makers about how to increase the conservation value of oil palm plantations for birds, while maintaining production levels.

2. Materials and methods

Study region

The study region is the province of Jambi, which is located in the center of the island of Sumatra, Indonesia (Darras et al., 2019, Drescher et al., 2016). Jambi climate is tropical humid, with a bimodal pattern reflected in two rainy seasons in March and December. Mean annual temperature and precipitation in the province of Jambi are $26.7 \pm 0.2°C$ and 2235 ± 381 mm respectively. In the province, only the Harapan rain forests and Bukit Duabelas National park retain large areas of rainforest in the center of the province (Teuscher et al., 2016).

Experimental sites

My study is embedded in two experiments located in oil palm company estates within the EFForTS project (Ecological and socioeconomic Functions of tropical lowland rainForest Transformation Systems): the oil palm management (Darras et al., 2019) and biodiversity enrichment experiments (Teuscher et al., 2016).

The oil palm management experiment established a cross factorial design to vary fertilizer and weeding treatments in 16 plots in four sites (Darras et al., 2019). Each plot was 50×50 m and has between 36 and 40 palms (Figure 1).Landscape topography in the plantation is flat and the mean altitude range is from 63 to 85 m elevation (Darras et al., 2019). The weeding treatment has two levels: The herbicide application, which corresponds to 1500 cm^3 glyphosate ha^{-1} yr^{-1} for the palm circle and 750 cm^3 glyphosate ha^{-1} yr^{-1} for the interrows, and the mechanical weeding level, which refers to cutting the ground vegetation mechanically. Both treatments were applied four times each year.
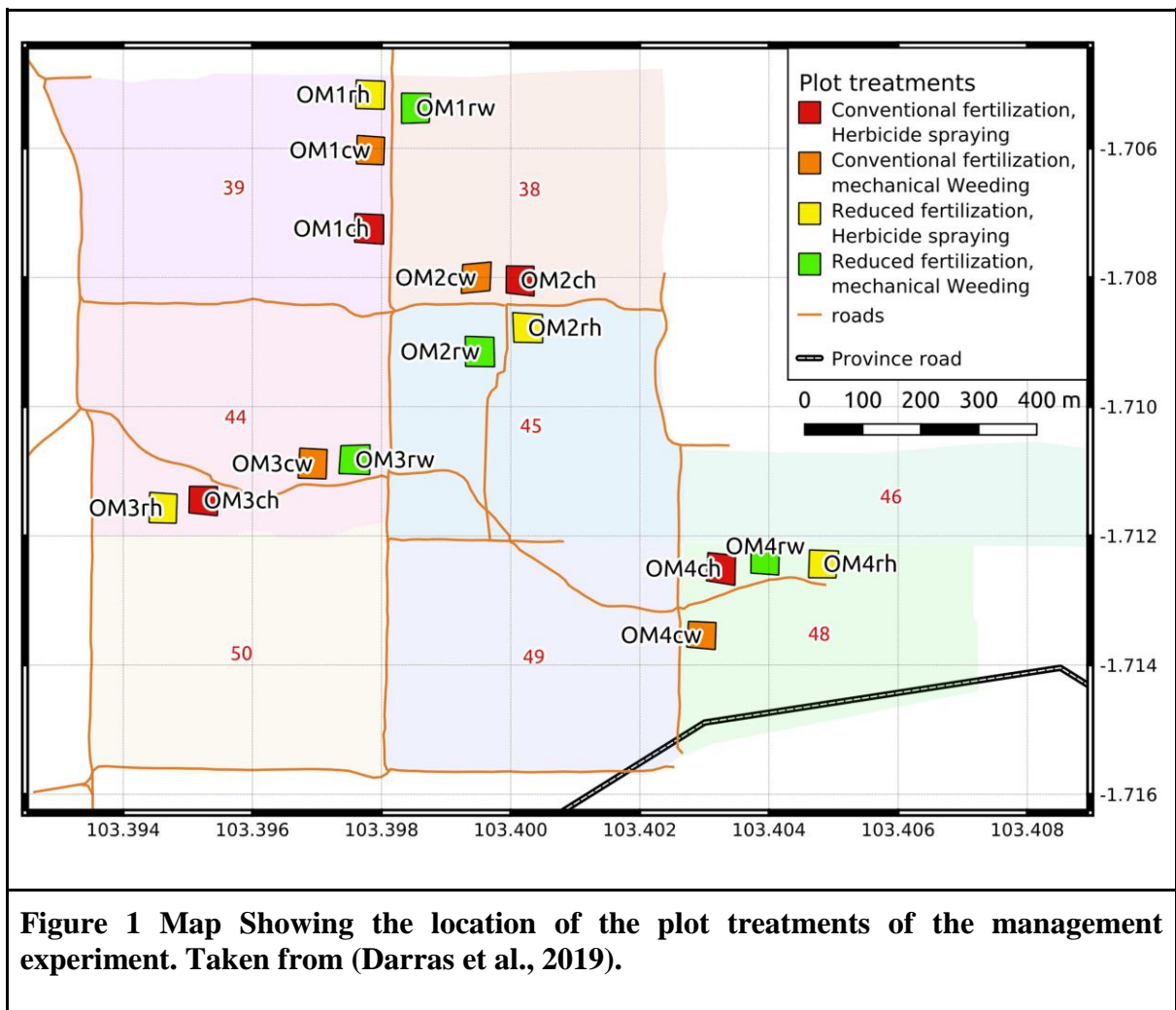

Figure 1 Map Showing the location of the plot treatments of the management experiment. Taken from (Darras et al., 2019).

The biodiversity enrichment experiment is located in the oil palm company estate of Humusindo. It involves the creation of tree islands with different plot size 5×5 (25 m^2), 10×10 m (100 m^2), 20×20 (400 m^2), and 40×40 (1,600 m^2), as well as different tree species richness levels (1,2,3,6 species and zero species) (Figure 2), and different tree species compositions, for a total of 24 mono-species plots and 24 multi-species plots (Teuscher et al., 2016; Zemp et al., 2019). Tree islands are areas inside the plantation where native trees were planted. The number of trees planted varied with plot size.
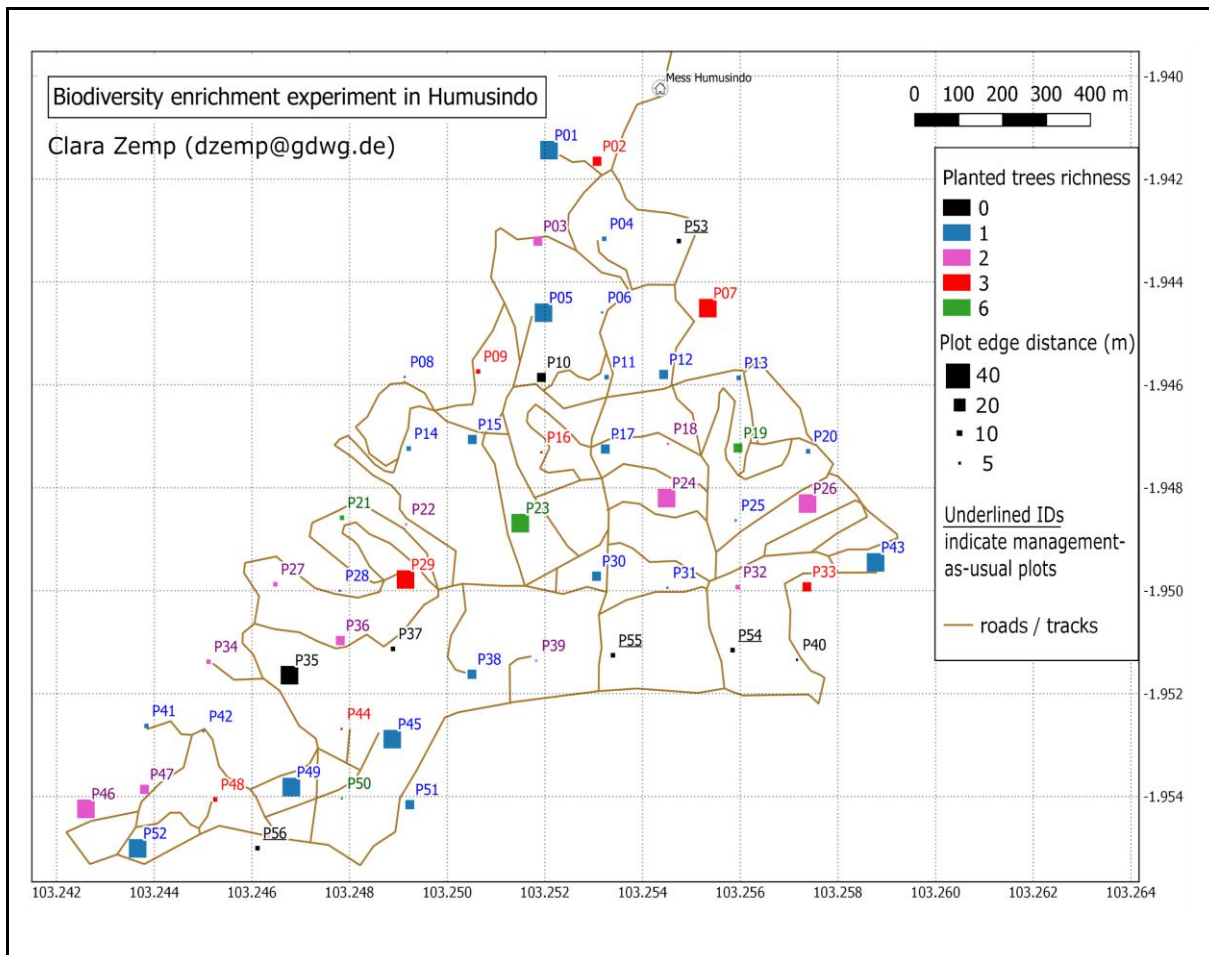
Figure 2 Map showing the location of the plot treatments of the biodiversity enrichment experiment.

Data collection

Bird data were collected in both experiments using a standardized protocol for sampling bird communities using autonomous sound recorders (Darras et al., 2019). In the management experiment, 8 plots were sampled simultaneously and recorders were placed in the center of the plots, recording during the morning and afternoon for two consecutive days in September

2017. For the enrichment experiment, 12 random plots were recorded simultaneously with recorders placed in the middle of each tree island in March 2017, producing data for 56 plots. We extracted 15 minutes of sound in the morning (starting sunrise) and in the afternoon (before sunset) from the recordings, for a total of 60 minutes per plot at a sampling rate of 22.05 *kHz*. The audio recordings were processed and analyzed using the website Biosounds (BioSounds, 2019). The whole process consists of three phases. First, sonograms of the recording are scanned, and the user tags each individual bird vocalisation, which records both the length and the frequency of the vocalization (Figure 3).
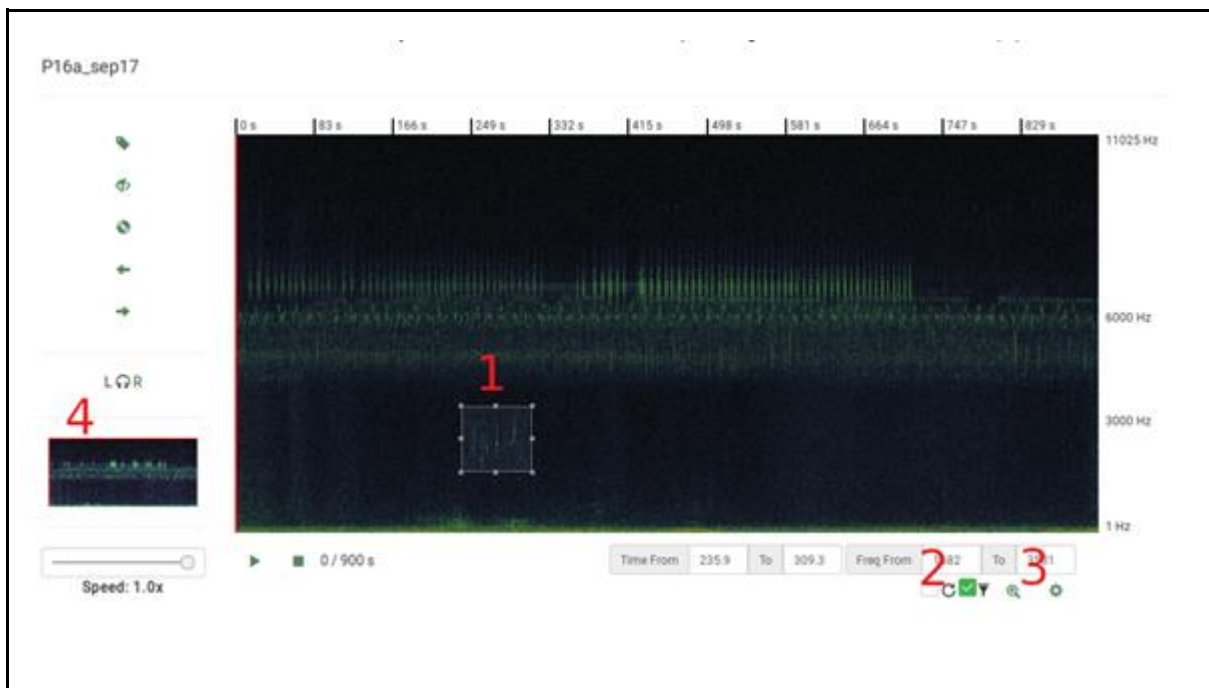

Figure 3 The interface of the program Biosounds and the way how the tags were done. 1. First the sound is tagged based on its frequency (y axis) and time (x axis). 2. Then you can use the function of filter allow and 3. I used the zoom to a have a 4. better visualization. After creating the tag, I identified the species and estimated the distance.

Second, each bird sound is identified at the species level or other taxonomic level (genus or family) (if the species could not be determined). Third, distance of each vocalization was estimated for each tag, after listening to a sound transmission sequence emitted from different distances (4 and 35 meters) in each plot (Darras et al., 2018,.BioSounds, 2019). For the management experiment, I included only individuals which were singing or calling up to 35 meters radius, because I wanted to have only the birds that actually were within the treatments. For the enrichment experiment, I included only individuals which were singing

or calling up to 28 meters radius for the same reason. The truncation distance was set to this value to include only the individuals which were actually in the plots.

Calls and songs were identified using birdlife (Birdlife, 2019) taxonomy and identifications confirmed using Xenocanto (xeno-canto, 2019) and the Macaulay library (Macaulay Library, 2019) as reference (audio and sonograms) libraries. I checked that each tagged sound matched a clear sonogram for the species in both libraries. Combined, both libraries have several recordings for all terrestrial breeding and migratory species present in Sumatra. In a few cases, a local expert ornithologist was consulted for confirming the identity of some recordings that could not been identified to species.

Data analysis

- **Bird diversity, abundance and activity**

I computed the total number of species detected in all recordings of each plot of the management experiment and enrichment experiment, to obtain total species richness per plot. Activity per species was quantified as the total time in seconds when a particular species was vocally active in the recording per plot. Total species activity was computed as the sum of all species activities per plot. I used the maximum number of individuals which were simultaneously heard in all recordings per plot as a conservative proxy of abundance per species. Then, I computed total bird abundance as the sum of abundances per species for each plot. To assess how diversity (using Shannon and Simpson indices) changes between treatments, I calculated Shannon exponential and Simpson indices for each plot using the abundance and richness data with the package "vegan" in R program. For the enrichment experiment, I excluded plots were no management was done as kept as usual plantations as well as those without trees, giving a total of 48 plots (Figure 2), because I was interested in exploring the effect of tree species richness *per se*. I only calculated diversity indices for the management experiment. In the enrichment experiment, there were more than 7 plots without bird detections within the chosen range, so that diversity indices had distributions that could not be handled by standard statistical models (even after transformation).

- **Dissimilarity in species composition**

In order to explore the degree of dissimilarity in species composition of bird assemblages between treatments, I used the Morisita-Horn index for the management experiment, because is not a biased estimation of dissimilarity (Jost. et al., 2011), and Horn index for the

enrichment experiment. I used Horn index for the enrichment experiment, because it is less sensible to a high number of singleton species and is based on abundance data, conferring it more statistical power (Jost. et al., 2011). I considered a comparison between bird assemblages as dissimilar if their values were > 0.5 and highly dissimilar if values > 0.75. In both cases, I used the package "vegan" in R. Furthermore, species composition per plot was visualised using nonmetric multidimensional scaling ordination (NMDS) using Bray Curtis distances with the package "vegan". This allowed me to assess the location in the ordination space of the bird species and assemblages for each plot, for exploring dissimilarity in species composition between treatments in both experiments. However, I could not assess the interaction between tree richness and plot size (a proxy for tree island size), because this was not supported by the *envfit* function in vegan.

- **Statistical analysis**

I used generalized linear models for modeling the effects of treatments of the management experiment on species richness, total bird activity and total species abundances. I used the Poisson family for species richness and abundance models and gamma family for the activity model, because this last variable did not follow a typical count variable distribution. When Poisson models were overdispersed, I used negative binomial models instead. I checked all these variables using diagnostic plots and histograms. I used the package DHARMa to assess the fit of the model. For the enrichment experiment, I used for species richness a generalized linear model, for abundance a negative binomial model and for activity a gamma model, in order to evaluate whether tree richness and plot size had an interaction and whether this interaction had a positive or negative effect on each of these response variables. I used the function emtrends of the package emmeans to explored the trend of these response variables with the interaction between tree richness and plot size. In the case of the management experiment, I used only the model summary to assess the significance of the effects of herbicide and mechanical weeding treatments on response variables. Finally, I used linear models for Shannon and Simpson diversity only for the management experiment.

3. Results

Bird species richness

- **Management experiment**

Species richness per plot was higher under chemical (SE= 0.14, $\bar{x}$= 1.77) than under mechanical weeding (SE=0.14, $\bar{x}$= 1.72) (Figure 4). The species richness model with Poisson distribution, showed that the difference was not significantly different from zero (P=0.83), implying that the result could be due to chance.
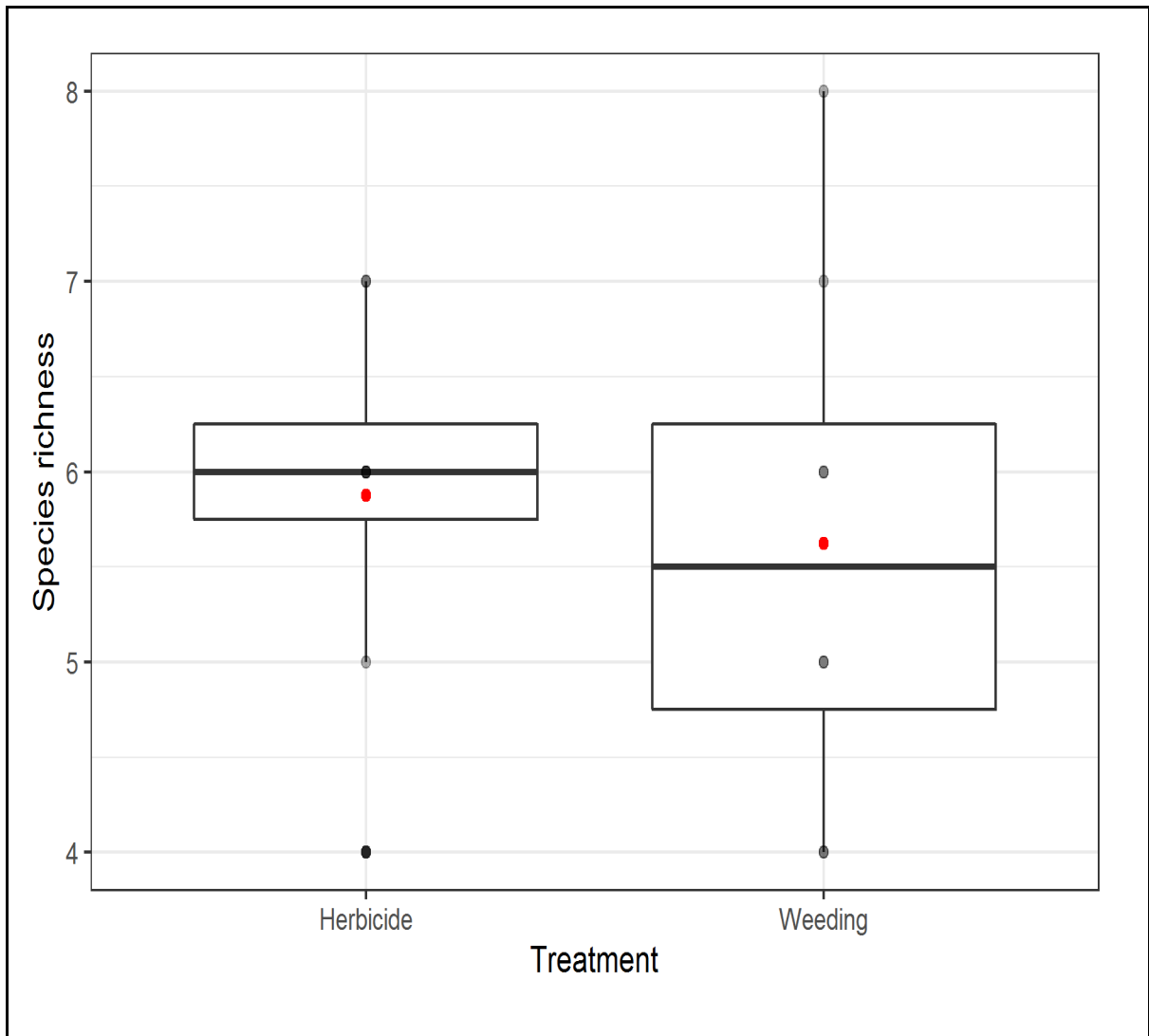

Figure 4 Species richness per plot, separated by treatment. Box plots represents the range of values of species richness, red points indicate the means. Black lines indicate the median.

- **Enrichment experiment**

The Poisson family species richness model was not overdispersed; its residuals indicated a good fit. The model revealed a significant positive interaction between tree island size and tree richness (P=0.016). Bird species richness significantly decreased with tree richness at plot sizes of 5×5 *m* (P= 0.079), 10×10 *m* (P=0.011), 20×20 *m* (P=0.054) and tended to increase at sizes of 40×40 *m* (Figure 5). This final trend was marginally significant (P= 0.09).

Figure 5 Bird species richness per plot against tree richness, separated by tree island size treatments. Points indicate the values per plot. Lines indicate the modeled trends.

Abundance

- **Management experiment**

Bird total abundances were higher under the herbicide treatment (SE=0.12, $\bar{x}$=2.01), and lower under the mechanical weeding (SE=0.13, $\bar{x}$= 1.90) (Figure 6). However, the Poisson abundance generalized linear model, showed that bird total abundances were not significantly different from zero (P=0.57), implying that the result could be due to chance.
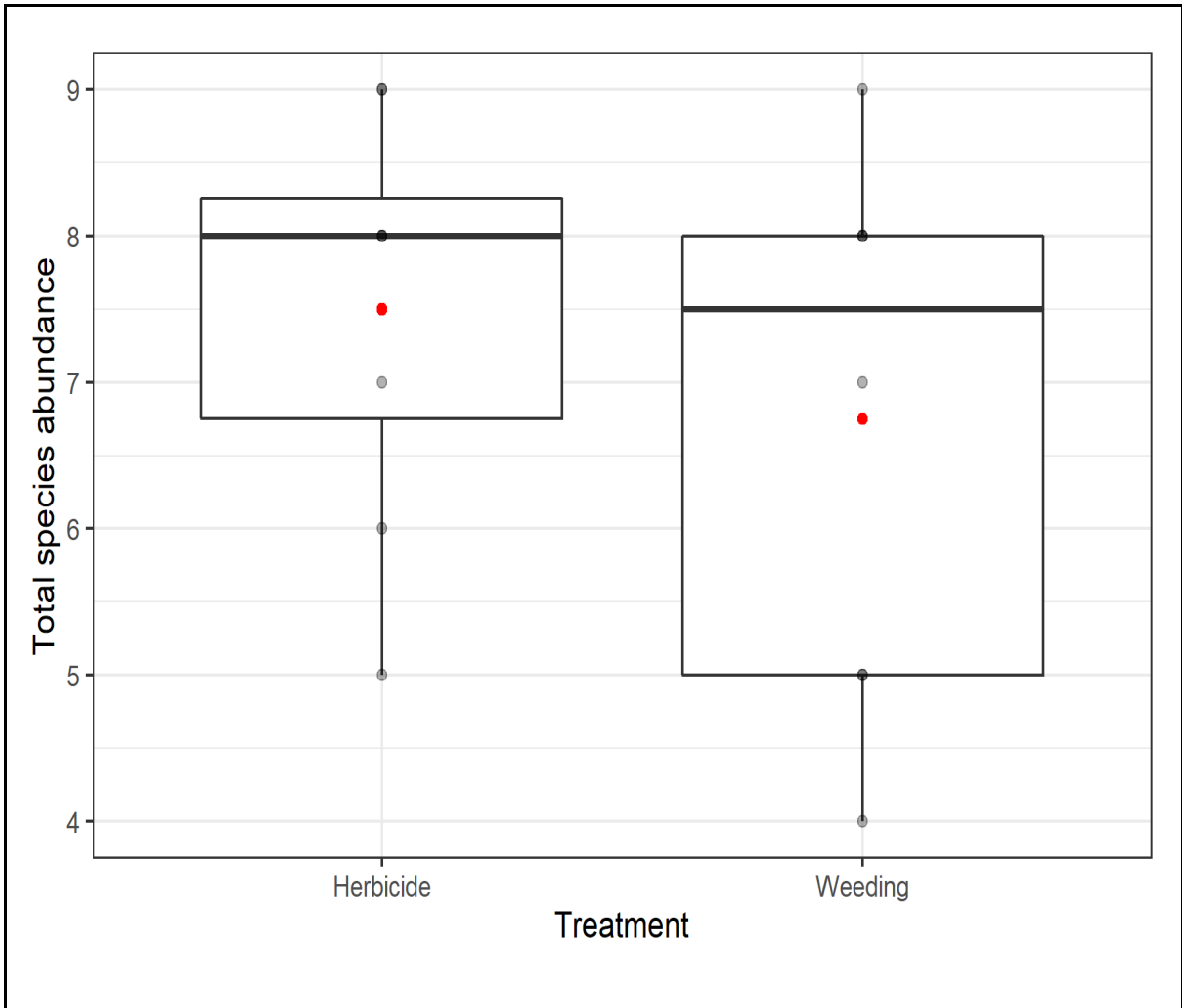
Figure 6 Total bird abundance per plot, separated by treatment. Box plots represent the range of values, red points indicate the means. Black lines indicate the median.

- **Enrichment experiment**

The Poisson model residuals were overdispersed, thus a negative binomial abundance model was used. Residuals indicated that this model was a good fit for the data. This model showed a significant positive interaction between tree richness and tree island size (P=0.014). Total species abundance tends to decline significantly with an increase in tree richness in the 5×5 *m* plots (P= 0.030) and 10×10 *m* plots (P=0.033). Furthermore, the decline was marginally significant at 20×20 *m* plots (P= 0.07). However, the increase with tree richness at 40×40 *m* plots was not significant (P=0.60) (Figure 7).
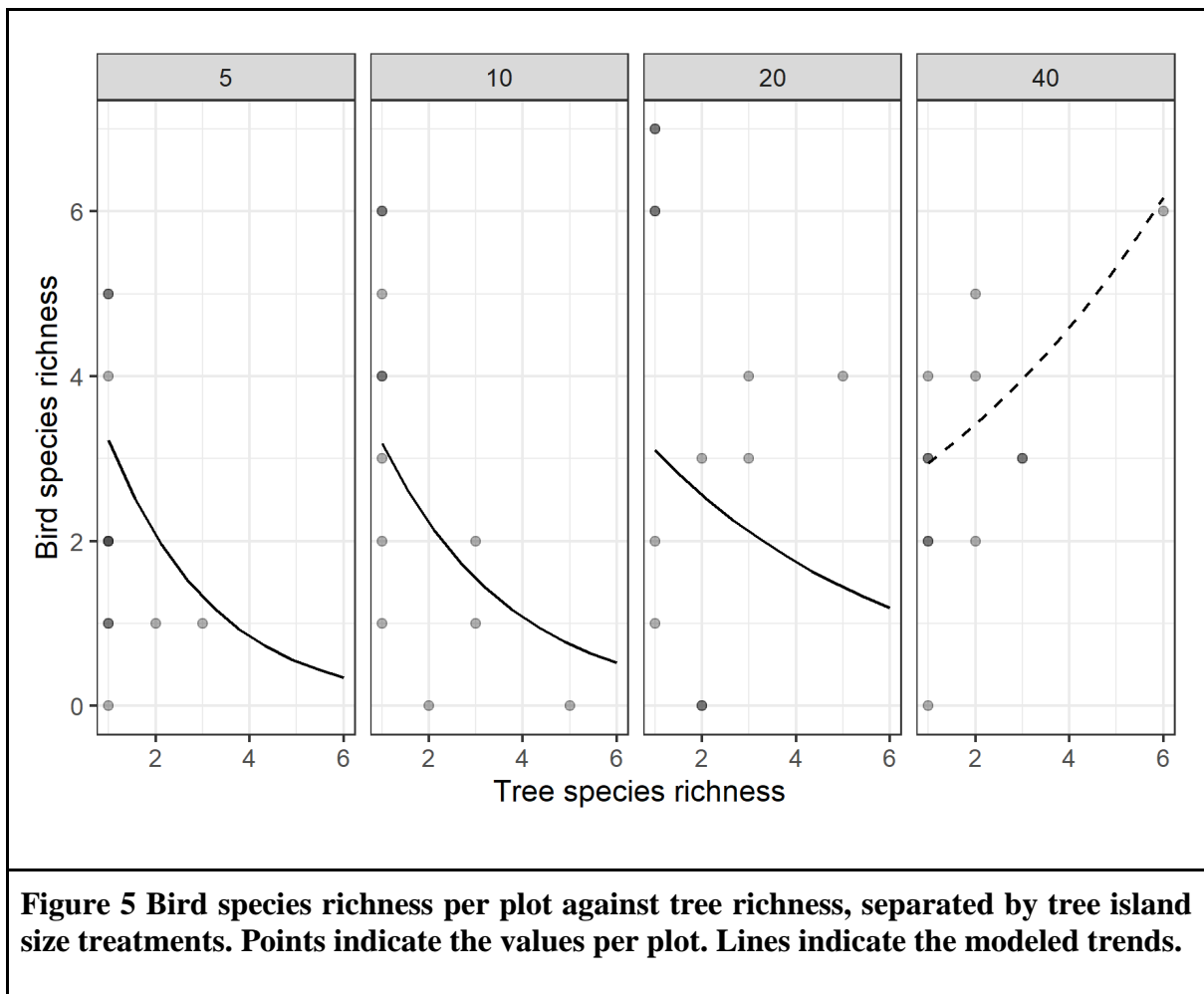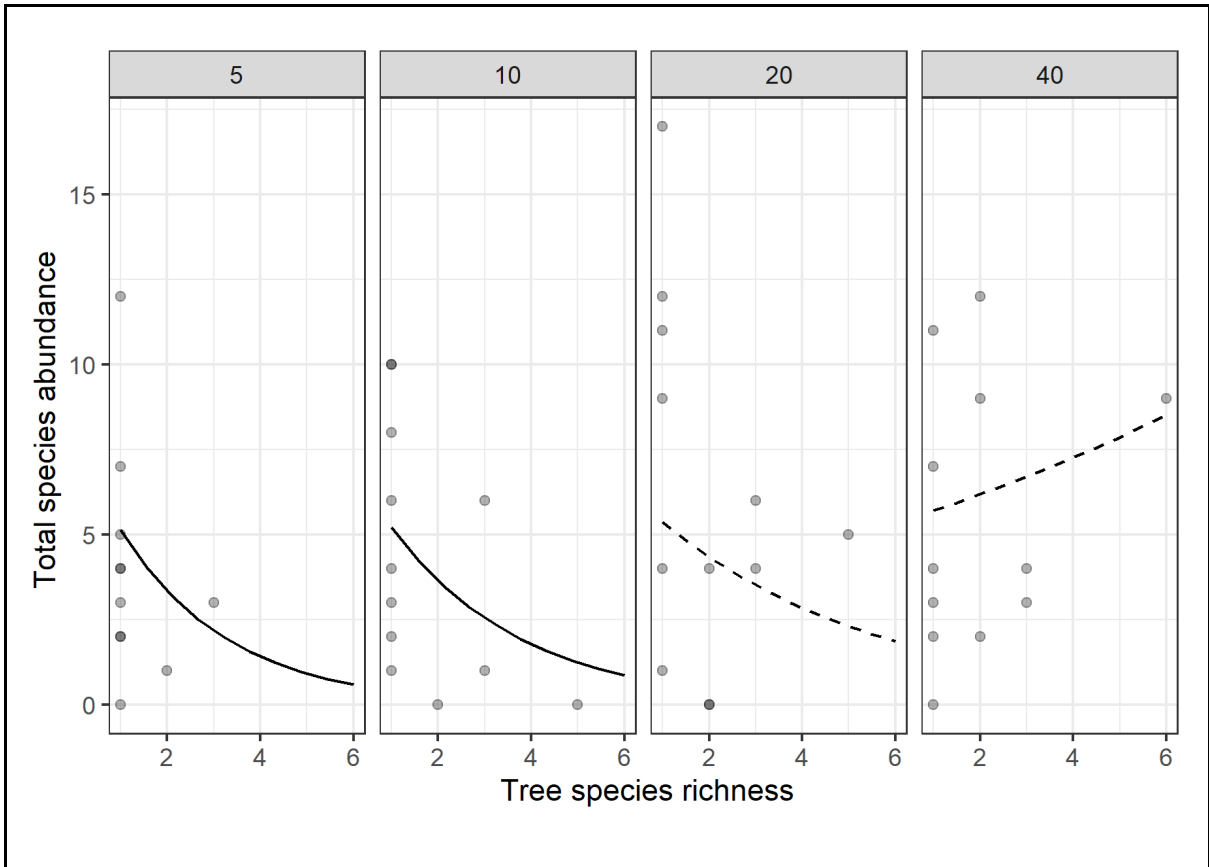
Figure 7 Total species abundances per plot against tree richness, separated by tree island size treatments. Points indicate the values per plot. Lines indicate the modeled trends.

Activity

- **Management experiment**

In contrast to species richness and total species abundances, total species activity was higher under the mechanical weeding (SE=0.33, $\bar{x}$= 7.78) and lower under the herbicide treatment (SE= 0.33, $\bar{x}$= 7.71) (Figure 8). However, a negative binomial model for activity was used and showed that this difference was not significantly different from zero (P=0.87).
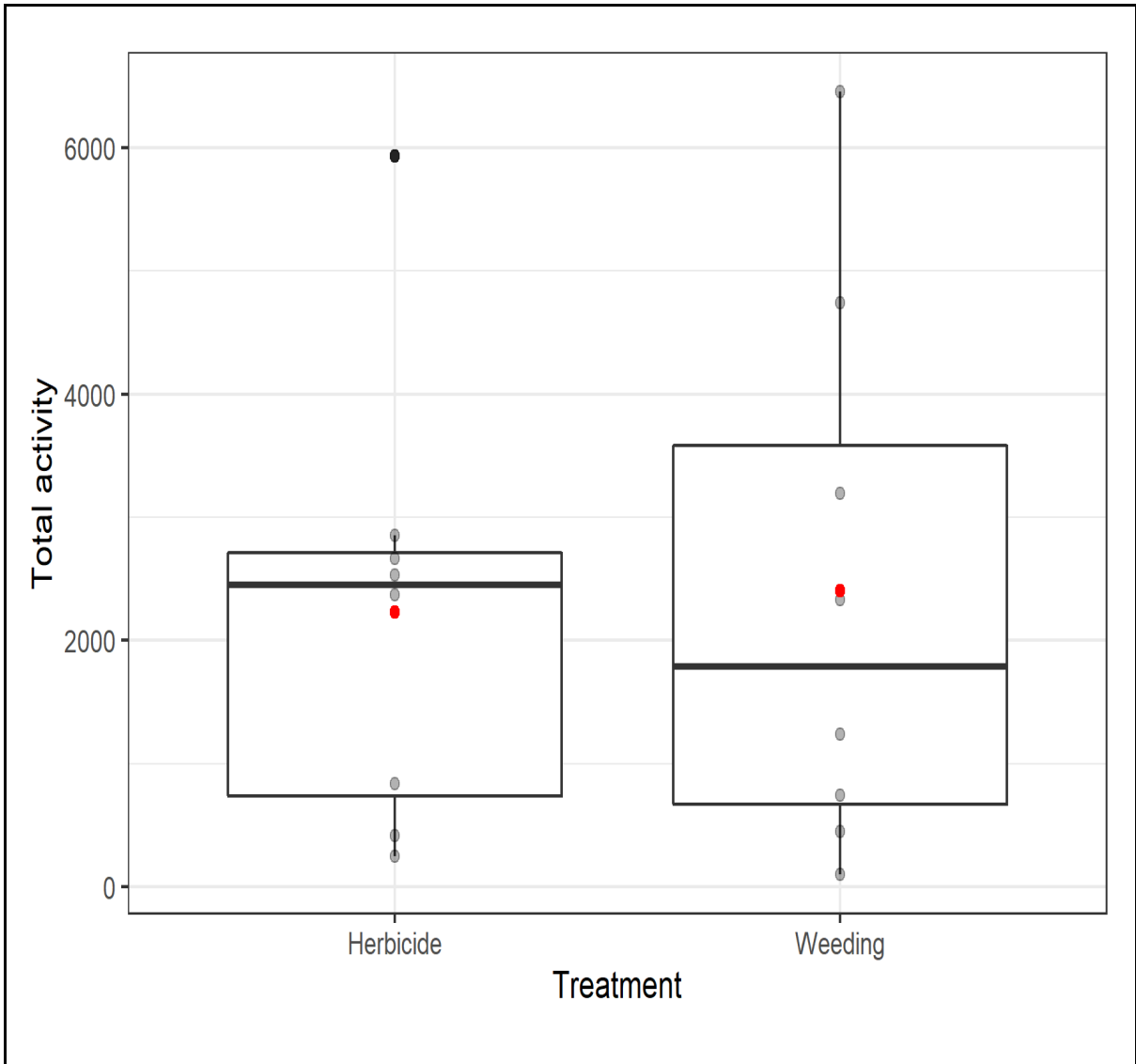
Figure 8 Total activity per plot, separated by treatment. Box plots represent the range of values of species abundances, red points indicate the means. Black lines indicate the median.

- **Enrichment experiment**

A gamma family model was used to model activity, because the distribution of the residuals and values of the response variable did not follow either a normal, Poisson, or negative binomial distribution. Residuals indicated that this model was a good fit for the data. There was a positive significant interaction between tree richness and tree island size (P=0.01). Total species activity significantly declined with tree richness in the 5×5 *m* (P=0.003), 10×10 *m* (P=0.003) and 20×20 *m* plots (P=0.007). However, activity did not significantly change at 40×40 *m* plots (P=0.94), with increasing tree richness (Figure 9).

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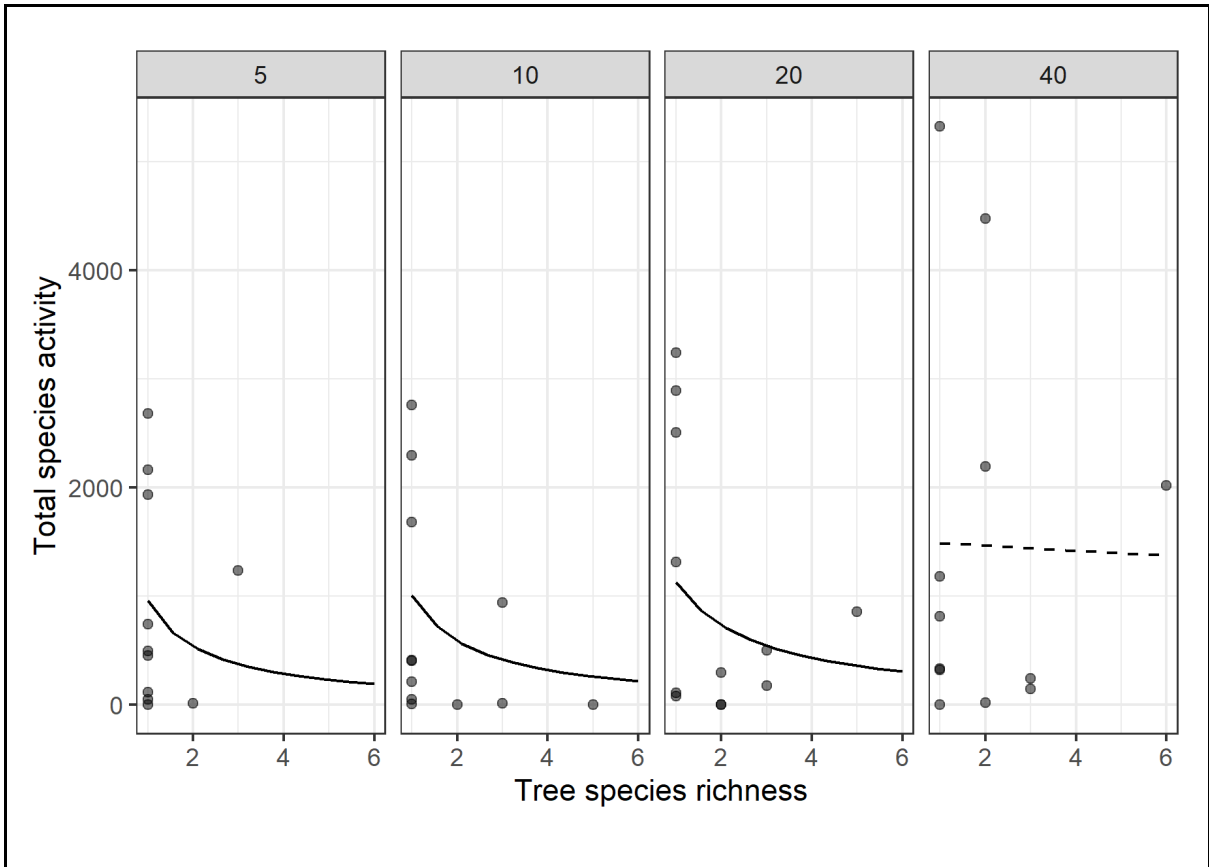
Figure 9 Total species activity against tree richness, separated by tree island size treatments. Lines indicates the modeled trends.

Bird diversity

- **Management experiment**

The mean Shannon and Simpson indices were higher under the herbicide (Shannon, SE=0.07, $\bar{x}$= 1.71, Simpson, SE=0.01, $\bar{x}$= 0.80) than under the mechanical weeding (Shannon, SE=0.07, $\bar{x}$= 1.65, Simpson, SE= 0.01, $\bar{x}$= 0.79) (Figure 10). However, the linear models showed that the difference in diversity between mechanical weeding and herbicide was not different from zero (Shannon P=0.61, Simpson: P=0.54), implying that these differences can be derived by chance (Figure).

Figure 10 Shannon and Simpson index values per plot, separated by treatment. Box plots represents the range of values of Shannon and Simpson diversity indices, Red points indicates the means. Black lines indicate the medians.
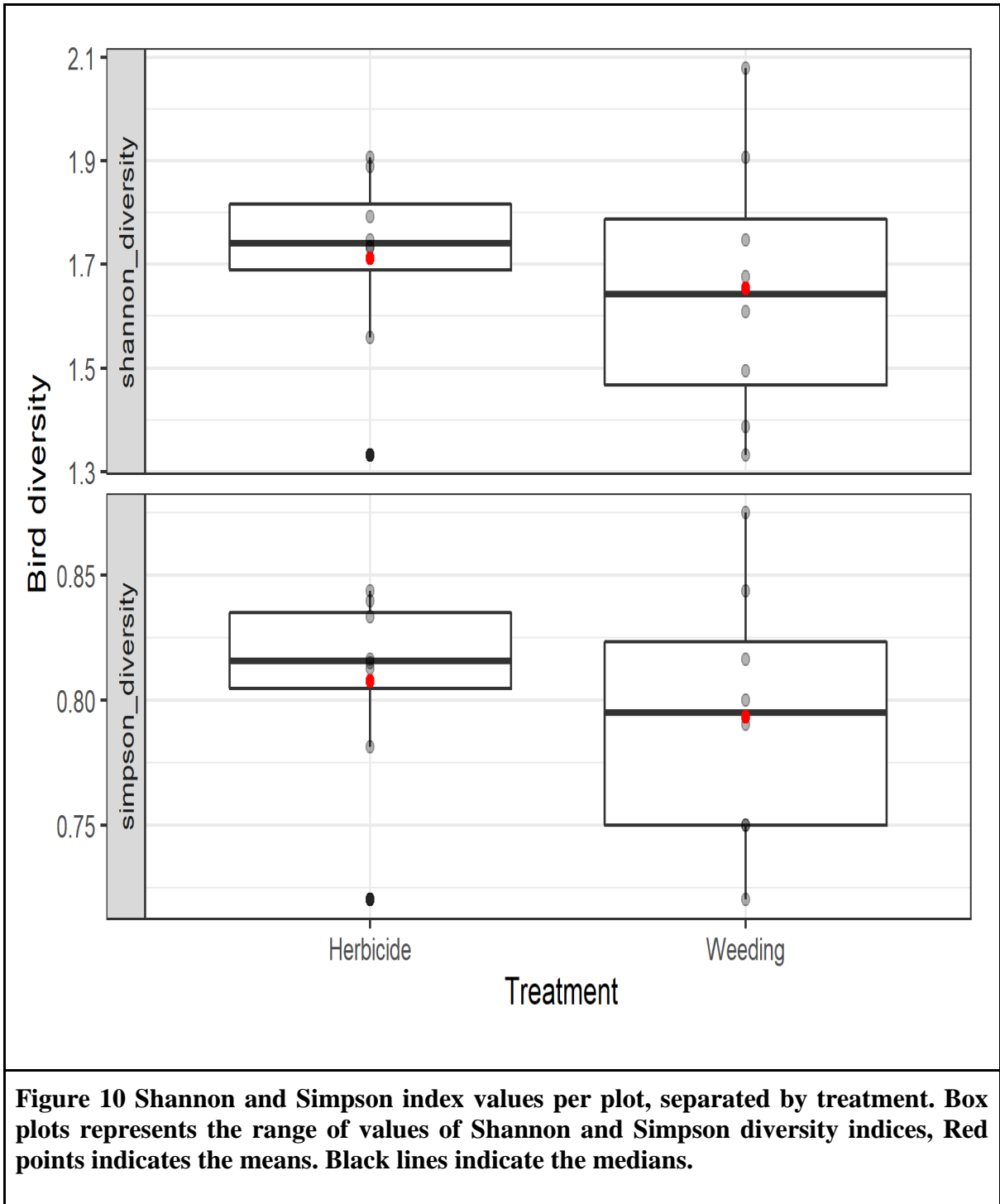
Dissimilarity in community composition

- **Management experiment**

Horn index dissimilarity values between plots belonging to either the mechanical or herbicide treatment were low (range:0-0.5) (Appendix). Moreover, non-metric multidimensional scaling (NMDS) ordination using Bray Curtis distances showed that the assemblages of plots from both treatments overlap (Figure 11).
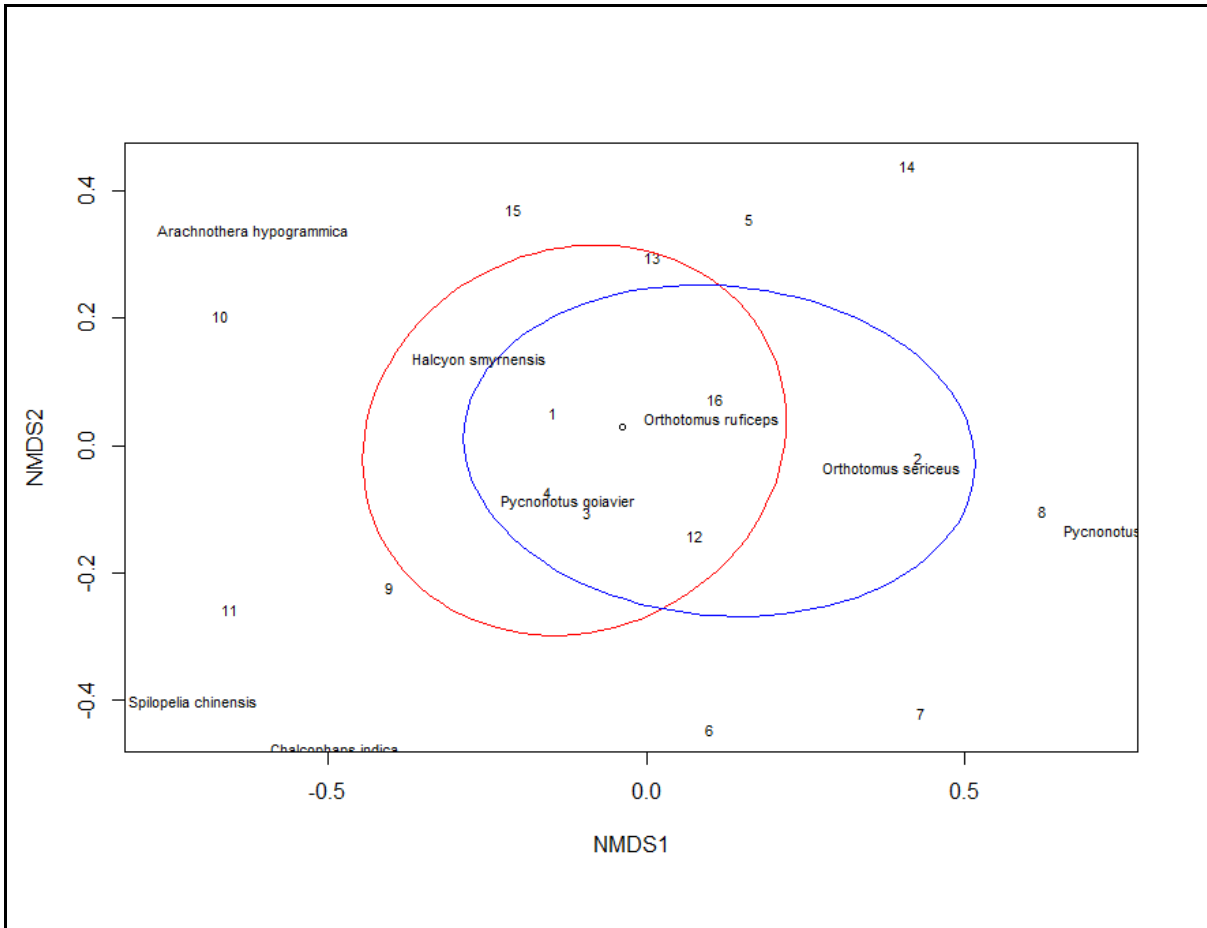
Figure 11 Non-metric multidimensional scaling (NMSDS) ordination using Bray Curtis distances for the bird assemblages of the herbicide and mechanical weeding treatment. Even numbers= weeding treatment, odd numbers= herbicide treatment. Circles represents 95% Confidence Intervals, Red: mechanical weeding, blue: herbicide. Species locations in the ordination space are shown.

- **Enrichment experiment**

Horn index values showed that 40×40 *m* and 20×20 *m* plots were dissimilar from 5×5 *m* and 10×10 *m* plots. However, NMDS using Bray-Curtis distances showed that plots located in different tree island size and richness treatments overlap in the ordination space, with the exception of the 40×40 *m* plots, where some plots were separated from the main clusters (Appendix).

4. **Discussion**

Different management practices within the oil palm ecosystem can have negative, positive or no detectable benefits for resident birds, depending of their interaction. Management practices such as tree richness and tree island size had a positive interaction. At high plot sizes and richness, I observed a positive effect on bird species richness and abundance, and

no measurable effect on activity. Other practices such as mechanical weeding and herbicides had a similar but weak detectable effect on the local bird assemblage.

Are bird species diversity, abundance, and activity higher in the mechanical treatment compared to the herbicide treatment?

Some pesticides such as Glyphosate can impact the abundance of bird prey (insects) and/or have a negative effect on plant cover, decreasing the quality of the habitats for bird foraging and reproduction (Cimadom et al., 2014). However, I did not detect a negative impact of herbicide treatment on bird species richness and abundance compared to the mechanical weeding treatment. In PTPN6, species richness and activity were not significantly different in herbicide and mechanical weeding treatments (Darras et al., 2019), and the results of the species richness, abundance, activity, and diversity models of the present study reinforce this previous finding. With respect to this study, I assessed more variables (abundance and diversity) and importantly, I explored species composition of the bird assemblages using dissimilarity measures which can give additional insights about changes in the local bird community. This weak differences between treatments can be product of the homogenization of habitat structure associated with oil palm plantations establishment, which can select for a restricted set of generalist species of the regional species pool, (Foster et al., 2011). This selection and exclusion of species can be a consequence of habitat filtering (Endenburg et al., 2019). Here, habitat filtering refers to the particular narrow range (filter) in environmental conditions (Bregman et al., 2015) experienced by the local bird assemblage within the oil palm plantation. This restricted range of conditions only allows a subset of bird species to colonize, survive, and adapt to oil palm plantations (Fitzherbert et al., 2008, Koh, 2008,.Danielsen et al., 2009, Foster et al., 2011, Prabowo et al., 2016). Despite the use particular weeding practices, other species fail to disperse inside the oil palm ecosystem and thus the observed differences are restricted by the limited species pool. Finally, because the treatments were relatively weak due to the weeding frequency, this could have a minor impact on birds, because they are adapted to forage in open areas, irrespective of local changes in plant cover and can use different foraging strata within the plantation.

Second, possibly pesticides have a lasting and slow impact on bird species richness and abundance in the long term (after several years or decades) via indirect (trophic) effects on plants and arthropods, and the present dataset simply did not show these long term trends. In summary, my results suggest that birds are not detectably affected by herbicide use in the

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present experiment, and they can persist, probably because plant cover loss has not reached a critical threshold level at local and landscape scales. For example, the occurrence of several bird species is related to the amount of suitable habitat available at the landscape scale, but in some species to local thresholds (Betts, Forbes, & Diamond, 2007). In Cameroon, (Ocampo-Ariza et al., 2019) found a threshold extinction at 24 % forest cover for the majority of the species. (Melo et al., 2018) found a threshold value of 29.5 % for tropical birds in their review. However, to my knowledge, specific critical threshold levels of habitat are unknown in the bird assemblage resident in this part of Sumatra, Indonesia. Moreover, ecological interactions such as predation and brood parasitism (Stratford & Robinson, 2005) can increase or decrease with changes in plant cover as a consequence of herbicides and impact bird diversity. However, bird responses to these antagonistic interactions, can be delayed and not easily detected and we still need to improve our understanding how predation and parasitism are affecting many tropical birds in oil palm plantations, including the species present in the study region.

Further research can assess activity trends of some common insectivorous species such as *Orthotomus sericeus* or *Prinia familiaris* as well as in different seasons and years under the use of herbicides, to explore whether changes in plant cover with herbicides will decrease their activity. Moreover, it is important to understand how the fitness of each bird species is impacted by changes in plant cover and diversity from herbicide use, to assess the prospects of the bird assemblage under the implementation of a particular management practice. To accomplish this, important life history traits associated with bird fitness such as clutch size, nestling growth rates, developmental rates, renesting rates (nest again in the place) (Ricklefs, 2000; Martin, 2015), and key ecological factors such as microhabitat preferences (Martin, 1998), prey abundance (Morrison et al., 2010; Sreekar et al., 2016) or predation risk (Fontaine & Martin, 2006; Visco & Sherry, 2015) should be evaluated in plots with herbicides and mechanical weeding, in order to understand whether herbicide use, via its negative impacts on plants, is indirectly influencing birds fitness and habitat preferences.

Can plot size and tree richness benefit bird species richness, abundance and activity? And what is the plot size and number of tree species required for benefiting birds?

Management practices such as tree richness and plots size (proxy for tree island size) interacted positively to determine bird species richness, abundance, and activity. Tree species richness has a positive effect on bird diversity, richness, abundance at higher plot

sizes. The positive effect of the interaction between tree island size and tree richness on bird richness and abundance, could be associated to the positive effects of area and habitat heterogeneity on bird foraging and diversity (MacArthur & MacArthur, 1961, Laurance et al., 2002; Morrison et al., 2010). The influence of area of habitats on diversity is a hallmark of ecological and biogeography theories (MacArthur R.H & Wilson, 1967; Rosenzweig, 1995, Brown & Lomolino, 2000, MacDonald, Anderson, Acorn, & Nielsen, 2018). Larger areas of native habitats or forest fragments usually harbor more species of birds (Ferraz et al., 2003), because they provide more food resources (Morrison et al., 2010), edge effects are reduced (Laurance et al., 2018), interspecific competition is lower (Bregman et al., 2015), mutualistic interactions are more resilient (Bovo et al., 2018;Emer et al., 2018) and the effects of multiple stressors are ameliorated compared to smaller areas or fragments and the matrix of non forest habitat (Gibson et al., 2013; W. F. Laurance et al., 2018). Although there is strong criticism against the importance of area *per se* on species richness (Burns, Berg, Bialynicka-Birula, Kratchmer, & Shortt, 2010; Fahrig, 2013; Valente & Betts, 2019), my results indicate that areas planted with trees above 40×40 *m* (1600 *m2*) only at high tree species richness benefits bird diversity, because probably they can represent a minimum area over which more species or individuals can use them as a foraging or reproductive habitat and a high number of trees species can increase vertical heterogeneity and provide more microhabitats and nesting sites.

Nevertheless, my results show that area alone is not enough and a high number of tree species is required for benefiting bird diversity This suggests that the combination of both can probably provide microhabitats and nesting opportunities for some edge species that are not found in the oil palms stand. This interaction can also reduce predation risk associated with open areas for these forest-edge species. Furthermore, having more tree species in bigger areas can decrease inter and intraspecific competition between these forest edge/secondary forest adapted species, because there will be more and more diverse available resources for them with more trees and species. Among these forest edge species, *Chalcophaps indica* and *Dicaeum trigonostigma* were registered more often in the 20×20 *m* and 40×40 *m* plots. However, it is also possible that birds within the oil palm plantation have divergent and independent responses to the area of trees planted and the tree species number, which can reflect the fact that different bird species and guilds have different responses to changes in habitat area (Thiollay, 1999; P. C. Stouffer, Bierregaard, Strong, & Lovejoy, 2006,.Lees & Peres, 2009), and that these responses are mainly mediated by their particular

traits as foraging strategies, nesting preferences and mutualistic associations as has been found in other tropical regions (Martin, 1998; P. Stouffer & Bierregaard, 1995, Bregman et al., 2016). However, I did not have detailed data of these specific traits per species in the study site for exploring in a more compelling way this possibility and more future research can be directed to explore this aspect.

An important aspect for management concerns to the specific area of habitat that can be required for benefiting birds in the oil palm landscape. It has been proven that increasing the area of tree islands (>144 *m2*) (Morrison et al., 2010) or forest fragments (>100 *ha*) (Laurance et al., 2002,.Ferraz et al., 2003) within agricultural landscapes can benefit bird diversity, activity and abundance (Laurance et al., 2002, Ferraz et al., 2003; Zahawi & Augspurger, 2006,.Fink et al., 2009; Morrison et al., 2010; Teuscher et al., 2016). For instance frugivorous birds visited large tree islands more often (64 *m2*) than smaller ones (Zahawi & Augspurger, 2006), and the rate of extinction of understory birds in small forest fragments of 5 and 10 *ha* was much higher than in larger fragments of 100 *ha* (Laurance et al., 2002). In the present study, areas of 5×5 *m*, 10×10 *m* and even 20×20 *m* plots probably are not large enough to increase bird richness and abundance, perhaps because birds more associated to forest edge do not have the traits to establish, forage and nest in smaller areas, or these small plots are not attractive for foraging to those birds that usually inhabit oil palm plantations. Furthermore, previous research showed that even in areas of 100 *ha*, there is a high probability that bird species will be extinct (Ferraz et al., 2003), and in a restoration context, areas of a few thousand square metres of planted trees were recommended for birds, when it is financially feasible (Morrison et al., 2010), indicating that investing in areas at least above 40×40 *m* plots (1600 *m2*) or even more for long term persistence will benefit bird diversity in oil palm plantations.

To my knowledge, no studies have explored the effect of the size of tree islands within oil palm plantations on bird richness and abundance besides the enrichment experiment. A previous analysis showed that tree islands hold more species but not more individuals or biomass than control plots without islands, and that plot size taken as a single factor had a positive effect on bird richness and tree richness taken as a single factor did not affect bird richness, abundance and biomass (Teuscher et al., 2016). Nevertheless, my study went beyond and found that the positive interaction between plot size and tree richness is having a positive effect on bird diversity and this effect matters in the biggest plots with high tree

richness, showing that these strategies can provide conservation benefits. Moreover, I explored bird activity, diversity and dissimilarity, which combined, provide a more complete picture of the bird assemblage of the oil palm plantation. However, tree islands planted in the experiment represent a highly simplified habitat compared to a remnant of primary or secondary forest and probably trees have not reached enough height to provide microhabitats of the canopy, and this can also explain why they failed to attract more bird species. This highlights the necessity to explore the responses of resident birds to an increase in the area of trees in oil palm plantations in other locations in Southeast Asia and tropical regions in South America and Africa and explore how the secondary succession associated with the trees planted in the plantation, affect temporal turnover on bird assemblages across the time.

My results suggest that tree richness only has a positive effect on bird richness and abundance starting from a plot size of about 40×40 $p$revious research showed a positive effect of tree richness on bird richness in oil palm smallholdings (50 ha) which resemble agroforestry systems in Malaysia (Atiqah, Yahya, Aisyah, Ashton-Butt, & Azhar, 2019), where trees were mainly fruiting trees such as mango, papaya, banana or coconut. In the case of the enrichment experiment, trees species were selected to provide several functions besides food production (Teuscher et al., 2016), and this can partially account for the differences between my study and (Atiqah et al., 2019).

Tree richness has a negative or neutral effect on bird species richness and abundance at small plot sizes. Possibly, food availability for some guilds, habitat preferences per species and distance of the plots to the close forest remnants are playing a role. For example, the majority of the species of frugivorous birds target particular trees such as the species of the genus *Ficus* in Asia (Corlett, 2017) or Mistletoes (Sreekar et al., 2016), and can show less preference for trees that do not produce many fruits, have fruits with other dispersal syndromes (traits for attracting bats or primates) or which have wind dispersal (Herrera, 2002; Ortiz-Pulido et al., 2007; Dehling et al., 2016).Trees in the enrichment experiment, were not selected to specifically attract frugivorous birds and the two species selected *Archidendron pauciflorum* and *Parkia speciosa* (Teuscher et al., 2016), are not mainly dispersed by birds, being the second one dispersed by bats and primates (Hodgkison, Balding, Zubald, & Kunz, 2003). Second, insectivorous birds registered in the present study can prefer to forage in open and disturbed areas and cannot be affected by tree planting and richness, because they have a wide dietary and habitat preferences, and they can exploit

different arthropod groups and microhabitats that those present in the planted trees. This is the case of some species such as *Orthotomus sericeus*, *Orthotomus ruficeps*, *Prinia familiaris* and *Pycnonotus goiavier,* which were among the most abundant species in the experiment. Moreover, they can even be negatively affected by the presence of more tree species, because trees can reduce light availability, which is associated with higher plant growth at the ground layer and associated increase in bird foraging (Sheldon, Styring, & Hosner, 2010). This was found in oil palm plantations in Malaysia, where a reduction in canopy cover positively influenced the number of foraging guilds (Azhar et al., 2013). Finally, habitat proximity and landscape pattern (i.e. configuration and composition) (Tscharntke et al., 2008, Haddad et al., 2017), can have a stronger influence on local bird richness and abundance than the treatment effects, especially for species more dependent of forests, which will not select habitats with more tree species in the plantation, because they represent lower quality habitats, they are very distant (> 80 km to the closest forest), and there are no forest corridors that connect the enrichment plots with the remnants of forest in the study region. Thus, forest birds are unlikely to be attracted to the enrichment plots. However, the situation can be different is the distance to the forest is shorter, in this hypothetical case, I could expect that more forest birds will be attracted to areas planted with trees in the oil palm plantations.

For the case of activity, other mechanisms could be operating besides feeding and habitat preferences. The interaction between tree richness and tree island size had a positive effect on bird activity only a high tree richness and plot size. Total species activity tended to decline with tree richness and tree island size with the notable exception of 40×40 *m* plots. The fact that species activity did not increase with the number of tree species at high plot sizes can be related to the breeding biology of the species. The majority of the species detected in the experiment have a monogamous breeding system in which territorial males hold fixed small territories along the year (HBW Alive, 2019). Vocal activity is mainly related to territory defense and female attraction, and males rarely abandon their territories even in structurally homogeneous habitats as oil palm plantations. This implies that increasing the area of planted tree or tree species within the oil palm plantation probably will not increase male activity, because their territories are delimited by antagonistic interactions between males or females' visits to their territories, rather than different tree species or more area with trees. This can occur in the set of generalist species that colonize oil palm plantations, which can hold spatially stable territories within the oil palm ecosystem without many trees. For these

oil palm-adapted species, probably more trees species or large areas with trees does not matter or even can interrupt their activity, because they are already adapted to open areas and disturbed habitats. In contrast, forest species can increase their vocal activity in the tree islands or places with more tree species, because these habitats are more similar to forest habitats, and males will defend them more strongly than non-forest or open habitats. For example, birdsong rates were higher under unlogged forest than under a logged forest, indicating strong vocal deference of territories by males in not altered forest (Pillay, Fletcher, Sieving, Udell, & Bernard, 2019).

However, these forest species very rarely or never disperse in habitats outside forest (Edwards et al., 2010), because they avoid open gaps (Lees & Peres, 2009). In summary, probably differences in territorial vocal activity between generalist oil palm-adapted species and forest species that uses the oil palm plantation can explain why increased area planted with high trees species richness, will not necessarily enhance bird vocal activity of the local oil palm bird assemblage. However, this hypothesis remains to be proven and more research in breeding biology, social behaviour and territoriality for several bird species in oil palm plantations is needed.

Are bird assemblages of mechanical and herbicide treatments dissimilar in species composition?

As expected, bird assemblages of both treatments are very similar, giving another line of evidence that herbicides and mechanical weeding are only weakly changing the resident bird assemblage in the oil palm plantation. In a similar way as with diversity, abundance, and activity, habitat filtering as a product of the landscape pattern is probably having a stronger effect on bird habitat preferences than the indirect negative effect of herbicides on arthropod diversity and abundance. This has been evidenced with bird assemblages in several agricultural landscapes (Sreekar et al., 2016; Zhang et al., 2017; Endenburg et al., 2019). For instance, the matrix around the plots of the treatments is composed mainly of oil palm monocultures, and this low heterogeneity in surrounding land cover affects species turnover between mechanical weeding and herbicide plots, because only a small subset of species of the original species pool can disperse and use the matrix.

Does dissimilarity in species composition of bird assemblages increases with differences in island size and tree richness?

Bird assemblages of the biggest plots (20×20 and 40×40 *m* plots) were more similar between them, and less compared to the smaller plots (5×5 and 10×10 *m* plots). Moreover, the 40×40 and 20×20 *m* plots shared some forest-edge species not commonly found in oil palms. However, the trend was that almost all the plots of different plot sizes as well as species richness were similar based on the NMDS (Appendix), indicating that dissimilarity did not increase with differences in island size and tree richness. The fact that some forest-edge species use the biggest plots 20×20 and 40×40 *m*, can be related with higher arthropod abundance in large tree islands as was suggested by (Morrison et al., 2010; Teuscher et al., 2016), and additional microhabitats such as those present in the trees, which are not present in the smallest habitats. However, I did not measure the availability of particular microhabitats and prey abundance for directly testing this hypothesis, and species dissimilarity can increase or decrease with an increase in the sampling effort or the temporal coverage (Jost. L et al., 2011).

5. **Conclusions**

My study shows different outcomes for conserving birds in oil palm plantations with the assessed management practices. First, it shows that using mechanical weeding instead of chemical weeding does not measurably benefit bird biodiversity, contrary to other groups such as plants and arthropods (Darras et al., 2019). However, these results can be greatly influenced by habitat filtering, which is a product of the landscape pattern in the study region. This mechanism could have a stronger influence on species dissimilarity and alpha diversity patterns such as local diversity, richness and abundance than local changes in plant cover and prey associated with herbicide use. Nevertheless, these indirect trophic mechanisms together with bird reproductive success, which can be behind the relationship between bird diversity and herbicide use, still wait to be explored in more detail. Second, my study provides evidence for a positive effect of the combination of two management practices such as planting trees (tree islands) and increase the number of tree species on bird diversity. Nevertheless, this positive effect only occurs at large tree island size ($> 40×40 \, m$) and high tree species richness. Moreover, importantly, my study provides for the first-time experimental evidence for a critical threshold size (40×40 *m*) and high tree richness level (> 6 species) for tree islands which can benefit bird diversity in a highly simplified landscape

as an oil palm plantation. Above this threshold, bird biodiversity can be maintained or these big diverse tree islands could function as stepping stones or corridors for increasing the connectivity between populations, increasing their conservation value in oil palm dominated states.

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Appendix

Species data for both experiments

Management experiment, species abundances per treatment

Species	Herbicide	mechanical weeding
Arachnothera hypogrammica	1	2
Blythipicus rubiginosus	0	1
Centropus sinensis	0	1
Chalcophaps indica	3	1
Dicaeum trigonostigma	1	0
Geopelia striata	0	1
Halcyon smyrnensis	10	5
Orthotomus ruficeps	9	5
Orthotomus sericeus	5	8
Prinia familiaris	8	11
Pycnonotus aurigaster	1	3
Pycnonotus goiavier	13	12
Spilopelia chinensis	4	1
Todiramphus chloris	3	1
Zosterops palpebrosus	2	1

Enrichment experiment, species abundances per treatment: tree richness

| Tree richnesstree richness	*Amaurornis phoenicurus*	*Orthotomus ruficeps*	*Pycnonotus goiavier*	*Spilopelia chinensis*	*Rhipidura javanica*	*Centropus bengalensis*
0	0	2	22	2	0	1
1	2	21	61	16	3	3
2	0	1	18	0	0	2
3	0	2	9	3	2	1
5	0	2	1	0	0	0
6	0	0	6	0	0	0
tree richness	*Pycnonotus aurigaster*	*Prinia familiaris*	*Chalcophaps indica*	*Orthotomus sericeus*	*Micropternus brachyurus*	*Orthotomus atrogularis*
0	7	16	0	7	1	0
1	28	19	4	12	1	2
2	3	0	4	9	0	0
3	5	3	0	0	0	0
5	0	2	0	0	0	0
6	1	2	1	1	0	0
tree richness	*Lanius cristatus*	*Dicaeum trigonostigma*	*Geopelia striata*	*Todiramphus chloris*	*Halcyon smyrnensis*	
0	1	2	2	0	0	
1	0	7	9	6	1	
2	0	1	0	1	3	
3	1	0	0	3	1	
5	0	0	1	0	0	
6	0	0	0	0	1	

Plot size

Plot size	Amaurornis phoenicurus	Orthotomus ruficeps	Spilopelia chinensis	Todiramphus chloris	Pycnonotus goiavier	Rhipidura javanica	Prinia familiaris
5	0	1	10	1	30	2	5
10	2	5	5	4	26	0	5
20	0	16	3	4	27	3	23
40	0	6	3	1	34	0	9

Plot size	Pycnonotus aurigaster	Orthotomus sericeus	Centropus bengalensis	Micropternus brachyurus	Orthotomus atrogularis	Chalcophaps indica	Lanius cristatus
5	11	3	1	1	0	0	1
10	7	5	0	1	1	2	0
20	16	3	2	0	1	0	0
40	10	18	4	0	0	7	1

Plot size	Dicaeum trigonostigma	Geopelia striata	Halcyon smyrnensis
5	2	3	2
10	2	3	1
20	5	5	0
40	1	1	3

Ordination enrichment
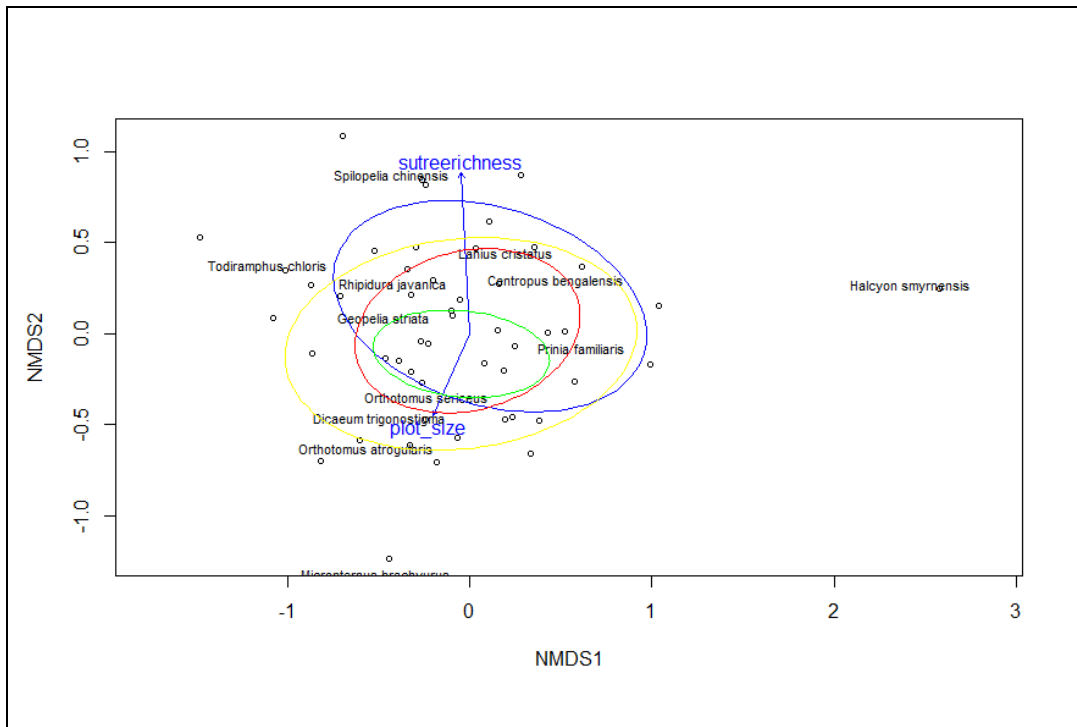
Circles represent 95% confidence intervals. Plot size treatments. Blue=5×5, yellow=10×10 m plots, Green=20×20 and red=40×40 m plots
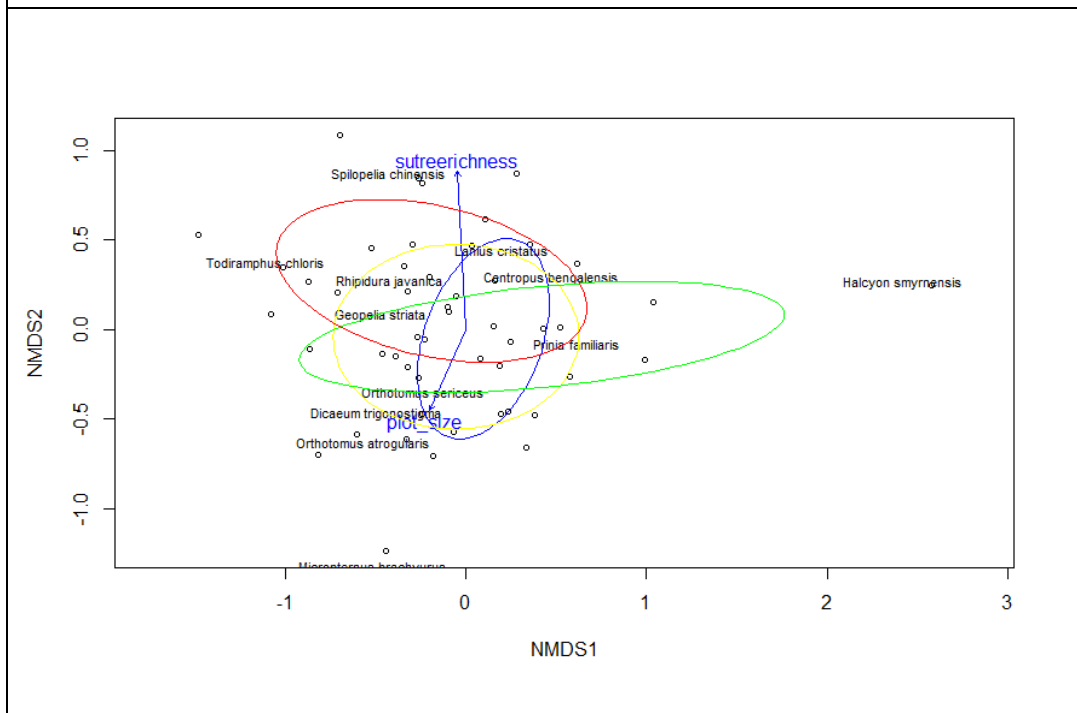
Circles represent 95% confidence intervals for Tree species richness treatments. Blue=1, yellow=2, Green=3, red=5. and 6.

I hereby assure that this thesis was exclusively made by myself and that I have used no other sources and aids then the ones enlisted