# Protected Area Zoning as a Strategy to Preserve Natural Soundscapes, Reduce Anthropogenic Noise Intrusion, and Conserve Biodiversity

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# Protected Area Zoning as a Strategy to Preserve Natural Soundscapes, Reduce Anthropogenic Noise Intrusion, and Conserve Biodiversity

**María Isabel Herrera-Montes**[1]

**Abstract**

Protected area zoning is a management strategy used to define and delimit land units for specific purposes, such as critical areas for conservation and areas for recreation activities. Nevertheless, human activities in and around protected areas produce anthropogenic noise that is difficult to mitigate and control. To assess the efficacy of protected area zoning in preserving natural soundscapes, controlling anthropogenic noise intrusion, and conserving biodiversity in El Yunque National Forest, Puerto Rico, I simultaneously sampled three management zones (protected, recreational, and buffer) with passive acoustic monitoring and conducted a soundscape analysis. There was no difference in the overall acoustic space used among the three management areas, but compositional differences among the soundscapes were detected. Such variation was related to differences in species composition along the elevation gradient, habitat transformation, and anthropogenic noise. Anthropogenic noise was more conspicuous in the buffer and recreational areas, where many bird species are classified as highly vulnerable to noise. Although the management zones in El Yunque National Forest were not created for the purpose of noise control, management is shown to be useful for minimizing noise intrusion in the strictly protected zone. In recreational and buffer areas, complementary strategies such as traffic limitations, limiting access to specific areas, and noise reduction educational programs should be implemented to maintain the natural soundscape while conserving biodiversity. Finally, the noise vulnerability classification proposed in this study could be a useful tool for assisting managers and researchers in defining priority strategies for sensitive species that require special attention and protection.

**Keywords**

passive acoustic monitoring, noise vulnerability classification, noise pollution, acoustic space use, protected area management

## Introduction

Protected areas are established to maintain biodiversity, preserve ecosystem process, and provide recreational and natural experiences for people. However, balancing biodiversity preservation and human use can be very challenging. A strategy applied to mitigate conflicts between different uses within protected areas is delimiting or zoning land units for specific purposes, such as critical areas for conservation or recreation activities (Sabatini, Verdiell, Rodriguez, &Vidal, 2007). Protected area zoning (PAZ) is widely applied in marine and terrestrial protected areas, and it is considered as an essential component of protected area management (Geneletti & van Duren, 2008; Hull et al., 2011). However, one of the main problems with zoning is that boundaries are often established without the necessary information about the distribution of the fauna and human activity patterns.

El Yunque National Forest (EYNF), a tropical forest in the U.S. National Forest System, traditionally uses PAZ to delimit wilderness, recreational, and administrative

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areas. El Yunque is the most iconic place in Puerto Rico providing environmental, economic, and social benefits for local and international visitors. Its management plan (U.S. Department of Agriculture Forest Service [USDA FS], 2018b, p 1) focuses on "an integrated vision of ecological, social, and economic sustainability and connecting to local communities." Currently, the forest is divided into nine management areas (Table 1), including delimitations such as a community interface resource zone with collaborative management, and byway management areas, to preserve and develop a scenic route. The recently updated plan proposed an adaptive approach to land and resource management, where monitoring programs are fundamental. However, noise regulations were not included even more than 600,000 people visit the area per year, and traffic volume exceeds more than 700 vehicles per day (USDA FS, 2018b).

Human activities around and within protected areas introduce new sources of noise, changing the natural soundscape (Barber et al., 2011; Buxton et al., 2017; Farina, 2014; Francis & Barber, 2013; Francis et al., 2017) to include a mix of biotic, abiotic, and anthropogenic noises (Pijanowski et al., 2011; Rodriguez et al., 2014). Studying these novel soundscapes can help to understand the dynamics between natural and anthropogenic sounds and assess possible effects on the biota (Deichmann et al., 2018; Farina, 2014). For example, soundscape analysis can provide information about animal community composition (Aide, Hernández-Serna, Campos-Cerqueira, Acevedo-Charry, & Deichmann, 2017; Campos-Cerqueira & Aide, 2017a; Farina & James, 2016; Krause & Farina, 2016) and its dynamics in urban areas (Fairbrass, Rennett, Williams, Titheridge, & Jones, 2017; Joo, Gage, & Kasten, 2011; Liu, Kang, Behm, & Luo, 2014) and natural areas (Burivalova et al., 2018; Krause, Gage, & Joo, 2011; Pekin, Jung, Villanueva-Rivera, Pijanowski, & Ahumada, 2012; Turner, Fischer, & Tzanopoulos, 2018; Tucker, Gage, Williamson, & Fuller, 2014). In addition, soundscapes have been used to evaluate the effects on fauna from high-noise levels associated with mining (Alvarez-Berríos et al., 2016; Duarte et al., 2015), natural gas exploitation (Deichmann, Hernández-Serna, Campos-Cerqueira, & Aide, 2017), and vehicle traffic near protected areas (Arévalo & Blau, 2018; Munro, Williamson, & Fuller, 2018).

Transportation, extraction activities, and development are the primary and widespread sources of noise detected in protected areas by the U.S. National Parks sound-monitoring program (2006, cited by Lynch, Joyce, & Fristrup, 2011). The monitoring program is part of the Natural Sounds and Night Skies Division and was established to study, preserve, and restore the natural soundscape in protected areas. As many anthropogenic sounds originate from outside of National Parks (Lynch et al., 2011) and most noise management strategies are created to improve the park visitor experience and not protect wildlife (Barber et al., 2010; Francis et al., 2017), noise management and soundscape conservation are a challenge (Barber et al., 2011; Barber, Crooks, & Fristrup, 2010; McGregor, Horn, Leonard, & Thomsen, 2013; Mennitt, Sherrill, & Fristrup, 2014).

To evaluate the effectiveness of PAZ on preserving the natural soundscape, controlling noise intrusion, and preserving animal biodiversity from the effect of anthropogenic noise, I simultaneously sampled the acoustic environment at 45 sites in three different management zones (protected, recreational, and buffer) in EYNF. I used descriptive and quantitative approaches to answer the following questions: (a) What is the relationship between animal species composition, species noise vulnerability, and anthropogenic noises among the three management zones? (b) Does management zone determine the amount and type of anthropogenic noises? and (c) How does management zone influence the soundscape structure and composition? The findings can help determine whether management zones are a good strategy for protecting the natural acoustic space and contribute to explaining the effect of anthropogenic noise intrusion on protected areas in general.

**Table 1.** Protected Management Areas in EYNF Delimited by Most Recent Management Plan (USDA FS, 2018b), and Management Zones Created to Evaluate the Soundscape and Noise Intrusion.

| EYNF delimited management areas (2018) | | Management zones |
|---|---|---|
| 1 | El Toro Wilderness | Protected |
| 2 | Research | Protected |
| 3 | Baño de Oro Research Natural Area | Protected |
| 4 | Administrative Management Area | Recreational |
| 5 | El Yunque Recreation Zone | Recreational |
| 6 | Communication and Recreation | Recreational |
| 7 | Wild and Scenic Rivers | Recreational |
| 8 | Scenic Byway Management Area (Puerto Rico Route 186) | Recreational |
| 9 | Community Interface Resource Management Area | Buffer |

*Note.* EYNF = El Yunque National Forest.

## Methods

### Study Area

The study was conducted in EYNF located in northeast Puerto Rico. EYNF mainly includes old secondary growth forests (>80 years). Vegetation or altitudinal zonation in the EYNF includes tabonuco forest, dominated by *Dacryodes excelsa* and located between 150 and 600 m a.s.l.; palo colorado forest dominated by *Cyrilla racemiflora*, between 600 and 950 m a.s.l; elfin forest dominated by *Eugenia borinquensis* and *Tabebuia rigida*, which occurs above 950 m; and patches of sierra palm forest, dominated by *Prestoea montana*, occurring across the entire elevational gradient (Harris, Lugo, Brown, & Heartsill-Scalley, 2012). EYNF is the most extensive protected area in Puerto Rico (115 $km^2$) covering 8.3% of the island. It is administered by the USDA FS (2018b).

### Soundscape Recording

I evaluated the soundscape structure and frequency composition in three management zones created for this study by combining the nine management areas delineated in EYNF Lands Resource Management Plan (USDA FS, 2018b). All three management zones had similar human intervention levels (Table 1).

1. *Protected*: Wilderness and research areas with no or little human intervention. These areas are located away from main roads but include some trails where recreational use is low, with approximately 1,000 visitors per year (less than 0.5% of total visitors in EYNF; USDA FS, 2018b). In this zone, sites were distributed at a mean elevation of 798 m a.s.l. The dominant forest types around the sites (i.e., within a 50 m radius) were palo colorado ($n=8$), elfin ($n=4$), tabonuco ($n=2$), and sierra palm ($n=1$).
2. *Recreational*: This zone includes wild scenic recreation river corridors, El Yunque recreational zone, and El Verde scenic byway management area. These areas include diverse recreational uses, with moderate to high human intervention. Depending on the season, the number of cars in the zone varies between 300 and 1,400, and the number of visitors between 700 and 3,500 per day (USDA FS, 2018b). The mean elevation in this area was 325 m a.s.l, and land cover around the sample points was dominated by tabonuco forest ($n=13$), young secondary forest ($n=1$), and palo colorado forest ($n=1$).
3. *Buffer management zone*: This zone includes areas around EYNF, with moderate to high levels of human intervention and use. This zone is a transition between protected and private lands. Human activity within this zone is variable; the northern buffer part has much more human activity (i.e., visitors) than the southern part (USDA FS, 2018b). The mean elevation in this zone was 233 m a.s.l. Land cover around the sample points was dominated by tabonuco forest ($n=7$), grasslands ($n=4$), mature secondary forest ($n=2$), and young secondary forest ($n=2$).

To select sites, I used the forest plan management areas map (USDA FS, 2018b). I selected 60 potential sample sites using Google Earth. I visited all 60 sites to confirm the management zone classification and its suitability for the study. Finally, within each management zone, I selected 15 sites for a total of 45 sampling locations (Figure 1). I used roads, trails, and recreational and administrative facilities to access the sites. All sites were in forested areas. In the protected area, sites were located far from the roads (411 m on average). Sites in the recreational zone were selected in areas used by visitors, near rivers, camping zones, hiking trails, or scenic byways; therefore, sites were on average closer to roads (62 m). In the buffer zone, sampling sites were primarily located near the roads (80 m on average).

Each sample site was visited during the wet season between March and June 2016. I sampled the soundscape using passive acoustic monitoring devices, which consist of an Android smartphone enclosed in a waterproof case, and an external Monoprice microphone, with flat response between 50 Hz and 20 kHz and a sensitivity of $-45$ dB $\pm$ 2 dB. Each recorder was placed in the forest and attached to a tree trunk at approximately 1.5 m above the ground. I used the ARBIMON Touch application (https://goo.gl/CbBavY) to program the recording device to sample for 1 min at 10-min intervals per 24 h, for a total of 144 recordings per day at a sampling rate of 44.1 kHz. Recorders sampled for 4 consecutive days. All recordings were stored, processed, and analyzed using the ARBIMON II platform (https://arbimon.sieve-analytics.com/).

### Animal Biodiversity and Soundscape Analysis

To determine whether animal biodiversity and soundscapes varied among the different management zones, I used three comparative approaches: (a) species composition, (b) soundscape composition, and (c) acoustic space use (ASU) and soundscape structure.

*Species composition and species noise vulnerability.* To assess for differences in species richness and composition among the management zones, I examined the three taxa of insects, amphibians, and birds at each site. I visually inspected the sonograms of a subsample of 48 recordings (12 per day $\times$ 4 days) per site (for a total of 2,160 one-min recordings). I counted the total species

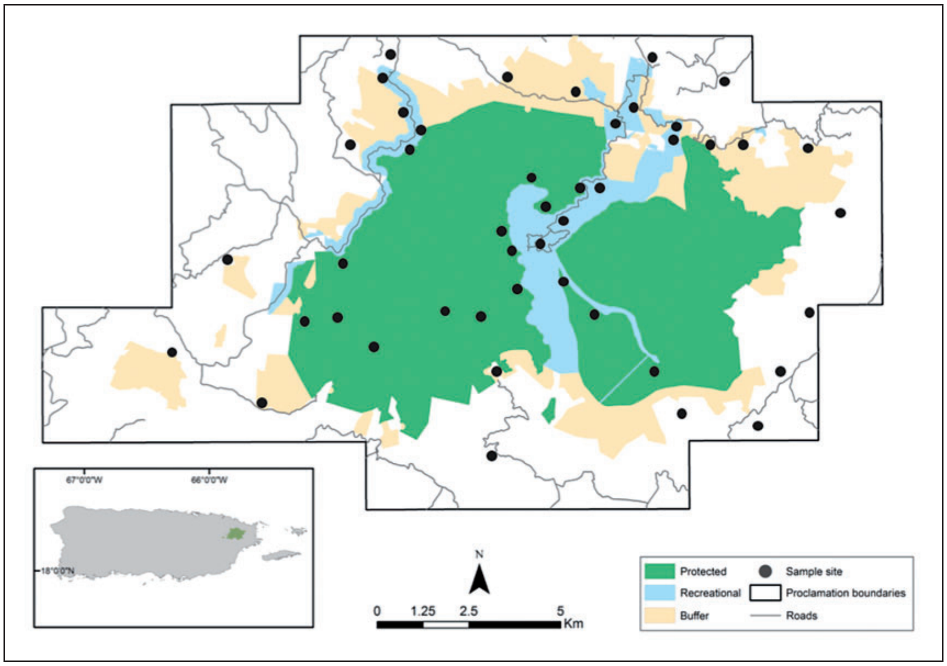


**Figure 1.** El Yunque National Forest study area. Location of sample sites is depicted. Different colors represent the management zones.

richness per site, and species occurrence by management zone, which was calculated as the number of sites where a species was detected within each zone (Table 2). I compared the species richness and species occurrence frequency per management zone using one-way analysis of variance (ANOVA) and a posterior Tukey post hoc comparison. For each species, I determined the minimum and maximum frequency of the call (kHz), and time of day of maximum activity, as variables to classify species into low, intermediate, and high vulnerability to anthropogenic noise (Table 2). High-risk species vocalized during the day and had calls below 5 kHz, which corresponds to the frequency range occupied by most anthropogenic noises. A species was classified as intermediate risk if it had one of the two criteria and low risk if it did not meet either criterion.

*Soundscape composition.* To determine sound sources composing the soundscape, I used the ARBIMON II Soundscape Composition tool to categorize sounds into geophony, biophony, or anthrophony. For each site, I visually inspected 24 one-min recordings per day for 4 days, for a total of 4,320 recordings across the 45 sites. In each recording, I registered *presence* (1) or *absence* (0) into the three main categories and 11 subcategories, as follows: anthrophony: aerial transportation, terrestrial transportation, machine, and humans sounds; biophony: insects, amphibians, birds, and domestic animals; and geophony: wind, rain, and moving water. These data were used to determine the frequency of occurrence in each sound type per site, calculated as the sum of presences divided by 4, which corresponded to the number of evaluated days. I compared occurrence frequency across management zones using a one-way ANOVA and a posterior Tukey post hoc comparison.

*ASU and soundscape structure.* To determine ASU at each site, I used the ARBIMON II Soundscape tool. With this tool, the user defines a group of recordings, time of aggregation (e.g., hour of day), frequency bin size, minimum threshold for the amplitude of a peak, and minimum distance in frequency (Hz) between peaks (Aide et al., 2017; Deichmann et al., 2017). I aggregated recordings according to the hour of day and used a frequency bin size of 172 Hz, with a peak filtering amplitude of 0.01, and 0 Hz for distance between peaks, to generate a three-dimensional matrix of ASU. In addition, I normalized the soundscapes, to control for the number of recordings collected at each site during each hour (Aide et al., 2017; Deichmann et al., 2017). The soundscape matrix data were used to determine the percentage of ASU, calculated as the number of frequency bins with activity greater than the amplitude threshold ($>0.01$) divided by the total number of bins in a day (24 h $\times$ 128 frequency bins $=$ 3,072 bins) times 100. I compared the percentage of ASU among the three management zones using an ANOVA.

The soundscape structure is an analysis of the frequency bins with activity greater than the amplitude threshold ($>0.01$). This can help distinguish the distribution of frequencies due to anthropogenic, abiotic, and biotic sources at each site. To determine whether the

**Table 2.** Species Name, Common Name, and Species Occurrence of Insects (Morphospecies), Amphibians, and Birds Detected in Three Different Management Zones at El Yunque National Forest.

| Species I morphospecies | English common name | Species occurrence (%) | | | Minimum–maximum call frequency (kHz) | Activity | Risk |
|---|---|---|---|---|---|---|---|
| | | Protected | Recreational | Buffer | | | |
| Insects | | | | | | | |
| M1 | | 0.9 | 1 | 1 | 4.5–5.0 | N | I |
| M2 | | 0.9 | 1 | 1 | 5.0–5.5 | N | L |
| M3 | | 0.9 | 0.9 | 0.9 | 6.0–6.5 | N | L |
| M4 | | 0.7 | 0.9 | 0.9 | 3.2–4.0 | N | I |
| M6 | | 0.3 | 0.8 | 0.9 | 6.0–6.7 | N | L |
| M7 | | 0.3 | 0.5 | 0.9 | 6.2–10.5 | N | L |
| M5 | | 0.7 | 0.9 | 0.8 | 3.6–4.2 | N | I |
| M8 | | 0.3 | 0.6 | 0.7 | 4.8–5.1 | N | I |
| M10 | | 0.2 | 0.7 | 0.7 | 17.5–19.0 | N | L |
| M12 | | 0.2 | 0.5 | 0.7 | 7.5–17.4 | N | L |
| M9 | | | 0.4 | 0.6 | 8.0–16.5 | N | L |
| M11 | | | 0.3 | 0.2 | 0.2–1.2 | N | I |
| M15 | | | 0.1 | 0.1 | 6.9–8.0 | N | L |
| M14 | | 0.7 | 0.1 | 0.1 | 12.5–21.5 | N | L |
| M13 | | 0.1 | 0.2 | 0.1 | 15.7–16.7 | N | L |
| M17 | | | | 0.1 | 5.0–12.0 | N | L |
| M16 | | 0.2 | | | 10.0–18.0 | N | L |
| Total species | | 13 | 15 | 16 | | | |
| Amphibians | | | | | | | |
| *Eleutherodactylus coqui* | Common coqui | 1 | 1 | 1 | 1.1–2.3 (1000 m)°<br>1.4–3.3 (100 m) | N–D | H |
| *Eleutherodactylus brittoni*[a,b] | Grass coqui | 0.3 | 0.6 | 0.7 | 3.6–6.0 | N–D | H |
| *Leptodactylus albilabris*[a] | White-lipped frog | 0.1 | 0.3 | 0.3 | 1.7–2.5 | N–D | H |
| *Eleutherodactylus antillensis* | Red-eye coqui | | 0.2 | 0.3 | 1.8–3.4 | N–D | H |
| *Eleutherodactylus cochranae* | Cochran's coqui | | | 0.3 | 3.7–4.8 | N | I |
| *Eleutherodactylus hedrickii*[a,b,c] | Hedrick's coqui | 0.5 | 0.3 | 0.1 | 2.9–3.4 | N | I |
| *Eleutherodactylus wightmanae*[a,b,c] | Melodius coqui | 0.1 | 0.1 | 0.1 | 2.2–4.0 | N | I |
| *Rinella marina* | Cane toad | | 0.1 | | 0.5–0.9 | N | I |
| *Eleutherodactylus portoricensis*[a,b,c] | Upland coqui | 0.8 | 0.1 | | 1.5–2.9 | N–D | H |
| *Eleutherodactylus unicolor** + [a] | Dwarf coqui | 0.9 | | | 3.0–4.5 | N–D | H |
| *Eleutherodactylus gryllus*[a,b,c] | Cricket coqui | 0.3 | | | 6.7–8.0 | N | L |
| *Eleutherodactylus locustus** + [a] | Locust coqui | 0.1 | | | 4.5–5.3 | N | I |
| *Eleutherodactylus richmondi*[a,b,c] | Richmond's coqui | 0.1 | | | 3.0–5.0 | N | I |
| Total species | | 10 | 8 | 7 | | | |
| Birds | | | | | | | |
| *Coereba flaveola* | Bananaquit | 1 | 1 | 1 | 5.0–12.5 | D | L |
| *Vireo altiloquus* | Black-whiskered vireo | 0.3 | 0.9 | 1 | 1.8–5.2 | D | H |
| *Coccyzus vielloti*[a] | Puerto Rican lizard-cuckoo | 0.4 | 0.7 | 0.9 | 0.5–3.7 | D | H |
| *Margarops fuscatus* | Pearly-eyed thrasher | 0.5 | 0.9 | 0.9 | 3.7–12.6 | D | H |
| *Patagioenas squamosa* | Scaly-naped pigeon | 0.8 | 0.8 | 0.9 | 0.3–0.7 | D | H |
| *Melanerpes portoricensis*[a] | Puerto Rican woodpecker | 0.5 | 0.7 | 0.9 | 0.7–2.3 | D | H |
| *Nesospingus especuliferus*[a] | Puerto Rican tanager | 1 | 1 | 0.9 | 5.3–13.5 | D | L |
| *Loxigilla portoricensis*[a] | Puerto Rican bullfinch | 1 | 1 | 0.8 | 1.5–10.7 | D | H |
| *Megascops nudipes*[a] | Puerto Rican screech-owl | 0.2 | 0.7 | 0.7 | 0.3–0.7 | N | L |
| *Todus mexicanus*[a] | Puerto Rican tody | 0.5 | 0.5 | 0.7 | 2.5–5.1 | D | H |
| *Tyrannus dominiscenis* | Gray kingbird | 0.1 | 0.1 | 0.6 | 3.7–5.0 | D–N | H |
| *Gallus gallus* | Red junglefowl | | | 0.5 | 0.7–9.5 | D–N | H |
| *Myiarchus antillarum*[a] | Puerto Rican flycatcher | | 0.1 | 0.3 | 3.9–4.7 | D | H |
| *Zenaida asiatica* | White-winged dove | | | 0.3 | 0.5–0.8 | D | H |
| *Spindalis portoricensis*[a] | Puerto Rican stripe-headed tanager | 0.9 | 0.1 | 0.3 | 7.2–11.4 | D | L |

(continued)

**Table 2.** Continued

| Species I morphospecies | English common name | Species occurrence (%) | | | Minimum–maximum call frequency (kHz) | Activity | Risk |
|---|---|---|---|---|---|---|---|
| | | Protected | Recreational | Buffer | | | |
| *Turdus plumbeus* | Red-legged thrush | | 0.5 | 0.3 | 1.8–12.2 | D | H |
| *Pavo ciristatus* | Common peafowl | | | 0.1 | 0.3–9.6 | D | H |
| *Zenaida aurita* | Zenaida dove | | | 0.1 | 0.4–0.7 | D | H |
| *Amazona vittata*[a,c] | Puerto Rican amazon | 0.1 | | 0.1 | 0.7–10.9 | D | H |
| *Euphonia musica* | Antillean euphonia | 0.1 | 0.1 | 0.1 | 3.1–4.8 | D | H |
| *Geotrygon montana* | Ruddy quail-dove | 0.1 | | | 0.3–0.7 | D | H |
| *Sethophaga angelae*[a,c] | Elfin woods warbler | 0.5 | | | 5.6–9.9 | D | L |
| Total species | | 16 | 15 | 20 | | | |
| Total | | 39 | 38 | 43 | | | |

*Note*. Species occurrence, expressed as a proportion (%), was calculated as the number of sites where a species was detected within each management zone ($N = 15$). For each species, the minimum and maximum frequency of the call and time of day of maximum activity were determined, as variables to classify species into low (L), intermediate (I), and high (H) vulnerability to anthropogenic noise (i.e., the range of traffic noise: 0–5 kHz). N = night; D = day.
[a]Endemic. [b]Species of conservation concern. [c]Endangered spp.

three management zones had different soundscape structure (i.e., frequencies composition), I compared data from soundscape matrices using a multivariate ANOVA dissimilarity test (*Adonis*). To establish the ordination of sites according with its soundscape frequency composition, I used a nonmetric multidimensional scaling analysis (NMDS), using Bray–Curtis dissimilarity distance, and 20 permutations, using the function *metaMDS*. In addition, I used the function *envfit*, to correlate environmental variables (elevation, land cover, distance to road, and distance to houses), animal variables (species richness and species occurrence for amphibians, birds, and insects), and soundscape composition variables (geophony, biophony, and anthrophony). The 36 significant variables ($p < .05$; Appendix A) where overlaid on the ordination for a better understanding of the NMDS variables. I used the Vegan package for all multivariate analysis. All statistical analyses were conducted in R (R version 3.3.2).

## Results

### Species Composition and Species Noise Vulnerability

A total of 17 insect morphospecies, 13 amphibian species, and 22 bird species were identified in the recordings, and species richness differed among the management zones (Figure 2 and Table 2). Insect species richness was highest in buffer areas (mean $= 9.733 \pm 2.186$ standard deviation [*SD*]) followed by recreational sites (mean $= 8.8 \pm 2.512$ *SD*) and protected areas (mean $= 6.133 \pm 2.133$ *SD*; $F = 10.4$, $p < .000$). Bird richness also differed among management zones ($F = 9.448$, $p < .001$). Protected areas had fewer bird species (mean $= 8 \pm 2.535$) than recreational (mean $= 9 \pm 1.772$ *SD*) and buffer areas (mean $= 11.4 \pm 2.229$ *SD*). Amphibian species richness also differed among management zones, with the highest number in protected areas (mean $= 4.066 \pm 1.437$ *SD*), followed by buffer areas (mean $= 2.933 \pm 1.032$ *SD*) and recreational (mean $= 2.666 \pm 1.046$ *SD*; Figure 2).

Eighteen (18) species were considered as having low vulnerability, 11 intermediate, and 23 high vulnerability based on the noise vulnerability classification. All three management zones had a similar distribution of vulnerability for insects, amphibians, and birds (Table 3). Overall, birds had the most species (77%) classified into the high vulnerability category, while 46% of amphibian species were included in this category.

### Soundscape Composition

I detected differences in the soundscape categories between management zones. Some frequencies of occurrence for anthrophony sounds were lower in protected areas when compared with other management zones ($F = 5.201$, $p < .001$). Specifically, human sound frequency differed between protected and recreational areas ($F = 3.849$, $p = .029$), while frequency for terrestrial transportation sounds in protected areas was lower than recorded for recreational and buffer areas ($F = 4.085$, $p = .023$). Geophony also differed among the management zones ($F = 2.36$, $p = .021$). Particularly, wind frequency was different ($F = 3.393$, $p = .043$) between protected and recreational areas (Figure 3) but not for buffer areas. Other geophony sounds (rain and water) did not differ among management types. Differences for biophony between management types were recorded for all three taxa ($F = 143.7$, $p < .001$). Presence of domestic animals was higher in buffer areas ($F = 12.61$, $p < .001$) when compared with protected and recreational areas, where presence was rare. Amphibian sounds occurred more frequently in protected than recreational areas ($F = 3.79$, $p = .03$),

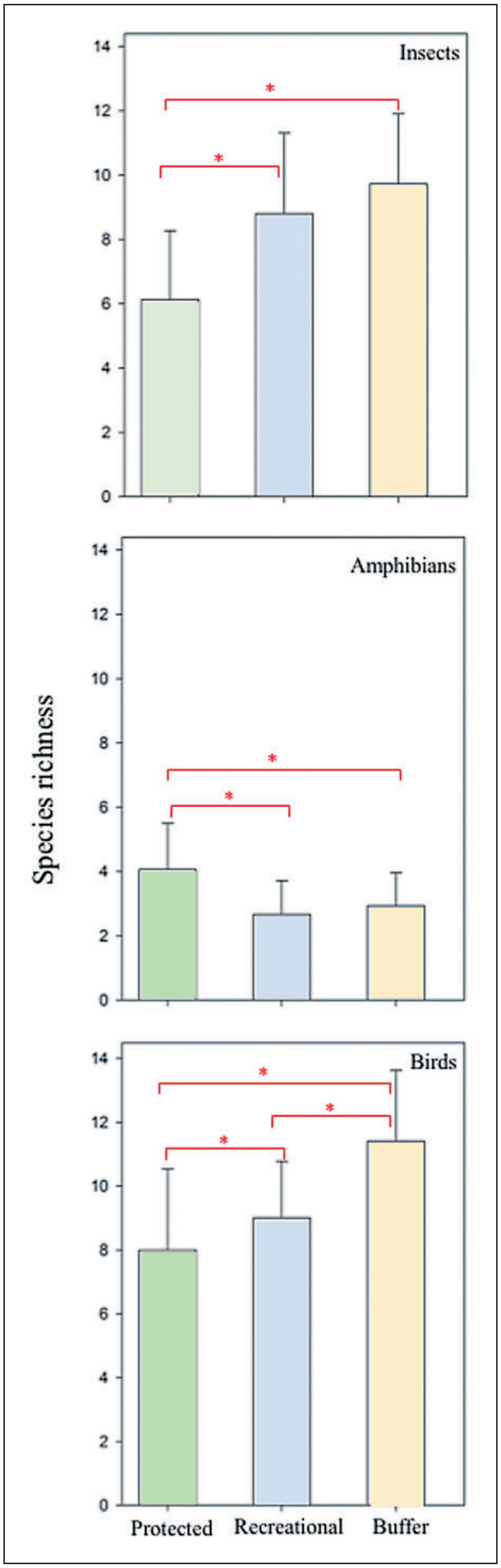


**Figure 2.** Species richness of insects, amphibians, and birds detected in three management zones at EYNF. Asterisks represent significant differences in species richness between management zones.

but no differences were detected when compared with buffer areas. Bird sounds was higher in the buffer zone (mean $= 0.517 \pm 0.06$ *SD*) than in the protected area (mean $= 0.478 \pm 0.08$ *SD*), but there was no difference detected for recreational areas ($F = 2.61$, $p = .06$; Figure 3).

### ASU and Soundscape Structure

I obtained a total of 51,200 one-min recordings: 15,176 in protected areas, 18,646 in recreational areas, and 17,378 in buffer areas. Visual representations of soundscapes from each management zone showed a lower abundance of sounds in protected areas compared with recreational and buffer areas, which showed similar patterns (Figure 4). Most of the acoustic activity occurred below 10 kHz, except in buffer areas where it reached up to 15 kHz. Higher frequencies in buffer areas were mainly associated with some insect groups (morphs 9, 10, and 11; Figure 4 and Table 2). In general, there was a nightly peak activity from 18:00 h to 06:00 h. During this period, frequencies were primarily below 5 kHz and related to insect and frogs calls, in particular the common coqui (*Eleutherodactylus coqui*), a generalist species present in all management zones. In protected areas, calling activity during the night was lower compared with recreational and buffer areas. However, protected areas had a unique peak around 3 kHz associated to the Dwarf coqui call (*Eleutherodactylus unicolor*), an acoustically conspicuous species restricted to these areas. During the day, between 07:00 h and 17:00 h, calling activity decreased in strictly protected areas, but some calling activity of *E. unicolor* were detected. In contrast, recreational and buffer areas had evident acoustic activity during the day between 2 and 3.5 kHz, mainly due to a few species of birds, for example, black-whiskered vireo, *Vireo altiloquus* and a few frog species, for example, common coqui (*E. coqui*) vocalizations (Figure 4 and Table 2).

There was no significant difference in ASU among management zones ($F = 2.43$, $p = .10$; Figure 5), but the distribution of frequencies (frequency composition) was different among them ($F = 6.29$, $p = .01$; Figure 6). These differences in soundscape frequency composition among the management zones were visualized in the NMDS ordination (stress= 0.17380; Figure 6). Almost 50% of the variance in the NMDS was explained by the first axis and mainly separated protected areas from recreational and buffer areas. Protected areas distribution in the multidimensional space was correlated with high elevation ($p = .001$) and less use of the acoustic space (ASU; $p = .001$). High levels of anthropogenic noise supported segregation of recreational and buffer sites from the protected sites. The second axis in the ordination explained 21.7% of the variance and contributed to separate

**Table 3.** Noise Vulnerability Classification for the Detected Species in El Yunque National Forest.

| | Protected | | | | Recreational | | | | Buffer | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Insect | Amphibian | Bird | Total | Insects | Amphibian | Bird | Total | Insects | Amphibian | Bird | Total |
| Low | 10 | 1 | 5 | 16 | 11 | 0 | 4 | 15 | 12 | 0 | 4 | 16 |
| Middle | 3 | 4 | 0 | 7 | 4 | 3 | 0 | 7 | 4 | 3 | 0 | 7 |
| High | 0 | 5 | 11 | 16 | 0 | 5 | 11 | 16 | 0 | 4 | 16 | 20 |
| Total | 13 | 10 | 16 | 39 | 15 | 8 | 15 | 38 | 16 | 7 | 20 | 43 |

*Note*. Information is provided by animal group in three management zones.

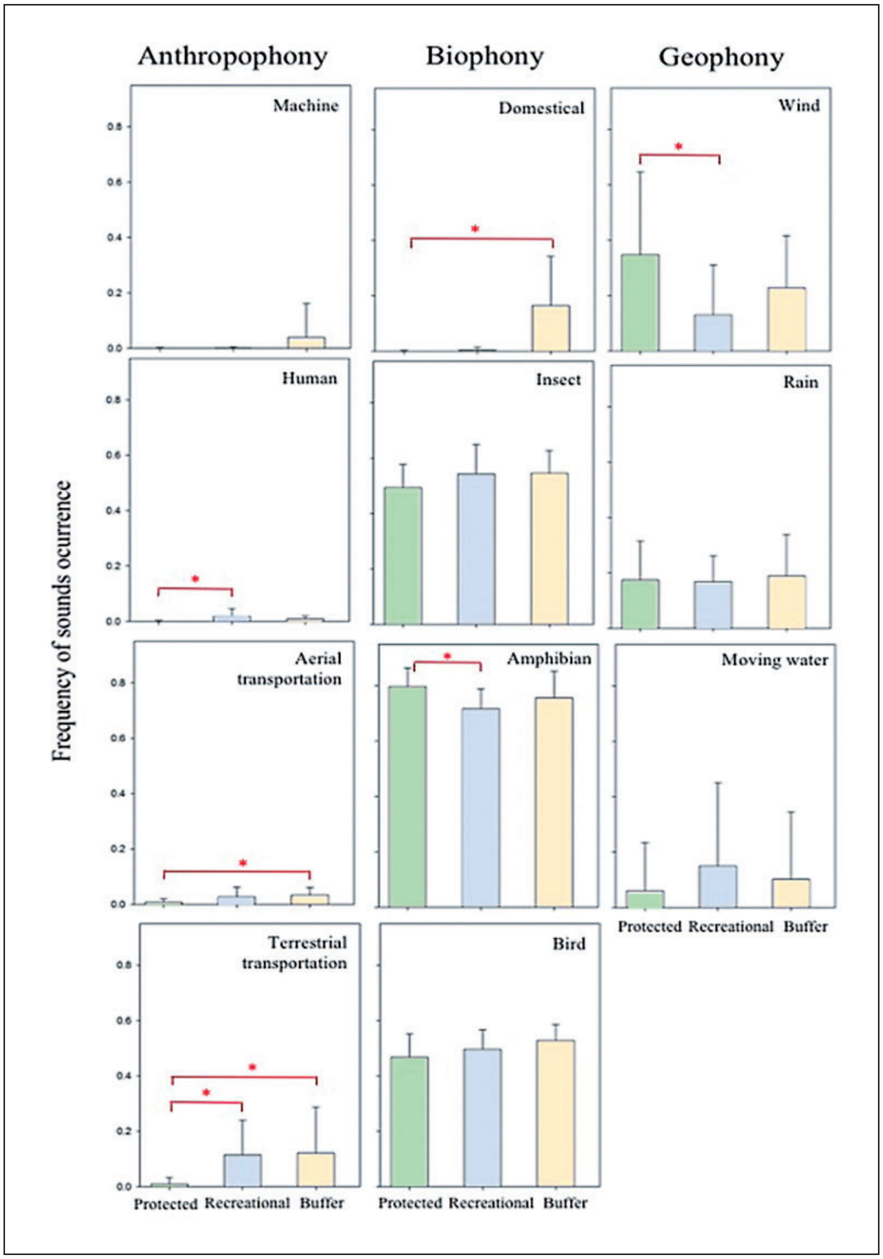


**Figure 3.** Soundscape composition for the three management zones. Sounds are classified by source: anthropophony, biophony, and geophony. Sound occurrence frequency per site was calculated as the sum of presences divided by four. Asterisks represent significant differences in the frequency of sound occurrence between management zones.

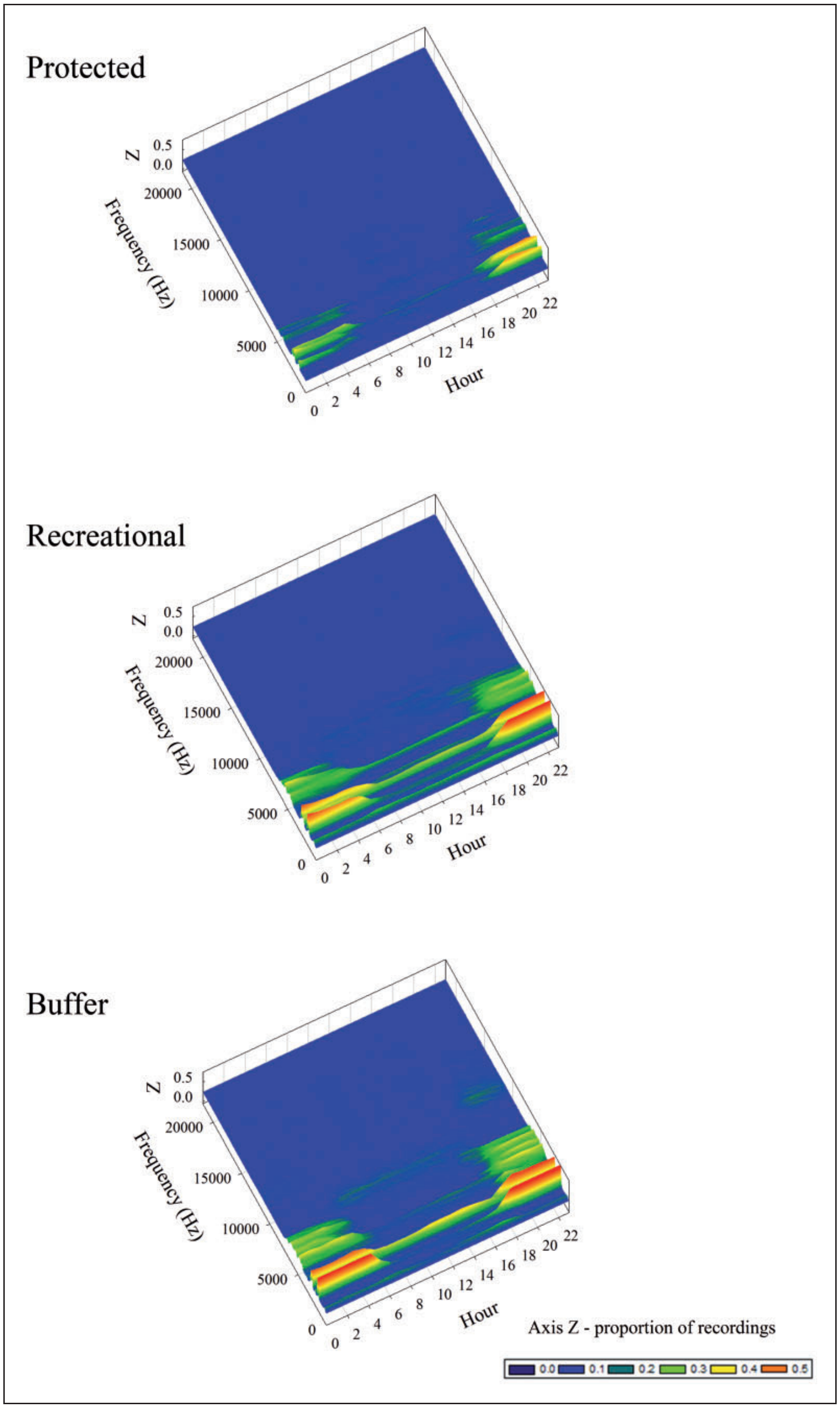


**Figure 4.** Visual representations of acoustic space use (ASU) from the three-management zones in the EYNF. The axes represent hour (*x*), frequency (*y*), and proportion of observations (*z*). The figure includes 3,072 time/frequency bins (24 h × 128 frequency bins). ASU was calculated by summing the number of time/frequency bins that were occupied.

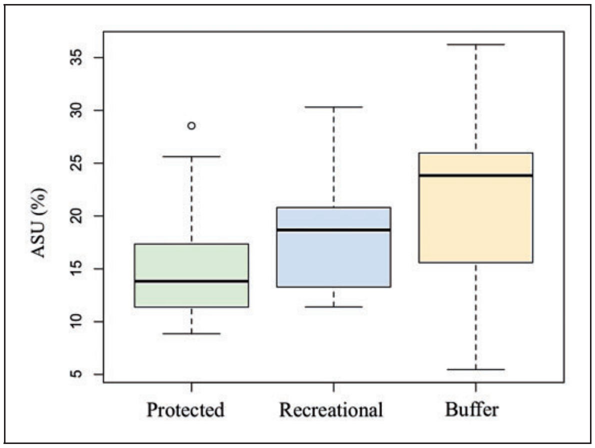


**Figure 5.** Percentage of ASU by protected area zoning in EYNF (ANOVA: $F = 2.43$, $p = .10$). Box plots illustrate the median (horizontal line within the box), 25 to 75th percentiles (the box), 10 to 90th percentiles (*T*-bar), and the values greater than the 10 to 90th percentiles (the points). ASU = acoustic space use.

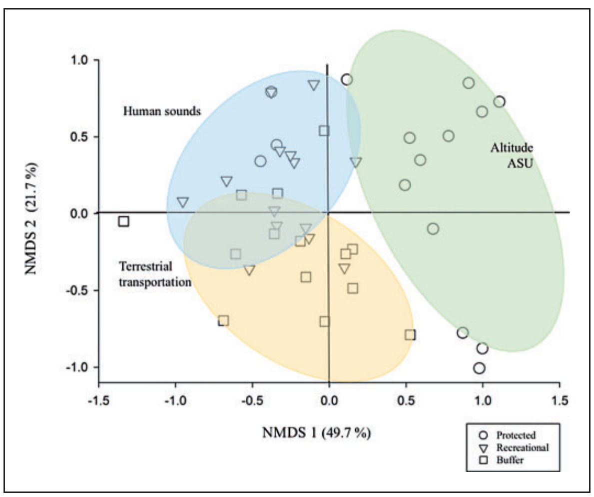


**Figure 6.** NMDS ordination of sites in EYNF for different management zones. Orientation was based on the composition of the time/frequency bins from the soundscape analysis. The variables shown in the figure were the most important separating sites along axis 1 and 2. ASU = acoustic space use; NMDS = nonmetric multidimensional scaling analysis.

recreational and buffer areas, based on the presence of human sounds ($p = .048$) and terrestrial transportation sounds ($p = .020$; Figure 6, Appendix A).

## Discussion

Anthropogenic noise is a serious problem for many protected areas (Buxton et al., 2017; Francis et al., 2017), as it can have detrimental effects on natural soundscapes (Arévalo & Blau, 2018; Kaiser et al., 2011; Krause et al., 2011; Sun & Narins, 2005), biodiversity (Shannon, Angeloni, Wittemyer, Fristrup, & Crooks, 2014), and visitor experience (Iglesias-Merchan, Diaz-Balteiro, & Soliño, 2014; Manning, Newman, Fristrup, Stack, & Pilcher, 2010). Despite these adverse effects, there is a lack of legislation and monitoring of sounds levels and noise intrusion in protected areas (Arévalo & Blau, 2018; Burivalova et al., 2018; Krause et al., 2011, Shannon et al., 2016). The results of this study provide evidence of how PAZ can be implemented as a valuable strategy to minimize noise intrusion and how the type of zoning influences the soundscape composition and determines the amount and type of anthropogenic noises that occur. For example, recreational and buffer areas had high levels of noise intrusion and, contrary to expected, higher species richness. However, many of the species in the recreational and buffer areas classified as highly vulnerable to noise, in comparison to the strictly protected areas in which noises were practically absent.

These findings are similar to those obtained from a recent broad analysis for U.S. protected areas, in which buffer zones had high-noise levels (dB; Buxton et al., 2017). In EYNF, noise presence in buffer zones can be directly related to the elevated level of residential development (Castro-Prieto et al., 2017), and the high and continuous movement of visitors accessing the forest by the main roads (Puerto Rico Routes 191, 186, 988, and 9966; Blauvelt, Breindel, Molinski, & Tetreault, 2008). The presence of anthropogenic noise is also evident in the recreational areas, mainly from vehicle traffic, and to a lesser extent from human voices and music. The noise intrusion in recreational areas is a common problem, particularly in sites with high numbers of visitors (Iglesias-Merchan et al., 2014, Manning et al., 2010), which in some cases exceed the recreation capacity, such as EYNF (Blauvelt et al., 2008). An abundance of visitors crowding narrow trails and flocking to popular areas produces high levels of social encounters, similar to those reported in urban areas (USDA FS, 2018b). Anthropogenic noise levels from tourist activities in EYNF exceed by up to 73% the standards recommended (i.e., 45 dB) for natural areas by the Junta de Calidad Ambiental de Puerto Rico (2008, cited by Blauvelt et al., 2008). However, despite the high levels of visitors and the associated anthropogenic noise, EYNF does not have noise regulations. From the perspective of some visitors, noise pollution in EYNF is a critical issue that needs to be addressed, because the sounds occurring in the area interfere with the natural quiet, limiting their park enjoyment (Blauvelt et al., 2008; USDA FS, 2018b).

Habitat disturbance, such as those caused by noise pollution, represents a threat to biodiversity because species persistence at local scales is determined by species–habitat interactions. In addition, not all species respond equally to habitat transformations. For example, endemic and endangered species, due to restricted distribution and small populations, tend to be more sensitive to disturbances, in contrast to introduced and generalist species (i.e., species common in all habitat types) which show high plasticity, taking advantage of anthropogenic habitat modifications (Francis, Ortega, & Cruz, 2009; A. Herrera-Montes & Brokaw, 2010; Suarez-Rubio & Thomlinson, 2009). This study reports different patterns in species composition among the three management zones observed, suggesting a relationship between the level of habitat disturbance and species presence. In protected areas, characterized by low habitat disturbance and minimal anthropogenic noises, there were a high number of endemic and endangered species, while non-native species were not detected. In buffer areas, which are transition zones with low protection levels, multiple uses, exhibited various levels of forest transformation pattern, and high anthropogenic noise levels, there was high species richness, but more than 50% of those corresponded to generalists (e.g., common coqui, and Bananaquit) species, common species using open or highly transformed habitats (e.g., Grass coqui, Gray kingbird), or introduced species (e.g., common peafowl and red junglefowl). In recreational areas, which perform the dual roles of protecting flora and fauna and provision natural experiences for visitors, and where forest transformation is moderated and mainly associated with recreational and trails areas that exhibit high levels of anthropogenic noises (e.g., transportation, human voices, and music), I detected high species richness. Species present in these areas included some generalist associated with disturbed areas (e.g., red-eye coqui, grass coqui, red-legged thrush, gray kingbird) and one exotic species (cane toad), suggesting that habitat transformation related with recreational activities could be promoting the presence of these particular species. Therefore, both the type and intensity of habitat transformation could be important factors that influence differences in soundscape composition and species diversity among management zones in EYNF.

Although anthropogenic activities are suggested as a main factor determining species richness and ASU in EYNF, elevation is also a critical factor that needs to be considered. The elevation gradient in EYNF is steep and rises from 100 to 1,074 m a.s.l in less than 8 km. This gradient promotes shifts in some abiotic parameters (e.g., temperature, humidity, and rain) which directly influence plant and animal diversity and their distribution (Campos-Cerqueira & Aide, 2017b; Campos-Cerqueira, Arendt, Wunderle, & Aide, 2017; Weaver & Gould, 2013; Wolda, 1987) and also affects changes in soundscape structure (Campos-Cerqueira & Aide, 2017a; Narins & Zelick, 1988). In this study, the protected areas evaluated were above 500 m, while recreational and buffer areas were all below this elevation. I observed that amphibian species richness was higher in protected areas, and the amphibian community was mainly composed of species associated with high elevations, such as the upland coqui *(Eleutherodactylus portorricensis*), the dwarf coqui (*E. unicolor*), and the cricket coqui (*Eleutherodactylus gryllus*; Table 2). In contrast, insect morphospecies richness was lower in protected areas, where suggesting elevation-associated factors such as low temperature and less oxygen availability may have imposed physiological constraints and limited insect distribution and presence (Dillon, Frazier, & Dudley, 2006).

Insects, amphibians, and birds are key groups structuring the acoustic space (Aide et al, 2017, Campos-Cerqueira & Aide, 2017b), but they are also extremely susceptible to noise disturbances (Costello & Symes, 2014; Lampe, Reinhold, & Schmoll, 2013; McClure, Ware., Carlisle, Kaltenecker, & Barber, 2013; Morley, Jones, & Radford, 2014; Narins, 1982; Simmons & Narins, 2018). Based on the noise intrusion susceptibility for these groups, I proposed a noise vulnerability classification according to the range of species call frequency and time of species vocalization. I anticipated that fewer species would be highly vulnerable to noise in recreational and buffer areas, in comparison to species occupying protected areas, because highly vulnerable species would tend to leave the noisy areas (M. I. Herrera-Montes & Aide, 2011; Joo et al., 2011). Likewise, staying in noisy areas would reduce their reproductive success (Halfwerk, Holleman, Lessells, & Slabbekoorn, 2011; Injaian, Taff, & Patricelli, 2018), leading to their eventual disappearance from noisy areas. However, I found more species highly vulnerable to noise, birds in particular, in the buffer and recreational areas compared with the protected areas. Interestingly, 41% of bird species categorized as highly vulnerable have calls with a broad frequency range beyond 5 kHz. Hence, their calls minimally overlap with the noise sources. Some of the highly vulnerable species are generalists with a wide distribution throughout Puerto Rico. Furthermore, generalist species tend to be more resilient and adaptable to disturbances and can adapt their vocalizations to noisy environments, especially if the level of noise is intermediate or low (i.e., human voices, music; Patón, Romero, Cuenca, & Escudero, 2012). Nevertheless, although some species can persist in noisy areas, their reproductive success may be compromised by noise-induced stress, threatening their long-term stability, and persistence in noisier environments (Kleist, Guralnick, Cruz, Lowry, & Francis, 2018). The proposed noise vulnerability classification may be useful for determining which species are at risk due to noise pollution. This classification can be improved by including other variables, which would provide more valuable information for managers and planners not only in protected areas but also in other land use types around the island.

Monitoring the entire soundscape by using passive acoustic monitoring and the soundscape analysis tools is a cost-effective method way that allows simultaneously sampling of multiple sites, all-day long for extended time periods, and provides enough information to better understand the sound and biodiversity dynamics (Aide et al., 2017; Deichmann et al., 2018; Farina et al., 2014).

In addition to the soundscape monitoring, research on species noise response and species population status and dynamics in noisy areas is highly recommended. Monitoring information could be used to develop noise propagation models (e.g., SpreaAD-GIS and CadnaA; Barber et al., 2011). Propagation models allow establishing the proportion of protected area affected by anthropogenic noises. These models use detailed and specific information about environmental (e.g., slope, temperature, wind, vegetation density) and noise characteristics (e.g., type of source, distance, periodicity, prevalence). In EYNF, this information could be complemented with monitoring of maximum vehicle capacity and visitor movements within the forest area to minimize the impact of recreational activities on biodiversity and natural quiet environments (USDA FS, 2018b)

## Implications for Conservation

Anthropogenic noise intrusion is almost impossible to eliminate within protected areas regardless the type of management applied (Buxton et al., 2017; Francis et al., 2017); therefore, suitable noise control strategies are necessary to maintain the protected area integrity and preserve the biodiversity. An important first step is to implement noise monitoring programs to understanding temporal and spatial dynamics of noise and its effects on biodiversity across the entire protected area. Using tools like automated acoustic monitoring, large areas can be evaluated, minimizing the costs of a long-term noise monitoring program, and providing valuable information to generate suitable noise control strategies. Implementing the noise vulnerability classification system for the species in protected areas, as proposed in this research, can be useful to determine which species could be at risk and thus be able to generate appropriate strategies to protect them. Moreover, policies such as limiting the number of vehicles in protected areas or closing roads and trails in critical habitats during breeding or nesting season (Patricelli, Blickley, & Hooper, 2013, Shannon et al., 2016) could be of great benefit for many species. In addition, visitor noise control education and awareness should also be implemented, particularly in recreational areas within the interior of protected areas (Iglesias-Merchan et al., 2014). In conclusion, noise pollution analyses should be incorporated into PAZ to ensure the protection and maintenance of biodiversity as well as the natural soundscape.

## Appendix A

**Table A1.** Eigenvalues Coordinates and Statistical Significance of Variables Fitted in the NMDS.

| | NMDS1 (49.7%) | NMDS2 (21.7%) | $r^2$ | Pr(>*r*) |
|---|---|---|---|---|
| Management zone | −.73258 | −.68069 | .4802 | .001*** |
| Environmental variables | | | | |
| Elevation | .79341 | .60869 | .6468 | .001*** |
| MW_Elfin | .93875 | .34459 | .2948 | .002** |
| MW_Palo.Colorado | .93139 | .36402 | .2037 | .009** |
| MW_Sierra.Palm | .84698 | .53163 | .1536 | .029* |
| MW_Tabonuco | −.96030 | −.27898 | .3566 | .001*** |
| Distance road | .96582 | −.25920 | .2942 | .004** |
| Animal variables | | | | |
| Total spp. richness | −.56094 | −.82786 | .1901 | .013* |
| Insects | | | | |
| Insect Mspp. richness | −.72799 | −.68559 | .2232 | .005** |
| Msp 1 | −.78539 | −.61900 | .3143 | .001*** |
| Msp 2 | −.76586 | −.64301 | .5215 | .001*** |
| Msp 3 | −.70535 | −.70886 | .1635 | .028* |
| Msp 6 | −.70199 | −.71218 | .3975 | .001*** |
| Msp 7 | −.45459 | −.89070 | .1527 | .033* |
| Msp 10 | −.96907 | −.24677 | .2044 | .012* |
| Msp 14 | .80491 | .59340 | .2478 | .002** |
| Amphibians | | | | |
| *Eleutherodactylus brittoni* | −.97635 | −.21618 | .2593 | .002** |
| *Eleutherodactylus portoricensis* | .88873 | .45843 | .5886 | .001*** |
| *Eleutherodactylus unicolor* | .93207 | .36227 | .6319 | .001*** |
| *Eleutherodactylus gryllus* | .58434 | .81151 | .1937 | .013* |
| *Eleutherodactylus antillensis* | −.20470 | −.97882 | .1649 | .021* |
| Birds | | | | |
| Birds spp. richness | −.57077 | −.82111 | .2355 | .005** |
| *Coccyzus vielloti* | −.45369 | −.89116 | .2442 | .002** |
| *Loxigilla portoricensis* | .92279 | .38529 | .2101 | .009** |
| *Margarops fuscatus* | −.99992 | −.01231 | .2054 | .010** |
| *Sethophaga angelae* | .98950 | −.14452 | .1798 | .009** |
| *Spindalis portoricensis* | .96158 | .27453 | .2612 | .003** |
| *Tyrannus dominiscenis* | −.21137 | −.97741 | .1379 | .041* |
| *Vireo altiloqus* | −.92804 | −.37247 | .6228 | .001*** |
| Soundscape variables | | | | |
| Acoustic space used | .55589 | −.83126 | .7169 | .001*** |
| Soundscape composition | | | | |
| Aerial transportation | −.75463 | −.65615 | .1560 | .031* |
| Terrestrial transportation | −.84514 | −.53455 | .1678 | .020* |
| Humans noises | −.71807 | .69597 | .1331 | .048* |
| Amphibians | .75924 | .65081 | .1937 | .010** |
| Birds | −.62287 | −.78233 | .1496 | .042* |
| Wind | .28375 | .95890 | .1689 | .025* |

*Note.* NMDS = nonmetric multidimensional scaling analysis.
***0.001; **0.01; *0.05.

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