ORIGINAL RESEARCH

How does FSC forest certification affect the acoustically active fauna in Madre de Dios, Peru?

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Abstract

Despite several efforts to quantify the effectiveness of forest certification in developing sustainable use of forest resources, there is little evidence that certified forests are more effective in conserving fauna than non-certified managed forest. To evaluate the impact of forest certification on the fauna, we compared the biodiversity in reference sites ($n = 23$), Forest Stewardship Council (FSC) certified management sites ($n = 24$) and non-FSC management sites ($n = 20$) in the Tahuamanu region of Peru, during the dry season of 2017. Specifically, we determined if the acoustic space used (ASU), soundscapes composition, and the bird richness and composition significantly varied among the three management types. Variation in ASU was best explained by management type and mean ASU in the FSC sites was significantly greater than the reference and non-FSC sites, possibly suggesting greater richness of acoustically active species. An ordination analysis of the soundscapes showed that there was a significant difference among the three management types. There was greater dissimilarity in soundscape composition between the FSC and non-FSC sites, and greater overlap between FSC and reference sites. Bird identifications resulted in 11,300 detections of 226 bird species. Bird species richness and composition were not significantly different among the management types, indicating, in this context, that birds may not be the best indicators of different management strategies. The weak discrimination by the bird community is likely due to their dispersal ability, undisturbed primary forest matrix, and the occurrence of bamboo patches. The differences in ASU among the management types were most likely due to differences in acoustically active insects, which may be more sensitive to changes in microhabitat differences. Our findings correspond with the conclusions of other studies that certified forests can maintain levels of fauna biodiversity similar to those of undisturbed primary forest in the Amazon region.

Introduction

Conserving tropical forests while providing economic opportunities for actors that depend on the forest is currently one of the paramount goals for many researchers and conservation biologists. Forest management certification (FMC) is a market-based strategy for conserving biodiversity while using forest resources (Romero et al.

2013). Since its appearance in the 1990s, FMC has received considerable attention from ecologists and economists interested in improving management practices in timber production forests. While some studies have shown environmental benefits of certified forests over non-certified forests (Burivalova et al. 2017), the majority of these studies focus on vegetation and abiotic responses and relatively few studies have addressed the effect of

FMC on fauna (Zagt et al. 2010). Given the lack of information about the fauna response to FMC, the evaluation of the effectiveness of management forest units on biodiversity come mainly from studies assessing the effect of a single forest management practice associated with forest certification (e.g. reduced-impact logging, establishment of riparian zones, identifying High Conservation Value Forest) (van Kuijk et al. 2009), and to our knowledge, no study has directly assessed the impacts of forest certification at the acoustic community level.

Timber production is a major threat to tropical ecosystems (Edwards et al. 2014). Extensive areas of the Brazilian Amazon forest (>19 823 km^2) have been used for logging activities, and more than 50 million m^3 of wood were extracted per year between 1999 and 2002 (Asner et al. 2005). In Perú, forestry concessions comprise c. 14% of the Peruvian Amazon (9 441 173 hectares) and in the Peruvian department of Madre de Dios they comprise 1 216 000 ha (http://geobosques.minam.gob.pe). In response to the high rate of deforestation and the increase in timber harvesting, the Forest Stewardship Council (FSC) was established in 1993 as a market-based tool to promote responsible forest management. Specifically, the goal was to ensure that the harvest of timber and non-timber forest products maintains the forest biodiversity, productivity and ecological processes. The FSC is one of the most visible Forest Management Certification (FMC) schemes and it uses a labelling system based on principles of ecological, economic, social and political sustainability to foster the responsible and sustainable use of the forest. Specific requirements for FSC certification regarding biodiversity conservation include: 1) maintenance of rare, threatened or endangered species and their habitats, 2) protection of representative samples of ecosystems, 3) prohibition of genetically modified organisms, 4) control of the use of exotic species and 5) with very few exceptions, the conversion of natural forests is prohibited. Unfortunately, FSC evaluation has mainly included indirect indicators of biodiversity conservation (e.g. measures of forest structure) (van Kuijk et al. 2009; Zagt et al. 2010), and evaluations of the effectiveness of certified forests on promoting the sustainable use of the forests have not convincingly demonstrated positive results (Romero et al. 2013).

Among the main limitations of the studies assessing the impact of FSC on biodiversity are the lack of unlogged reference areas, the absence of true replicate sites, the absence of Before-After-Control-Impact design and the fact that often treatments are not assigned randomly (Romero et al. 2013; França et al. 2016). In addition, data on the responses of the fauna to the certification schemes are limited to small geographical areas, non-simultaneous sampling due to logistic constraints, and the targeting of limited taxonomic groups, which combined compromise our understanding of the impact of certified management (or lack thereof) to maintain and conserve biodiversity. Furthermore, almost all information about the impact of FSC on faunal biodiversity comes from studies assessing the impact of its 'good management practices' component, such as reduced-impact logging (RIL) on fauna (van Kuijk et al. 2009). Forest management certification can include several management practices such as RIL, establishment of riparian buffer zones and corridors, identifying High Conservation Value Forest (HCVF), among others.

Among the practices associated with forest certification in tropical systems, RIL is the most studied in terms of its effects on biodiversity, and in general it is less detrimental to fauna than conventional logging practices (van Kuijk et al. 2009). A comprehensive study in Central Guiana showed that RIL practices had much less effect on assemblages of birds, bats and large mammals compared to conventional logging (Bicknell et al. 2015). Another multi-taxon study, in the Brazilian Amazon, found only minor effects of RIL on ants, arachnids, birds and mammals in comparison with conventional logging (Azevedo-Ramos et al. 2006). A comparison of RIL managed forest and control sites in the Brazilian Amazon found no significant change in bird species richness between the treatments (Wunderle et al. 2006). Finally, a meta-analysis also showed that RIL practices had fewer negative impacts on species abundance of birds, arthropods and mammals in comparison with conventional logging (Bicknell et al. 2014). While these are encouraging findings, there is no quantitative evidence that FSC certified operations are consistently adopting RIL. Therefore, the impact of FSC on fauna remains to be tested.

Although quantitative measurements of the effectiveness of forest management certification on fauna remains scarce, the use of satellite images have improved our understanding of how forest structure, or more specifically forest cover, varies between certified and non-certified forests. For instance, remote sensing has been successfully used to monitor Amazon deforestation, and more recently to monitor selective logging (Asner et al. 2005, 2006). These automated remote techniques have a key role in assessing human impacts on remote and large areas across a broad temporal scale. Satellite images can provide information on forest cover and structure, but it cannot directly provide information on the fauna inside the forest.

Passive acoustic monitoring (PAM) is a useful sampling technique that can provide information on the acoustically active proportion of the fauna (Marques et al. 2012; Kalan et al. 2015; Deichmann et al. 2017, 2018; Ribeiro et al. 2017). PAM provides a flexible and cost-effective sampling scheme to monitor many animal taxa

simultaneously, it can be used in a broad range of ecological and management studies, and all audio recordings along with the metadata can be permanently stored (Aide et al. 2013). PAM has been used to monitor population dynamics and activity patterns (Dorcas et al. 2009; Ospina et al. 2013), to monitor rare species and species of conservation concern (Campos-Cerqueira and Aide 2016; Wrege et al. 2017), to document human impacts (Deichmann et al. 2017), and shifts in species distributions (Campos-Cerqueira and Aide 2017a; Campos-Cerqueira et al. 2017). In addition, PAM has been used to document the health and stability of an ecosystem by providing information about the status of entire animal communities (Blumstein et al. 2011; Pijanowski et al. 2011; Staaterman et al. 2013; Fuller et al. 2015; Burivalova et al. 2018).

Among the many advantages of PAM is the ability to collect information of environmental sounds, or soundscapes, which includes not only the animal produced sounds (biophony) but also geophysically created sounds, such as rain and wind (geophony), and human produced sounds (anthropophony and/or technophony) such as speech, the sound of gunshots, bulldozers and chainsaws (Krause 1987). Composition analyses of the soundscapes can contribute to the understating of how species are distributed in the landscape (Campos-Cerqueira and Aide 2017b) and how human impacts, such as mining and oil exploration, affect and structure the acoustic communities (Alvarez-Berríos et al. 2016; Duarte et al. 2015,

Deichmann et al. 2017). In addition, soundscapes can be used to assess and compare biodiversity across habitats. For instance, species richness of insects, anurans, primates and birds are strongly and positively correlated with the proportion of acoustic space used (ASU) in an area (Aide et al. 2017). This means that sites with the higher number of acoustic species are expected to produce soundscapes that are more saturated (i.e. more acoustic activity across different acoustic frequencies). Nevertheless, there will be variation among species in the amount of acoustic space they occupy (Aide et al.2017). This novel approach can contribute to our understanding of ecological community dynamics and provide a useful tool for monitoring multiple taxonomic groups simultaneously.

In this study, we used PAM acquired data to document the response of the acoustically active fauna to three forest management types (i.e. FSC certified, non-certified, reference primary forest with no logging history). Specifically, we evaluated 1) how soundscapes composition and ASU vary among the three forest management types, and 2) how the bird community differs among the three forest management types.

Materials and Methods

Study area

The study was conducted in the province of Tahuamanu in the department of Madre de Dios, Peru (Fig. 1), in the
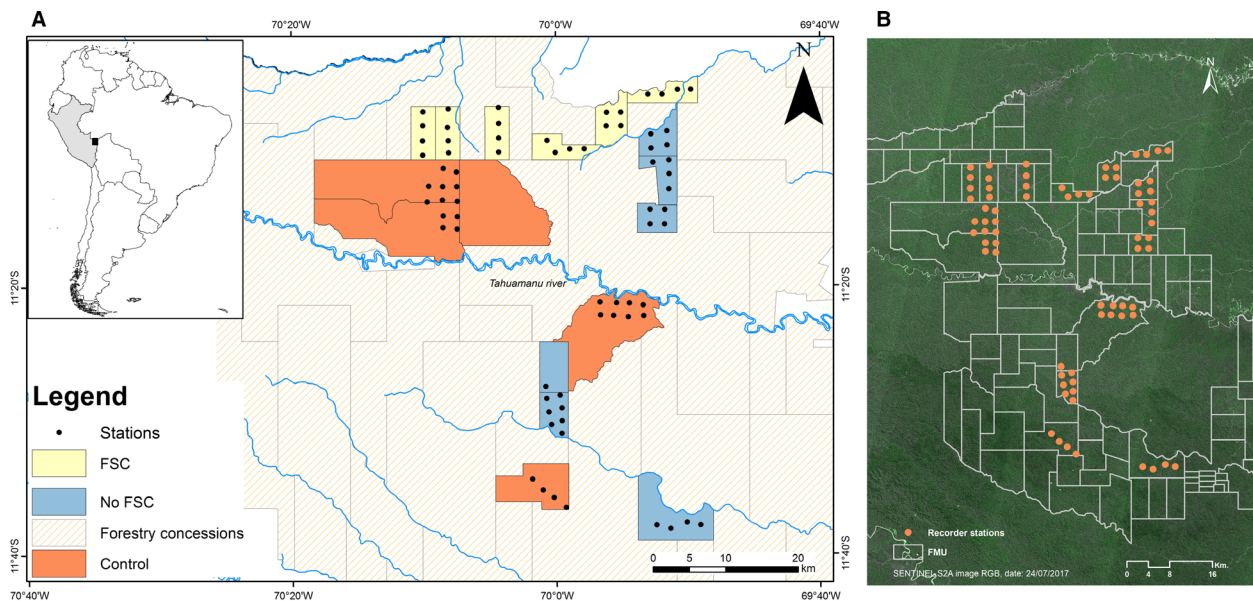
Figure 1. (A) Location of the study area in Tahumanu, Manu, Peru. Polygons represent Forest Management Units (FMU) as per concessions management plans. The colours represent the different forest management type and the dots represent the location of each acoustic recorder. (B) Satellite images (Sentinel) of the study area and selected FMUs and control area with locations of acoustic recorders.

south-western Amazon forest at an altitude between 160 and 380 m. Madre de Dios is a region with high biodiversity and includes important protected areas such as Manu National Park and Tambopata National Reserve. The average annual rainfall in this region is 2500–3500 mm, with a rainy season from November until May and a dry season from June to October, and a mean annual temperature of 24° (Tobler et al. 2013). The ecological system is characterized as a bamboo-dominated forest of the south-western Amazon (Josse et al. 2007).

Field work was conducted in four logging concessions: Chullachaqui (33 796 ha), Emini (43 812 ha), Maderacre (49 376 ha) and Maderyja (49 556 ha) (Table 1). Concession holders in Peru are required to develop a management plan every 5 years and an annual operating plan. Harvesting is carried out in blocks, which are logged on a 20-year harvest cycle. The size of blocks is variable (5000–50 000 ha) and depends of the concession area.

To assess the effects of both certified (FSC) and non-certified forest (non-FSC) management on biodiversity, we used a causal-comparative design. Thus, we compared biodiversity in both FSC and non-FSC logged concessions and reference sites (areas of primary forest with no logging history). All concessions have management plans and operated under governmental oversight. FSC standards for responsible forest management include environmental impact assessment, the maintenance of rare, threatened or endangered species and their habitats, protection of representative samples of ecosystems, control of hunting, fishing, trapping and collecting, and protection of water courses, water bodies, riparian zones and their connectivity among others (https://ic.fsc.org/en/what-is-fsc-certification/requirements-guidance). In addition, workers in all FSC certified concessions at Tahuamanu received RIL training through World Wildlife Fund–Peru in 2012. Among the RIL practices employed in the FSC concessions in our study area are: pre-harvest inventory, plunge cut, planned skidding, directional felling to reduce collateral damage. Non-FSC concessions did not have to adhere to the FSC standards and did not use RIL practices. FSC concessions in our study area had lower harvesting intensity in terms of number of trees and volume and had higher log recovery and damaged fewer commercial species during felling than non-FSC concessions (Goodman et al. 2019).

ARBIMON portable recorders (LG smartphone enclosed in a waterproof case with an external connector linked to a Monoprice condenser microphone with a weather shield) running the ARBIMON Touch application (https://goo.gl/CbBavY) were used to collect the audio recording. We sampled during the dry season, from 11 June to 20 July 2017, and although recordings were collected for approximately a month in each site analyses were based on 7 consecutive days. To maximize independence between sampling sites, recorders were deployed as isolated as possible from each other and from the FMU's borders. With few exceptions, all recorders were deployed 2 km from each other and from the FMU borders (Fig. 1 and Fig. S5). The distance of 2 km between sampling units minimizes spatial correlation (Aguilar-Amuchastegui and Henebry 2006; Shapiro et al. 2016,). Recorders were placed on trees at the height of 1.5 m and programmed to record 1 min of audio every 10 min for a total of 144, 1-min recordings per day, at a sampling rate of 44.1 kHz. We worked with 67 recorders and all management forests types were sampled simultaneously. Microphones have a flat response between 50 Hz to 20 kHz and a sensitivity of –45 dB ± 2 dB. Recorders were placed in 67 sites (24 – FSC certified management sites, 23 – reference sites and 20 – non-FSC certified management sites). Five sites were removed from the analyses due to recorder failure. Previous field tests conducted by our team indicate that vocalizations of the majority of bird and frog species can be detected by the recorders up to ~100 m and given that all recordings were made in a short time interval (~ 1 month), it is highly unlikely that the same individual will be detected by different recorders placed 2 km apart.

Explanatory variables

The soundscape and bird species richness and composition analyses were compared with 10 explanatory variables selected *a priori* (Table S1) given their reported effect on fauna (Thiollay 1997; Barlow et al. 2006; Burivalova et al. 2015; Chaves et al. 2017). These variables included: latitude, longitude, forest management type, distance to roads (metres), distance to rivers (metres), years since logging, two forest structure variables (ALOS-mean and ALOS-sd), calculated as change over time between specific years and two canopy heterogeneity variables (Sentinel-mean and Sentinel-sd derived from synthetic aperture radar (SAR) backscattering data (Mitchard et al. 2009; Fatoyinbo et al. 2017) acquired around the time of logging (in the case of ALOS-1 PALSAR data) and at the time of soundscape sampling in 2017 (Sentinel 1 data).

All continuous variables were standardized (i.e. rescaled to have a mean of zero) prior to the analyses. Additional information regarding description and measurements of explanatory variables can be found in the supplementary material section.

Soundscapes

Visual representations of the soundscapes (hereafter referred to as graphical soundscapes) were created for each of the 67 sites. First, a mean spectrum for each

audio file is created by computing a short-time Fourier transform (f = 44,100, wl = 256, wn = 'hanning', norm = FALSE) using the function *meanspec* in the *Seewave* package (Sueur et al. 2008) in R (R Core Team, 2014). Then we used the *fpeaks* function to detect frequency spectral peaks of each mean spectrum. The audio waveforms were scaled between -1 and 1, and thus spectral peaks were limited to maximum amplitude of 1. After all peaks were detected we then selected peaks using amplitude threshold. Frequency distance threshold was set to 0. The number of frequency peaks was determined by counting the number of recordings with a peak within each of the 128 frequency bins that were equal or greater than the amplitude threshold of 0.003. To control for the different number of recordings in each site and each time interval (i.e. hour), we divided the number of recordings with a peak in each time/frequency class by the total number of recordings collected during each hourly interval.

The graphical soundscapes were created in the soundscape analyses tool in the ARBIMON II platform (Fig. 2). The procedure includes creating a playlist for each site with all 1-minute recordings from 7 consecutive days (n = 1008) and then setting the parameters of the analysis in ARBIMON II platform. We followed published peer-review literature focused on studies with anurans, birds, insects and mammals for setting the parameters of the soundscapes (Aide et al. 2017; Campos-Cerqueira and Aide 2017a,b; Deichmann et al. 2017). The soundscape analysis tool allows the user to define the time scale of aggregation (e.g. hour, month or year), the frequency bin size, and the minimum threshold for the amplitude of a sound (i.e. intensity). We aggregated recordings at the time scale of hour of day (24 h), used a frequency bin size of 172 Hz, and an amplitude filtering threshold of 0.003. Different threshold values were tested in an exploratory analysis and we selected the amplitude threshold value that best differentiates between biological sounds and background noise. This resulted in a three-dimensional (x = hour, y = acoustic frequency, z = proportion of all recordings in each time/frequency bin with a frequency peak value > 0.003 amplitude) matrix of acoustic activity with a total of 3,072 time/frequency bins (24 h × 128 frequency bins). We chose to work with the entire soundscape because in our study area biophony (sounds produced by fauna) occurs in practically all acoustic frequencies, from 86 Hz (e.g. *Allouatta seniculus*) to 20 kHz (e.g. bats and insects). Damaged recordings (e.g. microphone malfunction) were excluded from the analyses. In addition, geophony was mainly restricted to only a few rain events (the study occurred during the dry season) and anthropogenic sounds were virtually absent during the study. We did not remove recordings containing sounds from rain prior to the analyses due its rarity and because we were interested in characterizing the entire acoustic system of each site (Towsey et al. 2014)

We defined the acoustic space used (ASU) as the per cent of time/frequency bins used in each site (24 h × 128 frequency bins = 3072 time/frequency bins). ASU was based on the graphical soundscapes. A time/frequency bin was considered 'used' if a sound with an amplitude > 0.003 was detected in that bin. Automated model selection and model averaging were used to detect the best explanatory variables for ASU. We used the function *glmulti* from the *Glmulti* package (Calcagno and de Mazancourt 2010) in R (R Core Team, 2014) to automatically generate all possible general linear models with ASU
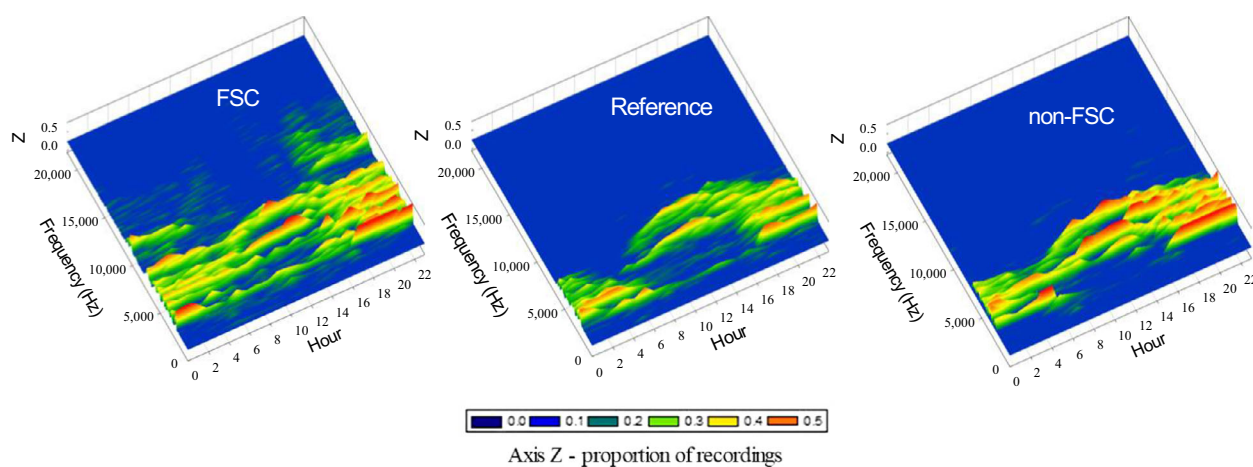
Figure 2. Visual representations of soundscapes from a sample of the three forest management types. The axes represent hour (x), frequency (y) and the proportion of observations (z). The figure includes 3072 time/frequency bins (24 h × 128 frequency bins). ASU was calculated by summing the number of time/frequency bins that were occupied.

and 10 explanatory variables (Table S1). Akaike information criterion (AICc) was used to determine the best models (Burnham 2004).

To determine the relationship among the 67 graphical soundscapes, we conducted a non-metric multidimensional scaling (NMDS) analysis. This technique locates the 67 sites in multidimensional space based on dissimilarities of the 3072 time/frequency bins of the graphical soundscape. These analyses were done in R (R Core Team, 2014) using the *Vegan* package (Oksanen et al. 2013). We used the function *envfit* to fit the environmental variables to the ordination, and the functions *adonis* and *betadiver* to perform a multivariate ANOVA to test if there was a significant difference in the mean similarity among the three management types.

Bird species richness and composition

To identify bird species in the recordings we manually inspected all recordings (i.e. visual and aural inspection of the recordings and spectrograms) from the first 3 non-consecutive days from each of the 67 sites (432 1-minute recordings per site). Three experienced ornithologists (Marconi Campos-Cerqueira, Christian Andretti and Gabriel Leite) listened to the recordings from 27, 20 and 20 sites, respectively. A balanced number of forest management types were included in the dataset for each ornithologist.

The presence or absence of each bird species was determined for each individual recording, and 432 1-minute recordings (3 days, 144 recordings per day) were evaluated per site. Songs and calls of these species were confirmed by comparing with sound databases (e.g. www.xe no-canto.org). Bird species that could not be identified were tagged as 'doubts'. Later, these doubts were grouped in a playlist, and were independently cross-reviewed by the experts to see if some calls or songs could be identified. Some genera included species with similar vocalizations (e.g. *Monasa*, *Pasarocolius*, *Hemitriccus*, *Poecilotriccus* and *Lophotriccus*) and were difficult to identify to species. These genera were excluded from the analyses. For the ordination analysis, we included only species that were detected in at least two sites.

To determine the relationship of the 67 sites and bird composition, we conducted a non-metric multidimensional scaling (NMDS) analysis. These analyses were done in R (R Core Team, 2014) using the *Vegan* package (Oksanen et al. 2013). We used the function *envfit* to fit the environmental variables to the ordination. We also used the functions *adonis* and *betadiver* to perform a multivariate ANOVA to test if there was a significant difference in the mean similarity among the three management types. Additional accumulation curve analyses (Colwell et al. 2014) can be found in the supplementary material section.

Results

Soundscapes

The acoustic space used (ASU) in the 67 sites varied from ~18 to 40%, with a mean and median around 24%. All the best fitting models for ASU (ΔAICc < 2) included forest management type (Table S2), and this variable received the best support in explaining variation in ASU (Fig. S1). ASU was significantly different among the three

Table 1. Summary of blocks sampled for acoustic monitoring in Tahuamanu. Number of blocks according to approved management plans.
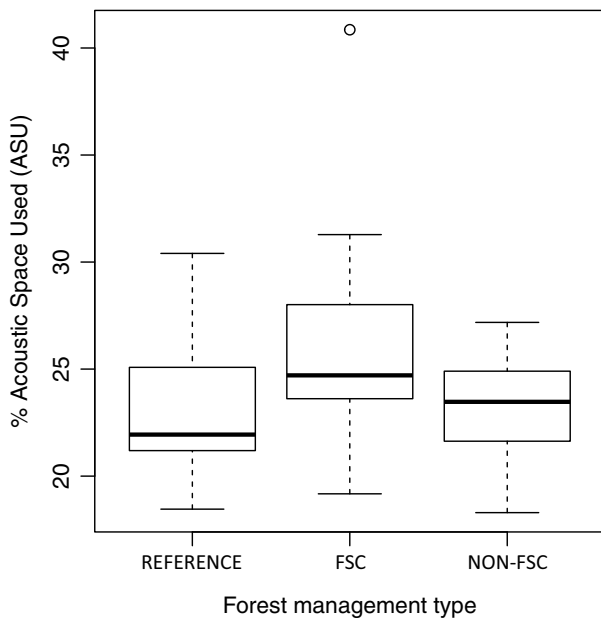
Management	Concession	Year logged	Years since logging	Block	Area (ha)	# Recorders
FSC	Maderacre	2008	9	7	2326	4
FSC	Maderacre	2009	8	8	2522	4
FSC	Maderacre	2011	6	10	2207	4
FSC	Maderyja	2008	9	6	2483	4
FSC	Maderyja	2009	8	10	2479	4
FSC	Maderyja	2011	6	9	2437	4
Non-FSC	Chullachaqui	2009	8	7-B	2742	1
Non-FSC	Chullachaqui	2010	7	8-B	2222	7
Non-FSC	Chullachaqui	2011	6	9	5825	4
Non-FSC	Emini	2008	9	6	2315	4
Non-FSC	Emini	2009	8	7	2404	4
Non-FSC	Emini	2011	6	9	2141	4
Reference	Maderacre	-	-	16	2749	8
Reference	Maderacre	-	-	17	2002	4
Reference	Maderacre	-	-	7-c	2725	8
Reference	Chullachaqui	-	-	13	5047	4

management types ($F = 4,70$, $P = 0.01$) and was significantly higher in the FSC sites than the reference and non-FSC groups (Fig. 3). This difference continued even when the outlier (51-FSC, ASU = 40.8%) was eliminated from the analysis. A post hoc comparison using Tukey HSD test indicated that the mean ASU in FSC was significantly different than the mean ASU of the reference sites ($P = 0.02$) and non-FSC sites ($P = 0.03$). However, the mean ASU in the reference sites and the non-FSC sites were not significantly different ($P = 0.98$).
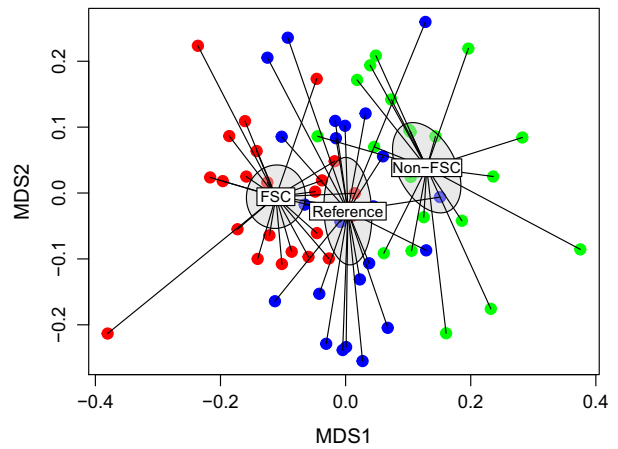
Soundscape composition was best visualized by an NMDS with three dimensions (Fig. 4 -stress = 0.19). The NMDS ordination using all the 3072 time/frequency bins (i.e. variables) showed a significant difference among the three management types ($R^2 = 0.30$, $P = 0.001$), distance from water sources ($R^2 = 0.20$, $P = 0.004$) and longitude ($R^2 = 0.16$, $P = 0.004$) (Table 2) (Fig. S2). A similar pattern can also be observed when using multivariate analysis of variance (*Adonis*) where forest management type ($R^2 = 0.07$, $P = 0.001$), distance from water sources ($R^2 = 0.02$, $P = 0.03$) were significant. The majority of the time-frequency bins that contributed to dissimilarities between sites occurred at night and at high frequencies (>10 kHz).

Bird Species richness and composition

In total, there were 11 300 bird detections across 29 084 manually validated recordings. Bird detection ranged from 37 to 357 per site (mean = 169, SD = 63) (Fig. 5).

Figure 4. NMDS ordination of the 67 sites based on the 3,072 time/frequency bins from each soundscape. The circles represent the standard error (95%) around the centroid for the three management types.

There was no significant difference in detections among the three management types (ANOVA $F = 0.08$, $P = 0.91$).

In total, we detected 226 species (Table S3). Bird species richness per site varied between 14 and 64 species (mean = 40, SD = 8.5) (Fig. 5). There was no significant difference in species richness among the three management types (ANOVA $F = 0.09$, $P = 0.90$). Bird accumulation curves indicated that the manually processing reached a satisfactory level of sampling effort (Fig. S3).

Bird species composition was best visualized by an NMDS with three dimensions (Fig. 6 stress = 0.24). The NMDS ordination using all species that occurred in at least two sites, showed no significant difference among

Figure 3. Boxplot of the percent of acoustic space used among the three forest management groups.

Table 2. Summary of the effect of explanatory variables on soundscape and bird composition based on results from NMDS ordination using all the 3072 time/frequency bins and from NMDS ordination using all species that occurred in at least two sites. Displayed are R-squared values. Bold values denote significant results ($P < 0.05$).

Explanatory variables	Soundscapes	Bird composition
Forest Management type	**0.30**	0.05
Years since logging	0.02	0.08
Distance from the river	**0.20**	0.02
Distance from the road	0.09	0.07
ALOS mean	0.05	**0.14**
Sentinel mean	0.04	**0.20**
Latitude	0.06	0.03
Longitude	**0.16**	0.09
Sentinel sd	0.01	0.07
ALOS sd	0.03	**0.03**
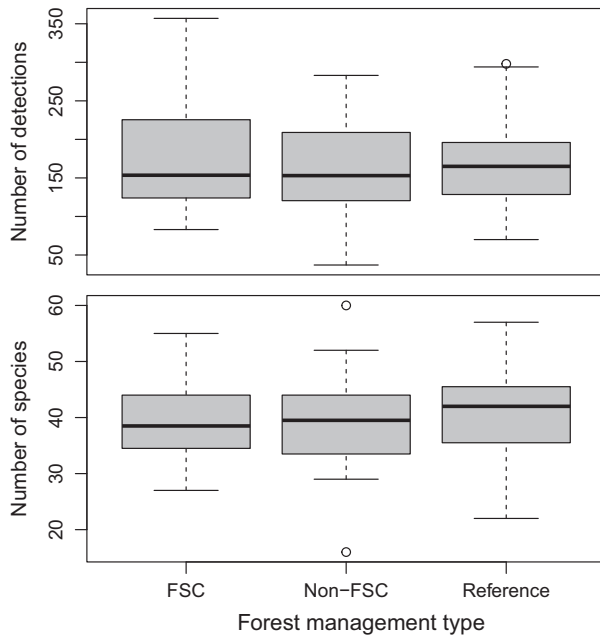
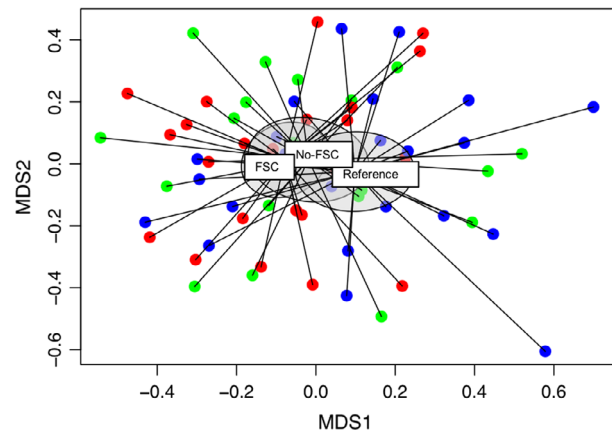**Figure 5.** The distribution of detections and number of detected species in the three forest management types.

Figure 6. NMDS ordination of the 67 sites based on the 180-species that occurred in at least two sites. The circles represent the 95% standard error around the centroid for the three management types. Blue points represent Reference sites, yellow points represent non-FSC sites and red points represent FSC sites.

the three management types. However, there was a significant effect of current forest structure heterogeneity (Sentinel [$R^2 = 0.20$, $P = 0.002$]) (Table 2, Fig.S4) and its dynamic change (ALOS-mean [$R^2 = 0.14$, $P = 0.009$] and ALOS-sd [$R^2 = 0.09$, $P = 0.043$]) on bird composition. This means that structural changes in the forest resulting from logging and its final outcomes by the time of survey explain in part the differences observed in bird communities. A multivariate analysis of variance showed a significant but weak difference among the three forest management types ($R^2 = 0.05$, $P = 0.001$) along with the significant effect of forest structure change (ALOS mean [$R^2 = 0.03$, $P = 0.001$]).

Discussion

The evaluation of the effectiveness of forest certification on fauna conservation is urgently needed to improve forest management standards. However, monitoring the response of several animal taxa simultaneously in the tropics is still a challenge. In this study, we present quantitative evidence on how the acoustically active fauna is responding to different forest management activities in the Peruvian Amazon. Acoustic space use was highest in the FSC certified sites, which is likely correlated with higher overall species richness (Aide et al. 2017). Soundscape composition was significantly different among the three management types, suggesting that there was a unique set of acoustic species associated with each

management types. Furthermore, there was greater dissimilarity in soundscape composition between the FSC and non-FSC sites, and greater overlap between FSC and reference sites. In contrast, bird species richness and composition were not significantly different among the forest management types.

The apparent contradiction of the effect of forest management type on overall species richness (ASU) and bird species richness is not unexpected since insects drive the use of the acoustic space (Aide et al. 2017). Acoustic differences between the sites were most prominent during the night and at high frequencies (>10 kHz), both characteristics consistent with the acoustic activity of katydids (Symes et al. 2018). In additional, there were few frog species, because the study was conducted during the dry season, and few mammals (mostly howler monkeys) in the recordings. Other studies have also found that insects calls have a disproportionally large contribution to soundscapes (Ferreira et al. 2018; Gasc et al. 2018). This means that the significant and higher overall species richness detected in the FSC sites are probably influenced by high insect richness or abundance in these areas. Consequently, a possible explanation for high ASU in the FSC sites is the intermediate disturbance hypothesis, in which insect species from both the reference and more disturbed sites are likely to co-occur in the FSC sites. Insect species are also likely to be driving the dissimilarity in soundscape composition among the forest management types given the weak discrimination by the bird community. In addition, the significant effect of distance from the river and longitude on soundscape composition is likely related with the variation in insect community since insects are more likely to respond to microhabitat variation. The

study area extends ~ 40 km from east to west and there maybe local changes in humidity and other microhabitat variables. For example, the distance of the sampling sites from rivers increased from east to west and this might have led to difference in microhabitat variables (e.g. humidity), which could affect insect abundance and composition. Together these results highlight the urgency for including insects into biodiversity assessments even though acoustic identification of insects in the tropics poses a significant challenge.

The lack of a strong effect of forest management type on bird species richness and composition may be related to several non-exclusive reasons. Several studies have demonstrated that the distance from undisturbed forest, the intensity of logging and species mobility have a significant influence on fauna responses to logging activities (Thiollay 1997; Barlow et al. 2006; Burivalova et al. 2015; Chaves et al. 2017). In the study area, FSC certified and non-certified blocks are embedded in a landscape matrix of continuous forest (Fig. 5S), and although recorders were 2 Km from the forest management units borders both the species pool of the surrounding sites and the high mobility exhibited by many bird species may facilitate the use of these logged sites. In addition, the Tahuamanu region has extensive areas covered by arborescent bamboo forest (*Guadua* sp.) with a specific fauna associated with it (Guilherme and Santos 2009) that is highly resilient to disturbances such as ground fire (de Carvalho et al. 2013). Therefore, the gaps created in the logged areas, both on FSC and non-FSC, may resemble the undisturbed forest matrix that has natural patches of bamboo and facilitates the use of this habitat for highly mobile and resilient fauna. Consequently, the reduced-impact logging from both FSC certified and non-certified forest and the undisturbed forest with extensive patches of bamboo were expected to minimize the likelihood of detecting strong effects of management on bird community richness and composition. Furthermore, the significant effect of forest structure and canopy heterogeneity on bird composition provide further evidence that landscape features, such as bamboo patches, are more critical in driving bird community than forest management types in the study area.

Comparison of studies on the effect of logging on fauna is difficult, given the differences in logging intensity, post-harvest time, forest type, matrix and sampling methods. In addition, there is a lack of studies assessing the response of fauna communities to FSC certified forest in the tropics. Nevertheless, there is evidence that bird richness and composition are not strongly affected by selective logging. Primary forests disturbed by logging in Brazilian Amazon (Pará) still retain high numbers of forest species (86% of the total regional species pool)

and have species richness similar to undisturbed forests (Moura et al. 2013). No differences in bird species richness were also found between reference and selectively logged areas in another Brazilian Amazon forest in the Tapajós National Forest (Pará) (Wunderle et al. 2006). The results from these studies support our findings that the bird community may not be the best indicator group for assessing the impact of forest management certification on fauna. In contrast, the strong positive correlation between acoustic space use (ASU) and forest management type along with a significant effect of forest management type on soundscape composition reinforce the utility of soundscapes analyses for monitoring fauna at the landscape level.

Acoustic monitoring has allowed us to overcome many of the limitations common to studies assessing the impact of FSC on biodiversity (e.g. sampling multi-taxonomic group and covering a large area over short time frame). One limitation of our study, and many others is the absence of information before logging. Nevertheless, our study provides information on the response of active acoustically fauna to forest management. Although our results should be considered with caution, they do indicate a significant change in soundscape composition across different forest management types. Furthermore, we provide quantitative evidence of only minor variation in bird richness and composition among the different management types. In addition, data acquired by acoustic sensors can be influenced by habitat characteristics, such as forest structure. Nevertheless, there was no significant difference among the treatments in terms of forest structure (ALOS mean and AloS-sd) and, thus, there is no evidence that structural differences are causing the observed patterns.

Conclusions

The soundscape analyses show greater ASU in the FSC sites, but most importantly, the composition of the soundscapes had greater overlap between the reference and FSC sites. Because ASU is strongly associated with overall species richness of acoustic species (e.g. anurans, birds, insects and mammals), our findings reinforce the conclusions of other studies that certified forests can maintain similar levels of fauna biodiversity to undisturbed primary forest in the Amazon region. In addition, we were able to generate an enormous and valuable data set on the acoustic environment of this high-diversity Amazonian forest region. For example, the analyses of these recordings provide one of the most detailed studies of an Amazon bird community (>200 species) regarding the distribution and vocal activity patterns. The collection of this data set was possible due to the use of acoustic

remote sensing (i.e. PAM) which allowed us to sample many sites simultaneously over a large spatial scale, overcoming many logistical limitations associated with traditional sampling techniques.

Future studies should focus on identification of insects and anurans, since these groups may exhibit less mobility than birds and they may be better indicators of variation in habitat structure, particularly at the site scale (m^2 – ha). The species-specific identification of these taxonomic groups will provide us a better measurement on how the composition of the fauna responds to different forest management activities. In addition, birds, frogs and insects presented marked daily patterns of acoustic activity, with insects and frogs dominating the nocturnal soundscapes. These daily variations in acoustic activity can be further explored to characterize a site and assess the influence of human activities in animal behaviour. This study provides a snapshot of the fauna responses to different forest management practices, but continuous or frequent monitoring is needed to determine the long-term impacts on fauna.

Acknowledgments

Data Accessibility

The acoustic data including recordings, sampling sites coordinates, elevation data, validation data and soundscapes data are permanently stored and available at https://arbimon.sieve-analytics.com/project/wwf-peru/dashboard.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Explanatory variables used in the soundscape and bird richness and composition analyses.
Table S2. Best fitting models (ΔAIC< 2) for the acoustic space used (ASU).
Table S3. Summary of estimates of species richness in the forest management types in Tahuamanu region of Peru.
Figure S1. Model-averaged importance of the predictors of environmental variables on the acoustic space used (ASU).
Figure S2. NMDS ordination of the 67 sites based on the 3,072 time/frequency bins from each soundscape with the effect of environmental variables.
Figure S3. Bird species accumulation curve in Tahuamanu region of Peru.
Figure S4. NMDS ordination of the 67 sites based on the 180-species that occurred in at least two sites with the effect of environmental variables.