UNIVERSIDADE ESTADUAL DE SANTA CRUZ
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA E CONSERVAÇÃO DA BIODIVERSIDADE

O que dizem os sons dos animais: influência de perturbações ambientais nas paisagens sonoras

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Ilhéus, Bahia
2022

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Tese apresentada ao Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade da Universidade Estadual de Santa Cruz como parte dos requisitos para obtenção do título de Doutora em Ecologia e Conservação da Biodiversidade.
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2022

G633 Gomes, Lidiane.
O que dizem os sons dos animais: influência de perturbações ambientais nas paisagens sonoras / Lidiane Gomes. – Ilhéus, BA: UESC, 2022.
149f. : il.

Orientador: Júlio Baumgarten
Tese (Doutorado) – Universidade Estadual de Santa Cruz. Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade – PPGECB
Inclui referências.

1. Som produzido por animais. 2. Ruído. 3. Natureza – Influência do homem. 4. Incêndios florestais. 5. Solo – Uso. 6. Monitorização ambiental. 7. Indicadores ambientais. I. Título.

CDD 591.594

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Dedico à minha mãe, Maria Lindomar Gomes,

a minha maior incentivadora para buscar novos desafios

AGRADECIMENTOS

Agradeço a todas as agências de financiamento, a FAPESB pela concessão da bolsa de doutorado e ao CNPq pelo auxílio financeiro de projetos no qual estive envolvida durante o doutorado.

Agradeço aos membros da banca, Larissa Sugai, Marina Duarte, Diego Llusia e Ignacio Gendriz, por aceitarem participar e contribuir com esse trabalho.

Agradeço ao meu orientador Júlio por todo apoio durante os anos de doutorado, pela confiança, pelas correções que melhoraram o trabalho.

Sou muito grata ao meu coorientar Mirco Solé, seu auxílio do primeiro dia até aqui são imensuráveis. Sem dúvida esse trabalho é fruto da sua confiança em me deixar livre para trabalhar e me apoiar quando preciso. Obrigada por ser uma inspiração como pessoa e profissional para todos os seus alunos.

Agradeço a minha coorientadora Renata por sua experiência e todo auxílio em absolutamente tudo relacionado a acústica, de pequenas dúvidas a questões complexas.

Agradeço a todos os meus amigos da UEFS, a minha pró Flora Juncá minha grande incentivadora para tentar doutorado, obrigada por todo acolhimento e ajuda sempre.

Agradeço a todo pessoal da UESC, especialmente as meninas que nos auxiliam com tanta atenção Amábille e Iky, agradeço também a Pavel Dodonov pela sua amizade no tempo que passamos juntos na UESC.

Agradeço ao Laboratório de Herpetologia Tropical, a melhor galera da UESC, obrigada por todos os momentos de risadas e cafés. Agradeço especialmente ao pessoal que estuda Ecologia do Movimento e Ecofisiologia pelas parcerias de trabalho e campo, ainda temos muito trabalho pela frente.

Agradeço a Caio, Fábio e Ícaro por toda ajuda, vocês foram essenciais para construção do nosso terceiro capítulo e identificação das espécies.

Aos meus amigos que passaram todos os perrengues possíveis e inimagináveis nos campos na Chapada Diamantina, Marcelo Sena, Edvaldo Neto, Vinícius Queiroz, Jéssica, Camila, Sidiane e Diana, podemos ficar sem comida agora sem risada jamais.

Agradeço por fazer parte de uma turma de doutorado maravilhosa, agradeço especialmente a esses amigos que tenho certeza que levarei para a vida, Fernando Bonfim, Arthur Bauer e Diego Flores.

Aos amigos que compartilhei a vida durante esses quatro anos de doutorado, Daniela Acosta, Daniela Mejila, Patrícia Gonzales, Erinaira Cardoso, Mariana Campêlo e Esperidião Neto.

Aos amigos de toda a vida, Josieia Teixeira, Juliana Ramos, Ivone Lima, Lívia Sandes, Diego Daltro, Gehisa Henrique e Ldiane Roque, obrigada por estarem comigo sempre.

Agradeço a minha família, minha irmã, meus primos e aos meus tios que são apoio constante na minha vida.

Aos meus pais, Maria Lindomar Gomes e Valdomiro Gomes Maurício, pelo apoio e incentivo em todos os momentos da minha vida, são eles os que mais se alegram com cada conquista, vocês são os melhores exemplos de pessoas que eu poderia me espelhar.

A Jonathan Mucherino, por seu apoio e incentivo incondicional, pelas incontáveis vezes que me ajudou no trabalho, no campo e na vida. Sem dúvida você faz parte de cada detalhe desse trabalho, seja em uma opinião de figura ou em uma revisão super crítica. Obrigada por dividir seu mundo comigo, por tornar meu mundo mais divertido e feliz.

Por último, gostaria de agradecer imensamente a todos os animais que cantaram nas gravações, quando parecia que o trabalho não teria fim foram os áudios cheios de som que me animaram e me embalaram nas madrugadas de trabalho.

Muito obrigada!

Resumo

Os animais utilizam diversos tipos de comunicação para trocar informações, a comunicação acústica é uma modalidade de transferência de mensagens usados por vários grupos de animais, por exemplo, diversos insetos, anfíbios, aves e mamíferos. Através da comunicação acústica os estudos tem adquirido várias informações sobre os animais, principalmente em relação ao comportamento animal. No entanto, os sons gerados pelos animais também podem revelar informações sobre a organização e dinâmica dos ecossistemas. A perturbação ou degradação pode causar mudanças na composição da comunidade, riqueza de espécies ou abundância da fauna vocal, isso resulta em mudanças no ambiente acústico. Devido a possibilidade de utilizar a comunicação acústica em diversos contextos, primeiramente realizamos uma meta-análise para verificar a influência do ruído antrópico para comunicação acústica animal, avaliamos se diferentes grupos de animais possuem um padrão geral para modificar seus parâmetros acústicos, como consequência do mascaramento sonoro causado pelo ruído antropogênico, encontramos que as aves aumentaram os parâmetros acústicos (frequências mínima, máxima e dominante, duração da nota e amplitude do canto). No capítulo dois, foram avaliados os efeitos dos incêndios florestais na paisagem sonora, investigamos as diferenças nos índices acústicos e nos tipos de sons dos locais que foram queimados e não queimados. Os índices acústicos indicaram maior atividade acústica em locais não queimados e a análise manual indicou uma quantidade maior de diferentes sons de aves em áreas não queimadas. Por fim, no capítulo três analisamos se a paisagem sonora refletiu diferenças em uma paisagem com diferentes tipos de exploração humana. Encontramos que os índices acústicos quem medem atividade sonora tiveram valores menores em habitats de plantação de seringal em comparação com habitats de floresta secundária e corte seletivo intenso. Através do nosso estudo verificamos que a comunicação acústica animal e a paisagem sonora refletem mudanças causadas por diferentes tipos de perturbações ambientais, isso mostra o potencial de utilizar os sons para compreensão dos ambientes.

Palavras-chave: Comunicação acústica, Ruído antropogênico, Incêndios, Mudança de uso da terra, Monitoramento acústico passivo, Índices acústicos.

Abstract

Animals use different types of communication to exchange information, acoustic communication is a message transfer modality used by various groups of animals, for example, some insects, amphibians, birds and mammals. Through acoustic communication, studies have acquired various information about animals, especially in relation to animal behavior, however, the sounds generated by animals can also reveal information about the organization and dynamics of ecosystems. Disturbance or degradation can cause changes in community composition, species richness or vocal fauna abundance, resulting in changes in the acoustic environment. Due to the possibility of using acoustic communication in different contexts, we first performed a meta-analysis to verify the influence of anthropic noise on animal acoustic communication. We evaluated whether different groups of animals have a general pattern to modify their acoustic parameters, as a consequence of the sound masking caused by anthropogenic noise, we found that birds increased the acoustic parameters (minimum, maximum and dominant frequencies, note duration and song amplitude). In the chapter two, the effects of wildfires on the soundscape were evaluated, we investigated the differences in the acoustic indices and types of sounds of the places that were burned and unburned. Acoustic indices indicated greater acoustic activity in unburned areas and manual analysis indicated a greater amount of bird sounds in unburned areas. Finally, in chapter three we analyse whether the soundscape reflected differences in a landscape with different types of human exploration. We found that the acoustic indices measuring sound activity had lower values in rubber plantation habitats compared to secondary forest habitats and intense selective logging. Through our study we verified that animal acoustic communication and the soundscape reflect changes caused by different types of environmental disturbances, this shows the potential of using sounds to understand environments.

Keywords: Acoustic communication, Anthropogenic noise, Wildfire, Land-use change, Passive acoustic monitoring, Acoustic indices.

Sumário

Introdução Geral

Comunicação acústica

A comunicação pode ser definida como a troca de informações entre indivíduos, realizada através da transmissão de um sinal por um emissor, destinado a um receptor que compreende essa informação (Bradbury and Vehrencamp 1998; Simmons 2003). Existem diferentes tipos de sinais utilizados na comunicação, por exemplo, sinais químicos, tácteis, visuais e acústicos, que podem ser utilizados juntos ou separados (Bradbury and Vehrencamp 1998).

A comunicação acústica é utilizada por diferentes grupos de animais, como aves, mamíferos, anfíbios e invertebrados. Os animais podem utilizar esse tipo de comunicação em vários contextos, por exemplo, na seleção sexual, defesa de território e para alertar sobre perigos (Gerhardt and Huber 2002). Os sinais acústicos são propagados através do ambiente, porém alguns fatores, como degradação e atenuação do som, podem atrapalhar a propagação sonora (Bradbury and Vehrencamp 1998). Quando o sinal perde informações durante a propagação, o receptor pode não conseguir discriminar o sinal (Wiley and Richards 1978), isso pode comprometer a eficiência da comunicação acústica.

Diversas linhas de pesquisa têm estudado a comunicação acústica. A bioacústica é uma área do conhecimento que estuda a comunicação animal. Ela concentra-se no comportamento acústico de indivíduos, grupos ou populações e geralmente está focada nas interações entre os indivíduos, com estudos voltados para produção, propagação e recepção do som (Towsey et al. 2014a). A bioacústica é considerada uma ciência interdisciplinar, com vínculos em diversas áreas, como etologia, fisiologia, neurobiologia e evolução (Towsey et al. 2014a). Porém, os sons dos animais vão além de estudos de comportamento acústico, através dos sons naturais e antropogênicos também é possível investigar as relações desses sons com o meio ambiente (Sueur and Farina, 2015).

A ecoacústica surgiu como uma área teórica e aplicada que estuda o som em uma ampla gama de escalas espaciais e temporais, para estudar a biodiversidade e outras questões ecológicas (Sueur and Farina 2015). Na ecoacústica o som é utilizado para inferir informações ecológicas, abrangendo a ecologia de populações, comunidades e paisagens (Pijanowski et al. 2011b; Sueur and Farina 2015).

Conhecendo a paisagem sonora

A paisagem sonora faz parte da área de pesquisa da ecoacústica, os estudos de paisagem sonora são destinado aos sons gerados por organismos e elementos presentes na paisagem (Pijanowski et al. 2011b, a). O termo “paisagem sonora” foi incialmente utilizado em estudo da percepção humana sobre paisagens urbanas (Southworth 1969). No entanto, “paisagem sonora” também vem sendo usado para se referir a características acústicas de ambientes naturais e ao conjunto de sons que estão associados a determinada localidade espacial (Schafer 1977; Pijanowski et al. 2011a, b). Uma paisagem sonora é composta por sons de diferentes fontes, os sons emitidos pelos seres vivos – biofonia, que engloba os sons emitidos por animais – zoofonia (Krause 1987; Pijanowski et al. 2011a; Ferreira et al. 2018), sons ambientais não biológicos de vento, chuva, trovão – geofonia e os sons gerados de atividade antrópicas, como industrias, aerogeradores e diversos tipos de transportes – antropofonia (Pijanowski et al. 2011a, b). Assim, os sons de uma paisagem, gerados pela biofonia, geofonia e antropofonia podem variar no espaço e no tempo, e podem refletir processos ecossistêmicos e atividades humanas (Pijanowski et al. 2011a).

Os diferentes tipos de sons de uma paisagem sonora estariam relacionados diretamente com as características da paisagem, essa relação causal levou ao uso de padrões de paisagem sonora como uma ferramenta rápida de avaliação em uma variedade de escalas espaciais e temporais, esperando refletir a condição ecológica ou a integridade de uma determinada área (Krause and Farina 2016).

Acústica aliada a tecnologia

O uso de ferramentas que avaliem de forma rápida a diversidade de espécies, e a dinâmica populacional em grandes escalas espaciais e temporais são necessários para auxiliar o monitoramento da biodiversidade (Tuia et al. 2022). Devido essas necessidades, tecnologias vêm se tornando essenciais para captar informações sobre a biodiversidade, uso de armadilhas fotográficas, satélites, drones e gravadores, são exemplos de aplicações de tecnologias no auxílio de estudos da biodiversidade (Pimm et al. 2015; Tuia et al. 2022).

Entre as tecnologias em expansão está o Monitoramento Acústico Passivo (MAP). O MAP é um método que se baseia em sistemas de gravação de som, usando sensores para obter gravações de forma automática por longos períodos, registrando os sons dos animais sem necessidade de uma pessoa operando o gravador (Gibb et al. 2019). O sistema de gravação automática do MAP permite que utilizando gravadores em cada área, várias áreas sejam amostradas ao mesmo tempo, com gravações contínuas e por longos períodos, sem causar o impacto de pesquisadores nas áreas amostradas (Sugai et al. 2019; Gibb et al. 2019). Assim, o MAP emergiu como um método cada vez mais econômico, em relação à métodos tradicionais de amostragem, e menos invasivo que outras técnicas de amostragem, pois necessita de um operador apenas para instalação e manutenção do equipamento (Towsey et al. 2014a; Gibb et al. 2019), sendo bastante utilizado em estudos de padrões de atividade e uso de habitat (Sugai et al. 2019).

Apesar do uso do MAP ser importante para auxiliar diversos tipos de estudo, como por exemplo, monitoramento de espécies e estudos de paisagens sonoras, ele produz um grande volume de dados acústicos. Isso gera uma incompatibilidade entre o volume de dados adquiridos para os estudos e a capacidade de processamento e análise pelos pesquisadores (Tuia et al. 2022). Dessa maneira, para que o MAP se torne uma ferramenta ainda mais eficiente para os estudos, são necessários avanços nas técnicas de análise dos dados acústicos.

Análises com índices acústicos

Para auxiliar o processamento dos dados acústicos foram desenvolvidos para prevês um aspecto da biodiversidade. Assim, um índice acústico é uma estatística que resume alguns aspectos da distribuição de energia acústica e informações em uma gravação (Towsey et al. 2014b). Os índices acústicos são usados como indicadores ecológicos, baseados na suposição de que a comunidade acústica é representativa da comunidade ecológica (Gasc et al. 2013). A partir dessas suposições, prevê-se que uma maior riqueza de espécies produzirá uma gama mais ampla de sinais, resultando em uma maior diversidade acústica (Sueur et al. 2008a, Pijanowski et al. 2011a, Gasc et al. 2013). Nos últimos anos o uso de índices tornou-se ainda mais viável devido a software gratuitos e desenvolvidos em linguagem de programação em Linux, R e Python, como os pacotes Seewave (Sueur et al. 2008b) e Soundecology (Villanueva-Rivera et al. 2011), AnalysisPrograms (Towsey et al., 2020) e Scikit-maad (Ulloa et al. 2021).

Muitos estudos tem buscando investigar a eficiência dos índices acústicos em avaliar a diversidade acústica, vários estudos encontraram relação da diversidade acústica com alguns índices acústicos testados (Machado et al. 2017, Mammides et al. 2017, Ng et al. 2018, Moreno-Gómez et al. 2019). Porém, ainda é necessário investigar a capacidade dos índices acústicos em diferenciar modificações nos habitats em diferentes biomas, principalmente avaliando locais com grande biodiversidade, como florestas tropicais.

Modificações ambientais e acústica

Os distúrbios humanos, como extração de madeira, caça, fragmentação de florestas e a agricultura produzem impactos na estrutura das comunidades (Joly et al. 2014). Essas modificações podem levar a uma redução da biodiversidade acústica, causada pelo declínio geral da diversidade (Sueur et al. 2021). Um dos tipos de perturbação ambiental é o ruído causado pelas atividades humanas, como indústria e meios de transportes. O som gerado pelo ruído antrópico é considerado um tipo de poluição ambiental (Harding et al. 2019). Quando o ruído sobrepõe ao som produzido pelos animais, no tempo e frequência, ocorre o efeito do mascaramento sonoro, que pode impedir que o som seja compreendido pelo receptor (Brumm and Slabbekoorn 2005; Wiley 2006). Além das consequências para comunicação, vários são os efeitos negativos atribuído ao ruído antrópico, como diminuição da riqueza de espécies, principalmente devido a evasão para outros locais (Francis et al. 2009; McClure et al. 2013), mudanças no comportamento (Shannon et al. 2016) e estresse devido a exposição ao ruído (Tennessen et al. 2016).

O ruído é uma das principais fontes de alterações ambientais que atingem a comunicação acústica. Porém, outras mudanças ambientais atingem a biodiversidade e podem ser avaliados através de abordagens acústicas, como paisagens sonoras. Os estudos de paisagens sonoras têm sido utilizados em vários tópicos que vão desde investigar os impactos de incêndios florestais (Gasc et al. 2018; Duarte et al. 2021), a descrição da homogeneização biótica (Burivalova et al. 2019). Investigaram também mudanças causadas por diferentes tipos de uso da terra (Burivalova et al. 2018; Müller et al. 2020; Dröge et al. 2021), e os efeitos de rodovias na paisagem (Khanaposhtani et al. 2019) e a restauração ambiental (Borker et al. 2020; Vega-Hidalgo et al. 2021). Esses estudos vêm mostrando que paisagem sonora pode ser uma abordagem viável para auxiliar pesquisas em diferentes tipos de alterações ambientais.

Estrutura da pesquisa

Este estudo está dividido em três capítulos, descreveremos um pouco sobre o contexto de cada artigo.

Capítulo I – Realizamos uma meta-análise sobre o efeito do ruido antrópico na modificação dos parâmetros acústicos dos sons, buscamos analisar se existe um padrão geral de mudança nos parâmetros acústicos para três grupos avaliados no estudo.

Capítulo II – Analisamos o efeito das queimadas na paisagem sonora, utilizamos os índices acústicos e análise manual das gravações para avaliar diferenças na biodiversidade acústica em locais queimados e não queimados na região da Chapada Diamantina, Bahia, Brasil

Capítulo III – Investigamos se a paisagem sonora reflete variação em paisagem com diferentes históricos de exploração humana na floresta tropical.

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Capítulo I

Influence of anthropogenic sounds on insect, anuran and bird acoustic signals: a meta-analysis

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Published: Frontiers in Ecology and Evolution, 28 February 2022

https://doi.org/10.3389/fevo.2022.827440

Abstract

Acoustic communication is a way of information exchange between individuals, and it is used by several animal species. Therefore, the detection, recognition and correct understanding of acoustic signals are key factors in effective communication. The priority of acoustic communication is effectiveness rather than perfection, being effective avoids affecting the sound-based communication system of the species. One of the factors that can affect effective communication is the overlap in time and frequency during signal transmission, known as signal masking. One type of sound that can cause masking is anthropogenic noise, which is currently increasing due to urban growth and consequently motorized transportation and machinery. When exposed to anthropogenic noise, animals can use compensatory mechanisms to deal with sound masking, such as the modification of acoustic parameters of their acoustic signal. Here, we performed a meta-analysis investigating whether different taxa have a general tendency for changes in acoustic parameters due to anthropogenic noise, we used taxa and acoustic parameters available in the literature that met the minimum criteria to perform a meta-analysis. We hypothesized that animals exposed to anthropogenic noise use compensation mechanisms, such as changes in dominant, maximum or minimum frequencies, call duration, note duration and call rate to deal with masking. We performed a meta-analysis, which synthesized information from 73 studies comprising 82 species of three taxa: insects, anurans and birds. Our results showed that in the presence of anthropogenic noise, insects did not change the acoustic parameters, while anurans increased call amplitude and birds increased dominant frequency, minimum and maximum frequencies, note duration and amplitude of their songs. The different responses of the groups to anthropogenic noise may be related to their particularities in the production and reception of sound or to the differences in the acoustic parameters considered between the taxa and also the lack of studies in some taxa.

Keywords: sound production, auditory masking, animal communication, vocal adjustments, plasticity, anthropophony, terrestrial fauna.

1. Introduction

Acoustic communication is widely used by animals to exchange information among individuals. It is accomplished through an acoustic signal generated by a sender, propagated through the environment and received by a receptor (Wiley and Richards, 1978; Ryan and Kime, 2003). Acoustic signals can reach long distances and carry information such as the identity, location and sexual status of the sender (Gerhardt and Huber, 2002). Their use is relevant in many contexts, such as attracting partners for breeding, territorial defense and danger alert (Gerhardt and Huber, 2002). When the communication process is not effective from emission to signal reception, interactions among communicating individuals are compromised.

Anthropogenic noise is a type of sound that can be considered as a kind of environmental pollution and that can interfere with the acoustic communication of animals (Harding et al., 2019). Usually, the anthropogenic noise energy is in the range from 1 to 4 kHz (Job et al., 2016), but for example a travelling truck can occupy a noise range from 1 to 8.4 kHz (Duarte et al., 2019). Several negative effects have been attributed to anthropogenic noise, such as decreased species richness and abundance (Francis et al., 2009; Benítez-López et al., 2010; McClure et al., 2013), altered biotic interactions (Shannon et al., 2016; Phillips et al., 2019), and physiological effects on individuals such as stress due to exposure to noise (Tennessen et al., 2016).

When there is an overlap in the time and frequency spectrum of the noise and the sound produced by species, masking effect occurs, which can inhibit the perception of acoustic signals of animals (Patterson and Green, 1978; Brumm and Slabbekoorn, 2005; Wiley, 2006). To avoid masking effects in noisy environments, animals can also alter calling behavior patterns, since individuals of many species modify calling activity periods (Sousa-Lima and Clark, 2008; Dominoni et al., 2016). Some animals can also adjust the properties of the acoustic signal, according to their phenotypic flexibility (Piersma and Drent, 2003), this phenomenon can even be transmitted from one generation to the next one, resulting in evolutionary changes (Brumm and Slabbekoorn, 2005). Masking caused by biotic or abiotic noise can influence the ecology and evolution of various sound communication systems in animals (Brumm and Slabbekoorn, 2005; Slabbekoorn and Ripmeester, 2008).

Anthropogenic noise occupies a sound frequency band similar to that used by some species of insects, anurans and birds. Studies suggest that a strategy to deal with this is altering the acoustic parameters (Hu and Cardoso, 2010; Lampe et al., 2012; McCarthy et al., 2013; Montague et al., 2013). Understanding whether changes in acoustic parameters caused by noise are responses to phenotypic or evolutionary plasticity has been investigated for biotic and abiotic noise (Brumm and Slabbekoorn, 2005; Slabbekoorn and Ripmeester, 2008). In insects, a study found that Grasshoppers raised under noisy conditions produced songs with higher maximum-frequency as adults, suggesting plasticity in this spectral property of sound (Lampe et al., 2014). In anurans, the frequency of call is conditioned by morphological constraints, such as body size, and is considered a parameter conserved between generations, nevertheless, individuals that live in environments with constant abiotic noise call at higher dominant frequencies than expected, suggesting evolutionary changes (Goutte et al., 2016; Röhr et al., 2016). In birds, evolutionary changes are also reported, proposing that biotic noise has shaped certain bird sound (Dubois and Martens 1984; Brumm and Slabbekoorn 2005), but changes are also suggested due to vocal plasticity (Gross et al., 2010; Bermúdez-Cuamatzin et al., 2012). Modification of acoustic parameters to avoid masking can compromise signal reception and affect its function (Patricelli and Blickley, 2006). The level of sound masking caused by anthropogenic noise and the ability to compensate for it may vary depending on the group of animals (Brumm and Slabbekoorn, 2005; Raboin and Elias, 2019).

Some review studies have investigated the effect of anthropogenic noise, evaluating changes in frequency (Roca et al., 2016), experimental studies (Kunc and Schmidt, 2021) or changes in the ocean soundscape (Duarte et al., 2021). Here, we performed a meta-analysis of the general patterns of each acoustic parameter that met the minimum criteria for a meta-analysis, investigating their changes as a consequence of anthropic noise in three groups. We hypothesize that animals exposed to noise will use compensation mechanisms to avoid masking. For some insects, anurans, and birds, sound emission is in the same frequency band as anthropogenic noise, so we predicted similar effects in the three investigated taxa. Specifically, we expected: (i) increase in the dominant, minimum and maximum frequencies, to avoid overlapping the same frequency range of the noise (Lampe, 2014; Grenat et al., 2019; Nemeth and Brumm, 2009;); (ii) increase in call/song duration, note duration and call/song rate, to increase the chances of being detected in the presence of noise (Kaiser and Hammers, 2009; Roca et al., 2016) and (iii) increase in amplitude, to be heard in an environment with anthropogenic noise (Zollinger and Brumm, 2011; Zhao et al., 2018).

2. Methods

2.1. Literature search

We searched for studies which investigated changes in signals through acoustic parameters modified by the action of anthropogenic sounds. We performed a systematic review following PRISMA protocol (Page et al., 2021). Searches were implemented on the Scopus and Web of Science platforms for all available years through January 2022. Searches were performed using the following keywords: (“noise*” OR “masking”) AND (“traffic*” OR “road*” OR “urban” OR “anthropic” OR “anthropogenic”) AND (“signal*” OR “call*” OR “vocalization*” OR "song*"). These keywords were searched in the title, abstract and keywords of the studies. The number of records obtained in the systematic review is presented in a flow chart (Figure 1, Table S1).

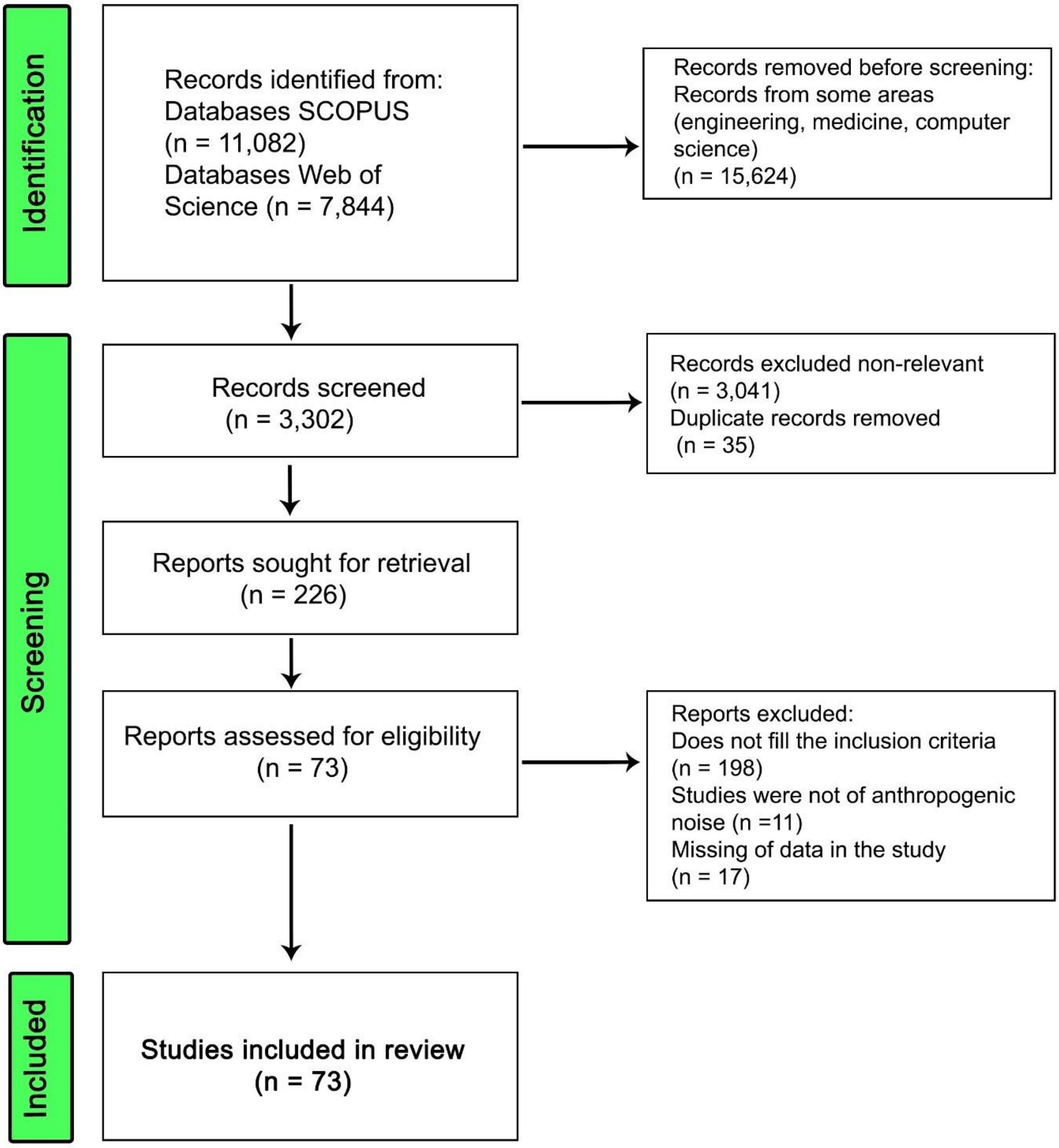

Figure 1. PRISMA flow diagram used for research of scientific articles for the study.

2.2. Criteria for study inclusion

We selected studies according to the following criteria: i) investigated the effect of anthropogenic sounds on the acoustic parameter, with control (not exposed to anthropogenic sounds) and treatment (exposed to anthropogenic noise), conducted through experiment or in nature; ii) studies with one or more acoustic parameters evaluated (e.g. dominant frequency, call duration, call rate); iii) terrestrial animals and iv) studies with information on: mean, standard deviation and number of individuals sampled for each treatment (control and noise), or studies with sufficient statistical information to allow calculation of effect size.

In our study, we had to deal with measurement errors, such as bias generated when extracting minimum and maximum frequency measurements visually from spectrograms. Beecher (1988) and Zollinger et al. (2012) reported similar problems for studying birdsong in noisy environments, for example, two sounds identical in frequency and amplitude can look markedly different on a spectrogram if there is some other higher amplitude sound in the background of a recording that is not present in the other, also noise can make it difficult to detect the minimum frequency of the signal in the spectrogram. To avoid measurement errors, it is recommended to use power or amplitude spectra (Zollinger et al., 2012). From the power spectra, the minimum and maximum frequency can be reliably measured (Zollinger et al., 2012; Brumm et al., 2017). We chose to include in our study only data from minimum and maximum frequencies measured in power spectrum or studies of experiments that controlled measurement errors. Therefore, we excluded from our database 82 individual responses that did not meet this criterion.

We built a database containing seven acoustic parameters: i) dominant frequency (the frequency that contains more sound energy); ii) minimum frequency (lowest frequency of sound), iii) maximum frequency (highest frequency of sound); iv) call duration (length from start to end of sound in insects and anurans; in birds the studies measure song duration (the start of the first element to the end of the last element of a song); v) note duration (length from start to end of a note of the song); vi) call/song rate (number of calls/ songs emitted over of time) and vii) call amplitude (sound pressure). Not all acoustic parameters were found in the three classes of animals that conform our database. The data obtained for insects includes the orders orthoptera and hemiptera, and in the literature we found the acoustic parameters dominant frequency and maximum frequency tested for anthropogenic noise. In anurans, we found only dominant frequency, call duration, call rate and call amplitude. For birds, we obtained data on all acoustic parameters, dominant frequency, maximum frequency, minimum frequency, song duration, note duration, song rate and song amplitude.

2.3. Effect sizes

For each study that we extracted the mean, standard deviation and number of individuals sampled for each treatment (control and noise), we calculated the effect size using Hedges' g statistic, using the "metafor" package (Viechtbauer, 2010). We extracted data found only in figures using the Get Data Graph Digitizer program (www.getdata-graph-digitizer.com). Data available only in figures with median and interquartile range had their mean and standard deviation estimated according to the method of Hozo et al. (2005). For studies that did not report the mean and standard deviation, we used the "esc" package (Lüdecke, 2019) to convert statistical test results into Hedges' g effect size measurements (Table S2). The analyses were performed in R environment (R Core Team, 2021).

2.4. Controlling for Phylogenetic Signal

Our samples include species from three taxonomic groups, then it was necessary to control the non-independence of the species, because the evolutionary history of these species can be shared. With the species of our dataset, we created a tree with the phylogenetic and taxonomic information obtained in Tree of Life Web Project website (http://tolweb.org), these data were obtained using the package “rotl” (Michonneau et al., 2016). The lengths of the branches of the phylogenetic tree were calculated using the method of Grafen (Grafen, 1989) and a correlation matrix of phylogenetic relatedness among species was constructed for our dataset, these steps were performed using the package “ape” (Paradis and Schliep, 2019), the analyses were performed in the R environment (R Core Team, 2021) (Figure S1). This correlation matrix of phylogenetic was inserted in our meta-analysis as a random variable. (see Section 2.5).

2.5. Meta-analysis

We tested the effect size of the data assuming that they were heterogeneous and performed a random-effects meta-analysis. We used a multilevel meta-analytical model to control non-independence between effect sizes using random variables in the model (Nakagawa and Santos, 2012; Nakagawa et al., 2017). We included “species” and “phylogenetic signal” as random variables in our model, species was included as a random variable to control for the effect of several studies investigating the same species. We built the model using the function rma.mv, and we adjusted it by using restricted maximum likelihood (REML). We included acoustic parameter as moderator in the model, for our result to be obtained for each acoustic parameter by taxon. The analyses were performed in the “metafor” package (Viechtbauer, 2010), in the R environment (R Core Team, 2021).

We also investigated the presence of outliers as they may affect the validity and robustness of the meta-analysis (Viechtbauer and Cheung, 2010), we detected their presence through Cook's distance. We removed data from our analysis with Cook's distance above five, leading to the exclusion of eight potential outliers from our data base (see result with outliers in Table S3).

2.6. Publication bias

To test the publication bias we used the Egger regression test (Egger et al., 1997). We maintained the same model structure used to evaluate the effect of anthropogenic noise for the acoustic parameters, but we changed the moderator that was the acoustic parameter by the sample variance. When the regression intercept significantly deviates from zero it is considered that the data are asymmetric and biased towards publication bias (Sterne and Egger, 2006). We considered the result with a tendency for publication bias when the intercept differed from zero at $p < 0.1$ (Egger et al., 1997). Additionally, we measured the level of heterogeneity of the meta-analysis using I^2, which describes the percentage of variation across the studies due to data heterogeneity (Higgins et al., 2003).

3. Results

We found a total of 73 studies (Figure 1), published between 2006 to January 2022 (Figure 2). The number of studies were conducted in 34 countries and varied for insects, anurans and birds (Figure 3). The most evaluated anthropogenic noise in the studies was urban and car traffic, but we also found noise generated by aircraft and gas compressor. From the studies we obtained 286 effect sizes, with individual responses distributed in the three taxa, where we found data for different acoustic parameters (Table 1). We obtained data from four insect species, 22 anuran species and 56 bird species, for a total of 82 species evaluated. The Egger's regression model was not significant, showing that our results are unaffected by the publication bias (intercept = 0.0438; C.I.= -0.37 to 0.46; $p = 0.8372$). Additionally, we observed a high level of heterogeneity ($I^2 = 92.99\%$).

For invertebrates, there was no change in the acoustic parameters when exposed to anthropogenic sounds (Table 1, Figure 4A). Anurans increased their call amplitude due to anthropogenic sounds (Table 1, Figure 4B). For birds the acoustic parameters dominant frequency, minimum frequency, maximum frequency, note duration and call amplitude increased in sites of anthropogenic noise (Table 1, Figure 4C).

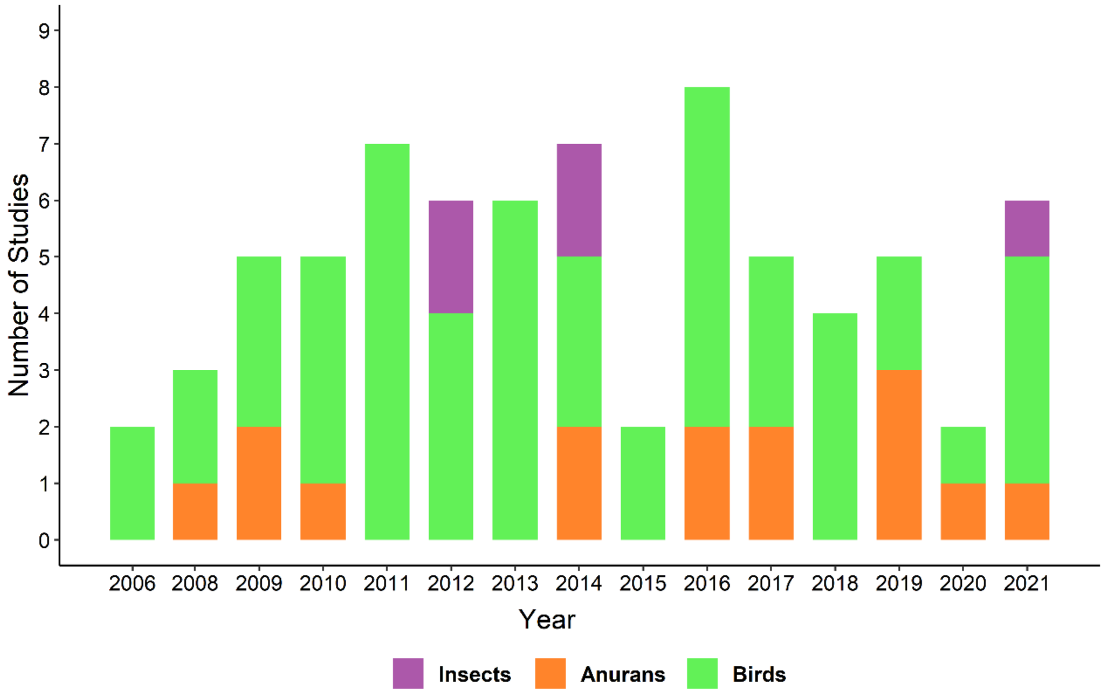

Figure 2. Studies included in the meta-analysis. Number of studies present in our database, separated by year and color-coded taxon.

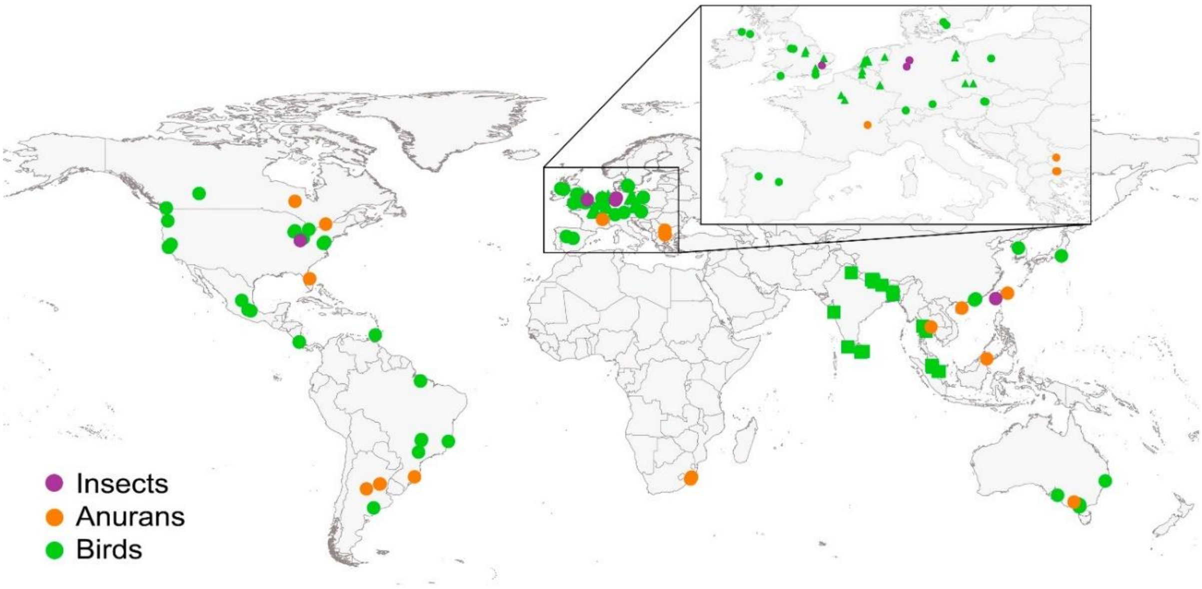

Figure 3. Geographic distribution of studied sites included in the meta-analysis. Color-coded bars represent different taxon, solid circles represent studies that had one or two sampling sites, and each different shape (square and triangle) represent a study that had more than two sampling sites.

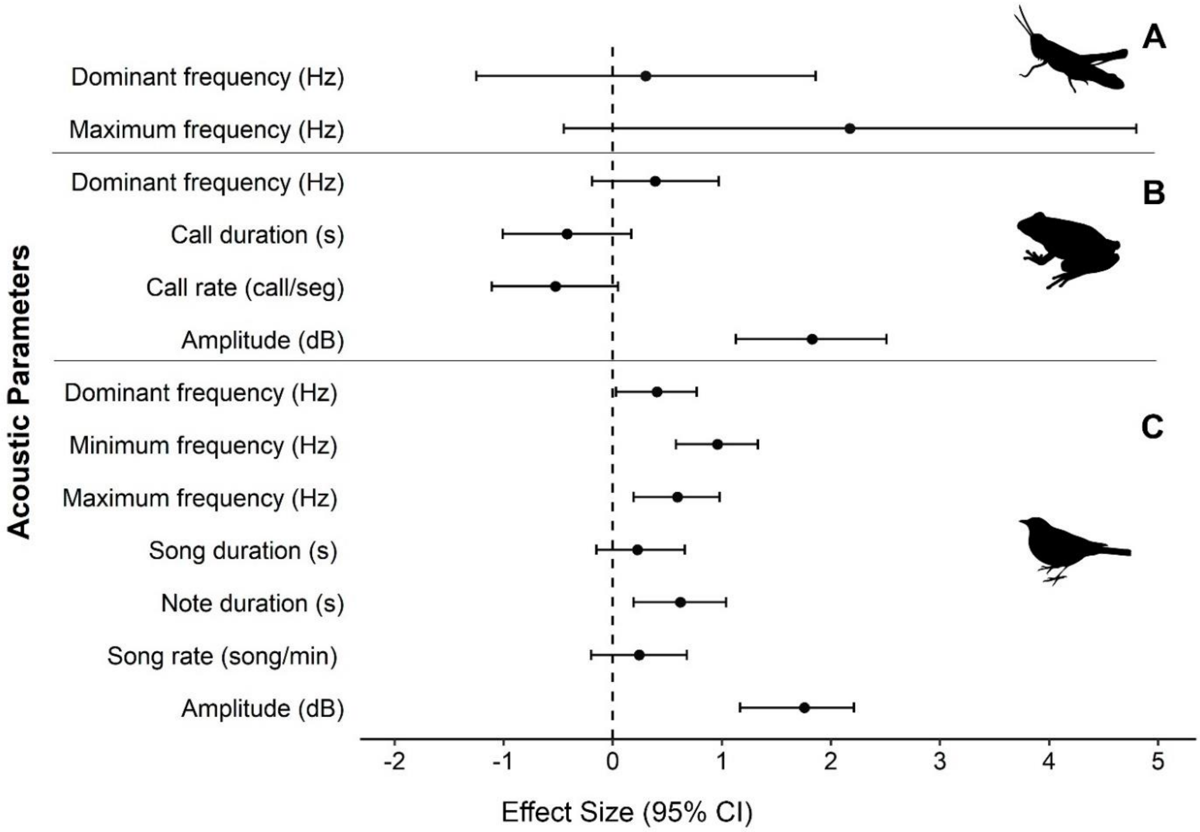

Figure 4. Forest plot representing effect of anthropogenic sounds for acoustic parameters. The mean effect size Hedges' g (represented by black circles) and confidence interval values of 95%

(bars) for each acoustic parameter, separated by taxon, (A) Insects, represented by the orders Orthoptera and Hemiptera, (B) Anurans and (C) Birds.

Table 1. Results of the multilevel meta-analysis. Number of records per acoustic parameter (n) evaluated by taxon, mean effect size (Hedges'g), lower limit, upper limit, standard error (se) and p-value. Significant results highlighted in bold.

Taxon	**Acoustic Parameter**	**n**	**Effect Size**	**Lower Limit**	**Upper Limit**	**se**	***p***
Insects	Dominant frequency (Hz)	3	0.301	-1.25	1.86	0.79	0.7048
	Maximum frequency (Hz)	3	2.174	-0.45	4.8	1.34	0.1053
Anurans	Dominant frequency (Hz)	28	0.388	-0.19	0.97	0.29	0.1901
	Call duration (s)	18	-0.42	-1.01	0.17	0.3	0.1702
	Call rate (call/seg)	27	-0.526	-1.11	0.05	0.29	0.0785
	Amplitude (dB)	7	1.828	1.13	2.51	0.35	< **.0001**
Birds	Dominant frequency (Hz)	58	0.4053	0.03	0.77	0.18	**0.03**
	Minimum frequency (Hz)	55	0.961	0.58	1.33	0.19	< **.0001**
	Maximum frequency (Hz)	33	0.593	0.19	0.98	0.2	**0.0031**
	Song duration (s)	24	0.225	-0.15	0.66	0.2	0.2203
	Note duration (s)	11	0.619	0.19	1.04	0.21	**0.0042**
	Song rate (song/min)	11	0.243	-0.1974	0.68	0.22	0.2789
	Amplitude (dB)	8	1.758	1.1657	2.2121	0.2669	< **.0001**

4. Discussion

Our study detected a general pattern for some acoustic parameters to change in response to anthropogenic noise, with different results for the three taxa studied. Birds show a general pattern to change several acoustic parameters, such as dominant frequency, minimum and maximum frequencies, note duration and song amplitude. Anurans suggest a general pattern to change only the amplitude of the call, for insects there were no changes in the general pattern for none of the investigated acoustic parameters.

For insects the number of studies that evaluated noise interference for acoustic communication was small, compared to the other groups, and this is reflected in the confidence interval of the results, which showed the need for more studies for this taxon. Despite the small number of studies for the group, we observed a tendency for frequencies to increase in the presence of noise, but our result was not significant. Other strategies can also be used by insects, Duarte et al. (2019) showed that *Gryllus* sp. reduced its sounds emission by 90% in the presence of truck noise, but it was not possible to test the generality of that acoustic parameter, because this parameter has not been tested in studies that allowed performing a meta-analysis. To decrease vocal activity can be a strategy to avoid masking, as individuals spend a lot of energy to emit an acoustic signal, calling more implies higher energy expenditure (Prestwich and Walker, 1981). However, we do not know how this affects the interactions mediated by acoustic communication.

Anurans increased call amplitude in the presence of noise. Our meta-analysis showed that this was the only acoustic parameter that responded to anthropogenic noise for anurans, showing that anurans can use the strategy of call with high intensity to avoid masking. Increased level of vocalization intensity according to noise, known as the “Lombard effect” (Brumm and Zollinger, 2011), has also been reported in studies with anurans that vocalize next to noisy environments, as streams (Halfwerk et al., 2016; Shen and Xu, 2016), although, some studies did not find evidence for the Lombard effect (Love and Bee, 2010; Zhao et al., 2018). Even though our results suggest the effect of anthropogenic noise on call amplitude, we interpret our results with caution, due to the low number of studies that evaluated this acoustic parameter and the difficulty in measuring the amplitude, which can be influenced by several factors, such as the direction of the signal emitter, among others.

Studies have shown how masking can affect anurans. For example, in several species that vocalize in sites with anthropogenic noise, the frequency of calls has increased (Parris et al., 2009; Cunnington and Fahrig, 2010; Grenat et al., 2019), although this response is not a general pattern for the group, as shown in our meta-analysis. Some studies that did not investigate a change in frequency due to noise, suggest an increase in the call rate, to increase chances of detection (Kaiser and Hammers, 2009; Roca et al., 2016). Our study showed an inverse tendency, with a decrease in the call rate, but the result was not significant, this tendency could be confirmed in the future with the increase in the number of studies.

In anurans, the consequences of changes in acoustic parameters caused by anthropogenic noise can affect sexual selection, as calls are used by females to choose males (Duellman and Trueb, 1985; Wells and Schwartz, 2007). For females of the group the preference for specific frequencies has been reported (Gerhardt, 1987; Ryan et al., 1992; Márquez and Bosch, 1997). In addition, in the presence of chorus and traffic noise, females decrease orientation towards the acoustic signal (Bee and Swanson, 2007). Another feature already shown is that males exposed to noise decrease the number of days present in the chorus and the duration of the chorus (Kaiser et al., 2011). These behavior changes were not investigated in our study, but changes in behavior when exposed to anthropogenic noise are also a mechanism used by anurans.

We suggest that birds showed a general tendency to change a higher number of acoustic parameters to avoid sound masking by anthropogenic noise. These mechanisms can benefit species that are exposed to anthropogenic noise, which is important to highlight this for the group. The number of acoustic parameters tested was greater compared to the other groups. The increasing signal frequencies may be advantageous in anthropogenic noise environment, where it has been shown that high frequencies are easier to detect (Ripmeester et al., 2010b; Pohl et al., 2012). But this may decrease signal efficiency for sexual selection and defense (Halfwerk et al., 2011). Some studies suggest that frequency depends on body size, larger birds produce songs with lower frequencies, so females can use song frequency as an indicator of male size in sexual selection (Gil and Gahr, 2002; Ryan and Brenowitz, 1985), thus, changes in frequencies songs can influence the preference of females. In addition, high frequency sounds may indicate that the transmitter is not hostile (Morton, 1977), this type of information can be used by males who defend territory. Therefore, modifying these signals may decrease communication efficiency, and males may be perceived as less attractive to females or less effective in the defense of territory (Mockford and Marshall, 2009).

Birds also increased note duration, longer duration of song and note can increase the chances of sound detection in the presence of anthropogenic noise. In birds, long song durations have been reported as responses to territory defense (Ripmeester et al., 2010a; Narango and Rodewald, 2016), however, in our study we found a general pattern only for note duration. Our results also suggest that the call amplitude increases in the presence of anthropogenic noise. Similar results have been shown in the literature for biotic noise, where studies have reported that the Lombard effect is a mechanism widely used by birds to avoid sound masking (Lampe et al., 2010; Zollinger and Brumm, 2011; Dorado-Correa et al., 2018; Singh et al., 2019). Zollinger and Brumm (2015) showed that changes in amplitude can have several costs for birds, for example, affecting sexual selection, defense of territory, condition and energy. Modifying the acoustic parameters can generate costs for birds, this should generate a loss/gain relationship, and the emitter should produce the most advantageous signal.

We showed a large difference between the number of studies by groups, the group of insects was the most neglected. These differences made it difficult to investigate a general pattern by taxon and to compare the same parameter in different taxa. Dominant frequency was the only acoustic parameter evaluated in the three groups. Although some studies suggested changes in this signal, change in the dominant frequency was a general pattern only in birds. This result may have occurred because the dominant frequency is considered an acoustic parameter difficult to change in insects and anurans, due to morphological restrictions (Castellano and Giacoma, 1998; Raboin and Elias, 2019). In birds, changes in frequency have been suggested, due to evolutionary and plastic responses to environmental changes (Morton, 1975; Bermúdez-Cuamatzin et al., 2012), and we emphasize that birds have anatomical characteristics that enable them to modulate the frequency and amplitude in vocal production, generating different types of singing (Riede and Goller, 2010; Ladich and Winkler, 2017), which does not occur in the other investigated groups. This is reflected in our results, which showed a general pattern for birds, changing the dominant, minimum and maximum frequencies of the sound. For anurans we tested call duration, in birds we tested song duration and note duration, in both we tested call/song rate, and we found a general pattern only for longer note duration in response to anthropogenic noise in birds. For call amplitude, anurans and birds increased signal amplitude, this was the only common change between both groups, increasing sound intensity due to noise is a feature widely used in vertebrates (Brumm and Zollinger, 2011). Thus, the birds group presented the most general patterns of responses to changes in acoustic parameters. Our meta-analysis showed all taxa either changed some acoustic parameter or showed a tendency to do so in environments with anthropogenic noise.

5. Conclusion

This work investigated the general patterns of changes in acoustic parameters caused by anthropogenic noise in insects, anurans and birds. Our approach showed that birds was the taxon with the most parameter changes, with dominant frequency, minimum and maximum frequencies, note duration and amplitude song, affected by anthropogenic noise in most studies that tested this effect. For anurans, a general pattern in the studies was an increase amplitude due to anthropogenic noise. Therefore, amplitude was the only parameter that changed in two different taxonomic groups. Additionally, we emphasized that the group of insects had few studies, thus this can influence the lack of a general pattern for the group. Additionally, considering the changes in the acoustic parameters, it is necessary to understand the consequences of these changes for each species. Questions such as the influence of these changes on the interactions mediated by animal acoustic communication need to be investigated deeply. Therefore, we emphasize that understanding these effects can contribute to strategies that minimize the consequences of anthropogenic noise for animals.

6. Acknowledgements

We are grateful to Marina H. L. Duarte, Lucas R. Forti and Robert J. Young for their contributions on the paper. LG thanks the Bahia State Research Support Foundation (FAPESB) for scholarships. RSSL thanks the Brazilian Council for Scientific and Technological Development (CNPq-Brazil) for their research grants (process number 312763/2019-0). MS also thanks CNPq (processes 304999/2015-6 and 309365/2019-8) for research grants.

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Supplementary material

Figure S1. The full phylogenetic tree used in the meta-analysis. Phylogenetic tree with emphasis for the taxonomic groups, * represents *Oecanthus* sps. and ** represents *Kurixalus chaseni*, there was no data for this species in the Tree of Life Web Project.

Table S1. Database used in the Systematic Review and Meta-Analyses.

E vc	classe	order	species	study_ type	noise	country	author	year	journal	volume	pag
01_in	Insecta	Orthoptera	*Oecanthus sps.*	playback	traffic	United States	Costello and Symes	2014	Animal Behaviour	95	15-22
02_in	Insecta	Orthoptera	*Chorthippus biguttulus*	nature	traffic	Germany	Lampe et al.	2012	Functional Ecology	26	1348-1354
03_in	Insecta	Orthoptera	*Chorthippus biguttulus*	playback	traffic	Germany	Lampe et al.	2014	Functional Ecology	28	660-668
04_in	Insecta	Hemiptera	*Cryptotympana takasogona*	nature	traffic	China	Shieh et al.	2012	Acta ethologica	15	33-38
01_an	Amphibia	Anura	*Anaxyrus quercicus*	playback	traffic	United States	Grace and Noss	2017	Animal Conservation	21	343-351
02_an	Amphibia	Anura	*Odontophrynus americanus*	nature	traffic	Argentina	Grenat et al.	2019	Ecological Indicators	99	67-73
04_an	Amphibia	Anura	*Hyla arborea*	playback	traffic	France	Lengagne	2008	Biological Conservation	141	2023-2031
06_an	Amphibia	Anura	*Rana clamitans*	nature	traffic	Canada	Cunnington and Fahrig	2010	Acta Oecologica	36	463-470
06_an	Amphibia	Anura	*Rana pipiens*	nature	traffic	Canada	Cunnington and Fahrig	2010	Acta Oecologica	36	463-470
06_an	Amphibia	Anura	*Hyla versicolor*	nature	traffic	Canada	Cunnington and Fahrig	2010	Acta Oecologica	36	463-470
06_an	Amphibia	Anura	*Bufo americanus*	nature	traffic	Canada	Cunnington and Fahrig	2010	Acta Oecologica	36	463-470
08_an	Amphibia	Anura	*Pseudacris crucifer*	playback	traffic	Canada	Hanna et al.	2014	Current Zoology	60	438-448
10_an	Amphibia	Anura	*Dendropsophus triangulum*	playback	traffic/ music	Thailand	Kaiser and Hammers	2009	Behaviour	146	1053-1069
12_an	Amphibia	Anura	*Boana bischoffi*	playback	traffic	Brazil	Caorsi et al.	2017	Plos one	30	01-14
12_an	Amphibia	Anura	*Boana leptolineata*	playback	traffic	Brazil	Caorsi et al.	2017	Plos one	30	01-14
13_an	Amphibia	Anura	*Litoria ewingii*	nature	traffic	Australia	Parris et al.	2009	Ecology and Society	14	01-23
13_an	Amphibia	Anura	*Crinia signifera*	nature	traffic	Australia	Parris et al.	2009	Ecology and Society	14	01-23

14_an	Amphibia	Anura	*Pelophylax ridibundus*	nature	traffic	Bulgaria	Lukanov et al.	2014	Journal of Zoology	10	359-364
17_an	Amphibia	Anura	*Hyperolius pickersgilli*	nature	aeronaves	South Africa	Kruger and Du Preez	2016	Ecol Res	31	393-405
20_an	Amphibia	Anura	*Kurixalus chaseni*	playback	traffic	Malaysia	Yi and Sheridan	2016	Raffles Bulletin of Zoology	67	77-82
23_an	Amphibia	Anura	*Hyla arborea*	nature	gas compressor	Bulgaria	Lukanov and Naumov	2019	Ecological Questions	30	55-60
01_av	Bird	Passeriformes	*Carpodacus mexicanus*	playback	urban	Mexico	Bermúdez-Cuamatzin et al.	2011	Biology letters	7	36-38
02_av	Bird	Passeriformes	*Emberiza schoeniclus*	nature and playback	traffic	Switzerland	Gross et al.	2010	The American Society of Naturalist	176	456-464
03_av	Bird	Columbiformes	*Streptopelia chinensis*	nature	traffic	China	Guo et al.	2016	Behavioural Processes	129	86-93
05_av	Bird	Passeriformes	*Copsychus saularis*	nature	traffic	Bangladesh; India; Malaysia; Nepal; Sri Lanka; Thailand	Hill et al.	2018	Integrative Zoology	13	194-205
07_av	Bird	Psittaciformes	*Trichoglossus haematodus*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Psittaciformes	*Platycercus eximius*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Anthochaera carunculata*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Manorina melanocephala*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Manorina melanophrys*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Strepera graculina*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Gymnorhina tibicen*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867

07_av	Bird	Passeriformes	*Cracticus torquatus*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Grallina cyanoleuca*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Rhipidura leucophrys*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Acridotheres tristis*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
07_av	Bird	Passeriformes	*Turdus merula*	nature	traffic	Australia	Hu and Cardoso	2010	Animal Behaviour	79	863-867
08_av	Bird	Passeriformes	*Spizella passerina*	nature	urban	United States	Job et al.	2016	Behavioral Ecology	27	1734-1744
09_av	Bird	Passeriformes	*Parus minor*	nature	traffic	Korea	Lee and Park	2018	Urban Ecosystems	22	01-07
11_av	Bird	Passeriformes	*Zonotrichia capensis*	nature	traffic	Argentina	Laiolo	2011	Revista Catalana d'Ornitologia	27	25-30
13_av	Bird	Passeriformes	*Zonotrichia leucophrys*	nature	traffic	United States	Luther and Derryberry	2012	Animal Behaviour	83	1059-1066
15_av	Bird	Passeriformes	*Gymnorhina tibicen*	nature	traffic	Australia	McCarthy et al.	2013	Notornis and Birds New Zealand	60	143-150
16_av	Bird	Passeriformes	*Erithacus rubecula*	playback	traffic	Ireland	McMullen et al.	2014	Behavioural Processes	103	125-128
17_av	Bird	Passeriformes	*Turdus merula*	nature	traffic	Spain	Mendes et al.	2011	Landscape and Urban Planning	99	51-57
18_av	Bird	Passeriformes	*Erithacus rubecula*	nature	traffic	Ireland	Montague et al.	2013	Behavioral Ecology	24	343-348
20_av	Bird	Passeriformes	*Colluricincla harmonica*	nature	traffic	Australia	Parris and Schneider	2009	Ecology and Society	14	01-24
20_av	Bird	Passeriformes	*Rhipidura fuliginosa*	nature	traffic	Australia	Parris and Schneider	2009	Ecology and Society	14	01-24
22_av	Bird	Passeriformes	*Poecile atricapillus*	nature	urban	Canada	Proppe et al.	2012	Journal of Avian Biology	43	01-08
23_av	Bird	Passeriformes	*Troglodytes aedon*	nature	traffic	Costa Rican	Redondo et al.	2013	The Int. Journal of Avian Science	155	621-625
24_av	Bird	Passeriformes	*Agelaius phoeniceus*	nature	urban	United States	Ríos-Chelén et al.	2015	Behavioral Ecology and Sociobiology	69	1139-1151
25_av	Bird	Passeriformes	*Agelaius phoeniceus*	playback	traffic	United States	Ríos-Chelèn et al.	2016	Behaviour	153	1445-1472
26_av	Bird	Passeriformes	*Turdus migratorius*	nature	urban	United States	Seger-Fullam et al.	2011	Bioacustics	20	267-276

26_av	Bird	Passeriformes	*Cardinalis cardinalis*	nature	urban	United States	Seger-Fullam et al.	2011	Bioacustics	20	267-276
28_av	Bird	Piciformes	*Venilliornis passerinus*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Piciformes	*Picumnus albosquamatus*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Cantorchilus leucotis*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Cyclarhis gujanensis*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Basileuterus culicivorus*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Myiothlypis flaveola*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Antilophia galeata*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Leptopogon amaurocephalus*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
28_av	Bird	Passeriformes	*Tolmomyias sulphurescens*	nature	urban	Brazil	Tolentino et al.	2018	Environmental Pollution	235	983-992
29_av	Bird	Passeriformes	*Phylloscopus collybita*	nature and playback	traffic	Netherlands	Verzijden et al.	2010	The Journal of Experimental Biology	213	2575-2581
30_av	Bird	Passeriformes	*Zosterops lateralis*	nature	urban	Australia	Potvin and Parris	2012	Ecology and Evolution	2	1977-1984
31_av	Bird	Passeriformes	*Turdus merula*	nature	urban	Austria	Nemeth and Brumm	2009	Animal Behaviour	78	637-641
35_av	Bird	Passeriformes	*Zosterops lateralis*	nature	urban	Australia	Potvin et al.	2014	Animal Behaviour	98	27-33
38_av	Bird	Passeriformes	*Erithacus rubecula*	playback	urban	Ireland	McLaughlin and Kunc	2012	Biology letters	9	02-04
39_av	Bird	Passeriformes	*Zonotrichia leucophrys*	nature	urban/traffic	United States	Derryberry et al.	2016	Plos one	11	01-17
40_av	Bird	Passeriformes	*Parus major*	nature	urban	Denmark	Huffeldt and Dabelsteen	2013	Ornis Fennica	90	94-102
41_av	Bird	Passeriformes	*Passer domesticus*	playback/nature	urban	Mexico	Bermúdez-Cuamatzin et al.	2018	Behavioural Processes	157	645-655
41_av	Bird	Passeriformes	*Thryomanes bewickii*	playback/nature	urban	Mexico	Bermúdez-Cuamatzin et al.	2018	Behavioural Processes	157	645-655

41_av	Bird	Passeriformes	*Melozone fusca*	playback/nature	urban	Mexico	Bermúdez-Cuamatzin et al.	2018	Behavioural Processes	157	645-655
41_av	Bird	Passeriformes	*Pheucticus melanocephalus*	playback/nature	urban	Mexico	Bermúdez-Cuamatzin et al.	2018	Behavioural Processes	157	645-655
45_av	Bird	Passeriformes	*Agelaius phoeniceus*	nature and playback	traffic	Canada	Hanna et al.	2011	Journal of Experimental Biology	214	3549-3556
48_av	Bird	Passeriformes	*Turdus merula*	nature	urban	Austria	Nemeth et al.	2013	Proceedings of the Royal Society	280	01-07
49_av	Bird	Passeriformes	*Parus major*	nature	urban	Netherlands; Belgium; France; Luxembourg; Germany; Czech Republic; England	Slabbekoorn and Boer-Visser	2006	Current Biology	16	2326-2331
50_av	Bird	Passeriformes	*Carpodacus mexicanus*	nature	urban	Mexico	Bermùdez-Cuamatzin et al.	2008	Behaviour	146	1269-1286
52_av	Bird	Passeriformes	*Troglodytes troglodytes*	nature	urban	Spain	Colino-Rabanal et al.	2016	Acta Ornithologica	51	13-22
53_av	Bird	Passeriformes	*Turdus migratorius*	nature	urban	United States	Dowling et al.	2011	Behavioral Ecology	11	201-209
53_av	Bird	Passeriformes	*Dumetella carolinensis*	nature	urban	United States	Dowling et al.	2011	Behavioral Ecology	11	201-209
53_av	Bird	Passeriformes	*Cardinalis cardinalis*	nature	urban	United States	Dowling et al.	2011	Behavioral Ecology	11	201-209
53_av	Bird	Passeriformes	*Throglodytes aedon*	nature	urban	United States	Dowling et al.	2011	Behavioral Ecology	11	201-209
54_av	Bird	Passeriformes	*Troglodytes pacificus*	nature	traffic	Canada	Gough et al.	2014	The Wilson Journal of Ornithology	126	269-278
56_av	Bird	Passeriformes	*Troglodytes musculus*	nature	urban	Brazil	Mendes et al.	2011	Hormero	26	85-93
57_av	Bird	Passeriformes	*Turdus leucomelas*	nature	urban	Brazil	Mendes et al.	2017	Revista de Biologia Tropical	65	633-642

58_av	Bird	Passeriformes	*Parus major*	nature	urban	Great Britain	Mockford and Marshall	2009	Proceedings of the Royal Society	276	2979-2985
59_av	Bird	Passeriformes	*Zonotrichia leucophrys*	playback	urban	United States	Moseley et al.	2018	Proceedings of the Royal Society	285	01-09
61_av	Bird	Passeriformes	*Parus major*	nature	urban	Spain	Salaberria and Gil	2010	Ardeola	57	03-11
62_av	Bird	Passeriformes	*Melospiza melodia*	nature	urban	United States	Wood and Yezerinac	2006	The Auk	123	650-659
01_in_21	Insecta	Orthoptera	*Gryllus bimaculatus*	playback	urban	Northern Ireland	Bent et al.	2021	Animal Behaviour	174	09-19
02_an_21	Amphibia	Anura	*Buergeria japonica*	nature	traffic	Japan	Legett et al.	2020	Ethology	126	576-583
01_av_21	Bird	Passeriformes	*Phylloscopus collybita*	nature	aircraft	United Kingdom	Wolfenden et al.	2019	Journal of Animal Ecology	88	1720-1731
02_av_21	Bird	Passeriformes	*Turdus philomelos*	nature	urban	Poland	Deoniziak and Osiejuk	2019	BMC Ecology	19	01-11
03_an_21	Amphibia	Anura	*Scinax nasicus*	nature	traffic	Argentina	Leon et al.	2019	Iheringia	109	01-08
03_av_21	Bird	Passeriformes	*Troglodytes aedon grenadensis*	nature	urban	Grenada	Cyr et al.	2020	Bioacustics		01-14
04_av_21	Bird	Passeriformes	*Zosterops lateralis*	experimental	urban	Australia	Potvin and Mulder	2013	Behavioral Ecology	26	1363-1368
05_av_21	Bird	Passeriformes	*Parus major*	experimental	urban	Germany	Templeton et al.	2016	Current Biology	26	1173-1174
06_av_21	Bird	Passeriformes	*Taeniopygia guttata*	experimental	urban	Canada	Potvin and MacDougall-Shacketon	2015	Animal Behaviour	107	201-207
01_an_22	Amphibia	Anura	*Polypedates megacephalus*	nature	aircraft	China	Zhao et al.	2021	Animal Behaviour	182	09-18
01_an_22	Amphibia	Anura	*Occidozyga lima*	nature	aircraft	China	Zhao et al.	2021	Animal Behaviour	182	09-18
01_an_22	Amphibia	Anura	*Hylarana guentheri*	nature	aircraft	China	Zhao et al.	2021	Animal Behaviour	182	09-18
01_an_22	Amphibia	Anura	*Microhyla fissipes*	nature	aircraft	China	Zhao et al.	2021	Animal Behaviour	182	09-18
02_av_22	Bird	Passeriformes	*Zosterops simplex*	nature	urban	Hong Kong	To et al.	2021	Behavioral Ecology	32	1042-1053
02_av_22	Bird	Passeriformes	*Passer montanus*	nature	urban	Hong Kong	To et al.	2021	Behavioral Ecology	32	1042-1053
02_av_22	Bird	Passeriformes	*Orthotomus sutorius*	nature	urban	Hong Kong	To et al.	2021	Behavioral Ecology	32	1042-1053
02_av_22	Bird	Passeriformes	*Pycnonotus jocosus*	nature	urban	Hong Kong	To et al.	2021	Behavioral Ecology	32	1042-1053

03_av_22	Bird	Passeriformes	*Troglodytes aedon*	experimental	urban	Brazil	Diniz and Duca	2021	Journal of Avian Biology	52	1-14
04_av_22	Bird	Passeriformes	*Turdus merula*	nature	aircraft	Spain	Sierro et al.	2017	Frontiers in Ecology and Evolution	5	1-13
05_av_22	Bird	Passeriformes	*Hirundo rustica*	nature	urban	Japan	Hasegawa et al.	2021	Biological Journal of the Linnean Society	133	57-67
06_av_22	Bird	Passeriformes	*Troglodytes aedon musculus*	nature	traffic	Brazil	Sementili-Cardoso and Donatelli	2021	Urban Ecosystems	24	1001-1009
07_av_22	Bird	Passeriformes	*Zonotrichia leucophrys nuttalli*	experimental	urban	United States	Gentry et al.	2017	Ecosphere	8	1-13

Table S2. Study data with effect size.

study	classe	species_study	species_phylogenetic_signal	signal	n_total	n_c	n_n	yi	vi
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	call rate	78	40	38	-1.48552	0.06447
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	call rate	76	40	36	-2.47587	0.090195
10_an	Anura	*Dendropsophus triangulum*	*dendropsophus triangulum*	call rate	44	22	22	5.4993	0.466546
10_an	Anura	*Dendropsophus triangulum*	*dendropsophus triangulum*	call rate	44	22	22	6.474746	0.611623
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	call rate	38	19	19	-1.28023	0.129186
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	call rate	38	19	19	-0.50728	0.109019
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	call rate	38	19	19	0.461969	0.108378
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	call rate	38	19	19	-0.09104	0.105384
17_an	Anura	*Hyperolius pickersgilli*	*hyperolius pickersgilli*	call rate	30	20	10	1.739534	0.207622
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	call rate	10	5	5	-1.03375	0.485076
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	call rate	10	5	5	0.364455	0.410575
02_an	Anura	*Odontophrynus americanus*	*odontophrynus americanus*	dominant frequency	330	178	152	1.471411	0.015515

04_an	Anura	*Hyla arborea*	*hyla arborea*	dominant frequency	42	21	21	0.97918	0.10777
04_an	Anura	*Hyla arborea*	*hyla arborea*	dominant frequency	42	21	21	0.709712	0.101821
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	dominant frequency	58	29	29	-0.60288	0.072315
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	dominant frequency	58	29	29	-0.85752	0.075742
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	dominant frequency	28	14	14	0.169459	0.143449
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	dominant frequency	20	6	14	-0.22344	0.143886
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	dominant frequency	28	14	14	0.414369	0.146396
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	dominant frequency	28	14	14	-0.59037	0.150041
14_an	Anura	*Pelophylax ridibundus*	*pelophylax ridibundus*	dominant frequency	50	25	25	-0.58345	0.08368
17_an	Anura	*Hyperolius pickersgilli*	*hyperolius pickersgilli*	dominant frequency	12	6	6	0.9122	0.383623
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	dominant frequency	10	5	5	-0.07405	0.400436
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	dominant frequency	10	5	5	1.168813	0.508759
02_an	Anura	*Odontophrynus americanus*	*odontophrynus americanus*	call duration	330	178	152	0.422843	0.012471
04_an	Anura	*Hyla arborea*	*hyla arborea*	call duration	42	21	21	-0.98111	0.107819
04_an	Anura	*Hyla arborea*	*hyla arborea*	call duration	42	21	21	2.019112	0.148523
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	call duration	58	29	29	-1.77577	0.098027
08_an	Anura	*Pseudacris crucifer*	*pseudacris crucifer*	call duration	58	29	29	-4.57568	0.26192
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	call duration	28	14	14	-1.33196	0.179425
12_an	Anura	*Boana bischoffi*	*boana bischoffi*	call duration	28	14	14	0.970826	0.162284
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	call duration	28	14	14	0.970826	0.162284
12_an	Anura	*Boana leptolineata*	*boana leptolineata*	call duration	28	14	14	1.941653	0.220564
23_an	Anura	*Hyla arborea*	*hyla arborea*	call duration	100	50	50	1.006986	0.045268
23_an	Anura	*Hyla arborea*	*hyla arborea*	dominant frequency	100	50	50	1.707724	0.055149
06_an	Anura	*Rana clamitans*	*rana clamitans*	call rate	50	25	25	-2.66253	0.156632
06_an	Anura	*Rana clamitans*	*rana clamitans*	call rate	48	25	23	-2.87573	0.176913
06_an	Anura	*Rana pipiens*	*rana pipiens*	call rate	24	12	12	-4.70538	0.713096
06_an	Anura	*Rana pipiens*	*rana pipiens*	call rate	17	12	5	-3.97311	0.878373
06_an	Anura	*Hyla versicolor*	*dryophytes versicolor*	call rate	22	11	11	-4.2881	0.685306

06_an	Anura	*Hyla versicolor*	*dryophytes versicolor*	call rate	19	11	8	-5.77485	1.308423
06_an	Anura	*Bufo americanus*	*anaxyrus americanus*	call rate	28	14	14	-0.67696	0.152303
06_an	Anura	*Bufo americanus*	*anaxyrus americanus*	call rate	20	14	6	0.003719	0.238096
06_an	Anura	*Hyla versicolor*	*dryophytes versicolor*	dominant frequency	19	11	8	0.068953	0.197132
06_an	Anura	*Bufo americanus*	*anaxyrus americanus*	dominant frequency	20	14	6	-1.0889	0.248042
06_an	Anura	*Rana clamitans*	*rana clamitans*	dominant frequency	50	25	25	5.409503	0.370134
06_an	Anura	*Hyla versicolor*	*dryophytes versicolor*	dominant frequency	22	11	11	-1.4643	0.217002
06_an	Anura	*Bufo americanus*	*anaxyrus americanus*	dominant frequency	28	14	14	0	0.134657
02_in	Insecta	*Chorthippus biguttulus*	*chorthippus biguttulus*	maximum frequency	188	94	94	3.889923	0.062339
03_in	Insecta	*Chorthippus biguttulus*	*chorthippus biguttulus*	maximum frequency	346	173	173	1.441608	0.014597
03_in	Insecta	*Chorthippus biguttulus*	*chorthippus biguttulus*	maximum frequency	346	173	173	2.674609	0.022011
04_in	Insecta	*Cryptotympana takasogona*	*cryptotympana takasagona*	dominant frequency	86	44	42	0.499628	0.048054
03_av	Bird	*Streptopelia chinensis*	*streptopelia chinensis*	dominant frequency	22	7	15	-0.16023	0.210227
03_av	Bird	*Streptopelia chinensis*	*streptopelia chinensis*	minimum frequency	22	7	15	0.438163	0.214781
03_av	Bird	*Streptopelia chinensis*	*streptopelia chinensis*	maximum frequency	22	7	15	-1.73741	0.292178
07_av	Bird	*Trichoglossus haematodus*	*trichoglossus haematodus*	dominant frequency	103	44	59	-1.06915	0.045435
07_av	Bird	*Platycercus eximius*	*platycercus eximius*	dominant frequency	29	19	10	0.886985	0.168206
07_av	Bird	*Anthochaera carunculata*	*anthochaera carunculata*	dominant frequency	82	49	33	0.288372	0.051243
07_av	Bird	*Anthochaera carunculata*	*anthochaera carunculata*	minimum frequency	82	49	33	2.476477	0.089898
07_av	Bird	*Manorina melanocephala*	*manorina melanocephala*	dominant frequency	55	31	24	4.928854	0.310918
07_av	Bird	*Manorina melanocephala*	*manorina melanocephala*	minimum frequency	55	31	24	2.957312	0.159242
07_av	Bird	*Strepera graculina*	*strepera graculina*	dominant frequency	27	17	10	-2.90894	0.340736
07_av	Bird	*Strepera graculina*	*strepera graculina*	minimum frequency	27	17	10	0	0.158824
07_av	Bird	*Gymnorhina tibicen*	*gymnorhina tibicen*	dominant frequency	75	56	19	-1.13601	0.079545
07_av	Bird	*Gymnorhina tibicen*	*gymnorhina tibicen*	minimum frequency	75	56	19	1.500674	0.086292
07_av	Bird	*Cracticus torquatus*	*cracticus torquatus*	dominant frequency	40	21	19	0	0.100251

07_av	Bird	*Cracticus torquatus*	*cracticus torquatus*	minimum frequency	40	21	19	2.204656	0.167283
07_av	Bird	*Grallina cyanoleuca*	*grallina cyanoleuca*	dominant frequency	57	23	34	0.887731	0.080289
07_av	Bird	*Grallina cyanoleuca*	*grallina cyanoleuca*	minimum frequency	57	23	34	1.455196	0.092772
07_av	Bird	*Rhipidura leucophrys*	*rhipidura leucophrys*	minimum frequency	24	9	15	0	0.177778
07_av	Bird	*Acridotheres tristis*	*acridotheres tristis*	dominant frequency	47	15	32	-0.15881	0.098208
07_av	Bird	*Acridotheres tristis*	*acridotheres tristis*	minimum frequency	47	15	32	1.858345	0.137837
07_av	Bird	*Turdus merula*	*turdus merula*	dominant frequency	26	11	15	-0.78523	0.171426
07_av	Bird	*Turdus merula*	*turdus merula*	minimum frequency	26	11	15	2.983162	0.357483
09_av	Bird	*Parus minor*	*parus minor*	maximum frequency	13	9	4	0.942267	0.408997
09_av	Bird	*Parus minor*	*parus minor*	minimum frequency	13	9	4	1.741126	0.524613
11_av	Bird	*Zonotrichia capensis*	*zonotrichia capensis*	minimum frequency	70	23	47	0.44563	0.066254
11_av	Bird	*Zonotrichia capensis*	*zonotrichia capensis*	minimum frequency	70	23	47	1.488691	0.08148
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	song duration	20	8	12	-3.16816	0.51695
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	maximum frequency	20	8	12	3.899688	0.675923
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	maximum frequency	20	8	12	2.527238	0.404713
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	maximum frequency	20	8	12	3.355704	0.554569
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	minimum frequency	20	8	12	0.268772	0.210554
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	minimum frequency	20	8	12	9.268113	2.849448
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	dominant frequency	20	8	12	3.332436	0.549784
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	dominant frequency	20	8	12	4.974053	0.969054
13_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	dominant frequency	20	8	12	5.969629	1.304053
15_av	Bird	*Gymnorhina tibicen*	*gymnorhina tibicen*	song duration	60	30	30	0	0.066667
15_av	Bird	*Gymnorhina tibicen*	*gymnorhina tibicen*	song rate	60	30	30	0	0.066667
17_av	Bird	*Turdus merula*	*turdus merula*	minimum frequency	18	9	9	0.953837	0.254115

17_av	Bird	*Turdus merula*	*turdus merula*	minimum frequency	18	9	9	2.058019	0.370695
17_av	Bird	*Turdus merula*	*turdus merula*	maximum frequency	18	9	9	1.094154	0.264189
17_av	Bird	*Turdus merula*	*turdus merula*	maximum frequency	18	9	9	1.976752	0.359201
18_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song duration	44	22	22	-3.15371	0.253127
18_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song rate	44	22	22	-3.80359	0.319122
23_av	Bird	*Troglodytes aedon*	*troglodytes aedon*	minimum frequency	20	14	6	6.961075	1.727996
23_av	Bird	*Troglodytes aedon*	*troglodytes aedon*	maximum frequency	20	14	6	-4.55809	0.876903
25_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	dominant frequency	18	9	9	-0.10555	0.222613
25_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	dominant frequency	16	8	8	0.828553	0.277985
30_av	Bird	*Zosterops lateralis*	*zosterops lateralis*	note duration	81	37	44	0.662753	0.052597
31_av	Bird	*Turdus merula*	*turdus merula*	song duration	33	17	16	-1.25811	0.148375
31_av	Bird	*Turdus merula*	*turdus merula*	dominant frequency	33	17	16	2.434857	0.222644
31_av	Bird	*Turdus merula*	*turdus merula*	dominant frequency	33	17	16	0.65796	0.128722
05_av	Bird	*Copsychus saularis*	*copsychus saularis*	song duration	23	12	11	1.073741	0.204173
22_av	Bird	*Poecile atricapillus*	*poecile atricapillus*	dominant frequency	156	78	78	5.345447	0.119479
01_av	Bird	*Carpodacus mexicanus*	*haemorhous mexicanus*	minimum frequency	20	10	10	2.735738	0.43012
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song duration	28	11	17	-0.93385	0.167708
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song duration	42	27	15	3.139559	0.232535
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song rate	28	11	17	-0.31989	0.151842
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song rate	42	27	15	-2.67821	0.197454
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song duration	18	9	9	-1.39355	0.290298
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song duration	28	14	14	0.302825	0.144747
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song rate	18	9	9	-2.75096	0.48751
02_av	Bird	*Emberiza schoeniclus*	*emberiza schoeniclus*	song rate	28	14	14	-2.40603	0.262179
16_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song duration	36	18	18	-4.45691	0.419025
16_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song rate	36	18	18	1.781354	0.160299
28_av	Bird	*Venilliornis passerinus*	*veniliornis passerinus*	dominant frequency	12	7	5	0.647602	0.368204
28_av	Bird	*Picumnus albosquamatus*	*picumnus albosquamatus*	dominant frequency	42	24	18	0.281718	0.09826

28_av	Bird	*Cantorchilus leucotis*	*thryothorus leucotis*	dominant frequency	49	25	24	0.933093	0.091286
28_av	Bird	*Cyclarhis gujanensis*	*cyclarhis gujanensis*	dominant frequency	67	35	32	0.120968	0.059937
28_av	Bird	*Basileuterus culicivorus*	*basileuterus culicivorus*	dominant frequency	77	41	36	1.112299	0.060613
28_av	Bird	*Myiothlypis flaveola*	*basileuterus flaveolus*	dominant frequency	65	27	38	0	0.063353
28_av	Bird	*Antilophia galeata*	*antilophia galeata*	dominant frequency	56	28	28	0.512616	0.073943
28_av	Bird	*Leptopogon amaurocephalus*	*leptopogon amaurocephalus*	dominant frequency	20	11	9	0.811835	0.222285
28_av	Bird	*Tolmomyias sulphurescens*	*tolmomyias sulphurescens*	dominant frequency	109	73	36	0.832285	0.044767
29_av	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	minimum frequency	21	11	10	10.51236	3.392048
35_av	Bird	*Zosterops lateralis*	*zosterops lateralis*	maximum frequency	34	17	17	0.057883	0.117702
35_av	Bird	*Zosterops lateralis*	*zosterops lateralis*	minimum frequency	34	17	17	-1.29237	0.145248
35_av	Bird	*Zosterops lateralis*	*zosterops lateralis*	dominant frequency	34	17	17	-1.00242	0.134253
35_av	Bird	*Zosterops lateralis*	*zosterops lateralis*	song duration	34	17	17	-0.91733	0.131553
38_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	minimum frequency	18	9	9	6.844339	1.86437
38_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	minimum frequency	18	9	9	8.979662	3.048853
38_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song duration	18	9	9	-1.42345	0.293251
38_av	Bird	*Erithacus rubecula*	*erithacus rubecula*	song duration	18	9	9	-3.44076	0.637232
39_av	Bird	*Zonotrichia leucophrys nuttalli*	*zonotrichia leucophrys nuttalli*	minimum frequency	98	42	56	1.626929	0.055708
40_av	Bird	*Parus major*	*parus major*	dominant frequency	29	12	17	-0.05341	0.142213
41_av	Bird	*Passer domesticus*	*passer domesticus*	dominant frequency	22	11	11	0.095325	0.182067
41_av	Bird	*Thryomanes bewickii*	*thryomanes bewickii*	dominant frequency	10	5	5	0.333496	0.408854
41_av	Bird	*Melozone fusca*	*kieneria fusca*	dominant frequency	32	16	16	-0.18082	0.125579
41_av	Bird	*Pheucticus melanocephalus*	*pheucticus melanocephalus*	dominant frequency	26	13	13	-0.44589	0.158312
48_av	Bird	*Turdus merula*	*turdus merula*	amplitude	33	17	16	1.1623	0.1427
48_av	Bird	*Turdus merula*	*turdus merula*	dominant frequency	33	17	16	0.526329	0.126058
59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	minimum frequency	17			0.501784	0.267067
59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	minimum frequency	17			0.505848	0.267221

59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	dominant frequency	17			0.772205	0.280053
59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	dominant frequency	17			0.328142	0.261635
59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	maximum frequency	17			0.013311	0.257582
59_av	Bird	*Zonotrichia leucophrys*	*zonotrichia leucophrys nuttalli*	maximum frequency	17			0.511417	0.267435
01_an	Anura	*Anaxyrus quercicus*	*anaxyrus quercicus*	call duration	21			0.8253	0.2081
01_an	Anura	*Anaxyrus quercicus*	*anaxyrus quercicus*	call rate	21			0.7448	0.2048
01_av	Bird	*Carpodacus mexicanus*	*haemorhous mexicanus*	song duration	20	10	10	0.5568	0.4566
01_av	Bird	*Carpodacus mexicanus*	*haemorhous mexicanus*	maximum frequency	20	10	10	0	0.2
52_av	Bird	*Troglodytes troglodytes*	*troglodytes troglodytes*	note duration	74			0.459	0.0555
52_av	Bird	*Troglodytes troglodytes*	*troglodytes troglodytes*	maximum frequency	74			0.5435	0.0561
52_av	Bird	*Troglodytes troglodytes*	*troglodytes troglodytes*	minimum frequency	74			0.3527	0.0549
53_av	Bird	*Turdus migratorius*	*turdus migratorius*	minimum frequency	7			0.9633	0.6649
53_av	Bird	*Dumetella carolinensis*	*dumetella carolinensis*	minimum frequency	8			5.1562	2.6975
53_av	Bird	*Cardinalis cardinalis*	*cardinalis cardinalis*	minimum frequency	45			0.5844	0.0928
53_av	Bird	*Dumetella carolinensis*	*dumetella carolinensis*	maximum frequency	8			1.8188	0.7734
53_av	Bird	*Cardinalis cardinalis*	*cardinalis cardinalis*	maximum frequency	45			0.6756	0.0941
53_av	Bird	*Throglodytes aedon*	*troglodytes aedon*	minimum frequency	16			0.7429	0.2693
56_av	Bird	*Troglodytes musculus*	*troglodytes musculus*	song duration	36			1.1134	0.1291
57_av	Bird	*Turdus leucomelas*	*turdus leucomelas*	minimum frequency	36			0.2258	0.119
57_av	Bird	*Turdus leucomelas*	*turdus leucomelas*	maximum frequency	36			0.9474	0.1242
57_av	Bird	*Turdus leucomelas*	*turdus leucomelas*	note duration	75			-0.2575	0.0538
62_av	Bird	*Melospiza melodia*	*melospiza melodia*	note duration	28			-0.5884	0.1494
58_av	Bird	*Parus major*	*parus major*	note duration	40	20	20	0.4581	0.1027
58_av	Bird	*Parus major*	*parus major*	dominant frequency	40	20	20	-0.8824	0.1101
26_av	Bird	*Cardinalis cardinalis*	*cardinalis cardinalis*	song duration	42			0.2141	0.0958
26_av	Bird	*Cardinalis cardinalis*	*cardinalis cardinalis*	song rate	42			0.503	0.0984
26_av	Bird	*Cardinalis cardinalis*	*cardinalis cardinalis*	dominant frequency	42			0.2365	0.0959

26_av	Bird	*Turdus migratorius*	*turdus migratorius*	song duration	53			0.1914	0.0758
26_av	Bird	*Turdus migratorius*	*turdus migratorius*	dominant frequency	53			0.0541	0.0755
26_av	Bird	*Turdus migratorius*	*turdus migratorius*	song rate	53			0.2182	0.0759
50_av	Bird	*Carpodacus mexicanus*	*haemorhous mexicanus*	note duration	35			-0.548	0.1188
45_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	minimum frequency	20			0.3409	0.2032
45_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	maximum frequency	20			0.2059	0.2012
45_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	minimum frequency	63	31	32	0.4128	0.0649
45_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	maximum frequency	63	31	32	0.7978	0.0687
61_av	Bird	*Parus major*	*parus major*	song duration	22			0.3407	0.1847
61_av	Bird	*Parus major*	*parus major*	dominant frequency	22			0.2752	0.1837
54_av	Bird	*Troglodytes pacificus*	*troglodytes pacificus*	song duration	52			0.5524	0.0799
49_av	Bird	*Parus major*	*parus major*	dominant frequency	10			0.6284	0.4242
49_av	Bird	*Parus major*	*parus major*	note duration	10			2.9957	0.95
08_av	Bird	*Spizella passerina*	*spizella passerina*	minimum frequency	45			1.0193	0.1008
08_av	Bird	*Spizella passerina*	*spizella passerina*	song duration	45			-0.2913	0.0763
24_av	Bird	*Agelaius phoeniceus*	*agelaius phoeniceus*	song rate	59			-0.0789	0.0728
01_in	Insecta	*Oecanthus sps.*	*oecanthus alexanderi*	dominant frequency	54			0.4391	0.0759
20_av	Bird	*Colluricincla harmonica*	*colluricincla harmonica*	dominant frequency	27			0.687222	0.162828
20_av	Bird	*Rhipidura fuliginosa*	*rhipidura fuliginosa*	dominant frequency	22			0.047731	0.176393
13_an	Anura	*Litoria ewingii*	*litoria ewingii*	dominant frequency	24			0.759454	0.187203
13_an	Anura	*Crinia signifera*	*crinia signifera*	dominant frequency	28			0.200675	0.141135
01_in_21	Insecta	*Gryllus bimaculatus*	*gryllus bimaculatus*	dominant frequency	25	18	7	-0.05919	0.198495
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	call rate	80	40	40	1.795961	0.07115
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	call rate	80	40	40	-2.37839	0.087092
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	call duration	42	21	21	-0.1505	0.095534
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	call duration	30	15	15	-0.7462	0.143937
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	dominant frequency	42	21	21	-1.45981	0.123091
02_an_21	Anura	*Buergeria japonica*	*buergeria japonica*	dominant frequency	30	15	15	0.769947	0.144622
01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	dominant frequency	68	30	38	-6.07576	0.346911

01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	dominant frequency	36	18	18	-0.99503	0.126459
01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	maximum frequency	36	18	18	-2.08497	0.178496
01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	maximum frequency	68	30	38	-4.39076	0.209672
01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	minimum frequency	68	30	38	-3.05788	0.132413
01_av_21	Bird	*Phylloscopus collybita*	*phylloscopus collybita*	minimum frequency	36	18	18	0.177509	0.1116
02_av_21	Bird	*Turdus philomelos*	*turdus philomelos*	minimum frequency	58	35	23	2.912786	0.150241
02_av_21	Bird	*Turdus philomelos*	*turdus philomelos*	dominant frequency	58	35	23	2.35512	0.123167
02_av_21	Bird	*Turdus philomelos*	*turdus philomelos*	minimum frequency	58	35	23	1.224586	0.08587
02_av_21	Bird	*Turdus philomelos*	*turdus philomelos*	dominant frequency	58	35	23	1.27459	0.087022
03_an_21	Anura	*Scinax nasicus*	*scinax nasicus*	dominant frequency	98	39	59	14.58177	1.170566
03_an_21	Anura	*Scinax nasicus*	*scinax nasicus*	call duration	98	39	59	-10.0624	0.579722
03_an_21	Anura	*Scinax nasicus*	*scinax nasicus*	call rate	98	39	59	-5.78016	0.219829
03_av_21	Bird	*Troglodytes aedon*	*troglodytes aedon*	minimum frequency	10	5	5	-0.12241	0.401193
03_av_21	Bird	*Troglodytes aedon*	*troglodytes aedon*	maximum frequency	10	5	5	-0.02837	0.400064
03_av_21	Bird	*Troglodytes aedon*	*troglodytes aedon*	song duration	10	5	5	0.221682	0.403912
06_an	Anura	*Bufo americanus*	*anaxyrus americanus*	amplitude	28	14	14	0.785168	0.155564
06_an	Anura	*Hyla versicolor*	*dryophytes versicolor*	amplitude	25	11	14	1.078843	0.189712
06_an	Anura	*Rana clamitans*	*rana clamitans*	amplitude	50	25	25	-3.31337	0.198675
06_an	Anura	*Rana pipiens*	*rana pipiens*	amplitude	34	17	17	-3.16932	0.28364
03_an_21	Anura	*Scinax nasicus*	*scinax nasicus*	amplitude	98	39	59	3.666631	0.113911
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	amplitude	10	5	5	0.803627	0.451414
20_an	Anura	*Kurixalus chaseni*	*kurixalus appendiculatus*	amplitude	10	5	5	1.132364	0.502082
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	minimum frequency	45	25	20	0.197276	0.090472
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	minimum frequency	45	25	20	1.116227	0.105101
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	amplitude	45	25	20	0.908082	0.099994
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	minimum frequency	45	25	20	-1.5646	0.119669
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	song duration	45	25	20	1.964878	0.136792
04_av_21	Bird	*Zosterops lateralis*	*zosterops lateralis*	amplitude	45	25	20	5.922805	0.51516
05_av_21	Bird	*Parus major*	*parus major*	amplitude	20	10	10	1.780491	0.297473

05_av_21	Bird	*Parus major*	*parus major*	dominant frequency	20	10	10	0.293516	0.202649
05_av_21	Bird	*Parus major*	*parus major*	minimum frequency	20	10	10	0.160154	0.200789
05_av_21	Bird	*Parus major*	*parus major*	maximum frequency	20	10	10	0.327542	0.203299
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	minimum frequency	20	10	10	0.031552	0.200031
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	maximum frequency	20	10	10	0.299795	0.202763
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	dominant frequency	20	10	10	0.332527	0.2034
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	amplitude	20	10	10	0.986002	0.229892
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	note duration	20	10	10	-0.07877	0.200191
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	minimum frequency	20	10	10	-0.92963	0.226572
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	maximum frequency	20	10	10	0.440792	0.205974
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	dominant frequency	20	10	10	-0.04588	0.200065
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	amplitude	20	10	10	0.223395	0.201534
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	note duration	20	10	10	-0.11293	0.200392
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	minimum frequency	20	10	10	-1.03644	0.233029
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	maximum frequency	20	10	10	-0.17844	0.200979
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	dominant frequency	20	10	10	0.236822	0.201724
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	amplitude	20	10	10	0.631603	0.212266
06_av_21	Bird	*Taeniopygia guttata*	*taeniopygia guttata*	note duration	20	10	10	0.687789	0.214545
01_an_22	Anura	*Polypedates megacephalus*	*polypedates megacephalus*	dominant frequency	34	17	17	0.396127	0.12024
01_an_22	Anura	*Polypedates megacephalus*	*polypedates megacephalus*	call rate	34	17	17	-0.64084	0.124434
01_an_22	Anura	*Polypedates megacephalus*	*polypedates megacephalus*	call duration	34	17	17	-0.40224	0.120321
01_an_22	Anura	*Occidozyga lima*	*occidozyga lima*	dominant frequency	38	19	19	0.153229	0.105606
01_an_22	Anura	*Occidozyga lima*	*occidozyga lima*	call rate	38	19	19	-0.11701	0.105463
01_an_22	Anura	*Occidozyga lima*	*occidozyga lima*	call duration	38	19	19	-0.08206	0.105361
01_an_22	Anura	*Hylarana guentheri*	*hylarana guentheri*	dominant frequency	36	18	18	0.03773	0.111133
01_an_22	Anura	*Hylarana guentheri*	*hylarana guentheri*	call rate	36	18	18	-0.36369	0.113161
01_an_22	Anura	*Hylarana guentheri*	*hylarana guentheri*	call duration	36	18	18	0.074104	0.111196

01_an_22	Anura	*Microhyla fissipes*	*microhyla fissipes*	dominant frequency	36	18	18	-0.01073	0.111113
01_an_22	Anura	*Microhyla fissipes*	*microhyla fissipes*	call rate	36	18	18	-0.43899	0.114098
01_an_22	Anura	*Microhyla fissipes*	*microhyla fissipes*	call duration	36	18	18	0.005364	0.111112
02_av_22	Bird	*Zosterops simplex*	*zosterops simplex*	minimum frequency	41	19	22	0.722868	0.105099
02_av_22	Bird	*Zosterops simplex*	*zosterops simplex*	maximum frequency	41	19	22	2.605206	0.189176
02_av_22	Bird	*Zosterops simplex*	*zosterops simplex*	dominant frequency	41	19	22	2.009183	0.152264
02_av_22	Bird	*Passer montanus*	*passer montanus*	minimum frequency	38	16	22	3.336464	0.270439
02_av_22	Bird	*Passer montanus*	*passer montanus*	maximum frequency	38	16	22	1.286163	0.1321
02_av_22	Bird	*Passer montanus*	*passer montanus*	dominant frequency	38	16	22	3.410746	0.277755
02_av_22	Bird	*Orthotomus sutorius*	*orthotomus sutorius*	minimum frequency	19	9	10	4.898892	0.997326
02_av_22	Bird	*Orthotomus sutorius*	*orthotomus sutorius*	maximum frequency	19	9	10	2.462629	0.409786
02_av_22	Bird	*Orthotomus sutorius*	*orthotomus sutorius*	dominant frequency	19	9	10	2.698319	0.449635
02_av_22	Bird	*Pycnonotus jocosus*	*pycnonotus jocosus*	minimum frequency	18	9	9	-0.84116	0.247025
02_av_22	Bird	*Pycnonotus jocosus*	*pycnonotus jocosus*	maximum frequency	18	9	9	-1.75301	0.329948
02_av_22	Bird	*Pycnonotus jocosus*	*pycnonotus jocosus*	dominant frequency	18	9	9	-1.80196	0.336047
03_av_22	Bird	*Troglodytes aedon musculus*	*troglodytes aedon*	song rate	30	11	19	0.279535	0.145029
03_av_22	Bird	*Troglodytes aedon musculus*	*troglodytes aedon*	song duration	30	11	19	0.421135	0.146918
03_av_22	Bird	*Troglodytes aedon musculus*	*troglodytes aedon*	minimum frequency	30	11	19	0.53069	0.148904
03_av_22	Bird	*Troglodytes aedon musculus*	*troglodytes aedon*	maximum frequency	30	11	19	0.077646	0.143655
04_av_22	Bird	*Turdus merula*	*turdus merula*	minimum frequency	32	16	16	0.108088	0.125207
04_av_22	Bird	*Turdus merula*	*turdus merula*	maximum frequency	32	16	16	0.077965	0.125108
04_av_22	Bird	*Turdus merula*	*turdus merula*	minimum frequency	32	16	16	0.119546	0.125253
04_av_22	Bird	*Turdus merula*	*turdus merula*	maximum frequency	32	16	16	-0.08331	0.125123
05_av_22	Bird	*Hirundo rustica*	*hirundo rustica*	note duration	36	25	43	-0.71045	0.067184
05_av_22	Bird	*Hirundo rustica*	*hirundo rustica*	dominant frequency	68	25	43	0.249583	0.063741
06_av_22	Bird	*Troglodytes aedon musculus*	*troglodytes aedon*	amplitude	50			1.60036	0.107686

07_av_22	Bird	*Zonotrichia leucophrys nuttalli*	*zonotrichia leucophrys nuttalli*	minimum frequency	34	17	17	-14.3456	3.518542
07_av_22	Bird	*Zonotrichia leucophrys nuttalli*	*zonotrichia leucophrys nuttalli*	maximum frequency	34	17	17	-0.08767	0.117774
07_av_22	Bird	*Zonotrichia leucophrys nuttalli*	*zonotrichia leucophrys nuttalli*	song duration	34	17	17	0	0.117647
07_av_22	Bird	*Zonotrichia leucophrys nuttalli*	*zonotrichia leucophrys nuttalli*	dominant frequency	34	17	17	0.010584	0.117649

Table S3. Result of the multilevel meta-analysis with outliers. Number of records per acoustic parameter, mean effect size (Hedges'g), lower limit, upper limit, standard error (se) and p-value. The results with outliers were similar to the results of the manuscript, with changes in the test values. However, there was no difference in the acoustic parameters affected by anthropogenic noise.

Taxon	**Acoustic Parameter**	**Effect Size**	**Lower Limit**	**Upper Limit**	**se**	***p***
Insects	dominant frequency (Hz)	0.301	-1.26	1.86	0.797	0.7053
	maximum frequency (Hz)	2.174	-0.46	4.81	1.345	0.1060
Anurans	dominant frequency (Hz)	0.419	-0.16	1.00	0.297	0.1580
	call duration (s)	-0.504	-1.67	0.09	0.300	0.0936
	call rate (call/seg)	-0.541	-1.12	0.04	0.299	0.0708
	Amplitude (dB)	1.828	1.13	2.51	0.352	< **.0001**
Birds	dominant frequency (Hz)	0.430	0.06	0.80	0.188	**0.0226**
	minimum frequency (Hz)	0.922	0.54	1.29	0.192	< **.0001**
	maximum frequency (Hz)	0.548	0.15	0.94	0.201	**0.0063**
	song duration (s)	0.259	-0.14	0.66	0.208	0.2129
	note duration (s)	0.579	0.15	1.00	0.216	**0.0075**
	song rate (song/min)	0.357	-0.07	0.79	0.221	0.1057
	Amplitude (dB)	1.724	1.24	2.20	0.243	< **.0001**

Table S1. References

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Capítulo II

Wildfire influence on the zoophony of a National Park

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Abstract

Wildfire is a type of environmental disturbance, which can cause diverse effects on biodiversity, such as loss of richness and changes in species composition. In our study, we evaluated the influence of wildfire on the soundscape. We used autonomous systems to record the soundscape of burned and unburned sites and evaluated the soundcape measuring two acoustic indices: Acoustic Diversity Index (ADI) and Acoustic Evenness Index (AEI). The zoophony was also characterized using the richness of sonotypes in both burned and unburned sites. We found that ADI values were higher at all times in unburned sites, indicating a greater diversity of vocal species. In contrast, AEI was higher in burned areas, indicating less spectral occupation, a more homogeneous, less diverse soundscape, and greater differences in bird sonotype richness among sites. Our results show that acoustic indices and sonotype richness are metrics that enable us to verify soundscape changes in areas affected by wildfire and that passive acoustic monitoring provides a cost-effective way to identify environmental changes caused by disturbances.

Key words: Passive Acoustic Monitoring, Acoustic Indices, Sonotype Richness, Environmental Disturbance, Animal Communication, Bioacoustics.

1. Introduction

Disturbances are ecological processes that cause temporary and spatial changes in communities and can alter their structure and function (White and Pickett 1985; Dornelas 2010). Disturbances can reduce or extinguish some species, on the other hand other species can establish themselves, generating changes in the diversity of the affected communities (Sousa 1984; Petraitis et al. 1989). These changes can be considered positive and negative for communities (Dornelas 2010), depending on the type and frequency of the disturbance (McCabe and Gotelli 2000; Miller et al. 2012).

Fire is a type of disturbance that occurs naturally in many ecosystems (Bowman et al. 2009). However, anthropic actions are also responsible for wildfires and together with environmental factors are responsible for the increase in the frequency of uncontrolled wildfires (Cochrane 2001; Bowman et al. 2009; Balch et al. 2017; Aragão et al. 2018). Frequent and intense wildfires threaten the stability of ecosystems, causing changes in the structure of the habitat (Barbosa and Fearnside 2005). In animals, in addition to reducing the abundance of populations, the change in the structure of vegetation after the fire can generate changes in the species composition (Barton et al. 2014; Berry et al. 2015; Camargo et al. 2018).

Several approaches are used to assess sites that have experienced disturbances, but few methods encompass various groups of animals. An approach that investigates several faunal groups is studies of soundscapes, which are the sounds occurring in an area, detected in determined periods of time (Pijanowski et al. 2011b, a). Soundscapes are classified into biophony, geophony and anthropophony (Pijanowski et al. 2011b, a). Biophony is used for biological sounds, also called “zoophony” (Florence, 1876; Ferreira et al. 2018), geophony are the sounds emitted by geophysical processes (e.g.: rain, wind and thunder) and anthropophony are the acoustic sounds produced by human-made objects (e.g.: cars, airplanes) (Pijanowski et al. 2011b, a).

Studies acoustic ecology (ecoacoustic) has been growing, ecoacoustic investigates the ecological role of sound, suggesting that the characteristics of the soundscape can reflect changes in the ecological state of the landscapes, where it is expected that the soundscapes can be used to assess the impacts of disturbances on wildlife (Pijanowski et al. 2011a). However, the advances in sound scape studies are linked to the development of tools that assist the analysis of big data, such as acoustic indices (Villanueva-Rivera et al. 2011; Towsey et al. 2014) and sound analysis softwares (Villanueva-Rivera and Pijanowiski 2018; Sueur 2008; Towsey et al. 2018). Thus, several studies have tested acoustic indices as indicators of biodiversity and sound detection algorithms in audio files (Fuller et al. 2015; Machado et al. 2017; Mammides et al. 2017; Ferreira et al. 2018; Ng et al. 2018; Moreno-Gómez et al. 2019; Campos et al. 2021). Only a few studies investigate the soundscape to assess the response of animal communities to disturbances (Lee et al. 2017; Gasc et al. 2018; Khanaposhtani et al. 2019; Doser et al. 2020; Duarte et al. 2021).

Two studies investigated the effect of wildfires on the soundscape (Gasc et al. 2018; Duarte et al. 2021). For Gasc et al. (2018) there was a reduction in the number of insect sounds in the burned sites. Duarte et al. (2021) monitored an area before the wildfire and observed the changes that occurred during one year and one month in these areas, showing a reduction in the sonic species of insects and bats after the wildfire.

The use of passive acoustic monitoring to verify changes that occur in a given area can be advantageous, because animals that emit sounds are easily detected, and sounds can be used to identify species. In this study, we use the differences in the recording of the zoophony of soundscapes to study changes in environments that have suffered wildfires compared to unburned ones. Our hypothesis is that environments that have not gone through wildfires have a more diverse and less uniform soundscape. We describe changes in the different types of sounds that make up the soundscape of burned and unburned sites, during 24 hours.

2. Methods

2.1. Study area and experimental design

The study was carried out in the Chapada Diamantina National Park (PNCD), localized in the center of Bahia state, in Brazil. It has an extension of 1520 km^2 in a mountainous region in the north of the Cadeia do Espinhaço, with altitudes that reach 2000 meters above sea level. The vegetation is composed of a mosaic with formations typical of the Caatinga, Cerrado, Campo Rupestre and some enclaves with deciduous and semi-deciduous formations associated with the Atlantic Forest (Juncá et al. 2005). The PNCD is a no use protection area in Brazil, created in 1985, with the intention of protecting fauna and flora due to its relevance and biodiversity (MMA 2007).

The areas within PNCD affected by wildfires were identified by the professionals from the Ministério do Meio Ambiente (MMA) that work in fighting wildfires in the region of the PNCD. We obtained fire data from the year 2008 to 2018, but in our study, we sampled unburned sites and sites that were burned in the years 2015 and 2018, because in the years 2016 and 2017 there were few areas with the occurrence of wildfires. In 2015, a large extension of the PNCD was affected by wildfires (Benfica 2019). After the identification of the areas affected by wildfires, we made four excursions to the areas. These areas are difficult to access, as they are usually located in high elevation within the PNCD, with no marked paths, making it difficult to fight fires in the PNCD (information provided personally by firefighters of the ICMBio brigade).

We conducted our excursions to install the equipment (see session “acoustic recording”) from March to June 2019. In the year 2020 we intended to carry out excursions in the same period, however we started sampling on March 17, and on March 22 the excursion was abruptly interrupted, due to the ordinance ICMBio nº 227/2020, that prohibited entry in the conservation units for all types of activity, where the PNCD is included. These measures were taken as a result of the COVID-19 pandemic. Sampling was carried out in the same season of the year, after the rains of the summer, when the activity of some groups of animals are more intense, for example the amphibians. However, we sampled burned and unburned sites on all excursions.

We installed equipment at 12 sampling points on the PNCD (Figure 1). All of these areas had a high altitude (Table S1) and the vegetation was Campo Rupestre. Half of these sampled sites were in areas burned and the other half in unburned areas. The unburned sites had no fire history since 2008 (Table S1). The sample sites in our study were 350 meters apart from each other and present similar characteristics: same type of vegetation, high altitudes and the presence of a stream nearby.

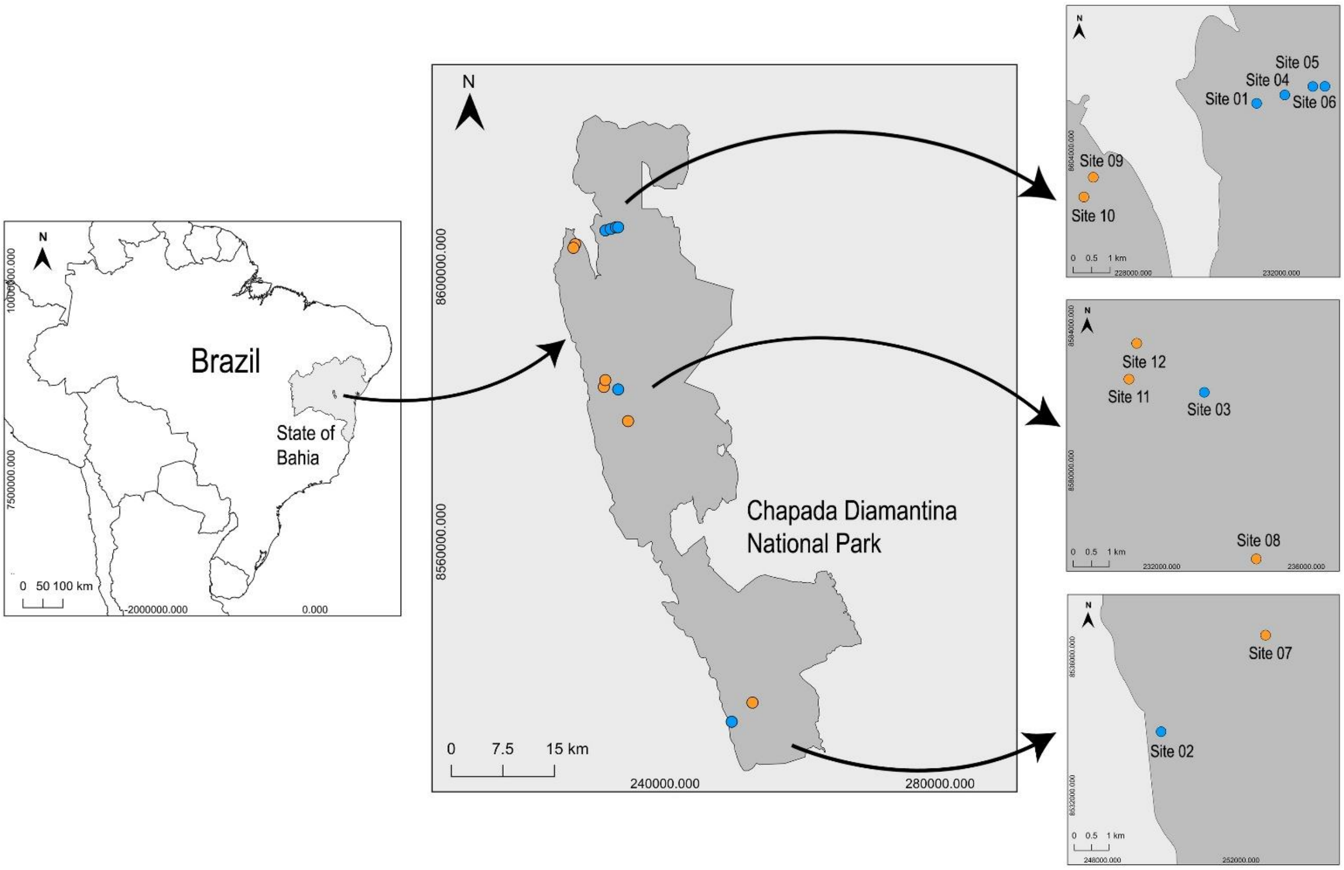

Figure 1. Localization of the 12 recorders at the sampled sites burned (orange) and unburned (blue), in the Chapada Diamantina National Park region, Bahia, Brazil

2.2. Acoustic recording

The recordings were made with automatic recorders Song Meter SM2BAT+ (Wildlife Acoustics Inc., USA), and with omnidirectional microphone weatherproof SMX-II (Wildlife Acoustics Inc., USA). The recorders were installed in a tree at an average height of 1.5 m and, about 2 meters away from the stream. The settings of the recorders were adjusted using the software Song Meter SM2 + Configuration Utility, version 3.2.4 (Wildlife Acoustics, Inc.). We recorded in mono, only on the left channel and with a sampling rate of 96 kHz, for a period of 24 hours, with files separated by the hour.

2.3. Processing and analysis of recordings

We recorded approximately 269 hours of audio. A few seconds in the beginning of each file were not registered, due to separation of files in hours. Also, there was malfunction in some recorders, therefore 04 hours from site 04 and 15 hours from site 08 are missing. To facilitate visual inspection of recordings, we first sectioned the audio files in to one-minute files, totaling 15296 1-minute-audio-files, using the tool “AudioCutter” within the AnalysisPrograms software (Towsey et al. 2020).

To calculate the acoustic indices, we did not include site 08 in the analysis, due to the missing files, for all other sites the indices were calculated for each one minute of audios. To choose which indices to calculate, we evaluated the results obtained by previous studies that verified acoustic indices as indicators of sound diversity (Fuller et al. 2015; Machado et al. 2017; Mammides et al. 2017; Ferreira et al. 2018; Moreno-Gómez et al. 2019). From this assessment, we excluded indices that assess anthropic disturbances and used the indices most indicated by those studies. We used Acoustic Diversity Index (ADI) as a proxy for species diversity, which quantifies the number of unique sounds at different frequency bands, indicating that these sounds are presumably by different taxa (Villanueva-Rivera et al. 2011). The ADI is based on the Shannon index and is derived by dividing the frequency spectrogram into bins and quantifying the proportion of sounds in each bin (Villanueva-Rivera et al. 2011). We configured this index with a 1000 Hz bandwidth bin and a threshold amplitude of -20 dB. We also use the Acoustic Evenness Index (AEI), which is also considered a proxy for species diversity, the AEI applies the Gini index, which is a measure of uniformity (Villanueva-Rivera et al. 2011). AEI varies from 0 to 1, with 0 representing perfect equality, i.e., sounds occurring equally across all frequency bands and 1 representing perfect inequality, with sounds occurring at a single frequency band (Villanueva-Rivera et al. 2011). The AEI configurations were the same as those described for the ADI. All analyses were performed using the “soundecology” package and the “multiple_sounds” function (Villanueva-Rivera and Pijanowiski 2018), in the program R version 4.0.2 (R Core Team 2020).

2.4 Sound detection and sonotype classification

We verified all sound files manually, in order to detect and identify the zoophony of the burned and unburned sites. We classified the detected animal sounds into sonotypes, which refer to acoustic morphospecies, defined as a note or series of notes that constitute a unique acoustic signal, and that presumably represents one type of sound of a species (Aide et al. 2017; Ferreira et al. 2018). We performed a visual and auditory inspection of sound files, registered all existing sonotypes every hour, and created a unique identification code for each sonotype. Next, we classified the zoophony in sonotypes from different taxonomic groups (insects, amphibians, birds and bats), using the number of sonotypes as a measure of richness. The presence of each sonotype was attributed to each hour of recording only once, independently of the number of times the sonotype appeared in that one hour recording. However, a sonotype may have appeared at the same time in burned and unburned sites and also in several hours during the recording period.

Visual and auditory analyses of all sound files were carried out in Raven Pro 1.6.1 software (Center for Conservation Bioacoustics, 2019). This stage was performed by only one researcher (LG) to avoid inter-analyst bias. When sonotypes were classified into different taxonomic groups. We created annotated spectrograms for each sonotype registered in the study (Supplementary Material), the spectrograms were created using the "seewave" package (Sueur et al. 2008), in the program R version 4.0.2 (R Core Team 2020).

2.5. Statistical analyses

To verify if there is a difference in the acoustic indices of the burned and unburned sites, we used Generalized Linear Mixed Models (GLMM). We performed a model for the Acoustic Diversity Index (ADI) and another model for the Acoustic Evenness Index (AEI). We used the values of the acoustic index of each minute as response variable, wildfire areas and control areas (categorized as burned and unburned), hours of the day and year of the sampling as explanatory variables, and different sites of sampling and years of fires as random variables. The models were created with the interaction between area (burned and unburned) and hours of the day. To adjust the model, we used the beta distribution, for ADI and AVI response variables. For the test of the ADI response variable, we transformed the data to proportion values from 0 to 1, using the "scales" package (Wickham and Seidel 2020). Also, for the ADI response variable, we assumed an inflated model of zeros, correcting this problem in the creation of the model. For AEI these adjustments were not necessary.

For GLMM we used the "glmmTMB" package (Brooks et al. 2017), the premises of the test were evaluated using the "DHARMa" package (Hartig 2020), with 1000 randomizations. The graphics were created using the "ggplot2" package (Wickham 2016). All analyses and graphs were performed in R environment, version 4.0.2 (R Core Team 2020).

3. Results

3.1. Differences in acoustic indices between burned and unburned sites

The results from the Acoustic Diversity Index (ADI) showed that there is an impact of wildfires on acoustic diversity, the hour of the day influenced the number of unique sounds at different frequency bands in burned and unburned sites. There was also variation in the average ADI at different times of the day (Table 1). In the burned sites, the ADI values were lower at all hours of the day, showing that there was less acoustic diversity in burned sites. There were differences in the periods with the least number of unique sounds at different frequency bands, as shown in average ADI values. In the unburned sites it was lowest at 18h, in the burned sites, the hours of 20h and 21h, had the lowest acoustic diversity (Figure 2).

The results from the Acoustic Evenness Index (AEI) show, that wildfires also impact how sonic species occupy the soundscape, during the hours of the day there was variation in the number of unique sounds in different frequency bands in burned and unburned sites. The AEI values are higher in the burned sites at different hours of the day (Table 1). The mean of the AEI values at all hours of the day showed that the soundscape of the burned sites was occupied by sounds at similar frequencies. The period between 18 to 23h had the highest average AEI in burned sites, faunal acoustic activity in the evening was occupied by species that used similar frequencies in burned sites. In the unburned sites, the acoustic evenness was highest at 18h (Figure 3).

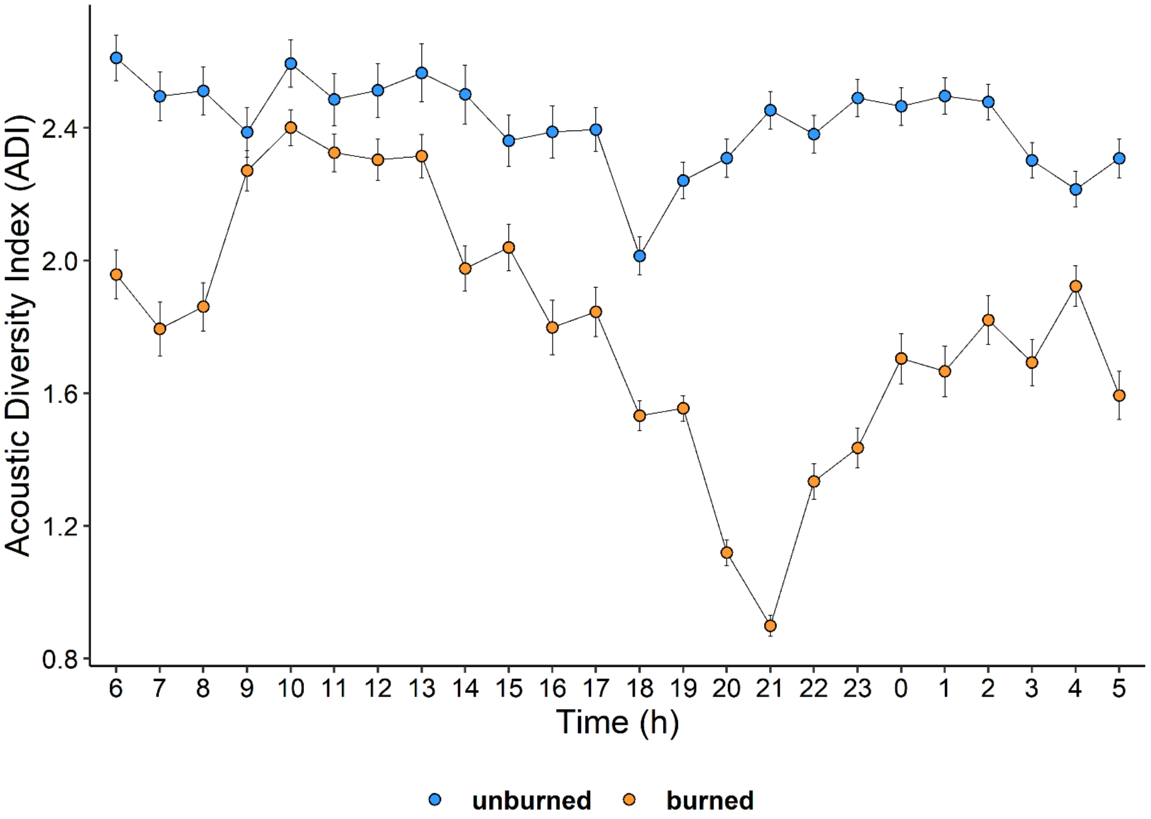

Figure 2. Differences from the mean and standard deviation of the Acoustic Diversity Index (ADI) of the burned and unburned sites.

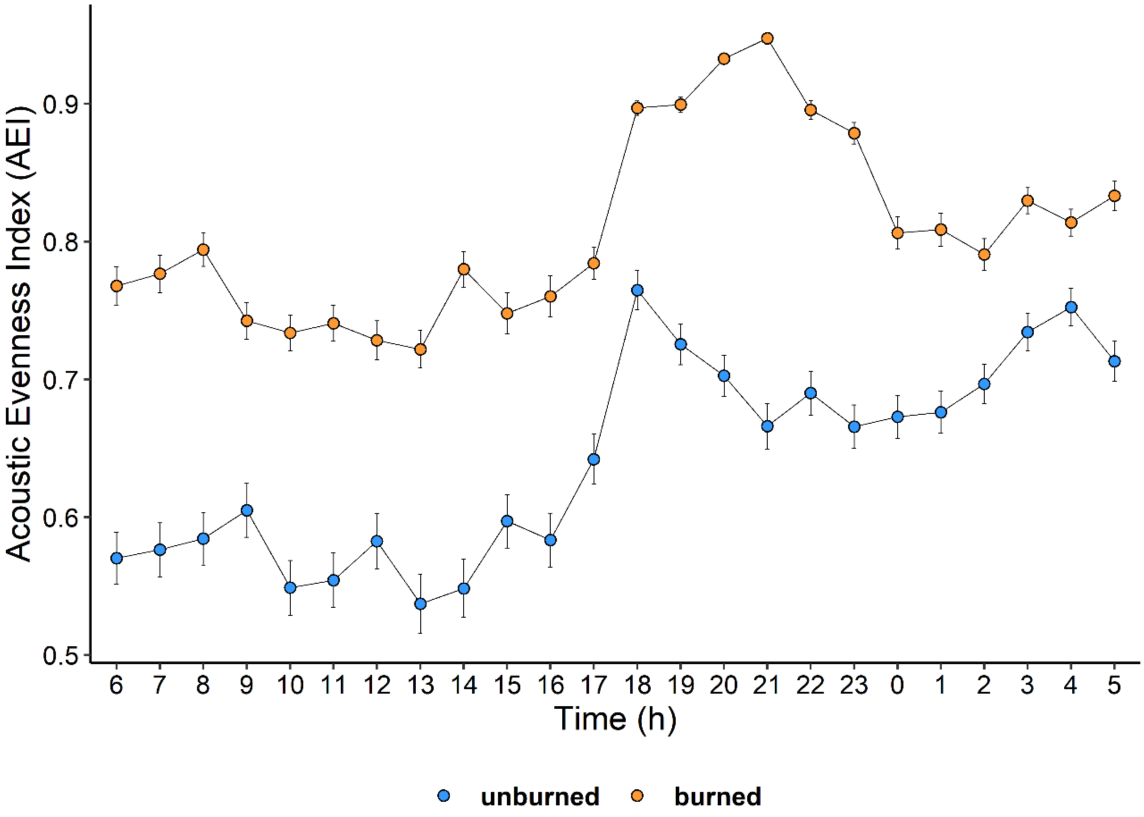

Figure 3. Differences from the mean and standard deviation of the Acoustic Evenness Index (AEI) of the burned and unburned sites.

Table 1. Results Generalized Linear Mixed Models (GLMM) comparing the values of Acoustic Diversity Index (ADI) and Acoustic Evenness Index (AEI) of the burned and unburned sites.

Acoustic index	Variable	Estimate	Standard error	z- value	*p*
ADI	Intercept *	1.170158	0.663695	1.763	0.077
	burned	-0.784941	0.688933	-1.139	0.254
	time	-0.004769	0.001446	-3.299	< 0.001
	sampling year	-0.720762	0.712705	-1.011	0.3118
	burned: time [1]	-0.008670	0.002080	-4.168	< 0.001
AVI	intercept *	0.454519	0.615196	0.739	0.459
	burned	0.589137	0.638597	0.923	0.356
	time	0.004128	0.001344	3.070	< 0.001
	sampling year	0.248265	0.660615	0.376	0.707
	burned: time [1]	0.021947	0.001958	11.211	< 0.001

* Intercept makes reference to unburned sites; [1] Difference of unburned sites

3.2. Sonotype richness in burned and unburned sites

In total, we recorded 85 sonotypes, 12 insect sonotypes, 6 amphibian/ anura sonotypes, 58 bird sonotypes and 9 bat sonotypes (Table S2). In Figure 4 we have examples of soundscapes with different sonotypes. For insects, we had eight sonotypes that occurred in both burned and unburned sites, one exclusive to unburned sites and three sonotypes that only occurred in burned sites. Amphibians had three sonotypes recorded in both sites, two recorded only in unburned sites and one exclusive to burned sites. In the group of bats, we had two sonotypes registered at the two areas, four registered only at the unburned sites and three registered only at the burned sites. The biggest difference between the richness of sonotypes in the burned and unburned sites was in the group of birds, from all 11 sonotypes that occurred in both sites, 31 sonotypes only occurred in the unburned sites and 16 sonotypes only in the burned sites (Table S2).

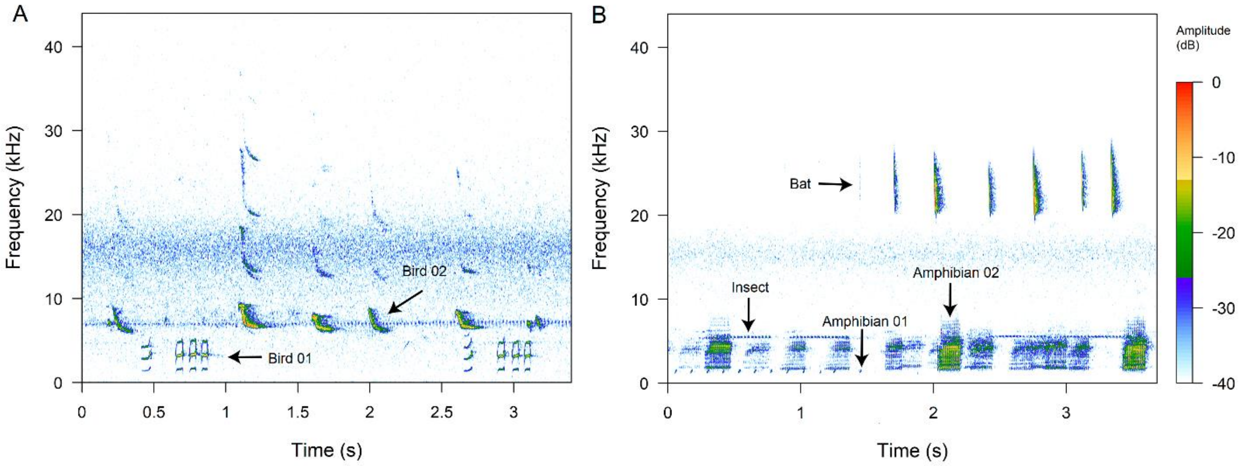

Figure 4. Examples of the zoophony found in the soundscape. a) day soundscape, with the presence of two birds. B) night soundscape, with the presence of two amphibians, one insect and one bat.

The number of registered sonotypes varied between areas, the unburned sites 01 and 02 being the ones with the highest richness of sonotypes (Figure 5). In total, 24 sonotypes were recorded in the burned and unburned sites, 38 sonotypes were recorded only in different unburned sites and 19 sonotypes registered in different burned sites. Eight sonotypes were recorded only in one burned and one unburned site (Figure 5). In the areas burned by wildfire, four sonotypes occurred in two burned sites and only one sonotype in three burned sites (Figure 5). Only two sonotypes were recorded in two unburned sites (Figure 5).

The richness of sonotypes also varied in the hours of the day in the burned and unburned sites. For insects, we obtained a constant richness of sonotypes throughout the night in the unburned sites (Figure 6A), while in the burned sites the richness varied throughout the night (Figure 6B). In the hours of 06h and 07h, we had a greater richness of sonotypes of birds in the unburned sites (Figure 6A). For amphibians, we had one additional sonotype in the unburned sites, for most of the night, compared to the burned sites (Figure 6A). In both areas, we observed one amphibian sonotype during part of the daytime period. In the burned sites at 13h there were only sonotypes of the group of birds active in the burned sites (Figure 6B). Also, we observed that at 05h, 06h and 17h we had more faunal groups since these are hours of transition between day and nighttime (Figure 6A, 6B).

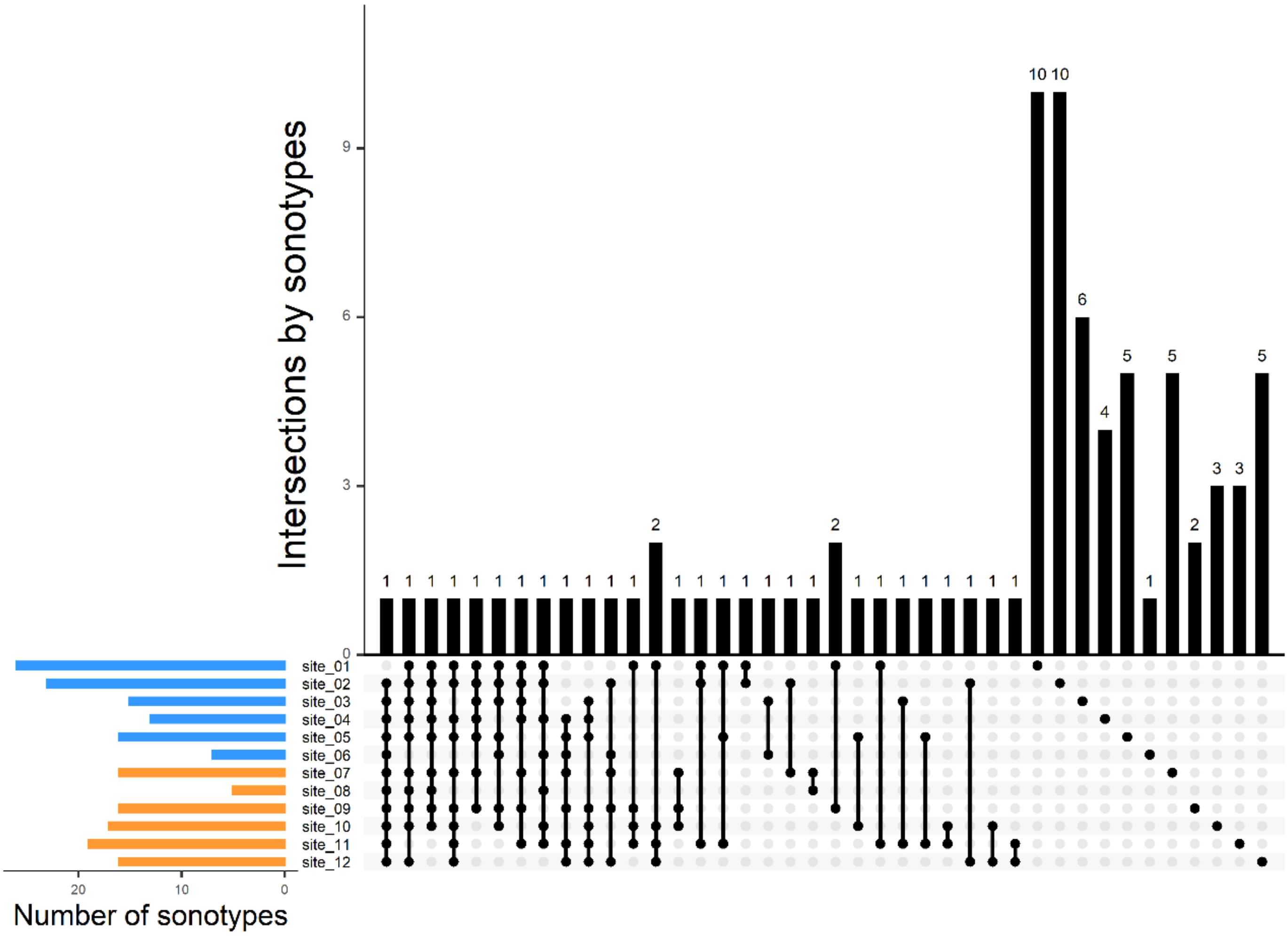

Figure 5. Sonotypes of richness found in each site and intersections between site, in richness of sonotypes, blue bars are from unburned sites, orange bars are from burned sites.

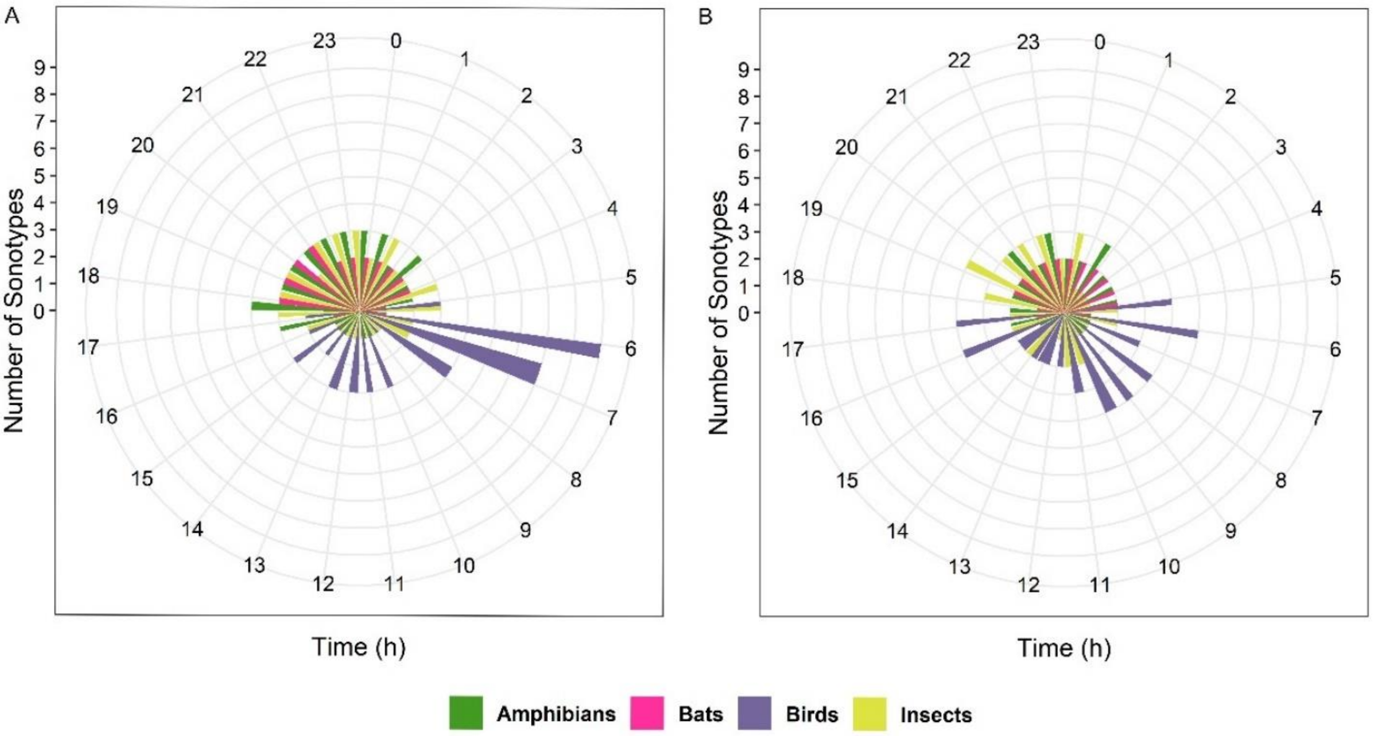

Figure 6. Sonotypes of richness by hours of the day and by groups, a) unburned sites. b) burned sites.

4. Discussion

4.1. Differences in acoustic indices between burned and unburned sites

ADI values were higher at all hours in the unburned sites, indicating that a greater range of frequencies are occupied by faunal acoustic activity in these sites, which suggest a greater diversity of vocal species in these locations. There was a greater difference between burned and unburned sites during the night. This may have occurred because the frequencies of the nocturnal faunal groups that emit sounds different bands. At night times there was greater activity of amphibians and insects, but bats were also active. Presence of species of nocturnal habits may be responsible for the difference in ADI in the burned and unburned sites at night. We also observed that from

09h to 11h, both burned and unburned areas had similar ADI values. During these hours the vocal activity of birds predominates and probably the acoustic activity of this group is similar despite the wildfire history. Other studies have also found differences in ADI after a disturbance. Lee et al. (2017) evaluated how smoke pollution interfered with biodiversity, ADI values remained low even 16 weeks after the smoke had disappeared.

Our result for the Acoustic Evenness Index (AEI) showed that the average was highest at all hours of the day in the burned sites indicating higher acoustic uniformity in the soundscape. The AEI values were close to one, between 18h and 23h, representing perfect inequality, meaning that the sounds that occupy few frequency bands. Probably this result was due to a reduction in the richness and constancy of sound activity (abundance) for insects, amphibians and bats. In the burned sites the AEI values were lower in the period from 6h to 16h, i.e., more frequency bands were occupied, presumably as more species were emitting sounds at different frequencies, since there is a greater diurnal activity of birds, which occupied frequency bands between 1-20kHz.

Other studies have also evaluated the effect of fire on the soundscape, but with different indices. Gasc et al. (2018) used the bioacoustic index (BIO) and reported that two years after the fire, in a sample carried out in March, the BIO values were lower in the burned sites. The authors attributed this difference to the absence or reduction of cicadas, however after a new sample undertaken in October, the variation was no longer observed. Duarte et al. (2021) used Acoustic Complexity Index (ACI) and Power Spectral Density (PSD), to assess changes in the soundscape before and after a wildfire, comparing indices after one year and one month from the wildfire. Duarte et al. (2021) verified that before the wildfire the zoophony in the (soon to be) burned and unburned sites were similar and, immediately after the fire the first two samples showed that the zoophony was greater in the burned sites during the day, at night the zoophony was greater in the unburned sites, with variation in the indices between the burned and unburned sites during the rest of the sampling period. One year after the wildfire, they compared the acoustic indices in the burned and unburned locations again and found zoophony to be similar, which suggests the burned area may have recovered its original (or similar) soundscape characteristics.

We observed that some sites that suffered wildfires in 2015, had fire marks on their vegetation, while at other sites with recent fires (2018) the marks were not so evident. Although our study was carried out after wildfires, there was also variation in the acoustic indices. The wildfire marks can vary significantly according to the sites, with sites recovering faster than others. These variations in the landscape after the wildfires may be one of the factors that directly interfere in the return of the animal species to sites impacted by the fire.

4.2. Sonotype richness in burned and unburned sites

We found differences in the sonotype richness of almost all groups between the burned and unburned sites. Amphibians, birds and bats had more sonotypes in the unburned sites, compared to the burned sites. However, this difference was greater for birds, only 11 sonotypes occurred in both sites, with 31 sonotypes occurring only in the unburned sites and 16 only in the burned sites. Birds respond in different ways to fire disturbances. Insectivorous birds can benefit from the reduction of vegetation caused by fire, as the detection of insects becomes easier (Milesi et al. 2002), while birds who build nests in trees can lose nesting sites (Milesi et al. 2002). Lindenmayer et al. (2008) reported that in sites that have a more heterogeneous vegetation structure, such as the forest, bird richness recovered faster after fire than in structurally simple vegetation sites. Barton et al. (2014) showed that changes in vegetation structure affect the composition of bird species, even if the richness is not affected. In our study, the change in vegetation structure can be one of the factors that explain the variation in the composition and richness of the sonotypes in the burned and unburned sites for birds. In addition, birds can have multiple vocalizations. Therefore, in our study, we can consider that some sonotypes can be different calls from the same species.

In our study we did not identify differences in the number of insects as we had a very small difference between the areas. This result suggests that the insects probably had returned to occupy the disturbed areas. Studies report an absence and reduction of the abundance of cicadas in the burned sites (Gasc et al. 2018) a month after the wildfire, a reduction in the number of insects in the burned sites (Duarte et al. 2021), however these studies also show a recovery of this group over time. It is likely that in ours the richness of insects has recovered.

For amphibians/anurans, the three sonotypes found in both sites were predominant in our records and in almost all sites, demonstrating that they are widely distributed within the PNCD. Studies have shown that anurans that occur in Cerrado areas are adapted to survive during and after fires (Drummond et al. 2018). In addition, a review study demonstrated the lack of response of amphibians/anurans to fire, revealing that species and assemblages were both negatively or positively affected by fire (Anjos et al. 2021).

For bats we had a small difference in the composition of sonotypes, however the richness was similar, with only one more sonotype in the unburned sites. We observed a change in the presence of activity, in some sites the sound activity was intense and in others the activity was lower. However, we did not evaluate the activity of each group in the different sites studied, we only suggest that the activity was higher in the unburned sites due to the higher ADI values in those sites. Studies have shown that bats are quite resilient to fires and this does not strongly affect the occupation of the sites by them (Austin et al. 2020; Blakey et al. 2021). In our study we used a low sampling rate for bat recordings, this affected the richness found, future studies should use a higher sampling rate.

We observed the richness of sonotypes by groups and hours of the day. During the night we had a small variation in the richness of sonotypes in the burned and unburned sites. We observed a change in the acoustic activity of bats. During the day, the most active times for groups were at dawn, times when birds are entering activity and groups such as amphibians and bats are still active. We observed similarities and differences between the richness of sonotypes in all locations, as shown in Figure 05, and we found that many sites had their own richness of sonotypes, this richness being greater in unburned sites. Future studies should be carried out evaluating, in addition to richness, the difference in composition between disturbed and non-disturbed sites.

5. Conclusion

We conclude that in unburned sites there was greater sound activity and the sounds occupied larger frequency bands. These findings indicate that unburned sites have a greater diversity and lower uniformity of sonic species. Also, we found that birds showed the greatest difference between burned and unburned sites, with greater richness of sonotypes in unburned sites, but we emphasize that this discovery must take into account the multiple songs that can occur in birds compared to other groups. Our study is one of the pioneers in evaluating the effects of wildfires through soundscape studies. Our findings demonstrate that monitoring only the sounds after a time of wildfires, biodiversity changes can be determined and tracked through time. Therefore, our research highlights that soundscape studies can be used to monitor and assess the impact of disturbance and we suggest that future research should aim at evaluating disturbed soundscapes for a long period allowing for the understanding of the changes that disturbance causes in biodiversity and species phenology and how these changes vary over time.

6. Acknowledgements

We thank Marcelo Sena do Nascimento, Edvaldo Moreira da Silva Neto, Vinícius Queiroz Menezes and Camila Souza Batista for help in the field. LG thanks the Bahia State Research Support Foundation (FAPESB) for the scholarships. This study was financed by the Brazilian Council for Scientific and Technological Development (CNPq-Brazil), CNPq/ICMBio/FAPs nº 18/2017 (process 421431/2017-2). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. RSSL and MS thank the Brazilian Council for Scientific and Technological Development (CNPq-Brazil) for their research grants (process number 312763/2019-0 and 309365/2019-8, respectively).

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Supplementary data

Table S1 - Details of sites and sampling periods

Site	Coordinates	Altitude (m)	Sampling site	Burned year	Sampling year
site 01	12°36'18.05"S, 41°28'21.54"O	1320	unburned	-	2019
site 02	13°15'7.88"S, 41°18'37.71"O	1104	unburned	-	2019
site 03	12°48'50.90"S, 41°27'27.22"O	1194	unburned	-	2020
site 04	12°36'11.37"S, 41°27'56.71"O	1310	unburned	-	2020
site 05	12°36'2.96"S, 41°27'33.38"O	1293	unburned	-	2020
site 06	12°36'3.24"S, 41°27'21.64"O	1281	unburned	-	2020
site 07	13°13'37.42"S, 41°16'54.97"O	1151	burned	2015	2019
site 08	12°51'20.69"S, 41°26'42.62"O	1215	burned	2018	2019
site 09	12°37'21.46"S, 41°30'49.49"O	1163	burned	2015	2019
site 10	12°37'38.71"S, 41°30'58.10"O	1137	burned	2018	2020
site 11	12°48'37.93"S, 41°28'37.70"O	1248	burned	2018	2020
site 12	12°48'5.76"S, 41°28'30.29"O	1252	burned	2018	2020

Table S2 - Descriptions of the sonotypes found in the study, by group and site of occurrence.

Sonotype	Group	Sites
sonotype 1	amphibia	site 01, site 02, site 03, site 04, site 05, site 07, site 08, site 09, site 10
sonotype 2	amphibia	site 02, site 03, site 04, site 05, site 06, site 07, site 08, site 09, site 10, site 11, site 12
sonotype 3	amphibia	site 01, site 02, site 03, site 04, site 07, site 09, site 11
sonotype 4	bat	site 01, site 02, site 04, site 05, site 07, site 09, site 10, site 11, site 12
sonotype 5	insect	site 01, site 02, site 03, site 05, site 06, site 09, site 10
sonotype 6	insect	site 01, site 09, site 10, site 11
sonotype 7	bird	site 01, site 09
sonotype 8	bird	site 04, site 05, site 06, site 07, site 09, site 11, site 12
sonotype 9	bird	site 01, site 02, site 03, site 04, site 05, site 07, site 08, site 09, site 10, site 12
sonotype 10	bird	site 09
sonotype 11	bird	site 01, site 02, site 03, site 04, site 05, site 07, site 09
sonotype 12	insect	site 02, site 06, site 07, site 09, site 12
sonotype 13	bird	site 07, site 09, site 10
sonotype 14	bird	site 01, site 09
sonotype 15	insect	site 03, site 04, site 05, site 09, site 10, site 11, site 12

sonotype 16	insect	site 09
sonotype 17	amphibia	site 02
sonotype 18	insect	site 01, site 02, site 04, site 06, site 08, site 10, site 11
sonotype 19	insect	site 02
sonotype 20	insect	site 01, site 02, site 11
sonotype 21	bird	site 01, site 02
sonotype 22	bird	site 02
sonotype 23	bird	site 02, site 07
sonotype 24	bat	site 02
sonotype 25	bird	site 02
sonotype 26	bird	site 02
sonotype 27	bird	site 02
sonotype 28	bird	site 02
sonotype 29	bird	site 02
sonotype 30	bird	site 02
sonotype 31	insect	site 02, site 12
sonotype 32	bird	site 03
sonotype 33	bird	site 03
sonotype 34	bird	site 03
sonotype 35	bat	site 03, site 11
sonotype 36	bat	site 03
sonotype 37	bird	site 03, site 06
sonotype 38	bird	site 03
sonotype 39	bird	site 03
sonotype 40	bird	site 04
sonotype 41	bat	site 04
sonotype 42	bat	site 04
sonotype 43	bird	site 04
sonotype 44	bird	site 01, site 05, site 11
sonotype 45	bird	site 01
sonotype 46	bird	site 05
sonotype 47	bird	site 05
sonotype 48	bird	site 05
sonotype 49	bird	site 05, site 11
sonotype 50	bird	site 05

sonotype 51	bird	site 05
sonotype 52	bird	site 05, site 10
sonotype 53	bird	site 06
sonotype 54	bird	site 01
sonotype 55	amphibia	site 01
sonotype 56	insect	site 01, site 11
sonotype 57	bird	site 01
sonotype 58	bird	site 01, site 10, site 11, site 12
sonotype 59	bird	site 01
sonotype 60	bird	site 01
sonotype 61	bird	site 01
sonotype 62	bird	site 01
sonotype 63	bird	site 01, site 10, site 11, site 12
sonotype 64	bird	site 01
sonotype 65	bird	site 01
sonotype 66	bat	site 07
sonotype 67	insect	site 07, site 08
sonotype 68	bird	site 07
sonotype 69	bird	site 07
sonotype 70	bird	site 07
sonotype 71	bat	site 07
sonotype 72	bird	site 10
sonotype 73	bird	site 10, site 12
sonotype 74	bird	site 10
sonotype 75	insect	site 10
sonotype 76	bird	site 10, site 11
sonotype 77	bird	site 11
sonotype 78	bird	site 11
sonotype 79	bird	site 11
sonotype 80	bird	site 11, site 12
sonotype 81	amphibia	site 12
sonotype 82	bat	site 12
sonotype 83	bird	site 12
sonotype 84	bird	site 12
sonotype 85	bird	site 12

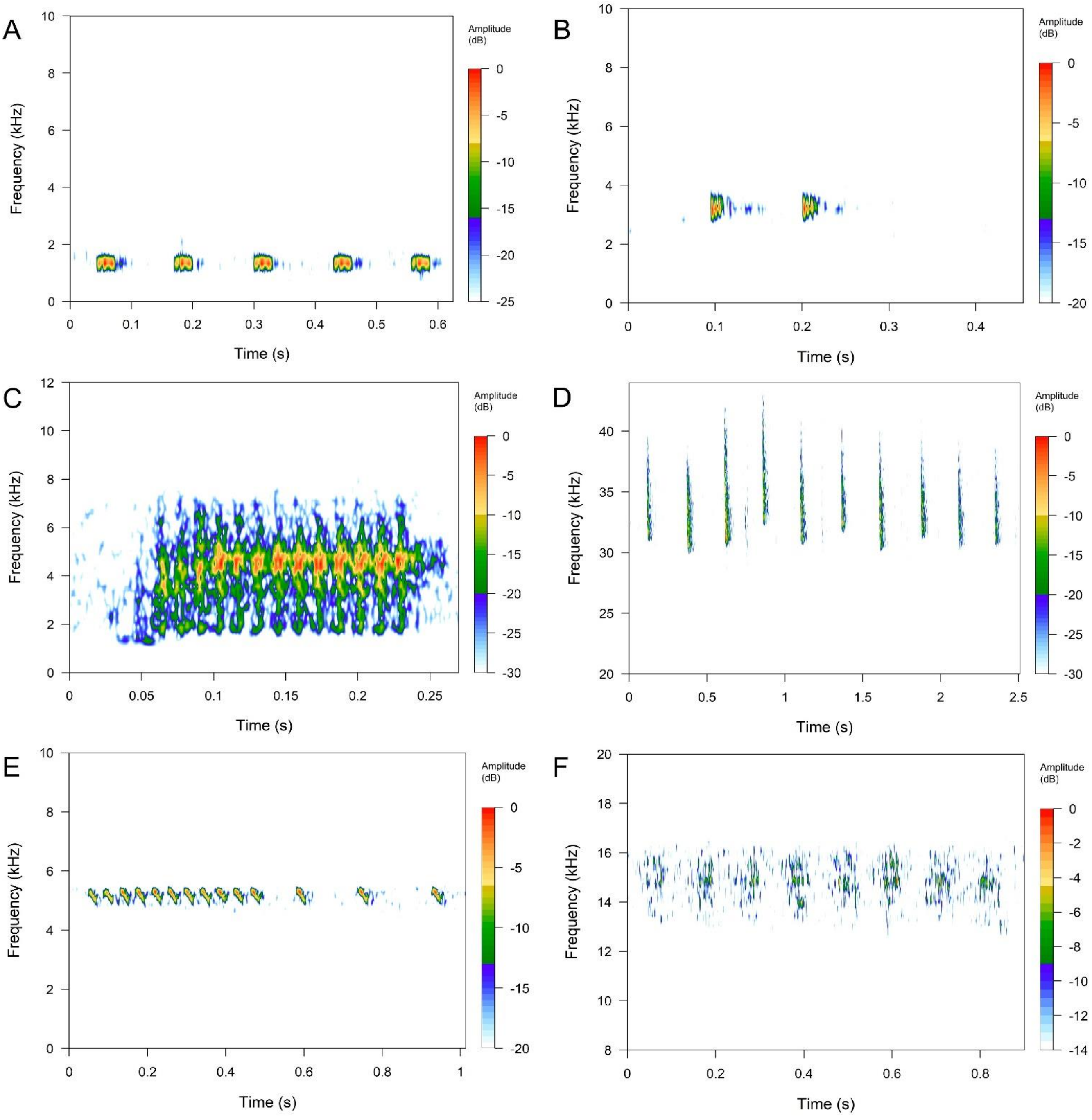

Figure S1 - Examples of sonotypes found in the analyses, visualized with the configuration window = 512 and overlap = 85, a) sonotype 01, b) sonotype 02, c) sonotype 03, d) sonotype 04, e) sonotype 05 and f) sonotype 06.

***Capítulo** III*

Soundscape analyses show variation among tropical forest with different levels of logging and exploitation

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Abstract

Habitat loss is considered one of the factors that causes a decrease in biodiversity in the tropics. Many efforts have been made to protect and restore tropical forests, but it is difficult to quantify biodiversity and assess restoration areas. Studies have used soundscape analyses to gain information about the landscape, using acoustic indices as indicators of the health of faunal communities. We aimed to assess the changes in acoustic indices in habitats with different types of human exploitation and to evaluate the variation in acoustic indices during the hours of the day among these different habitats. The recordings were performed using passive acoustic monitoring (PAM), deriving from those 15 acoustic indices to assess the characteristics of each environment. Eight acoustic indices tested showed differences among habitat categories. The results of the acoustic indices suggest that in rubber plantations (RP) there was less sound activity, followed by rubber-forest plantations (RFP) and lightly selectively logged (LSL), while habitats of young secondary forests (YSF), mature secondary forests (MSF) and intensively selectively logged forests (ISL) there was more sound activity, which indicates greater faunal activity. This study shows changes in the acoustic indices among habitats with differences in landscape structure in tropical forests, which can be useful for evaluating areas with high species richness, such as the Atlantic Forest.

Keywords: Ecoacoustics; Acoustic indices; Passive Acoustic Monitoring; Secondary Forest; Land-use change; Landscape ecology.

1. Introduction

The Atlantic Forest has one of the highest species richness and high level of plant and vertebrate endemism in the world (Myers et al. 2000, Mittermeier et al. 2004). Due to human expansion, most of the Atlantic Forest are fragments of vegetation (Ribeiro et al. 2009), caused mainly by replacing the forest with degraded areas, pastures, agriculture, silviculture and urban areas (Joly et al. 2014). Brazil has approximately 28 to 30 million hectares of forest cover of the Atlantic Forest biome (Rezende et al. 2018, Rosa et al. 2021). However, the current forest cover is a result of modifications of old-growth forests to young forests that remain in areas less attractive for mechanized agriculture, causing an uneven spatial distribution and an increase in forest isolation (Rosa et al. 2021).

The destruction and modification of forests increases the need to conserve biodiversity (Gardner et al. 2009, Rosa et al. 2021). One of the most used ways to restore forest areas is through natural regeneration, which occurs through the spontaneous recovery of native tree species, which colonize and establish in abandoned areas or on areas that have experienced natural disturbances (Shono et al. 2007, Cramer et al. 2008). Forest restoration can also occur through active restoration, with the planting of native seedlings, direct seeding, and manipulation of disturbance regimes, which accelerate the forest recovery process (Rey Benayas et al. 2008, DellaSala et al. 2003).

It is difficult to predict the success of forest restoration and consequently the recovery of biodiversity (Crouzeilles et al. 2017, Hobb and Harris 2001). Additionally, habitat degradation and loss can increase biodiversity decline (Laurence et al. 2012), this generates the need for information that quantifies the state of biodiversity (Balmford et al. 2005, Schmeller et al. 2017). The development and accessibility of technologies has been an essential tool for extracting information on biodiversity (e.g.: camera traps, audio recorders, satellite tags, drones) (Tuia et al.

2022, Pimm et al. 2015). One type of expanding method is passive acoustic monitoring (PAM) (Sugai et al. 2018, Gibb et al. 2018), that uses autonomous audio recorders, as a cheap, non-invasive and viable technique, for fauna survey through auditory detection (Acevedo and Villanueva-Rivera 2006, Gibb et al. 2018).

The PAM is used for monitoring of various types of environmental sounds, known collectively as soundscape (Pijanowski et al. 2011a). The soundscape encompasses sounds of live organisms (biophony), natural sounds of physical processes (geophony), and sounds caused by human activities (anthropophony) (Pijanowski et al. 2011b). Different metrics for the quantification of the soundscape have been developed, such as acoustic indices (Suer et al. 2008, Towsey et al. 2014, Ulloa et al. 2021). Acoustic index is a statistic that summarizes some aspects of the structure and distribution of acoustic energy and information in an audio recording, and may reflect ecological processes (Towsey et al. 2014). Several studies have used acoustic indices to test the ability of soundscapes to generate information about the ecological conditions of habitats (Hayaski et al. 2020, Maio-Le Ng et al. 2018, Kranaposhtani et al. 2019, Lee et al. 2017, Borker et al. 2019, Fuller et al. 2015, Machado et al. 2017, Müller et al. 2022, Oliveira et al. 2021, Dröge et al. 2021, Sánchez-Giraldo et al. 2021).

In threatened landscapes, such as tropical forests, studies indicate the need for acoustic monitoring, for environmental assessment and as a source of information about this biome (Scarpelli et al. 2019, Gibb et al. 2019, Deichmann et al. 2018). Studies in tropical forests show the potential to use soundscapes, for example, to uncover daily and seasonal changes in biodiversity (Oliveira et al. 2021) or to show that soundscapes respond to changes in canopy coverage (Do Nascimento et al. 2020). They have also been used to analyse differences in land use (Burivalova et al. 2018; Scarpelli et al. 2021; Dröge et al. 2021; Müller et al. 2022b, a), and to show the homogenization of landscapes explored (Burivalova et al. 2019) among other analyses.

In our study, we investigated changes in the soundscape in different Atlantic Forest habitats, as rubber plantations or forest areas with different histories of human exploration, which have been abandoned at different points in time, and are habitats of forest regeneration or have had selective logging of trees. Specifically, we tested: (i) differences in acoustic indices among six types of habitats and (ii) the daily variation of the soundscape within each of these habitats.

2. Materials and methods

2.1. Study area and design

We conducted our study of the 3 to the 11 of October 2015, in the Reserva Ecológica Michelin (REM), located in southern Bahia, northeastern Brazil (Figure 1). The private reserve is situated within the municipalities of Igrapiúna and Ituberá (13º50'S, 39º10'W). According to Veloso et al. (1991), the region is characterized as a Dense Rain Forest of Lowlands. The reserve comprises 3,096 ha, of which 1,800 ha are represented by lowland evergreen hill forest distributed in three main fragments (Vila 5/Pancada Grande – 625 ha; Pacangê – 550 ha; and Luiz Inácio – 140 ha). The Pacangê fragment is contiguous with a 13,000 ha forest. The reserve has a long history of human disturbance, mostly manioc farming and decades of intensive logging. Forest is predominantly secondary, at different stages of regeneration, with small patches of more intact forests on the steepest slopes and ridge tops. The remainder of the reserve consists of wetlands, small forest fragments and rubber plantations (*Hevea brasiliensis*) enriched with native forest trees (Flesher and Laufer 2013).

Site sampling were carried out in the following habitats categories: i) Rubber plantations (RP); ii) Rubber-forest plantations (RFP): iii) Young secondary forest (YSF); iv) Mature secondary forests (MSF); v) Intensively selectively logged (ISL) and vi) Lightly selectively logged (LSL) (more details in the Figure 2). We used these habitat categories because forest cover metrics used in landscape ecology do not differentiate between habitats. We selected three sampling units in each habitat category, totaling 18 sampling units summing all six categories. Sites of the same habitat category were located at least 1 km away from each other, and all the sites were located with a minimum distance of 100 m from the forest edge and water bodies such as streams and pools were at a minimum distance of 200 m from each sample unit.

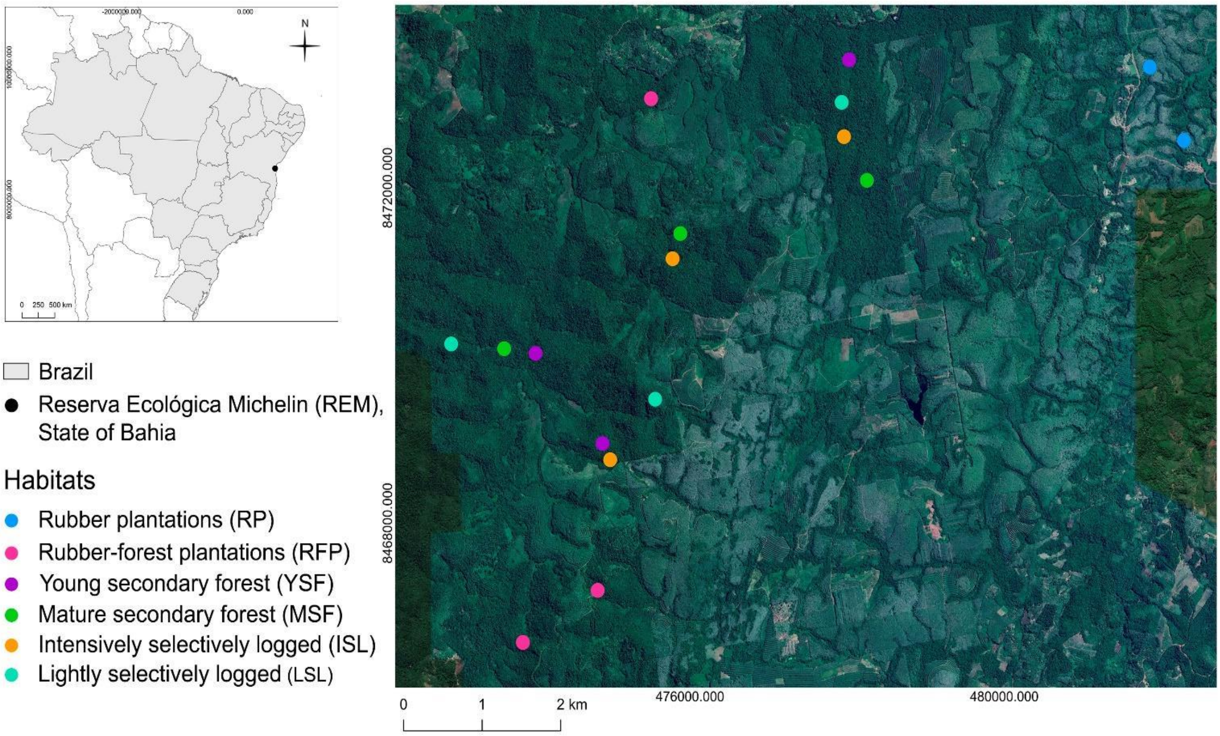


Figure 1. Satellite image of Reserva Ecológica Michelin (REM) with 17 sites, distributed in six habitat categories. Color code represents the different categories of habitats sampled.

2.2. Sound recordings

In all sampling sites we installed one autonomous recorder (Song Meter SM2BAT+, Wildlife Acoustics Inc., USA), with an omnidirectional weatherproof microphone SMX-II (Wildlife Acoustics Inc., USA), attached to a tree 1,5 m above the ground. Each recorder was set to record for five minutes, every half hour, 24 hours a day for four days. We used a sampling rate of 96000 Hz, with mono recordings. In total, we sampled 17 sites, since data from one site in the RP was ost due to theft of two recorders in this habitat category. In total we used 3248 audio files of 5 minutes, 16 files were corrupted or damaged, probably due to recorder malfunction.

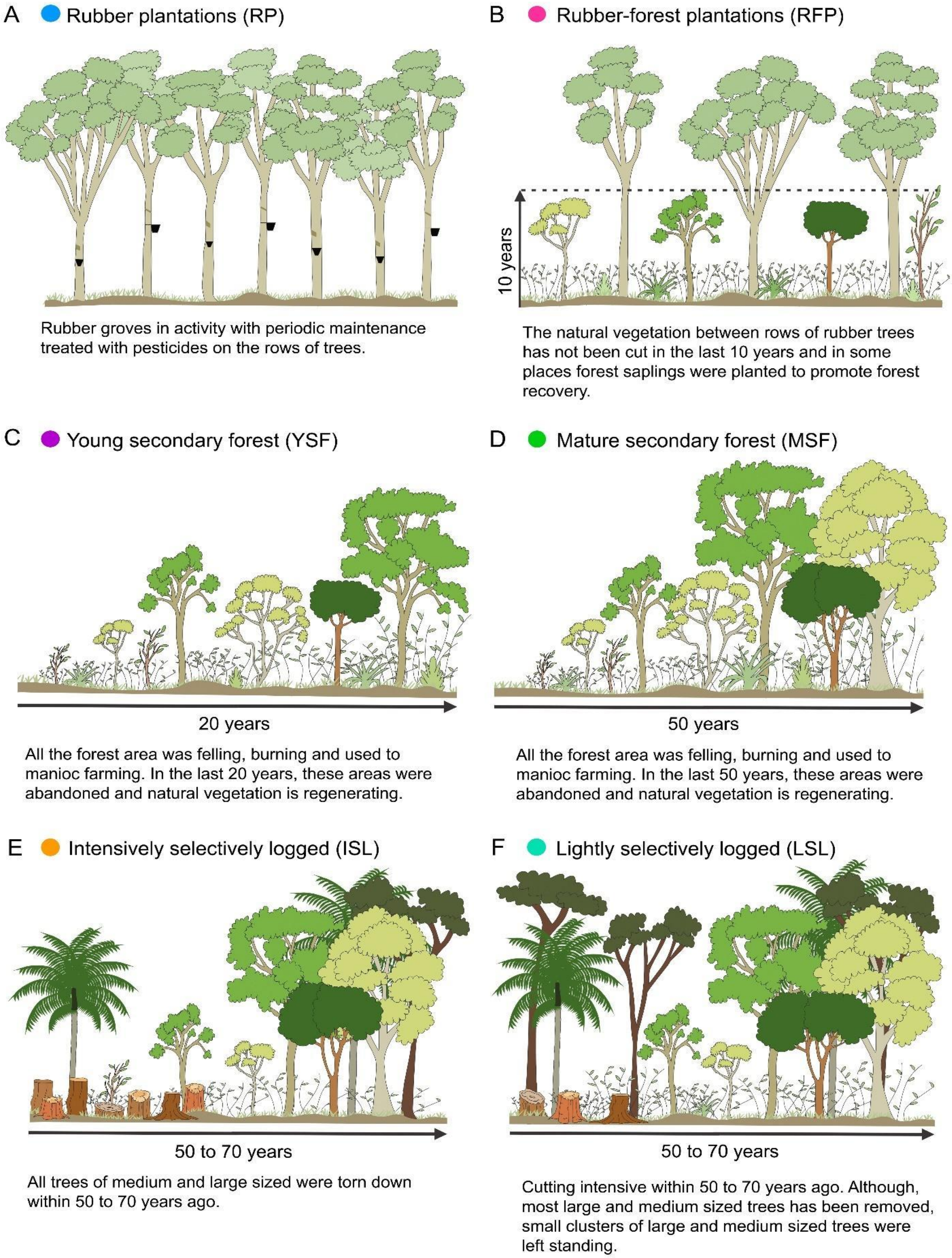
2.3. Acoustic indices

We analysed the acoustic indices through the software AnalysisPrograms (https://github.com/QutEcoacoustics/audio-analysis, Towsey et al. 2020). Our 5-minute files were cut into one-minute files, and for each file we generated a summary of various spectral indices (Tabela 1). We analysed a total of 15 acoustic indices.

Table 1. Description of the acoustic indices calculated in this study. References correspond to the original description of each index.

Index	Description
Background Noise (BGN)	Estimate of the background noise in each one-minute recording, calculated from the decibel waveform (Towsey 2017).
Signal to Noise Ratio (SNR)	Difference between the maximum decibel value in the decibel envelope and the decibel value of BGN. (Towsey 2017).
Activity (ACT)	Fraction of values in the noise-reduced decibel envelope that exceed the threshold, θ = 3 dB (Towsey 2017).
Events Per Second (EVN)	Number of acoustic events per second, averaged over the same noise-reduced one-minute segment. The acoustic event is defined when the decibel envelope crosses a BGN + 3 dB threshold (Towsey 2017).
Low Frequency Cover (LFC)	Fraction of noise-reduced decibel spectrogram that exceed 3 dB in the low-frequency band (below 1 kHz) (Towsey 2017).
Mid Frequency Cover (MFC)	Fraction of noise-reduced decibel spectrogram that exceed 3 dB in the mid-frequency band (1-11 kHz) (Towsey 2017).

High Frequency Cover (HFC)	Fraction of noise-reduced decibel spectrogram that exceed 3 dB in the high-frequency band (11-48 kHz) (Towsey 2017).
Spectral Peak Density (SPD)	A measure of the number of cells in the mid-frequency band of a one-minute spectrogram that are identified as being local maxima. Not normalized to be independent of frame size and frame overlap (Towsey 2017).
Temporal Entropy (ENT)	Measurement of concentration of acoustic energy each frequency bin, calculated from the wave envelope (Towsey 2017).
Entropy of Average Spectrum (EAS)	Measurement of concentration of mean energy in the mid-band of the mean energy spectrum (Towsey 2017).
Entropy of the Spectral Peaks (EPS)	Measurement of concentration of spectral maxima values in the mid frequency band (1 – 11 kHz) (Towsey 2017).
Entropy of Coefficient of Variation (ECV)	Similar to EAS, but the mid-band spectrum is derived from the variance divided by the mean of the energy values in each frequency bin (Towsey 2017)
Acoustic Complexity Index (ACI)	Measurement of variability in sound intensities within a recording by examining short-time averaged changes in acoustic energy across frequency bins. Calculated for the average of the mid-band ACI values. Originally developed to reflect bird activity, but highly sensitive to some non-biological sound sources, such as rain (Pieretti et al. 2011; Towsey 2017).
Cluster Count (CLS)	The number of distinct spectral clusters in the mid-frequency band of a one-minute segment of recording (Towsey 2017).
Normalized Difference Soundscape Index (NDSI)	Estimate of the level of anthropogenic disturbance on the soundscape. Calculates the ratio of signal power in the frequency bands between anthrophony and biophony (Kasten et al. 2012).



A ● Rubber plantations (RP)

Rubber groves in activity with periodic maintenance treated with pesticides on the rows of trees.

B ● Rubber-forest plantations (RFP)

The natural vegetation between rows of rubber trees has not been cut in the last 10 years and in some places forest saplings were planted to promote forest recovery.

C ● Young secondary forest (YSF)

All the forest area was felling, burning and used to manioc farming. In the last 20 years, these areas were abandoned and natural vegetation is regenerating.

D ● Mature secondary forest (MSF)

All the forest area was felling, burning and used to manioc farming. In the last 50 years, these areas were abandoned and natural vegetation is regenerating.

E ● Intensively selectively logged (ISL)

All trees of medium and large sized were torn down within 50 to 70 years ago.

F ● Lightly selectively logged (LSL)

Cutting intensive within 50 to 70 years ago. Although, most large and medium sized trees has been removed, small clusters of large and medium sized trees were left standing.

Figure 2. Sampled habitat categories, the circles represent the color code of the different categories.

2.4. Statistical analysis

A correlation matrix was performed to remove highly correlated acoustic indices. Indices with Pearson correlation values > 0.75 were removed from the analyses. We used Generalized Linear Mixed Models (GLMM), to verify if there were changes in the values of acoustic indices in the different sampling habitats. We generated models for each investigated acoustic index. Acoustic index values were used as response variable, and sampling habitat and time as explanatory variables, each day and sampling location were inserted as random variables in the model. To investigate if the spatial distribution explained the similarity between the sites, spatial autocorrelation was tested, through Moran I, the geographic coordinates of each location were used as explanatory variables in the model (Beale et al. 2010). The models changed the adjustments according to the indices, for BGN, SNR, MFC, LFC, NDSI, SPD, EAS and ECV, the gaussian distribution was used, a logarithmic transformation of the data was performed to SPD, for CLS we used the genpois distribution, gamma distribution was used for ACI and for EVN the tweedie distribution. It was necessary to scaled the results of the acoustic indices BGN and NDSI, scaled between 0 and 1, to adjust the data to the distribution. We used "glmmTMB" package (Brooks et al. 2017), for GLMM and the analyses were performed in the R environment version 4.0.2 (R Core Team 2022).

3. Results

We analysed a total of 16240 1-minute audio files, covering all six sampled habitat categories. Acoustic indices Activity (ACT), High Frequency Cover (HFC) and Temporal Entropy (ENT) were highly correlated with other acoustic indices and removed from our analysis (Figure S1), in total we evaluated 12 acoustic indices. We did not find spatial auto-correlation in the distribution of the sampled sites (p = 0.539).

Of the tested acoustic indices, eight responded to different habitat categories (Table 2). Signal to Noise Ratio (SNR) index values were higher in most habitat categories (RFP, YSF, MSF, ISL and LSL) compared to those in RP (Figure 3A). Events Per Second (EVN) index values were higher in YSF, MSF, ISL and LSL when compared to RP (Figure 3B). Mid-frequency Cover (MFC) and Cluster Count (CLS) indices showed no significant difference between RP and LSL, but in the habitat categories RFP, YSF, MSF and ISL, these two indices showed higher mean values than those from RP (Figures 3C and 3H). Entropy of the Spectral Peaks (EPS) and Acoustic Complexity Index (ACI) showed significant mean values for YSF, the values of these acoustic indices were lower for EPS and higher for ACI, for YSF in relation to RP, in the other habitat categories there were no significant difference (Figures 3D and 3G). For The Entropy of the Average Spectrum (EAS) only the RFP habitat had significantly lower EAS mean values than RP (Figure 3E). For Entropy of the Spectrum of Coefficients of Variation (ECV) only the ISL habitat showed a significant result, in ISL the average of ECV was higher than in relation to RP (Figure 3F).

Time influenced in almost all the acoustic indices tested, only for Low-frequency Cover (LFC) there was no significant change according to the hours of the day (Table 2). The acoustic indices Background Noise (BGN), Low-frequency Cover (LFC), Spectral Peak Density (SPD) and Normalized Difference Soundscape Index (NDSI) showed an effect for habitat categories only in the interaction between habitat and time (Figure 4).

For the results of the interaction of time with habitat, the indices showed different results, according to the categories of habitats. In most hours of the day the average of the Background Noise (BGN) mean values were lower in the categories of habitats RFP, ISL, LSL in relation to RP, however for YSF the mean of BGN was higher than in RP (Figure 4A). For Low-frequency Cover (LFC) the mean values of RFP and YSF were higher at most times of the day when compared to RP (Figure 4B). For Spectral Peak Density (SPD) the mean values were higher in most hours of the day for YSF, MSF, ISL and LSL when compared to RP (Figure 4C). For five acoustic indices, Normalized Difference Soundscape Index (NDSI), Signal to Noise Ratio (SNR), Events Per Second (EVN), Acoustic Complexity Index (ACI) and Cluster Count (CLS), the mean were higher in the most hours of the day in the habitat categories of RFP, YSF, MSF, ISL and LSL than in relation to RP (Figure 4D, Figures S2, S3, S8 and S9). There was variation in the mean values of Entropy of the Spectral Peaks (EPS), i.e., the values were lower for RFP, MSF and ISL in relation to RP, in most hours of the day (Figure S5). The mean values of Entropy of the Average Spectrum (EAS) were lower in RFP, YSF and ISL at most hours of the day than in RP (Figure S6). The interaction between habitat and time was positive and significant in MSF and ISL, in these habitats at all hours of the day the mean of Entropy of the Spectrum of Coefficients of Variation (ECV) was higher than in RP (Figure S7).

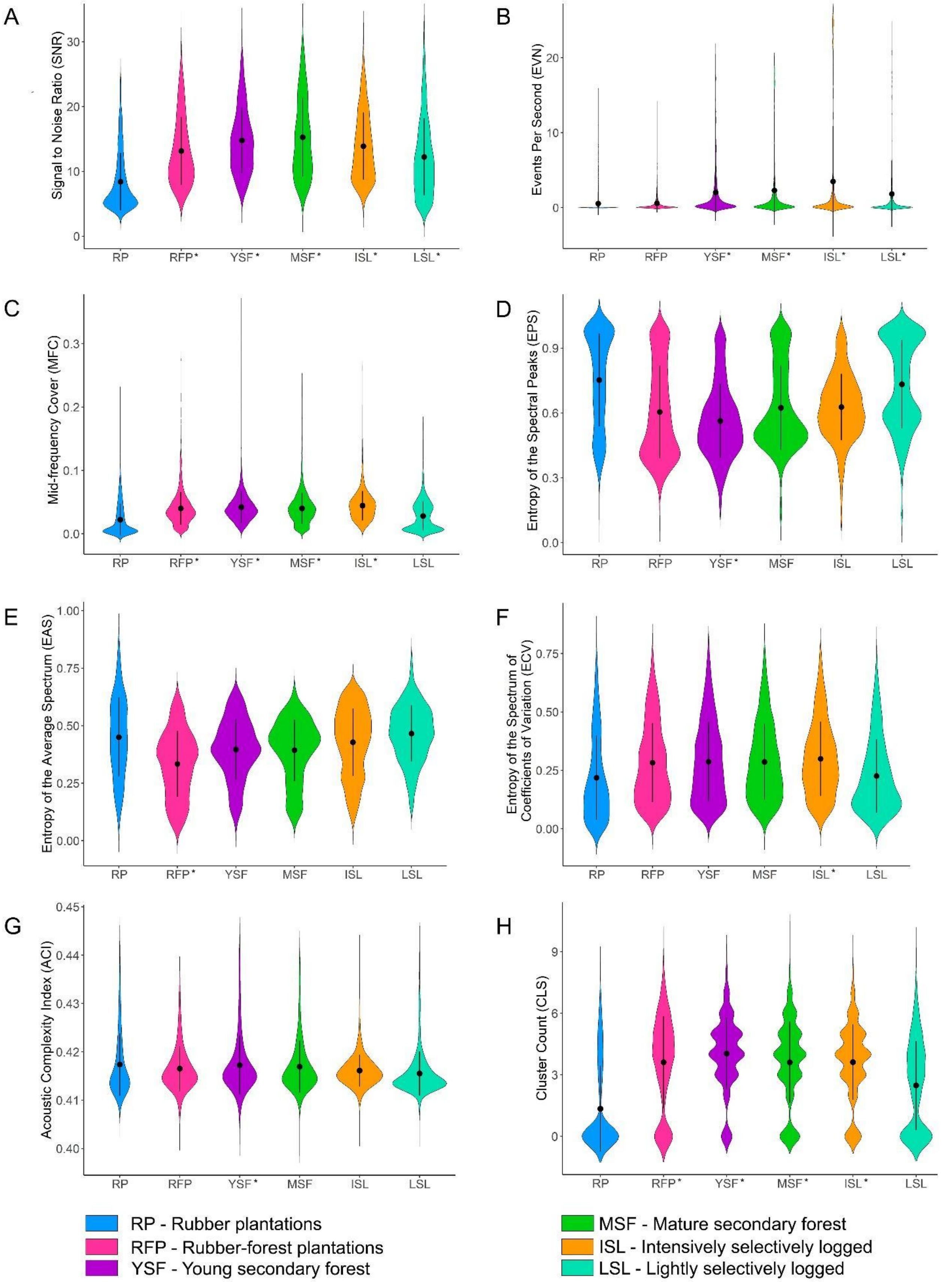


Figure 3. The mean values of the six habitat categories sampled for different acoustic indices, * represents habitats for which the results were significant.

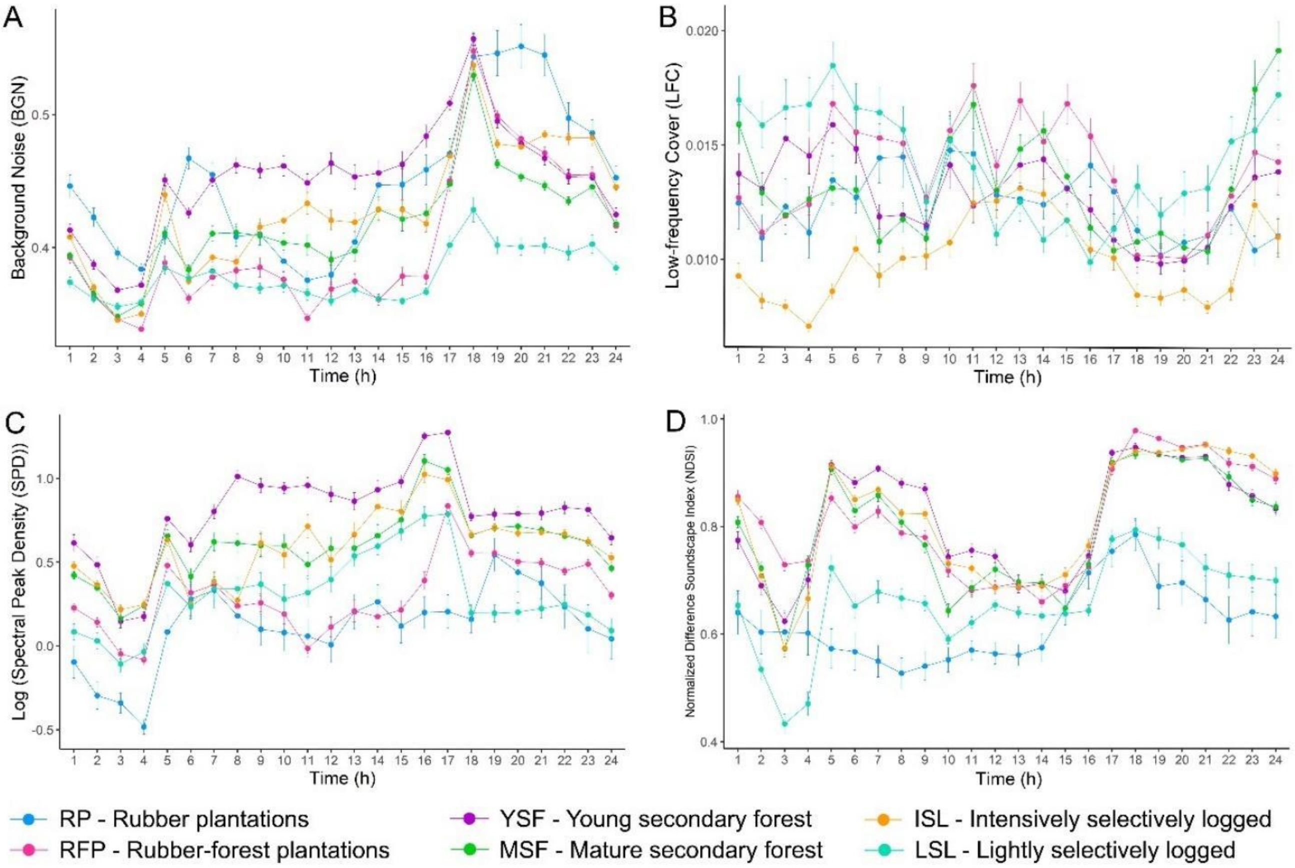


Figure 4. The mean values of the six habitat categories sampled for different acoustic indices every hour, during 24 hours.

Table 2. Generalized Linear Mixed Models (GLMM) results for 12 acoustic indices and for six categories of habitats, time, and interaction between habitats and time. Habitats categories: Rubber plantations (RP); Rubber-forest plantations (RFP): Young secondary forest (YSF); Mature secondary forests (MSF); Intensively selectively logged (ISL); Lightly selectively logged (LSL). In bold the significant results.

Acoustic index	**Variable**	**Estimate**	**Standard error**	**z- value**	***p***
Background Noise (BGN)	Intercept	0.3904	0.0243	16.06	< **0.001**
	RFP	-0.0538	0.0313	-1.716	0.086
	YSF	0.0184	0.0313	0.587	0.557
	MSF	-0.0228	0.0313	-0.727	0.466
	ISL	-0.0281	0.0313	-0.897	0.369
	LSL	-0.0145	0.0314	-0.464	0.642
	Time	0.0043	0.0002	19.97	< **0.001**
	Time: RFP	0.0010	0.0002	3.832	< **0.001**
	Time: YSF	-0.0008	0.0002	-3.255	< **0.001**
	Time: MSF	-0.0004	0.0002	-1.693	0.0904
	Time: ISL	0.0010	0.0002	3.668	< **0.001**
	Time: LSL	-0.0026	0.0002	-9.435	< **0.001**
Signal to Noise Ratio (SNR)	Intercept	7.3343	1.6083	4.560	< **0.001**
	RFP	7.9475	2.076	3.828	< **0.001**
	YSF	9.3763	2.0759	4.517	< **0.001**
	MSF	8.8432	2.076	4.260	< **0.001**
	ISL	8.8155	2.0761	4.246	< **0.001**
	LSL	6.6622	2.0762	3.209	< **0.001**
	Time	0.0832	0.0161	5.171	< **0.001**
	Time: RFP	-0.2526	0.0204	-12.34	< **0.001**
	Time: YSF	-0.2369	0.0204	-11.61	< **0.001**
	Time: MSF	-0.1582	0.0204	-7.735	< **0.001**
	Time: ISL	-0.2651	0.0205	-12.90	< **0.001**
	Time: LSL	-0.2261	0.0205	-11.00	< **0.001**
Events Per Second (EVN)	Intercept	-2.2743	0.9154	-2.484	**0.0129**
	RFP	1.4100	1.1818	1.193	0.2328
	YSF	3.4634	1.1813	2.932	**0.0033**
	MSF	3.0933	1.1813	2.618	**0.0088**
	ISL	2.2984	1.1814	2.526	**0.0115**
	LSL	2.8671	1.1815	2.427	**0.0152**
	Time	0.0567	0.0057	9.852	< **0.001**
	Time: RFP	-0.0471	0.0078	-6.000	< **0.001**

	Time: YSF	-0.0838	0.0076	-11.03	< **0.001**
	Time: MSF	-0.0803	0.0076	-10.57	< **0.001**
	Time: ISL	-0.0768	0.0075	-10.15	< **0.001**
	Time: LSL	-0.1263	0.0078	-16.01	< **0.001**
Mid-frequency Cover (MFC)	Intercept	-4.7846	0.3677	-13.01	< **0.001**
	RFP	1.2729	0.4747	2.681	**0.0073**
	YSF	1.4449	0.4747	3.044	**0.0023**
	MSF	1.2590	0.4747	2.652	**0.008**
	ISL	1.4343	0.4747	3.021	**0.0025**
	LSL	0.5387	0.4747	1.135	0.2564
	Time	0.0215	0.0019	10.78	< **0.001**
	Time: RFP	-0.0164	0.0025	-6.445	< **0.001**
	Time: YSF	-0.0204	0.0025	-8.017	< **0.001**
	Time: MSF	-0.0146	0.0025	-5.767	< **0.001**
	Time: ISL	-0.0146	0.0025	-5.768	< **0.001**
	Time: LSL	-0.0022	0.0025	-0.894	0.3713
Low-frequency Cover (LFC)	Intercept	-4.5115	0.1134	-39.75	< **0.001**
	RFP	0.1781	0.1464	1.22	0.2236
	YSF	0.1297	0.1464	0.89	0.3755
	MSF	0.0680	0.1464	0.46	0.6421
	ISL	-0.2619	0.1464	-1.79	0.0735
	LSL	0.0643	0.1464	0.44	0.6604
	Time	-0.0012	0.0017	-0.70	0.4841
	Time: RFP	-0.0063	0.0022	-2.82	**0.0048**
	Time: YSF	-0.0099	0.0022	-4.42	< **0.001**
	Time: MSF	-0.0023	0.0022	-1.03	0.3051
	Time: ISL	0.0038	0.0022	1.71	0.0871
	Time: LSL	-0.0040	0.0022	-1.81	0.0693
Entropy of the Spectral Peaks (EPS)	Intercept	0.8085	0.0632	12.77	< **0.001**
	RFP	-0.0701	0.0817	-0.858	0.3908
	YSF	-0.1789	0.0817	-2.190	**0.0284**
	MSF	-0.1050	0.0817	-1.286	0.1984
	ISL	-0.1500	0.0871	-1.837	0.0662

	LSL	0.0359	0.0817	-0.440	0.6599
	Time	-0.0042	0.0005	-7.599	< **0.001**
	Time: RFP	-0.0065	0.0070	-9.211	< **0.001**
	Time: YSF	-0.001	0.0070	-1.528	0.1266
	Time: MSF	-0.0021	0.0007	-3.016	**0.0025**
	Time: ISL	0.0017	0.0007	2.407	**0.016**
	Time: LSL	0.0010	0.0007	1.451	0.1466
Entropy of the Average Spectrum (EAS)	Intercept	0.4337	0.0291	14.90	< **0.001**
	RFP	-0.0998	0.0375	-2.657	**0.0078**
	YSF	-0.0328	0.0375	-0.875	0.3813
	MSF	-0.0540	0.0375	-1.439	0.1501
	ISL	-0.0611	0.0375	-1.706	0.0879
	LSL	0.0063	0.0375	0.169	0.866
	Time	0.0018	0.0005	3.540	**0.0004**
	Time: RFP	-0.0017	0.0006	-2.730	**0.0063**
	Time: YSF	-0.0027	0.0006	-4.152	< **0.001**
	Time: MSF	-0.0012	0.0006	-1.919	0.0549
	Time: ISL	0.0018	0.0006	2.797	**0.0051**
	Time: LSL	-0.0003	0.0006	-0.540	0.5893
Entropy of the Spectrum of Coefficients of Variation (ECV)	Intercept	0.1816	0.0353	5.143	< **0.001**
	RFP	0.0805	0.0455	1.766	0.0773
	YSF	0.0852	0.0455	1.871	0.0613
	MSF	0.0893	0.0455	1.959	0.05
	ISL	0.1127	0.0455	2.475	**0.0133**
	LSL	0.0151	0.0455	0.333	0.7388
	Time	0.0026	0.0005	5.011	< **0.001**
	Time: RFP	-0.0010	0.0006	-1.520	0.1284
	Time: YSF	-0.0010	0.0006	-1.567	0.117
	Time: MSF	-0.0014	0.0006	-2.143	**0.0321**
	Time: ISL	-0.0022	0.0006	-3.346	**0.0008**
	Time: LSL	-0.0003	0.0006	-0.521	0.6023
Spectral Peak	Intercept	-0.0878	0.3017	-0.291	0.7709
	RFP	0.1806	0.3895	0.464	0.6427

Density (SPD)	YSF	0.6762	0.3895	1.736	0.0825
	MSF	0.4891	0.3895	1.256	0.2092
	ISL	0.5884	0.3895	1.510	0.1309
	LSL	0.2900	0.3895	0.745	0.4566
	Time	0.0201	0.0014	13.790	< **0.001**
	Time: RFP	-0.0026	0.0018	-1.462	0.1437
	Time: YSF	-0.0038	0.0018	-2.139	**0.0325**
	Time: MSF	-0.0041	0.0018	-2.289	**0.0221**
	Time: ISL	-0.0080	0.0018	-4.334	< **0.001**
	Time: LSL	-0.0114	0.0018	-6.314	< **0.001**
Normalized Difference Soundscape Index (NDSI)	Intercept	0.7548	0.0445	16.94	< **0.001**
	RFP	0.8792	0.0575	1.528	0.1263
	YSF	0.0942	0.0575	1.638	0.1014
	MSF	0.0758	0.0575	1.318	0.1875
	ISL	0.0761	0.0575	1.324	0.1852
	LSL	-0.0013	0.0575	-0.023	0.9818
	Time	0.0020	0.002	7.718	< **0.001**
	Time: RFP	0.0017	0.0003	5.154	< **0.001**
	Time: YSF	0.0012	0.0003	3.791	**0.0001**
	Time: MSF	0.0017	0.0003	5.412	< **0.001**
	Time: ISL	0.0026	0.0003	8.076	< **0.001**
	Time: LSL	0.0022	0.0003	6.804	< **0.001**
Acoustic Complexity Index (ACI)	Intercept	-0.8800	0.0036	-244.53	< **0.001**
	RFP	0.0083	0.0046	1.80	0.0713
	YSF	0.0137	0.0046	2.95	**0.0031**
	MSF	0.0084	0.0046	1.81	0.0695
	ISL	0.0082	0.0046	0.71	0.4799
	LSL	0.0022	0.0046	0.48	0.6334
	Time	0.0005	0.00003	16.1	< **0.001**
	Time: RFP	-0.0008	0.00004	-18.52	< **0.001**
	Time: YSF	-0.0011	0.00004	-24.62	< **0.001**
	Time: MSF	-0.0007	0.00004	-16.67	< **0.001**
	Time: ISL	-0.0005	0.00003	-11.22	< **0.001**

	Time: LSL	-0.0005	0.00003	-14.69	< **0.001**
Cluster Count (CLS)	Intercept	-0.9134	0.54434	-1.678	0.0933
	RFP	2.2013	0.70033	3.143	**0.0016**
	YSF	2.2840	0.70003	3.261	**0.0011**
	MSF	2.0698	0.7003	2.955	**0.0031**
	ISL	2.1993	0.7003	3.140	**0.0016**
	LSL	1.2185	0.7009	1.739	0.0821
	Time	0.0198	0.0034	5.698	< **0.001**
	Time: RFP	-0.0215	0.0038	-5.657	< **0.001**
	Time: YSF	-0.0170	0.0037	-4.529	< **0.001**
	Time: MSF	-0.0122	0.0038	-3.207	**0.0013**
	Time: ISL	-0.0202	0.0038	-5.327	< **0.001**
	Time: LSL	-0.0156	0.0039	-3.967	< **0.001**

4. Discussion

Signal to Noise Ratio (SNR) indices showed higher mean values for secondary forest habitats (YSF and MSF), which suggests that in these habitats the sounds were captured with higher amplitude, since SNR is measured using the amplitude (dB) of sounds to estimate this soundscape metric. We expected that this index would have higher values in environments with low density of vegetation, such as rubber plantations, because in these habitats, fewer obstacles facilitate the propagation of sound, reducing the attenuation of sound (Wiley and Richards 1978). Despite the evidence from the literature showing that in areas with less vegetation the SNR values were higher (Scarpelli et al. 2021), in our study, the rubber plantation (RP), where the vegetation is more open, SNR values were lower, which leads us to believe that this index can also measure lack of faunal acoustic activity, because in RP the indices that measure acoustic activity were always lower in relation to other, more biodiverse, habitats.

Events Per Second (EVN) had higher values in secondary forest (YSF and MSF) and intensively selectively logged areas (ISL), which suggests that the number of acoustic events, measured through the amplitude (dB) of sounds, is higher in these habitats. More acoustic events are expected in areas with higher faunal activity; higher EVN values have been reported in agricultural areas than in forest, however this was attributed to intense sound activity in these agricultural areas (Scarpelli et al. 2021).

The mean values of Mid Frequency Cover (MFC) were higher in RFP, YSF, MSF and ISL. This index measures activity at the average frequency of recording, in our study 1-11 kHz, this frequency range was widely used by birds, anurans and insects in our recordings. We expected to find a lower value for the rubber plantation area (RP), due to the species-poor faunal community in this habitat. However, we did not expect the lowest value of this index in MFC and in the lightly selectively logged habitat (LSL). We manually evaluated the recordings, verifying that there were fewer insects in the LSL habitat, when compared to YSF, MSF and ISL habitats. This must have caused the lower values in the LSL habitat.

The Entropy of the Spectral Peaks (EPS) and the Entropy of Average Spectrum (EAS) had high values in the rubber plantation area (RP). This result was expected, because the entropy indices provide a measure of the concentration of energy distribution (Towsey 2017), so it was expected that sound activity energy was concentrated in a few frequency bands where the faunal community is smaller, while in areas where many species are vocalizing the energy would be distributed in several frequency bands. For the Entropy of Coefficient of Variation (ECV) index, the result was different from what was expected, with the rubber plantation (RP) lower than the other habitats. Scarpelli et al. (2021) showed that entropy indices were not consistent in their study, with variation in the result of the three tested indices (EAS, EPS and ECV), in our study we also found a difference in the results, but only in the ECV index.

Acoustic Complexity Index (ACI) showed a higher average in young secondary forest (YSF), but the difference in values for this habitat was very small in relation to the other categories of habitats. For the different types of land use, no distinct pattern was found for the ACI (Dröge et al. 2021), nor were ACI values higher in sites with less vegetation (Scarpelli et al. 2021). Other studies have not found a relationship between ACI and the richness of acoustic species (Mammides et al. 2017; Ferreira et al. 2018; Ross et al. 2021). In this study, we also did not consider ACI as a good indicator of biodiversity.

Our result showed that Cluster Count (CLS) values were higher in RFP, YSF, MSF, LSL and lower in RP and LSL. Since this index measures clusters in the mid-frequency band (1-11 kHz), it was expected that more bird species would generate higher values, which should increase the cluster count (Towsey 2017). In RP, there are fewer resources for animals, thus, there are probably fewer acoustic species in this area. For LSL, as already mentioned, we found lower insect activity in this habitat. As insects are also present in the mid-frequency band, we believe this is the reason for the low values of LSL, and not the lack of avian acoustic activity in this habitat.

Background Noise (BGN) had higher values in YSF most of the day. This habitat presented intense sound activity, including insects. BGN estimates the constant noise in a recording. We suppose that the constant activity of insects in YSF and ISL were responsible for the high values of BGN. Another study also reported higher BGN values in protected areas than in areas of human activities, and related this result to constant insect stridulation activity in the protected area (Campos et al. 2021).

The Low Frequency Cover (LFC) index evaluated the low frequency band, in our study 0 – 1 kHz. This band is widely used for anthropogenic sounds. In our results we did not find a significant difference in most habitats, we can only highlight that ISL had lower values in most hours of the day. However, manually evaluating the recordings, only RP presented noise in this frequency range, probably because it is a more open area, the wind noise, and not anthropophony, was responsible for this value. In the other habitat categories this frequency band had no noise and rare acoustic events.

Spectral Peak Density (SPD) was higher in secondary forest (YSF and MSF) and selectively logged (ISL and LSL) habitats, at various times of the day. These high values are likely due to higher sound activity in these habitats. For Scarpelli et al. (2021) SPD values were also higher in the forest than in places with less vegetation, and attributed to biophonic activity.

We found higher Normalized Difference Soundscape Index (NDSI) values for the RFP, YSF, MSF and ISL habitats; high values of this index indicate more biological sounds, which may suggest that these habitats have a greater faunal community. Other studies have also shown a positive relationship between this index and ecological conditions (Fuller et al. 2015; Khanaposhtani et al. 2019; Do Nascimento et al. 2020).

The variation in time of acoustic indices in the soundscape showed activity throughout the day, with some higher indices at dawn and dusk, times associated with greater bird activity. These times are considered peak vocal activity in tropical forest areas (Burivalova et al. 2018).

We showed large differences between the rubber plantation (RP) and forest restoration habitats, suggesting that plantation areas have a lower acoustic fauna. RP are agricultural areas that are constantly managed, with the use of pesticides and clearing of the areas. Pesticides were used in the rubber plantations, which can contribute to the loss of species (Devine and Furlong 2007). Manually analysing the recordings of the rubber plantations, we verified that this was the only habitat that presented anthropic sounds, generated by cars or the use of machines in the plantation. Some species can avoid areas with anthropogenic noise (Francis et al. 2009). These different factors likely lowered the index values in RP. In the other sampled habitats, the differences between the results of the indices were smaller. However, we suggest that the YSF, MSF and ISL habitats have more vocalizing species, as they were the best evaluated habitats in most indices that measure biodiversity. In these habitats, manual analysis showed a more intense sound activity in the frequency bands above 20 kHz. These frequency bands are widely occupied by insect and bat sounds. Even using a band considered low for studies of bats, we detected that bats were constantly present in the recordings. We found only one study that recorded at the same sample rate as our study, and it was also reported high bat activity in natural regeneration habitats (Vega-Hidalgo et al. 2021).

In our study, we did not have sampling in untouched forest for comparison with forest restoration habitats. Some studies have suggested that mature or untouched forests housed a larger richness of acoustic species (Burivalova et al. 2018; Dröge et al. 2021). However, also less diversity of sound types was found in mature forest than in restoration sites (Vega-Hidalgo et al. 2021) and Barbaro et al. (2022) showed that not always areas of greater vegetation complexity supported greater acoustic diversity. Other studies showed that land use type and landscape structure affected acoustic diversity (Müller et al. 2022a), and that the increase in tree species richness in a young plantation in the rainforest had positive effects on the acoustic community (Müller et al. 2022b). Here, we suggest that among the various levels of vegetation exploitation, secondary forest and intense selectively logged habitats had the highest sound activity, which may indicate that in these habitats there was a larger faunal community.

5. Conclusions

Acoustic indices showed changes in different categories of habitats in the Atlantic Forest. Most of the acoustic indices that assess the condition of the environments showed higher values in environments where a richer faunal community was expected, with the exception of some indices, such as ACI and ECV. Through the acoustic indices we can suggest that the rubber plantation (RP) was the habitat that had the lowest richness of acoustic species or acoustic activity, while the secondary forest habitats (YSF and MSF) and intense selectively logged forest (ISL) had more richness of acoustic species or greater acoustic activity. In this work we also found a constant activity of bats in the recordings, this group is widely studied through PAM (Sugai et al. 2019), however this taxon is rare in soundscape studies, and should be included in studies that evaluate the health of environments. Through our findings we showed that even using a few days of the soundscape recordings, it was possible to verify changes among the sampled habitats. This is an indicator of the potential of the soundscape to assess and monitor habitat quality in recovering areas. In addition, in the Atlantic Forest biome that suffers from habitat loss, soundscape studies can be allies in conservation research, and the recordings can be used as data libraries of the acoustic community of multiple biomes.

6. Acknowledgments

We thank the Center for Biodiversity Studies of the Reserva Ecologica Michelin for logistical support, especially to Kevin Flesher. LG thanks the Bahia State Research Support Foundation (FAPESB) for the scholarships. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. RSSL and MS thank the Brazilian Council for Scientific and Technological Development (CNPq-Brazil) for their research grant (process numbers 312763/2019-0 and process 309365/2019-8, respectively).

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Supplementary data

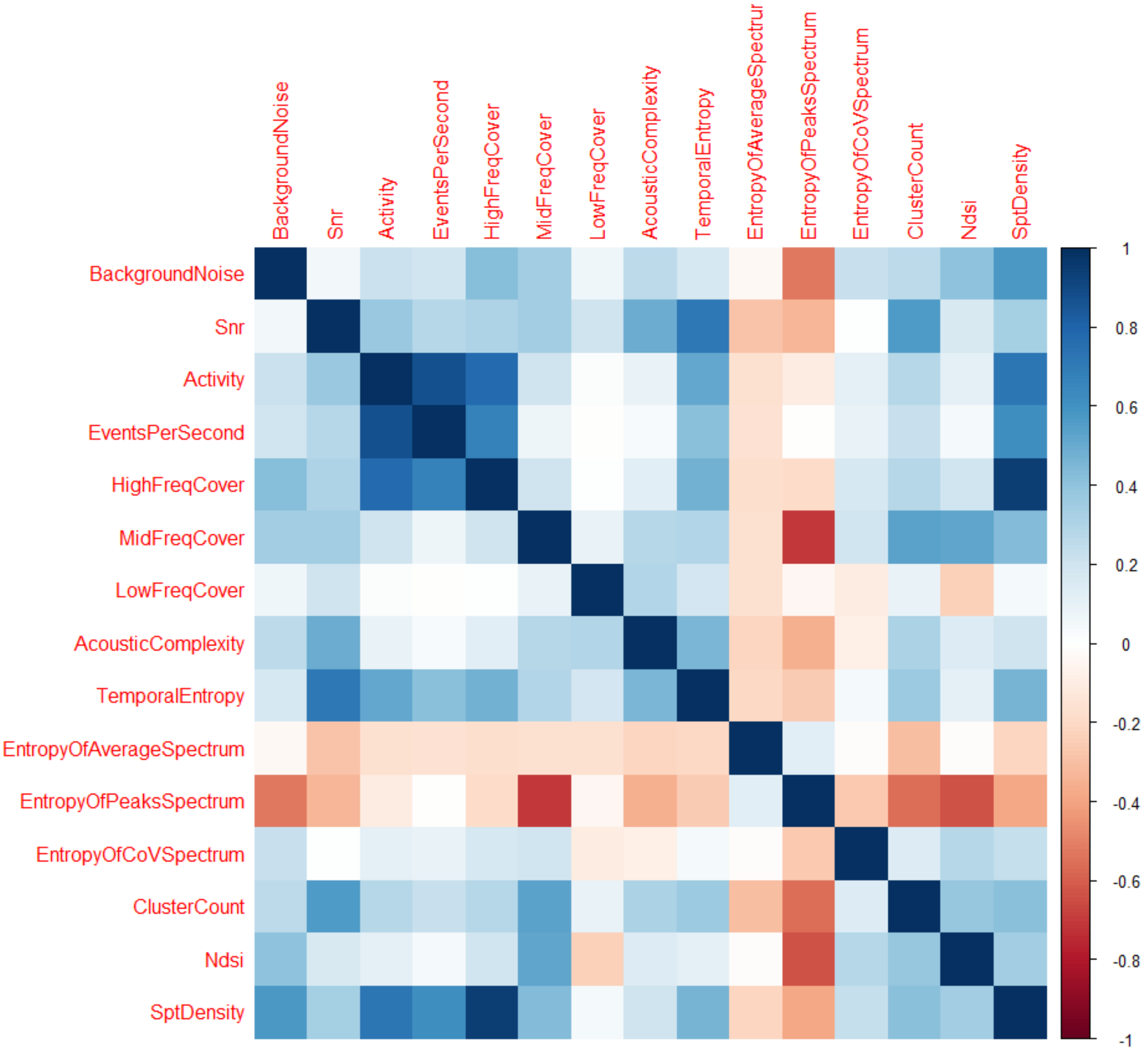

Figure S1. Correlation matrix of fifteen indices evaluated for the complete dataset.

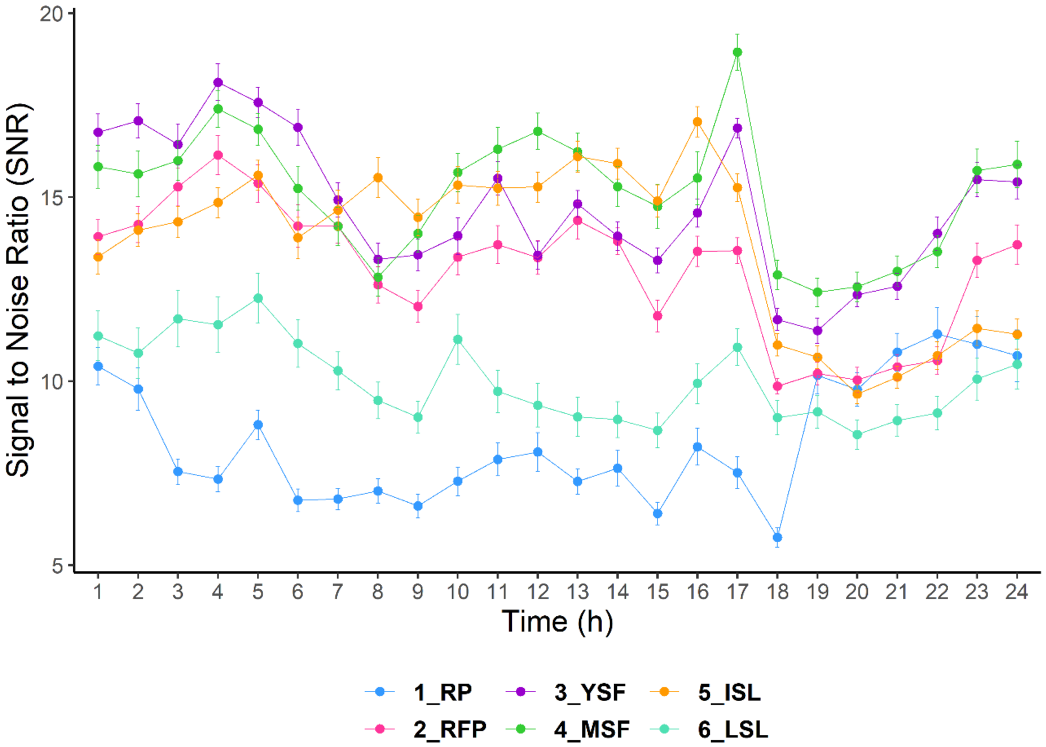

Figure S2. The mean values of the six habitat categories sampled each hour for the Signal to Noise Ratio (SNR) index.

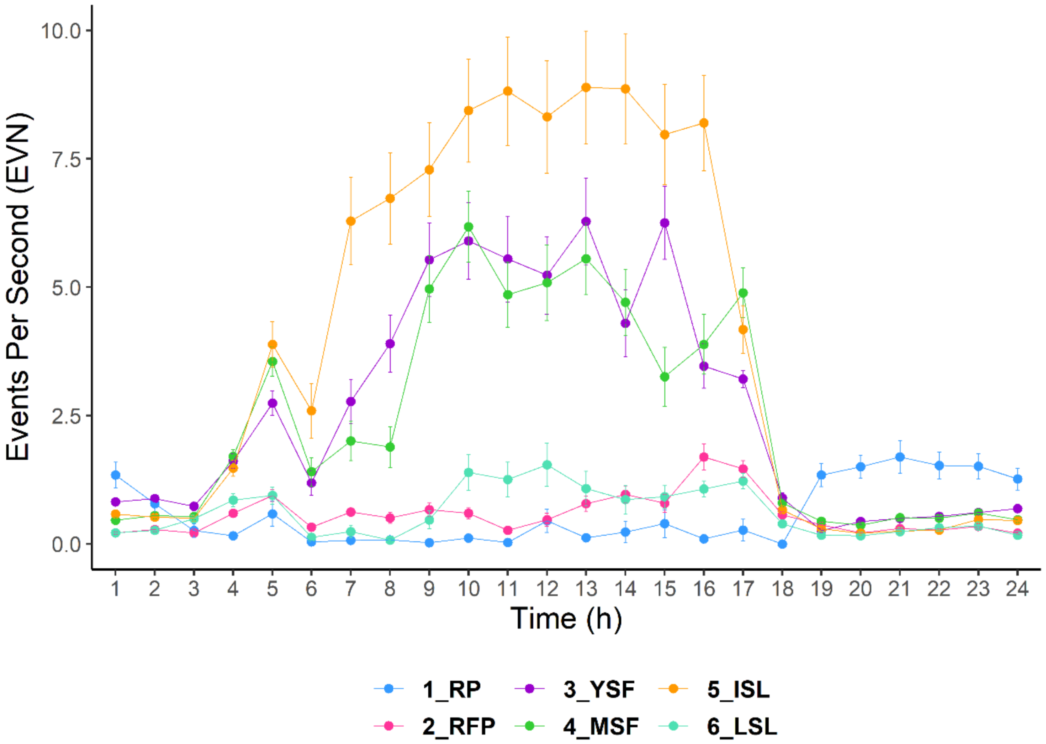

Figure S3. The mean values of the six habitat categories sampled each hour for the Events Per Second (EVN) index.

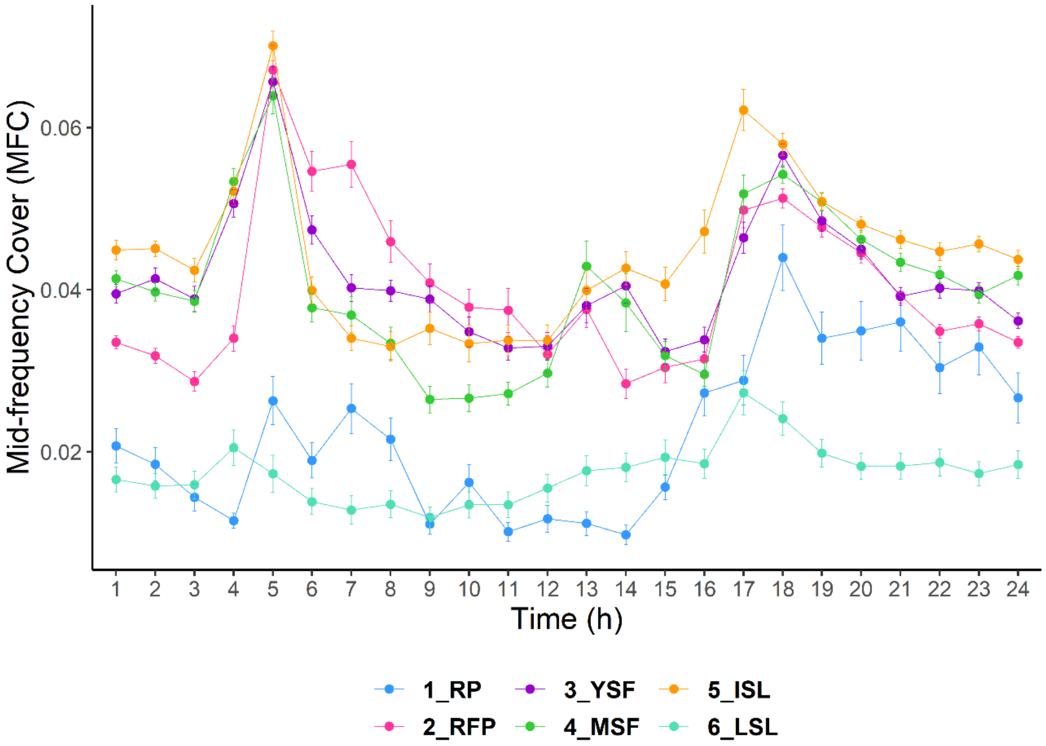

Figure S4. The mean values of the six habitat categories sampled each hour for the Mid-frequency Cover (MFC) index.

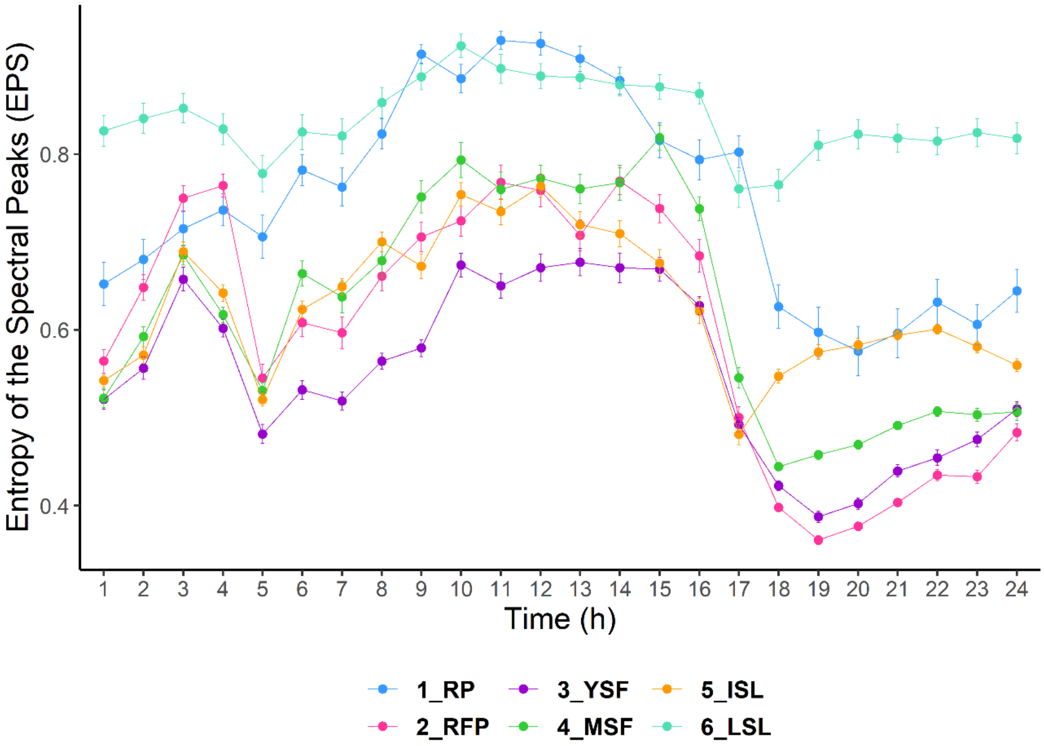

Figure S5. The mean values of the six habitat categories sampled each hour for the Entropy of the Spectral Peaks (EPS) index.

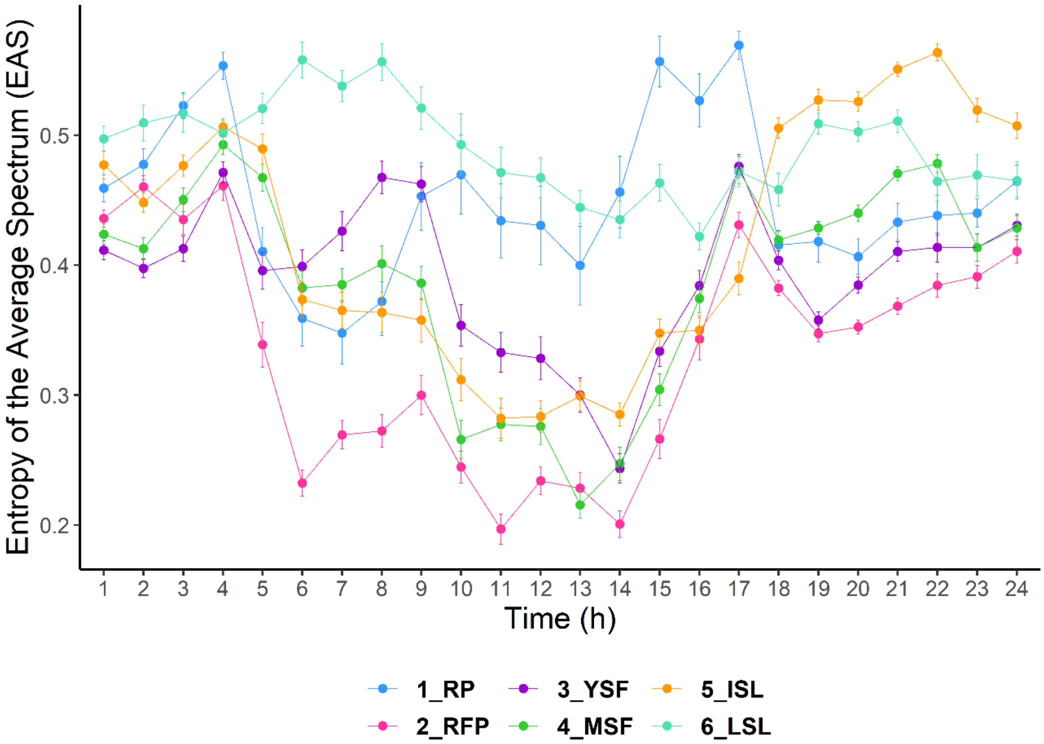

Figure S6. The mean values of the six habitat categories sampled each hour for the Entropy of the Average Spectrum (EAS) index.

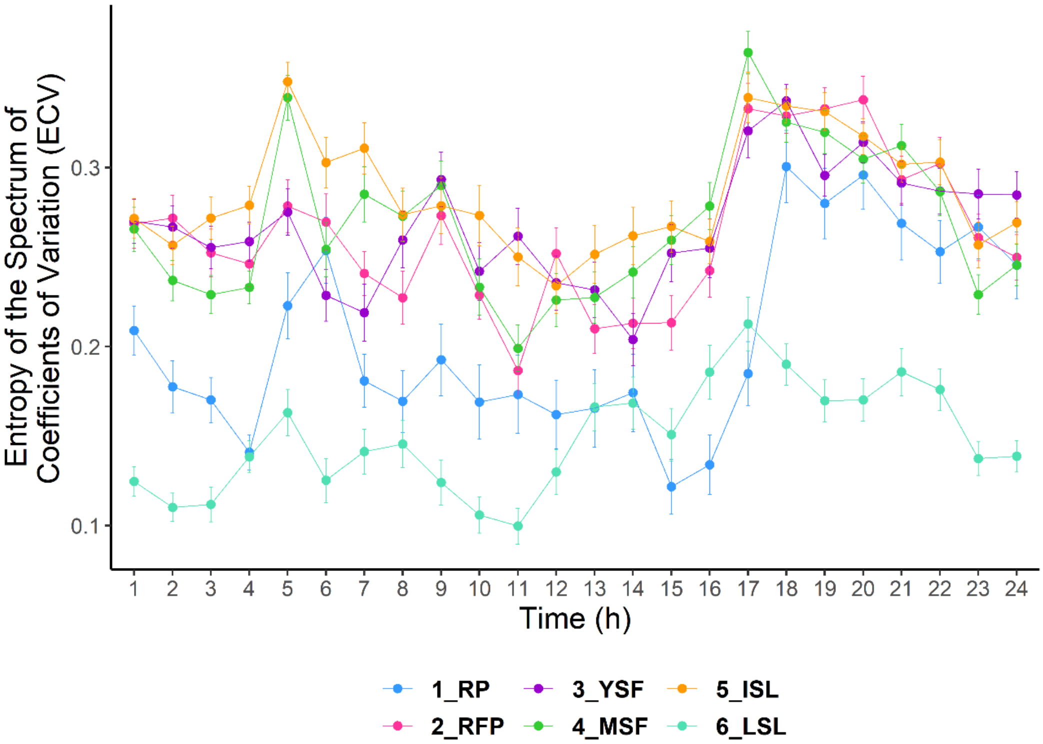

Figure S7. The mean values of the six habitat categories sampled each hour for the Entropy of the Spectrum of Coefficients of Variation (ECV) index.

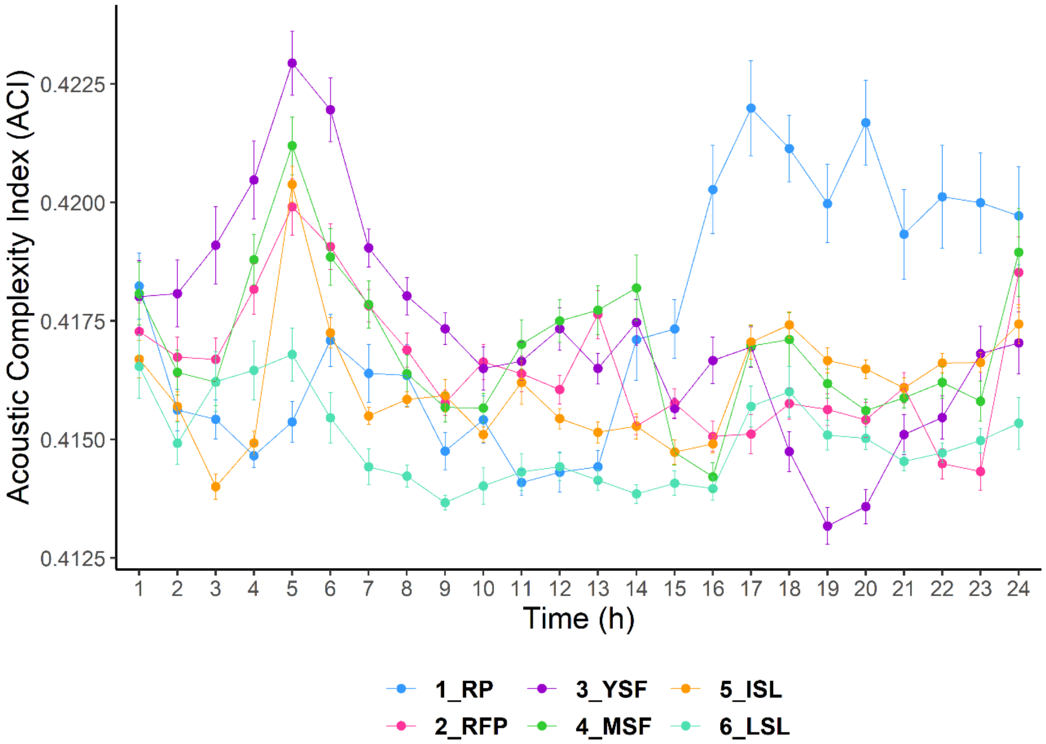

Figure S8. The mean values of the six habitat categories sampled each hour for the Acoustic Complexity Index (ACI).

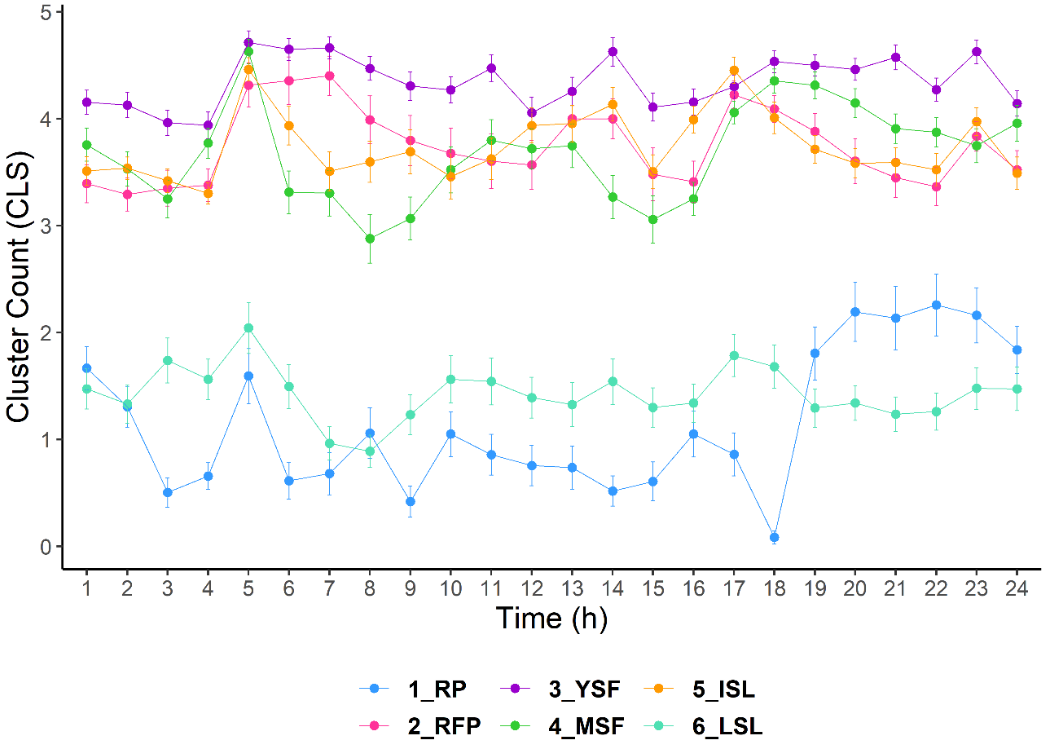

Figure S9. The mean values of the six habitat categories sampled each hour for the Cluster Count (CLS).

Considerações finais

Investigamos a influência do ruido antrópico na fauna acústica através de uma meta-análise, mostramos que aves foi o grupo avaliado com uma quantidade maior de parâmetros acústicos modificados, possivelmente devido ao efeito do mascaramento causado pelo ruido. As aves também foi o grupo com uma maior quantidade de estudos e parâmetros acústicos testados. Os anuros mostraram um padrão geral de aumentar a amplitude em consequência do ruido antrópico. Já os insetos são carentes em números de estudos, o que impossibilitou mostrar a tendência geral para esse grupo.

As investigações que avaliaram se modificações no ambiente são refletidas através de estudos de paisagens sonoras, indicaram que em locais que sofreram com efeito de incêndios florestais os índices acústicos revelaram uma menor diversidade acústica e maior homogeneização da paisagem sonora, a zoofonia desses locais revelaram um menor números de sons diferentes em locais queimados, mas ressaltamos que esse resultado foi maior para o grupo de aves, porém muitas espécies de aves possuem diferentes tipos de cantos, o que poderia influenciar no nosso resultado. Também utilizando paisagem sonora verificamos que diferentes habitats de Floresta Atlântica responderam aos índices acústicos de forma diferente, locais com plantações de seringal tiveram valores de média menores em todos os índices que avaliaram a qualidade do ambiente, enquanto os habitats que estão em fase de restauração, como florestas secundárias e corte seletivo intenso tiveram médias maiores.

Os dados desta pesquisa mostraram que utilizando a comunicação acústica conseguimos inferir sobre o efeito do ruído antropogênico para comunicação animal, além disso, podemos usar as informações acústicas para avaliar ambientes, através dos estudos de paisagens sonoras conseguimos verificar características diferentes em ambientes que passaram por perturbações.

Essa pesquisa faz parte de uma área de estudo bastante jovem, estudos de ecoacústica aumentaram na última década, seus avanços estão diretamente ligados a inovações tecnológicas. Assim, nosso estudo é um dos precursores realizados em diferentes biomas do Brasil e que buscou avaliar diferentes tipos de perturbações antrópicas, essas informações colaboram para o crescimento dessa área de estudo e também mostra a aplicabilidade de estudos de paisagem sonora auxiliando a ecologia de conservação.