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MURILO MINELLO

O USO DE ÍNDICES ECOACÚSTICOS PARA O MONITORAMENTO DE ECOSSISTEMAS MARINHOS

ARRAIAL DO CABO / RJ
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Tese de doutorado apresentada ao Instituto de Estudos do Mar Almirante Paulo Moreira e à Universidade Federal Fluminense, como requisito parcial para a obtenção do grau de Doutor em Biotecnologia Marinha.

Orientador: Prof. Dr. Leandro Calado

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RESUMO

O monitoramento de ecossistemas costeiros marinhos enfrenta desafios significativos devido à sua complexidade ambiental, biológica e ecológica. Apesar de ser um tema emergente, a ecologia acústica oferece soluções promissoras para aprimorar a eficácia desses esforços de monitoramento ambiental. O estudo da paisagem acústica submarina, combinado com a aplicação de índices ecoacústicos, destaca-se como uma ferramenta capaz de monitorar vastas extensões por longos períodos, mesmo sob condições adversas e com custos relativamente menores. Os índices ecoacústicos, que são métricas quantitativas usadas para caracterizar e analisar os padrões sonoros em uma paisagem acústica específica, têm diversas aplicações. Eles podem ser empregados para avaliar a complexidade acústica e a diversidade de espécies em uma paisagem acústica, permitindo inferências sobre a diversidade biológica e a qualidade ambiental de um ecossistema em particular. Este estudo tem como objetivo investigar experiências relevantes referentes à aplicação de índices ecoacústicos em ecossistemas marinhos, identificando desafios e limitações, e propondo avanços. Uma necessidade evidenciada pela revisão bibliográfica é a de testar a aplicação desses índices em uma gama diversificada de condições ambientais. Desta forma, quatro índices ecoacústicos foram avaliados sob diferentes condições de luminosidade, temperatura da água, intensidade e direção dos ventos, bem como no número de embarcações na paisagem acústica próxima à ilha de Cabo Frio, em Arraial do Cabo (RJ). Cabe frisar que uma compreensão profunda de como as variáveis ambientais impactam na interpretação dos índices ecoacústicos é um pré-requisito para o desenvolvimento de um sistema de monitoramento eficiente, capaz de distinguir eventos comuns de situações atípicas. Além disso, para superar outra limitação apontada na revisão bibliográfica sobre a dificuldade de comparar os valores dos índices entre diferentes estudos, este estudo inicia a discussão sobre a criação de um novo índice fundamentado na relação entre biofonia, geofonia e tecnofonia. Por fim, um painel interativo é proposto, integrando índices ecoacústicos e variáveis ambientais, gerando um produto biotecnológico marinho de grande potencial como uma ferramenta para o monitoramento de ecossistemas marinhos.

Palavras-chaves: Paisagem acústica, monitoramento acústico passivo, ecologia acústica, biotecnologia ambiental.

ABSTRACT

Monitoring of coastal marine ecosystems faces significant challenges due to their environmental, biological, and ecological complexity. Despite being an emerging field, acoustic ecology offers promising solutions to improve the effectiveness of these environmental monitoring efforts. The study of the underwater soundscape, combined with the application of ecoacoustic indices, stands out as a tool capable of monitoring vast stretches for long periods, even under adverse conditions and at relatively lower costs. Acoustic indices, which are quantitative metrics used to characterize and analyze sound patterns in a specific soundscape, have a variety of applications. They can be used to assess acoustic complexity and species diversity in a soundscape, allowing inferences about the biological diversity and environmental quality of a particular ecosystem. This study aims to investigate relevant experiences related to the application of acoustic indices in marine ecosystems, identifying challenges and limitations, and proposing advances. A need highlighted by the literature review is to test the application of these indices in a wide range of environmental conditions. Thus, four acoustic indices were evaluated under different conditions of light, water temperature, wind intensity and direction, as well as the number of vessels in the acoustic landscape near the island of Cabo Frio, in Arraial do Cabo (RJ). It is important to emphasize that a deep understanding of how environmental variables impact the interpretation of acoustic indices is a prerequisite for the development of an efficient monitoring system, capable of distinguishing common events from atypical situations. In addition, to overcome another limitation pointed out in the literature review on the difficulty of comparing index values between different studies, this study begins the discussion on the creation of a new index based on the relationship between biophony, geophony, and technophony. Finally, an interactive dashboard is proposed, integrating acoustic indices and environmental variables, generating a marine biotechnological product with great potential as a tool for monitoring marine ecosystems.

Key-words: Marine soundscape, passive acoustic monitoring, acoustic ecology, environmental biotechnology.

SUMÁRIO

1 INTRODUÇÃO

Os ecossistemas marinhos costeiros desempenham um papel fundamental no equilíbrio ambiental e na sustentabilidade global, oferecendo uma ampla gama de serviços ecossistêmicos essenciais, tais como fornecimento de alimentos e produtos, proteção costeira, berçário de espécies, atividades recreativas e turísticas, etc (SALA; KNOWLTON, 2006; CRAIN et al., 2009; COOLEY et al., 2022). No entanto, essas áreas enfrentam múltiplas ameaças decorrentes da ação humana, das mudanças climáticas e da degradação dos ecossistemas (WORM et al., 2006; MAGURRAN et al., 2010; MIRTL et al., 2018). Para preservar esses ecossistemas com elevada, porém vulnerável biodiversidade, é essencial aprimorar de forma contínua os sistemas de monitoramento marinho costeiros (PALUMBI et al., 2009). Esses avanços podem auxiliar na identificação dos impactos costeiros e indicar melhores opções para gestores ambientais, permitindo análises mais precisas, rápidas e eficazes.

O monitoramento marinho costeiro tradicional frequentemente enfrenta desafios de precisão, atualização e integração de dados (MÍGUEZ et al., 2019). Essas dificuldades podem resultar em diagnósticos tardios e tomadas de decisão insuficientemente embasadas, comprometendo a eficácia das ações de conservação (PALUMBI et al., 2009). Adicionalmente, a complexidade dos ecossistemas costeiros requer uma abordagem multidisciplinar, considerando fatores físicos, químicos e biológicos (NESSHÖVER et al., 2017). Nesse cenário, aprimorar os sistemas de monitoramento é fundamental para atender às demandas atuais de análise e previsão de impactos.

Os impactos costeiros são diversos, podendo variar desde a poluição/contaminação da água por resíduos, abrangendo problemas como derramamentos de óleo, poluição sonora subaquática, introdução de espécies exóticas, sobrepesca, mudanças climáticas, etc (CRAIN et al., 2009). As unidades de conservação marinhas, responsáveis pela proteção e manutenção desses ecossistemas, enfrentam o desafio de identificar, quantificar e responder a esses impactos de maneira eficaz (KENNISH, 2022). O aprimoramento dos sistemas de monitoramento marinho possibilitaria a detecção precoce de alguns desses impactos, permitindo que as unidades de conservação adotassem medidas proativas para minimizar danos e promover a restauração dos ecossistemas afetados.

Unidades de conservação marinhas frequentemente lidam com desafios significativos no monitoramento contínuo das mudanças ambientais (FONNER; BELLANGER; WARLICK, 2020). De acordo com a *World Database on Protected Areas* (WDPA, 2023), existem 13.983 unidades de conservação marinhas no mundo. De acordo com o Ministério do Meio Ambiente (MMA, 2023), são 190 unidades de conservação marinhas no Brasil, cobrindo uma área total de 2,5 milhões de quilômetros quadrados. Essas unidades protegem uma variedade de ecossistemas marinhos, incluindo recifes de coral, manguezais, costões rochosos e áreas de pesca artesanal. As limitações de recursos, como um número limitado de analistas ambientais qualificados e escassez de financiamento, frequentemente dificultam a aquisição de equipamentos avançados e a realização de pesquisas que seriam fundamentais para que estas unidades pudessem exercer todas suas funções (LUNDQUIST; GRANEK, 2005; FONNER; BELLANGER; WARLICK, 2020). Essa escassez de recursos pode resultar em lacunas de informação, prejudicando a compreensão completa das mudanças ambientais e, consequentemente, a tomada de decisões fundamentadas. Portanto, é fundamental desenvolver mecanismos mais eficazes e eficientes, que sejam acessíveis em termos de custo e recursos humanos, a fim de gerenciar as unidades de conservação marinhas (WILHELM et al., 2014).

Com a finalidade de comparar e/ou avaliar fenômenos ou características específicas de um determinado ambiente de uma maneira mais rápida pode-se recorrer a índices, que são métricas quantitativas que condensam informações complexas e variadas (CARIGNAN; VILLARD, 2002; NIEMI; MCDONALD, 2004; ROMBOUTS et al., 2013). Os índices ecológicos têm emergido como ferramentas fundamentais no campo da ecologia, possibilitando uma avaliação precisa e quantitativa sobre os ecossistemas (NIEMI; MCDONALD, 2004). São muitos os índices ecológicos existentes, e a aplicação destes oferece uma abordagem sistemática para medir diversos aspectos da biodiversidade, qualidade ambiental e dinâmica das comunidades biológicas (ROMBOUTS et al., 2013). A objetividade e comparabilidade inerentes a esses índices permitem avaliações consistentes ao longo do tempo e entre diferentes áreas geográficas, destacando seu papel importante na tomada de decisões (KENNISH, 2022).

Apesar das promissoras potencialidades dos índices ecológicos, é importante reconhecer suas fragilidades específicas (CARIGNAN; VILLARD, 2002). A simplificação excessiva de sistemas ecológicos complexos em medidas únicas pode levar a uma perda de informações essenciais, ocultando nuances importantes das interações entre espécies e fatores ambientais (NIEMI; MCDONALD, 2004). Além disso, a sensibilidade desses índices a variações metodológicas ressalta a necessidade de diretrizes rigorosas e padronizadas, a fim de garantir a comparabilidade dos resultados entre estudos (MAGURRAN; MCGILL, 2010). A dependência crítica de dados confiáveis e precisos é também um desafio, uma vez que a ausência ou a má qualidade desses dados podem comprometer as avaliações e limitar a eficácia das estratégias de gestão baseadas nos índices (NIEMI; MCDONALD, 2004; MAGURRAN; MCGILL, 2010). Portanto, a utilização de índices ecológicos deve ser abordada com um entendimento cauteloso de suas limitações, complementando-se com abordagens qualitativas e conhecimento local para uma análise ecossistêmica mais abrangente e precisa.

Ainda que os índices tenham o papel de facilitar e acelerar o processo de entendimento daquilo que ocorre nos ambientes, muitas vezes torna-se complicado extrair/coletar todos os dados necessários para o levantamento de diversidade de espécies em campo, por exemplo (PURVIS; HECTOR, 2000; MAGURRAN; MCGILL, 2010). Neste sentido, a acústica submarina pode se apresentar como uma ferramenta poderosa dada sua capacidade de monitorar extensas áreas, por períodos longos, mesmo sob condições adversas e com relativo baixo custo (BLUMSTEIN et al., 2011; HAVLIK; PREDRAGOVIC; DUARTE, 2022).

O Monitoramento Acústico Passivo (MAP) pode facilitar o acompanhamento de espécies-alvo desde a saúde de indivíduos dentro de uma população, ou estudos de densidade populacional, e até mesmo acompanhar deslocamentos desta população em uma determinada área (MARQUES et al., 2011; LUCAS et al., 2015; RISCH et al., 2014; BARROSO; XAVIER; FERREIRA, 2023). Por outro lado, esta ferramenta permite avaliações mais amplas ao considerar toda a paisagem acústica presente, possibilitando apreciações quanto à comunidade biológica (DESIDERÀ et al., 2019), quanto à qualidade do ambiente (SUEUR et al., 2014) e sobre possíveis mudanças e impactos ambientais (LAIOLO, 2010; BITTENCOURT et al., 2020; PIERETTI; DANOVARO, 2020; ELIZABETH et al., 2021).

Muitos desses estudos que se propõem a estudar a paisagem acústica como um todo, considerando diversas fontes sonoras, se vale do uso de índices ecoacústicos para ajudar na descrição e/ou interpretação daquilo que está ocorrendo no ambiente (SUEUR et al., 2014). Este campo da Ecologia Acústica emerge como uma disciplina relativamente recente (FARINA, 2018). Apesar da abundância de índices existentes (FARINA; LI, 2022), sua aplicação requer avaliação em diversas condições, com o propósito de desvelar todo o potencial inerente e, sobretudo, discernir suas limitações intrínsecas.

Diante dos desafios previamente discutidos, relacionados ao monitoramento da paisagem acústica submarina, todo esforço direcionado ao aprimoramento dessa ferramenta voltada para o acompanhamento de ecossistemas marinhos representa um avanço notável no campo da biotecnologia ambiental marinha (RAMOS et al., 2023). Conforme definido por Singh (2017), a biotecnologia consiste na aplicação integrada de princípios científicos e de engenharia com o propósito de obter produtos e serviços úteis mediante o emprego de sistemas biológicos. Nesse contexto, considera-se o som gerado pelas diversas fontes do ambiente como um produto biotecnológico com potencial aplicação na área da proteção ambiental.

Portanto, com o objetivo de propor bases teóricas para ajudar na criação de um sistema de avaliação de ecossistemas marinhos baseado em índices ecoacústicos integrados, este trabalho foi dividido em três capítulos. No primeiro capítulo apresenta-se uma revisão sobre o uso dos índices ecoacústicos em ambientes marinhos, os principais desafios, críticas e questionamentos quanto aos seus usos (MINELLO; CALADO; XAVIER, 2021). No segundo capítulo, calculam-se alguns índices ecoacústicos na paisagem acústica de Arraial do Cabo (RJ) em diferentes condições ambientais. No terceiro capítulo, apresenta-se uma proposta de criação de um novo índice, baseado nas diferentes fontes acústicas, com a finalidade de criar uma proposta que facilite a comparação entre diferentes ecossistemas. Por fim, nas conclusões finais, destacam-se as principais inferências delineadas nos três capítulos precedentes. Além disso, é apresentado um resumo por meio de um painel interativo, que sintetiza a proposta de integração de variáveis e índices ecoacústicos em um sistema de monitoramento marinho.

2 OBJETIVOS

2.2 OBJETIVO GERAL

Avaliar a aplicação de índices ecoacústicos como métricas quantitativas para a caracterização de ecossistemas marinhos.

2.3 OBJETIVOS ESPECÍFICOS

● Examinar experiências recentes sobre o uso de índices ecoacústicos em ecossistemas marinhos;

● Analisar a correlação entre índices ecoacústicos e parâmetros abióticos por meio da análise dos dados obtidos na enseada da Praia da Ilha, Arraial do Cabo, RJ;

● Propor uma discussão sobre um novo índice ecoacústico com a finalidade de facilitar a comparação entre ecossistemas;

● Propor um modelo de painel interativo, demonstrando sua utilidade no âmbito de um sistema de monitoramento de ecossistemas marinhos, baseado na integração de índices ecoacústicos e variáveis ambientais.

3 CAPÍTULO I: *Ecoacoustic indices in marine ecosystems: a review on recent developments, challenges, and future directions*

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Review Article

Ecoacoustic indices in marine ecosystems: a review on recent developments, challenges, and future directions

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Soundscape ecology has gained prominence in the monitoring of marine ecosystems due to its non-invasive characteristics and spatiotemporal efficiency. However, the development of ecoacoustic indices is a recent field that needs to address many challenges to fulfill its great potential, especially in the context of marine ecology. Here, we reviewed the most recent studies that used ecoacoustic indices in marine ecosystems. The literature search was conducted in the *Scopus* (Elsevier) database and used the chain referral sampling in the list of references of each publication. In total, we identified 27 publications that used ecoacoustic indices in marine environments such as coral reefs, rocky shores, coastal regions, and offshore regions. A total of four major limitations were identified and addressed, including: the challenge to find adequate acoustic bioindicators; the lack of a universal index or standardized protocol; the issue that most acoustic indices applied to marine environments have been developed to be used in terrestrial environments; and the lack of studies that have tested ecoacoustic indices under different environmental conditions. Once these challenges are addressed, the analysis of marine sound based on the interpretation of ecoacoustic indices has a great potential to become one of the most cost-effective tools for monitoring environments.

Keywords: bioacoustics, environment quality, index, passive acoustic monitoring, soundscape ecology.

Introduction

Environmental monitoring has been widely used as a tool to understand ecosystem functioning, track biodiversity patterns, and identify potential threats to biological communities (Magurran *et al.*, 2010; Mirtl *et al.*, 2018). Data gathered from monitoring surveys is also a valuable resource to environmental conservation and management programs (Picone *et al.*, 2020). Environmental surveys are often logistically demanding and require a multidisciplinary team to collect and identify species, record abiotic parameters, perform chemical assays, and among other forms of data collection and analysis (Borja *et al.*, 2008; Curtin and Prellezo, 2010; Martinez-Haro *et al.*, 2015). Acoustic monitoring is a powerful, cost-effective tool to be paired with traditional sampling methods because it collects data continuously, at large ecological scales, and in a less invasive and non-extractive manner (Sueur *et al.*, 2014; Desiderà *et al.*, 2019). In *Silent Spring*, Carson (1962) was one of the first to recommend the use of sound perception to monitor biological communities. More recently, Pijanowski *et al.*, (2011) presented soundscape ecology as a new field of study.

Sound plays an important role in the ecology of marine organisms. Visibility in the water column is often very limited as particulate materials and plankton blooms increase turbidity, and light is absorbed unevenly; not reaching certain depths (Utne, 1997). Instead of relying on sight, several marine species have evolved to use sound waves, which propagate in all directions and are more efficiently transmitted, to explore the surrounding environment (Schafer, 1994). As a result, hearing is considered the dominant sense among aquatic animals (Cotter, 2008; Popper and Hawkins, 2019). Particle motion and pressure play an important role in sound perception of aquatic animals (Nedelec *et al.*, 2016). Since marine species are very sensitive to sound, the soundscape influences species behaviour and community dynamics, and, therefore, can be used as an indicator of environmental quality in marine ecosystems (Farina, 2014).

The field of soundscape ecology has grown over the years, and has great potential to provide robust tools for acoustically monitoring species, populations, and communities (Pijanowski *et al.*, 2011; Farina, 2012). Marine ecosystems can be particularly challenging to monitor due to the complexity created by sound wave scattering in underwater conditions and factors that affect wave propagation, such as wave attenuation and reflection (Ducklow *et al.*, 2009; Costello *et al.*, 2017; Hughes *et al.*, 2017; Schluter and Pennell, 2017; Desiderà *et al.*, 2019). Underwater acoustics research needs to understand, map, and incorporate the complexity inherent to the way sound waves behave in the aquatic medium to create more efficient environmental monitoring systems, and to be able to encompass larger time and spatial scales.

Ecoacoustic indices have a great potential to contribute to faster and broader assessments of the environment (Towsey *et al.*, 2014). Robust environmental indices are a cost-effective resource to monitor and manage ecosystems, where it may not be feasible to measure many parameters directly (Dale and Beyeler, 2001). In this context, Sueur and Farina (2015) classified the major ecoacoustic indices areas of application as: biodiversity assessment; habitat assessment; population ecology; community ecology; landscape ecology; and conservation biology.

Here, we review studies that have developed and tested ecoacoustic indices focused on marine habitat assessment. In some studies, the authors refer to ecoacoustic indices as the indicators of environmental "health" or "quality." In this study, we refer to them as the indicators of environmental "status" as in Rice (2003); aiming for a less-subjective approach. We compiled a list of the main indices and the locations where they were used, including the major challenges faced by the research groups. Then, we addressed the main obstacles and possibilities for advances in the field of soundscape ecology.

Methods

We compiled a list of research articles that were published by December 23rd, 2020 using the Scopus (Elsevier) database, where we applied the following filters of keywords, title, or abstract: "*biophony*" or "*ecoacoustic*" or "*soundscape*," "*indices*" or "*index*," and "*marine*" or "*sea*" or "*ocean*." Then, we accessed the list of references of each article and used the chain referral sampling method, or "snowball sampling" (Wenzel, 2017), to ensure that all relevant publications were considered. The results from the "snowball sampling" were added to the initial list of references from Scopus. We analysed each study to determine which index was applied and what was the original application of the index. We also included information about the study such as the main objectives, location, year and duration of sampling, research institute, authorship, and limitations about the index pointed by the authors.

Results

Ecoacoustic indices applied to marine ecosystems

The literature search resulted in a list of 27 references that have utilized ecoacoustic indices in marine environments, 21 from the Scopus database and six additional articles after the "snowball sampling" (Table 1). Among the total of 27 references, nine were review articles and ten accounted for books or book chapters. Therefore, we found eight original research articles that described 11 different ecoacoustic indices for the first time (Table 2). A total of six studies created and proposed eight indices for terrestrial ecosystems, and only two studies developed new indices applied to marine environments (Table 2). Among the total of 11 ecoacoustic indices, the *Acoustic Complexity Index* was the most used (Figure 1). The first study that tested these indices in marine ecosystems was published in 2013 (Figure 2). Since the pioneering work of McWilliam and Hawkins (2013), there has been an increasing use of soundscape ecology indices applied to marine environments. The details of indices calculation are described in Sueur *et al.* (2008). Coastal ecosystems were the most studied marine environments, especially coral reef systems (Table 1). There was a greater concentration of studies in Oceania, Europe, and North America (Figure 3). A total of two studies collected data during a relatively long period of time, of approximately 8 years (Blondel and Hatta 2017, McPherson *et al.* 2016). Blondel and Hatta (2017) started collecting data in the 1990s in Vancouver Island, British Columbia, Canada, for the research program Ocean Networks Canada. McPherson *et al.* (2016) studied marine soundscapes at ten sampling sites around Australia, starting in 2010.

Discussion

Some of the articles took an optimistic stance regarding the use of these ecoacoustic indices in marine environments (Harris and Radford 2014; Lillis *et al.*, 2014; Parks *et al.*, 2014; Bertucci *et al.*, 2016; Butler *et al.*, 2016; Pieretti *et al.*, 2017; Rice *et al.*, 2017; Akamatsu *et al.*, 2018; Ceraulo *et al.*, 2018; Gordon *et al.*, 2018; Elise *et al.*, 2019a, b). Others were more conservative and drew attention to the demand for new indices that may be more suitable to underwater conditions (Staaterman *et al.*, 2014; Kaplan *et al.*, 2015; Buscaino *et al.*, 2016; Harris *et al.*, 2016; McPherson *et al.*, 2016; Parsons *et al.*, 2016; Blondel and Hatta, 2017; Bohnenstiehl *et al.*, 2018; Siddagangaiah *et al.*, 2019; Bertucci *et al.*, 2020; Davies *et al.*, 2020). Considering the most recent review papers, Mooney *et al.*, (2020) and Pieretti and Danovaro (2020) pointed out the need for further studies on the use of ecoacoustic indices in marine environments as there was no clear relationship between marine biodiversity indices and values generated by acoustic indices developed in terrestrial ecosystems.

Identifying challenges and limitations

All reviewed publications emphasized that underwater acoustics hold great potential for monitoring environmental changes. Several studies also brought to light its challenges and limitations. Mooney *et al.*, (2020) suggested that propagation-related aspects and the interference of anthropogenic noise into the soundscape are potential challenges when applying current acoustic indices to assess marine biodiversity. Some of the recommendations proposed by Mooney *et al.*, (2020) are related to increasing replication, prioritizing site selection, and comparing different environments. Trenkel *et al.* (2011) drew attention to the challenges in the use of acoustic monitoring in ecosystem-based management that are related to identifying climate change scenarios using large-scale datasets, or to the interpretation of single-species results in fish stock assessment. Bohnen-

Table 1. Publications that used ecoacoustic indices in marine ecosystems.

Authors	*Tested ecoacoustic indices*	*Sampled area/country*
McWilliam and Hawkins (2013)	Acoustic Diversity Index (ADI); Acoustic Complexity Index (ACI)	Inshore marine soundscapes: mud, cliff, and gravel; Lough Hyne, Ireland
Harris and Radford (2014)	Acoustic Complexity Index (ACI); Acoustic Richness Index (AR); Acoustic Entropy Index (H)	Coral reef, Nordic reef; Pinnacle and OneSpot in northeastern New Zealand
Lillis *et al.* (2014)	Acoustic Entropy (H); Spectral Dissimilarity Index (Df)	Estuarine soundscapes, oyster reefs x soft-bottom habitats; Pamlico Sound, North Carolina, USA
Parks *et al.* (2014)	Acoustic Biodiversity Index (H)	Ocean basins, three-cabled arrays in: South Atlantic, Indian, and North Pacific Ocean;
Staaterman *et al.* (2014)	Acoustic Complexity Index (ACI)	Sand Island Reef and Pickles Reef, Florida, USA
Kaplan *et al.* (2015)	Acoustic Entropy (H); Acoustic Complexity Index (ACI)	Coral reef; Tektite and Yawzi Point, Ram Head, Virgin Islands National Park, USA
Buscaino *et al.* (2016)	Acoustic Complexity Index (ACI)	Shallow waters of a Mediterranean marine protected area; Sicilia, Italy
Butler *et al.* (2016)	Acoustic Complexity Index (ACI)	Near-shore waters of the Florida Keys; Florida, USA
Harris *et al.* (2016)	Acoustic Entropy Index (H); Acoustic Richness (AR); Acoustic Complexity Index (ACI)	Coral reefs; north-eastern New Zealand
McPherson *et al.* (2016)	Acoustic Variability Index (AVI);	Coast around Australia
Parsons *et al.* (2016)	Power Spectral Probability Density (PSPD) plots and the Dynamic Range Indicator (DRI)	Temperate estuary, tropical estuary, tropical nearshore reef, tropical offshore reef, and tropical coastal site; all around Australia
Picciulin *et al.* (2016)	Acoustic Complexity Index (ACI)	Mussel Farm, Adriatic Sea, Jesolo, Italy
Bertucci *et al.* (2016)	Acoustic Complexity Index (ACI)	Coral reefs; Moorea Island, South Pacific
Blondel and Hatta (2017)	Acoustic Complexity Index (ACI)	Offshore; Vancouver Island, British Columbia, Canada
Pieretti *et al.* (2017)	Acoustic Complexity Index (ACI)	Adriatic Sea, and Mediterranean Sea; Italy
Rice *et al.* (2017)	Acoustic Entropy (H); Acoustic Diversity Index (ADI); Acoustic Complexity Index (ACI)	The coasts of Georgia and eastern Florida; USA
Akamatsu *et al.* (2018)	Shannon Index (H')	Coral reef, Sesoko Island, the north-west of Okinawa Island; Japan
Bohnenstiehl *et al.* (2018)	Acoustic Complexity Index (ACI); Acoustic Entropy (H)	Simulated soundscape experiment
Ceraulo *et al.* (2018)	Acoustic Complexity Index (ACI)	Posidonia "bank" and sandy habitats, Mediterranean shallow water; Sicilia, Italy
Gordon *et al.* (2018)	Acoustic Complexity Index (ACI); Acoustic Richness (AR);	Coral reef, Lizard Island; Australia
Elise *et al.* (2019a)	Bioacoustic Index (BI); Spectral Entropy (Hf); Temporal Entropy (Ht); Acoustic Entropy Index (H); Acoustic Complexity Index (ACI)	Coral reef, Europa Island, in the southern Mozambique (about 300 km from the nearest shore of Madagascar)
Elise *et al.* (2019b)	Acoustic Complexity Index (ACI)	Coral reef, Reunion Island (Indian Ocean) and New Caledonia, Pacific Ocean
Siddagangaiah *et al.* (2019)	Acoustic Complexity-Index (ACI); Acoustic Diversity Index (ADI); Bioacoustic Index (BI)	Changhua and Miaoli in the Taiwan Strait
Bertucci *et al.* (2020)	Acoustic Complexity Index (ACI)	Bora Bora Island, South Pacific Ocean; French Polynesia
Davies *et al.* (2020)	Acoustic Complexity Index (ACI)	Rocky reef, Lyme Bay, south coast of the England
Carriço *et al.* (2020)	Acoustic Complexity Index (ACI)	Volcanic Island coast; Azores, Portugal
Bittencourt *et al.* (2020)	Acoustic Complexity Index (ACI)	Diverse coastal area; Rio de Janeiro, Brazil

stiehl *et al.*, (2018) showed that some indices can be modulated by acoustic variations emitted by a single sound-producing species.

Here, we identified four major limitations in the field of soundscape ecology in marine environments. First, is the challenge to find adequate acoustic bioindicators. Second, the lack of a universal index or standardized protocol is a potentially increasing bias caused by different methodologies, and impairing the comparison of results across studies. The third issue is that most acoustic indices applied to marine environments have been developed and validated to be used in terrestrial environments. Finally, there is lack of studies that have tested ecoacoustic indices under different environmental conditions to address the effects of abiotic variables (e.g. daylight, tide, temperature, wind, and earthquakes) on the results. In the following sections, we further developed each one of the four limitations and proposed future directions in the field.

Acoustic bioindicators of ecosystems status

Not all marine species emit detectable sound and, while other species are disproportionally dominant in the soundscape. One of the greatest challenges in using acoustics as a way of monitoring environmental status is to associate these most acoustically representative species with environmental status, i.e. to find

Table 2. The authors, the ecoacoustic index developed, and the main objectives/ecosystem of each one of the eight studies that published the original ecoacoustic indices that have been applied to marine environments. A total of nine indices were created for terrestrial environments, and applied to marine environments (Bioacoustic Index—BI; Temporal Entropy—Ht; Spectral Entropy—Hf; Acoustic Entropy Index—H; Spectral Dissimilarity Index—Df; Shannon's Index—H'; Acoustic Complexity Index—ACI; Acoustic Richness—AR; and Acoustic Diversity Index—ADI). A total of three indices were developed and validated in marine ecosystems (Power Spectral Probability Density—PSPD plots; Dynamic Range Indicator—DRI; and Acoustic Variability Index—AVI).

Ecoacoustic indices	*Authors*	*Objective/ecosystem/country*
BI	Boelman *et al.* (2007)	Compare native and exotic birds' abundance in a Hawaiian submontane ecosystem invaded by Morella trees (EUA).
Ht, Hf, H, and Df	Sueur *et al.* (2008)	Compare two dry lowland coastal forests with different degrees of degradation located in the Rufiji valley (Tanzania).
H'	Villanueva-Rivera *et al.* (2011)	Collected sound from eight different terrestrial ecosystems: from preserved forests to abandoned farms and urban areas in Tippecanoe County, Indiana (EUA).
ACI	Pieretti *et al.* (2011)	To infer the singing activity of an avian community in the Beech Mountain forest, Tuscan-Emilian Apennine National Park (Italy).
AR	Depraetere *et al.* (2012)	Three sampling sites: a mature forest, a young forest, and at the frontier between cornfield and a forest, all in the Parc Naturel Régional of Vallée de Chevreuse, south-west of Paris (France).
ADI	Pekin *et al.* (2012)	Soundscape was taken from a lowland neotropical rainforest between the La Selva biological station and the Braulio Carrillo National Park (Costa Rica).
PSPD and DRI	Parsons *et al.* (2016)	Reported fish choruses from different sites, like temperate estuary, tropical estuary, nearshore and offshore reefs, and tropical coastal (Australia).
AVI	McPherson *et al.* (2016)	Acoustic data collected by a long-term monitoring program in marine environments in Australia.

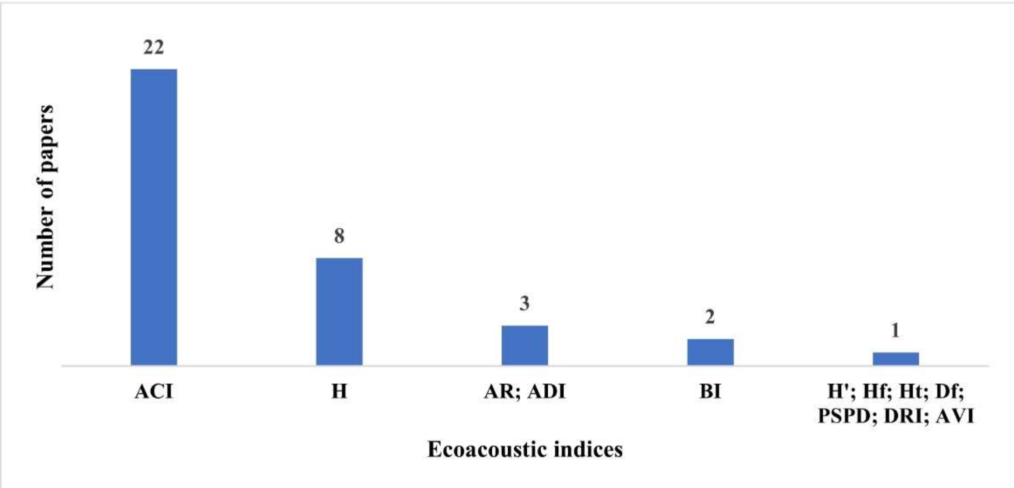

Figure 1. Number of publications that used each ecoacoustic index. *Acoustic Complexity Index* (ACI); *Acoustic Entropy Index* (H); *Acoustic Richness* (AR); *Acoustic Diversity Index* (ADI); *Bioacoustic Index* (BI); *Shannon's Index* (H'); *Spectral Entropy* (Hf), *Temporal Entropy* (Ht), and *Spectral Dissimilarity Index* (Df); *Power Spectral Probability Density* (PSPD) plots and the *Dynamic Range Indicator* (DRI); and *Acoustic Variability Index* (AVI).

robust bioindicators (Cooper *et al.*, 2009). Acoustic bioindicator species should have a distinct set of characteristics, such as clear and detectable sound emissions, widespread spatial and seasonal distributions, consistent life cycles, and sensitivity to environmental changes (Hilty and Merenlender, 2000). Finding species that have these key characteristics and determining their population dynamics and interactions with the biological community are priorities in the field of soundscape ecology (Mooney *et al.*, 2020). Coastal urchin populations are considered great acoustic bioindicators, because they are the major contributors to the underwater choruses and provide important ecological services such as assisting larvae of key reef species to orient themselves towards onshore and find settlement sites (Radford *et al.*, 2008). More often, however, choosing acoustic bioindicators is a challenging task. For example, snapping shrimps can be easily detected and acoustically monitored, but are not good environmental bioindicators of coral reef health because they are abundant in both healthy and degraded reefs (Lammers *et al.*, 2008; Butler *et al.*, 2017). Cooper *et al.* (2009)

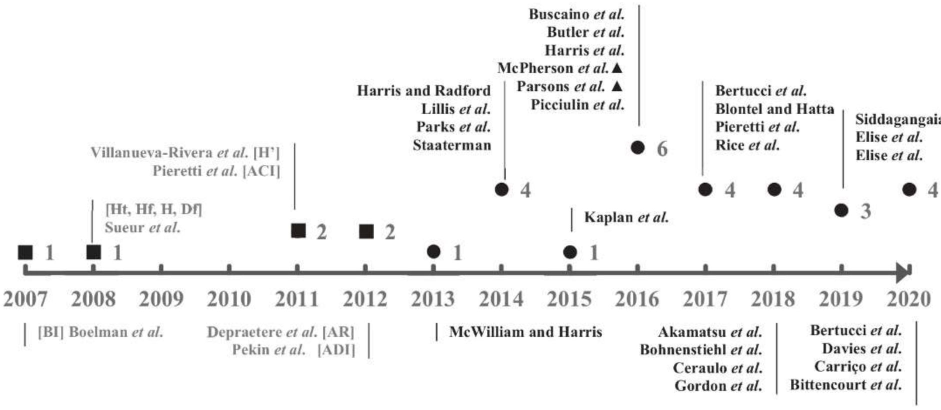

Figure 2. Timeline of soundscape ecology publications: (1) studies that proposed ecoacoustic indices, initially for terrestrial ecosystems (■); (2) studies that applied ecoacoustic indices to marine ecosystems (●); and (3) studies that designed ecoacoustic indices specific to marine ecosystems (▲).

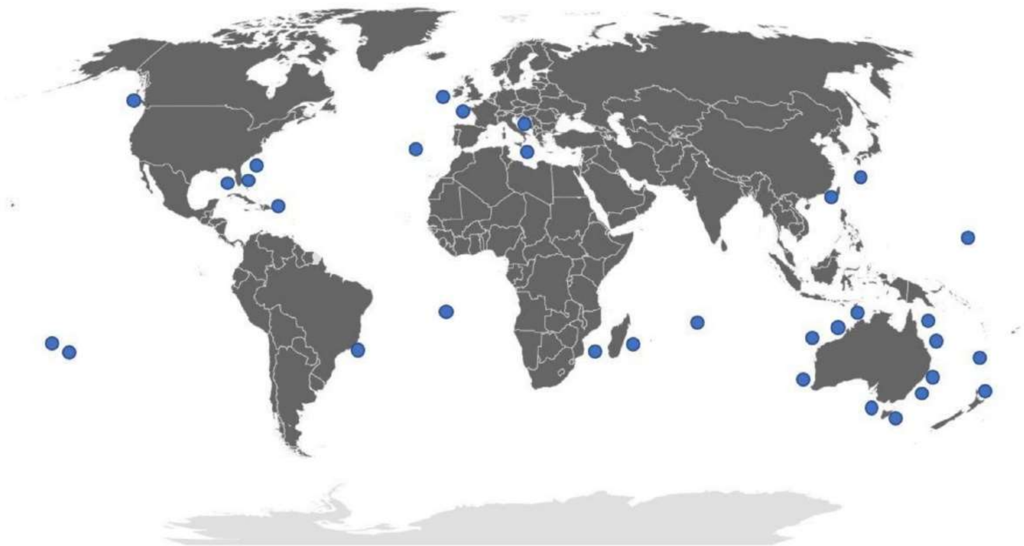

Figure 3. Global map with schematic geographical localization of environments that were assessed from ecoacoustic indices.

recognized the difficulty in monitoring coral reef ecosystems and reviewed 21 candidate bioindicators that responded to changes in water quality, and to short- and long-term changes in community composition, but there was no mention of the use of acoustics. Coral reefs host an exceptional biodiversity of sessile species that are sensitive to human activities, and the use of acoustic techniques in reef environments is a promising approach to monitor coastal ecosystem status (Obura and Grimsditch 2009, 2019).

Another important issue is that soundscape ecology studies should have a clear objective for the use of the bioindicator species. In general, acoustic bioindicators seem to be more effective to indicate the degree of pollution or environmental status than to reflect the local biodiversity (Moreno *et al.*, 2007; Stephens *et al.*, 2015). Furthermore, going from the species level to analyse the community may require the development of new ecoacoustic indices or the adjustment of existing ones (Farina *et al.* 2018; Sandoval *et al.*, 2018). Ecoacoustic indices should be integrated to the search for one or a few species that qualify as ecological-disturbance indicator species (Caro, 2010) to expand the use of acoustic signals to the level of ecosystems (Pjanowski *et al.*, 2011; Pieretti and Donavaro, 2020).

Standardized methodology and protocols

When we compared the methodology used across ecoacoustic studies, we noticed that there is a great variation in the type and quality of hydrophones, the sample rate, and bandwidth used for acoustic recording, and different daytime periods. There was a large variability in the recording rates (Lindseth and Lobel 2018), ranging from 10 s long recordings every 4 min (Loscascio and Burton, 2015) to continuous recordings for 48 h (Pieretti *et al.*, 2017). Frequency rates or bandwidth range also varied a lot, going from 2 to 250 kHz, and self-generated equipment noise produced artificial high values of ACI (Nguyen Hong Duc *et al.*, 2021). Variability in sampling designs across soundscape ecology studies is inevitable as specific research objectives require different logistics. However, a standardized acoustic index would facilitate the comparison between different studies (Blanchard *et al.* 2010). The wide variation in the equipment and methodology used in short and small-scale studies greatly affect the results produced by the same acoustic index, compromising comparisons across studies (Lindseth and Lobel 2018). For example, analysing at least 48 h of acoustic data is a fundamental source of preliminary data to account for circadian and circatidal rhythms in marine ecosystems (Tessmar-Raible *et al.*, 2011), which should be a standard protocol adopted by soundscape ecology studies. Furthermore, it is crucial to standardize data analysis pipelines and output metrics to generate comparable results (Lindseth and Lobel 2018). A standardized protocol for each ecoacoustic index would improve this as a tool for ecosystem comparison and assessment of ecosystem status (Miksis-Olds and Martin 2018). The use of indices to assess marine environments is still very incipient and standardization is crucial for the evolution of this field of soundscape ecology applied to marine ecosystems (Ainslie *et al.*, 2018). The next step would be to develop a general index that facilitates such comparisons. Gibb *et al.* (2018) addressed opportunities and challenges for soundscape studies, and emphasized the need for collaborative work to improve possibilities for Passive Acoustic Monitoring (PAM) globally.

Terrestrial vs. aquatic ecosystems

The influence of changes in environmental parameters on the community behaviour and/or sound wave propagation needs to be further understood and incorporated to ecoacoustic indices calculation and validation (Pieretti *et al.*, 2011; Desiderà *et al.*, 2019; Davies *et al.*, 2020). Indices that have been validated in terrestrial environments should be used with care in underwater conditions, since there are fundamental differences in the propagation of sound between the two environments (Blondel and Hatta, 2017). Sound propagates faster and spreads over larger areas in water when compared to air, among other interferences and reflections that occur in underwater conditions (Mooney *et al.*, 2020). Therefore, indices that were developed in terrestrial environments should be validated in aquatic environments and exhaustively tested to confirm their effectiveness.

Among all the articles reviewed in our study, only Parsons *et al.* (2016) and McPherson *et al.* (2016) designed a new ecoacoustic index specific to marine ecosystems. Other ecoacoustic indices were made by modifying or adapting pre-existing indices. Pekin *et al.* (2012) calculated diversity across frequency bands using an acoustic diversity index (ADI) based on the Shannon index, and on indices developed by Pijanowiski *et al.* (2011) and Villanueva-Rivera *et al.* (2011). MacPherson *et al.* (2016), developed the acoustic variability index after some changes in the ACI_{ft} created by Farina *et al.* (2016).

Environmental acoustics and modeling

Ecoacoustic indices, need to consider anthropogenic and environmental parameters to produce an accurate interpretation of the biological community. Human-dominated landscapes are generally detrimental to natural soundscapes (Rossi *et al.* 2017). Environmental factors or natural events can also affect the values produced by the acoustic indices. For example, Gottesman *et al.* 2020demonstrated that healthy kelp forests could have an acoustic quieting effect by attenuating some specific frequencies. Calado *et al.* (2018) showed that coastal upwelling changed water conditions in a short period of time and drastically altered the propagation or production of underwater sound. These events can cause some momentary biological reaction or alter the way the sound is propagated, masking the environmental interpretation.

Environmental indices should be able to provide a comprehensive and quick interpretation of the environmental status to be considered a robust management tool (Girardin *et al.*, 1999; Wang *et al.*, 2014). Stephens *et al.* (2015) emphasized the difficulties in developing unambiguous indices and models in ecology, which were mainly due to the vast network of cause and effect of variables with non-linear behaviour. The Acoustic Complexity Index (ACI), for example, often produces inconsistent and non-significant results (Kaplan *et al.* 2015; Bohnenstiehl *et al.*, 2018; Lyon *et al.*, 2019; Dimoff *et al.*, 2021). A wide range of variables may interact, and mask values obtained by acoustic indices. The integrated use of measured ecoacoustic indices and environmental data, creates a "complex" or "composite system" (Girardin *et al.* 1999; Heink and Kowarik 2010; Koppe *et al.* 2004; Mitchell *et al.* 1995). Girardin *et al.*, (1999) reinforces the need of "composite indicators," i.e. the use of models associated with several simple indexes to compose more reliable systems for interpreting the environment. Koppe *et al.* (2004), mentioned the use of "complex indices" to better describe the physiological heat load in a heat health warning system. Koppe *et al.* (2004) calls "complex indices" because it associates meteorological data and heat budget models with physiological parameters to identify situations that adversely affect human health. Mitchell *et al.*, (1995) mentioned the use of "complex" and "composite indices" to present a methodology for the construction of indicators of sustainable development.

A monitoring system must be able to assess and respond to different environments subject to diverse events. For this, it is necessary to expose and test the ecoacoustic indices to the greatest possible complexity of situations and evaluate their suitability for environmental interpretation. For this purpose, Sethi *et al.* (2019) suggest the combination of machine learning and a set of universal acoustic features, to produce an automated and efficient monitoring of ecosystems. Mapping and monitoring events (e.g. storms, coastal upwelling, transit of vessels, and movement of target species) through an acoustic perspective should be a priority. Then, predicting or monitoring the response of the biological community (e.g. coral bleaching and distribution of invasive species) would be possible. Therefore, we believe that soundscape monitoring, especially if associated with robust abiotic models of the environment, can be a remarkable tool for ecological studies.

Conclusion

All the 27 references analysed in this review exemplified the growing use of ecoacoustic indices in marine environments, from 2013 to 2020. These publications showed that there is a great potential in the use of ecoacoustic indices as an environmental monitoring tool. However, they also indicated that improvements are necessary to achieve a reliable interpretation of these indices to assess ecosystem status. Therefore, there must be a collective effort in creating and testing new indices that will be able to describe the environment in underwater conditions.

Another important effort would be to describe and map the influence of other variables in soundscape ecology, to understand how they interfere on the ecoacoustic indices interpretation. Anthropogenic noise, environmental changes, and the overgrowth of a particular species can alter the acoustic landscape and mask the effectiveness of ecoacoustic indices. This may be the most audacious task, as there is a wide range of factors simultaneously influencing biological communities and physical conditions. The integration of environmental models and machine-learning techniques into multiple ecoacoustic indices could result in a composite or complex monitoring system able to improve the understanding of the underwater soundscape.

Once these knowledge gaps are addressed, it will be possible to realize the full potential of acoustic monitoring to understand changes in marine environments based on long-term ecological research. The improvements in the ecoacoustic indices can, therefore, turn underwater acoustics into an economically advantageous tool that uses passive and non-destructive sampling to monitor large areas over a long period of time.

Data availability statement

No new data were generated or analysed in support of this research.

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4 CAPÍTULO II: *Exploring ecoacoustic indices in response to soundscapes in a marine protected area exposed to coastal upwelling*

ABSTRACT

Ecoacoustic indices have the potential to become an important tool for monitoring marine ecosystems because they take passive and non-invasive measurements over wide spatial and temporal ranges. However, the performance and limitations of marine ecoacoustic indices are not yet fully understood. This study evaluated the Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Bioacoustic Index (H), and Normalized Difference Sound Index (NDSI) ecoacoustic indices applied to a marine protected area (MPA) in a coastal upwelling region. Environmental variables such water temperature, wind direction, solar radiation, and vessel traffic as were recorded between September and December 2018 off Arraial do Cabo, Rio de Janeiro, Brazil. Principal component analysis showed that the ACI index was correlated with the number of vessels, while the ADI and H indices were correlated with water temperature. After categorizing specific moments, it was observed that the ACI was the best index for differentiating specific times of day, while the ADI was ideal for distinguishing between moments with and without vessel presence. Consequently, the ACI and ADI showed the best performance overall. This study identified the main variables influencing the soundscape of a productive upwelling region and intensely used MPA. Furthermore, this research has laid the foundation for further exploration and the development of a robust, non-invasive tool for monitoring marine environments.

key-words: Soundscape Ecology, Passive Acoustic Monitoring; Biophony, Geophony; Anthropophony.

INTRODUCTION

Soundscape ecology is a field that studies the sounds produced by living organisms and their interactions with the environment (PIJANOWSKI et al., 2011). The soundscape, or the sum of all sounds present in a particular environment, can provide important information about ecosystem health (QI et al., 2008) and diversity (LIN et al., 2021; ALCOCER et al., 2022). Bioacoustic tools can be applied to monitor responses across a wide range of ecological levels (SUEUR and FARINA, 2015). Acoustic data collected at the organism level, such as physiological responses (ROMANO et al., 2004) or the presence of target species (KORNELIUSSEN et al., 2016), can be used to infer populational parameters (e.g., population size and density) (MARQUES et al., 2013) and community dynamics (e.g., diversity and environmental changes) (KRAUSE and FARINA, 2016). Ecoacoustic indices emerge as powerful tools in this context, providing valuable insights for a comprehensive understanding of ecological patterns and processes (SUEUR and FARINA, 2015).

The use of acoustic indices in ecology offers several advantages by reducing data complexity, enabling comparisons between different environments, and facilitating the integration of acoustic data with other types of data, such as environmental and biological data (NIEMI and MCDONALD, 2004). Acoustic indices facilitate the analysis of the marine soundscape and promptly provide results to support data-informed decisions, making them especially important for resource and habitat management (RAJAN et al., 2019; BENOCCI et al., 2020). By summarizing complex acoustic data into a single value, acoustic indices provide a streamlined way to understand the soundscape. However, the use of indices also has limitations. Acoustic indices are sensitive to the quantity and quality of the collected data, which need to be carefully examined to ensure accurate analysis (BRADFER-LAWRENCE et al., 2019). Otherwise, the indices may not reflect environmental complexity and provide a misleading picture of ecosystem conditions (DALE and BEYELER, 2001).

Environmental variables such as water temperature (CALADO et al., 2018), as well as biological variables like the presence of predators (LADICH et al., 2022), and also anthropic variables such as vessel traffic (GARRETT et al., 2016), can significantly influence the interpretation of marine ecoacoustic indices. To ensure the validity of results, it is important to use indices in conjunction with other environmental data and consider these limitations and their assumptions (MINELLO et al., 2021). The next step to further advance this field would be automated analysis of large datasets to enhance the interpretation of ecosystem functioning (WILLIANS et al., 2022).

The use of acoustic indices is a relatively recent development in the field of soundscape ecology, and further research exploring their use is crucial (FARINA and LI, 2021). Baseline data on the behavior of ecoacoustic indices in target environments such as marine protected areas (MPAs) is scarce, which impairs the use of acoustic indices to monitor extreme events (e.g., thermal anomalies) and anthropogenic impact (e.g., vessel traffic) (RICE, 2003). The Marine Extractive Reserve of Arraial do Cabo is one of the most important MPAs in Brazil, located in a highly biodiverse and productive upwelling region that supports thriving artisanal fisheries and tourism (ROGERS et al., 2014; LIMA and COUTINHO, 2016). Therefore, Arraial do Cabo offers a unique model system to investigate the behavior and applicability of ecoacoustic indices in response to environmental variables related to boat traffic and upwelling events. Here, we compare four ecoacoustic indices acting in a marine soundscape by identifying how they interpret environmental conditions off Arraial do Cabo. By understanding how the indices perform, more efficient monitoring tools can be created to investigate complex events that are key for marine conservation, such as overfishing, climate change, or water quality.

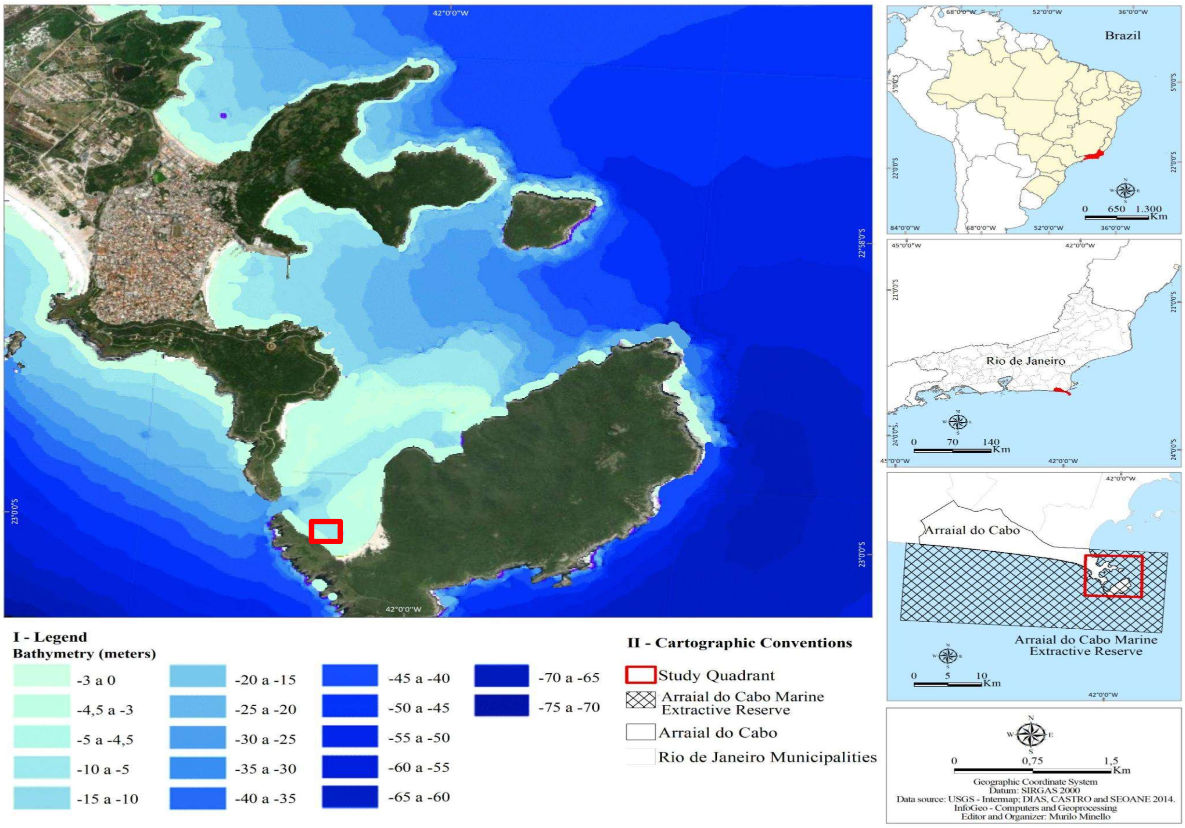
METHODS

THE STUDY SITE: ARRAIAL DO CABO MARINE COASTAL REGION

This work was carried out in Arraial do Cabo, a coastal city in the state of Rio de Janeiro, Brazil (Fig. 1). Its modern history is intrinsically linked to the salt industry and alkali production (CARVALHO et al., 2021), artisanal fishing, tourism and, occasionally, the small local port supports the oil extraction industry (PEREIRA, 2014; SILVA et al., 2018). The creation of the marine conservation unit, Resex Mar Arraial do Cabo in 1997 (BRASIL, 1997), aimed at protecting both marine life and local traditional fishing practices, was an important milestone for local management (BRAGA et al., 2016).

One of the main environmental factors that characterize this coastal region is the upwelling that occurs due to the morphology of the seabed and prevailing winds (NE). This process can drastically modify marine environmental conditions in just a few hours, turning the coastal waters from warm temperatures (20 to 26ºC) to cold, nutrient-rich waters (14 to 18ºC), which typically promote primary productivity and consequently decreasing light availability in the water column for days (COELHO-SOUZA et al., 2012), in a coastal region known for their water transparency (Fig. 1).

Figure 1. Coastal bathymetric map indicating the location of the acoustic acquisition system in the study area: Arraial do Cabo, Rio de Janeiro, Brazil.



DATA COLLECTION

The recording system consisted of a stainless-steel pyramid structure with a hydrophone installed approximately 8 meters below the waterline and about 7 meters away from the rocky shore. This methodology was developed and validated as part of the Biocom project and further details are described in the studies by JESUS et al. (2020) and LOUZA et al. (2019).

The audio recordings available for this study correspond to the period from September to December 2018. The data was collected using a fixed acquisition system equipped with hydrophone (4 channels Marsensing Ltda's digital model Hyd TP-1). The system was configured with a sampling frequency of 52.7 kHz, 24-bit resolution, sensitivity of -174.9 dB re 1V/1µPa, and a flat response between 0.1 and 40 kHz. Acoustic recordings were conducted at a duty cycle of 20%, i.e, 1 minute every 5 minutes. To calculate the Sound Pressure Level (SPL), each one-minute audio file (wav file) was divided into 60 one-second blocks. For each block of one second, the Power Spectral Density (PSD) was calculated using the Welch periodogram (from the Python Scipy library) with an overlap of 50% and a resolution of 8192 points. From these 60 PSDs, the SPL50 (50th SPL percentile or median) was estimated for each 60s.

For examining the behavior of the acoustic indices, we recorded the number of vessels per day circulating in the region and water temperature, obtained through communication with the team at the Admiral Paulo Moreira Sea Studies Institute (IEAPM). Solar Radiation (kJ/m²), Wind Intensity (m/s), and Wind Direction (°(gr)) data were obtained from the National Institute of Meteorology (INMET). Each day was divided into four periods based on solar light variation: daytime, nighttime, dawn, and dusk as proposed by CAMPBELL et al. (2019).

PCA ANALYSIS

We performed a Principal Component Analysis (PCA) on a dataset consisting of 10 randomly selected full days between September and December 2018. The analysis included environmental variables such as Day, Hour, Solar Radiation, Wind Intensity and Direction, Water Temperature, Number of Vessels (as shown in Table 1), as well as the Sound Pressure Level divided into three frequency bands: G1 (112 to 890 Hz), G2 (891 to 2239 Hz), and G3 (2240 to 22390 Hz). Additionally, we considered ecoacoustic indices, namely the Acoustic Complexity Index (ACI) (PIERETTI et al., 2011); Normalized Difference Sound Index (NDSI) (KASTEN et al., 2012); Bioacoustic Index (H) (BOELMAN et al., 2007); Acoustic Diversity Index (ADI) (VILLANUEVA-RIVERA et al., 2011). The ecoacoustic indices were analyzed using the Soundecology package in R.

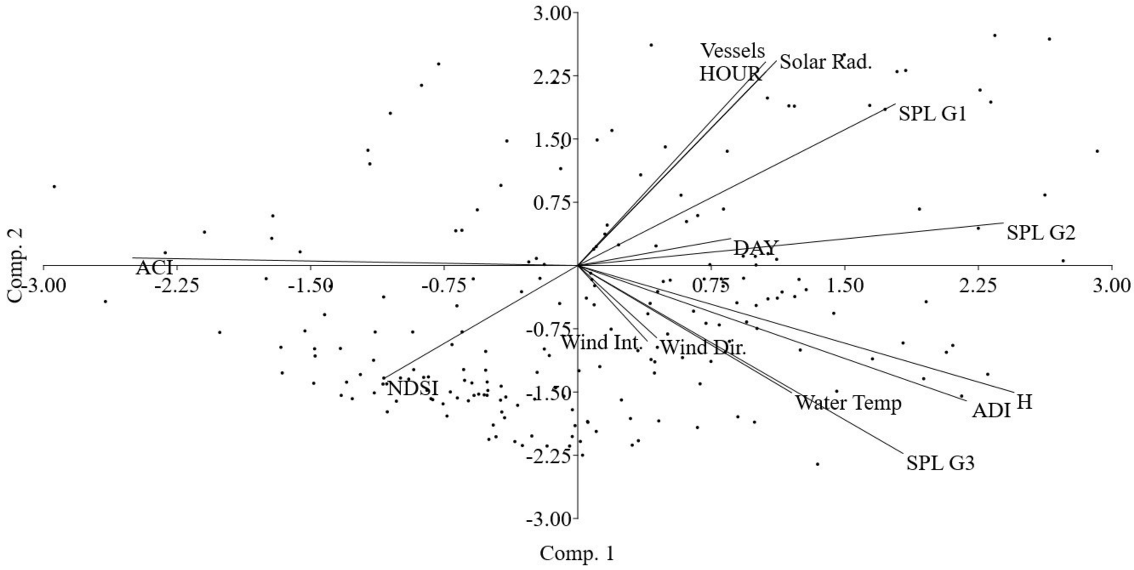
Table 1. The environmental variables classification and their corresponding sampling sizes or recording numbers (n), enabling the analysis of principal components and their correlations with the acoustic data.

Variable	Classes	n (total 240)
Day	Business days = 0 Weekends, holidays, recess, school holidays = 1	168 72
Hour	Night (20 to 4h) = 0 Dawn (5 to 7h) and Evening (18 to 19h) = 1 Day (8 to 17h) = 2	90 50 100
Wind Intensity (m/s)	No Wind (<1m/s) = 0 Light Wind (>1; <7m/s) = 1 Strong Wind (>7m/s) = 2	3 172 65
Wind Direction (º(gr))	Quadrants: N/E (0 to 90º(gr)) = 0 E/S (91 to 180º(gr)) = 1 S/W (181 to 270º(gr)) = 2 W/N (271 to 359º(gr)) = 3	 30 27 82 101
Water Temperature (ºC)	Cold Water (<20ºC) = 0 Warm Water (>20;<24ºC) = 1 Hot Water (>24ºC) = 2	57 177 6
Radiation (kJ/m^2)	No Radiation (<5) = 0 Ligth Radiation (5 to 1.212) = 1 Strong Radiation (>1.212) = 2	112 67 61
Vessels (n)	No Vessels (<30)=0 Few Vessels (30 to 99)=1 Many Vessels (>100)=2	191 28 21

RESULTS

The environmental variables showed clear correlations to specific sound pressure levels and acoustic indices according to the Principal Component Analysis (PCA) (Fig. 2). Solar radiation, time of day, and number of vessels overlap and exhibit strong correlation and are closely associated with SPL G1, indicating their significant influence on lower frequency range of soundscape. The Acoustic Complexity Index (ACI) positively correlated with precipitation while showing a negative correlation to number of vessels. Water temperature showed a stronger correlation with wind intensity and direction, which have a stronger influence on SPL G3, i.e., higher frequencies.

Figure 2. Principal Component Analysis of environmental variables, ecoacoustic indices and sound pressure level conducted on a dataset comprising 10 randomly selected complete days between September and December 2018. The analyzed variables include: day, hour, solar radiation, wind intensity and direction, water temperature, number of vessels, sound pressure Level divided into three frequency bands: G1 (112 to 890 Hz), G2 (891 to 2239 Hz), and G3 (2240 to 22390 Hz), as well as the Acoustic Complexity Index (ACI), the Acoustic Diversity Index (ADI), the Bioacoustic Index (H) and Normalized Difference Sound Index (NDSI).



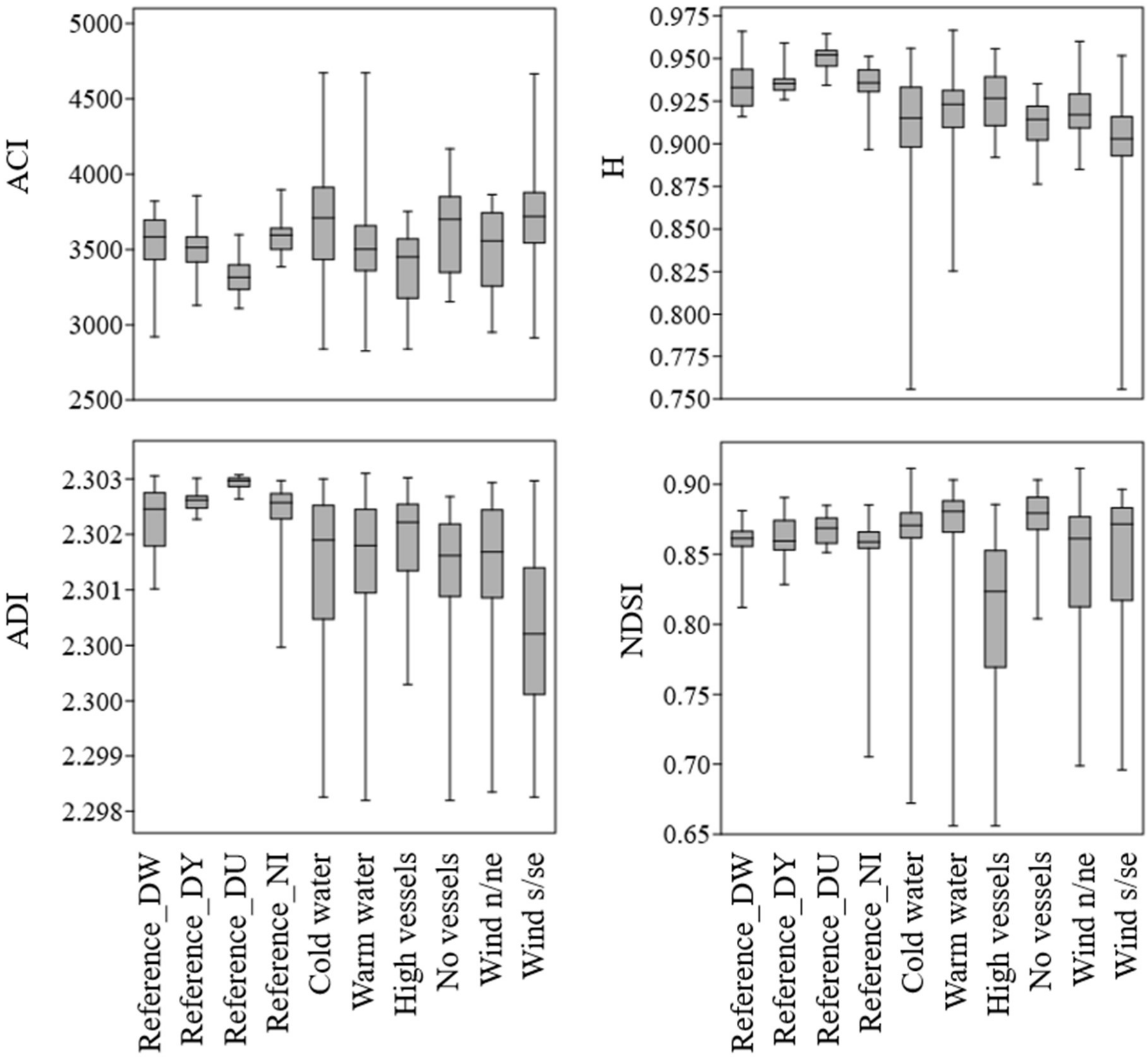
Through PCA analysis, it was possible to identify the influence of key environmental variables and their correlations with sound pressure level (SPL) values and ecoacoustic indices. After this analysis, we searched among the obtained data of the environmental variables for moments where all possible combinations could be found, to apply the acoustic indices in these specific moments and verify if they were able to differentiate all the identified categories. The 10 categories found are listed in Table 2.

Table 2. The 10 categories and their corresponding combinations of observed variables. Each category is represented by a specific abbreviation, and the sample count indicates the number of samples corresponding to each category.

N	Abbreviation	Sample Size	Description
1	Reference_DW	84	Water temperature between 21 and 23°C, wind under 2m/s, during dawn period “DW” (5 to 7am)
2	Reference_DY	60	Water temperature between 21 and 23°C, wind under 2m/s, during daytime “DY” (8am to 5pm)
3	Reference_DU	24	Water temperature between 21 and 23°C, wind under 2m/s), during dusk period “DU” (6 to 7pm)
4	Reference_NI	120	Water temperature between 21 and 23°C, wind under 2m/s), during nighttime “NI” (after 8pm)
5	Cold water	600	When water temperature was under 20°C
6	Warm water	864	When water temperature was above 24°C
7	High vessels	144	When the number of vessels was over 100
8	No vessels	336	When the number of vessels was under 10
9	Wind n/ne	132	When wind intensity was above 3m/s and direction between 0-80º(gr)
10	Wind s/se	108	When wind intensity was above 3m/s and direction between 0-80º(gr)

The ACI, ADI, H, and NDSI indices obtained for each analyzed category (Table 2) were compared separately within their respective sets. These comparisons included the comparison of the reference categories to assess differences among the following time periods: dawn, day, dusk, and night. Pairwise comparisons were made between moments with cold water and moments with warm water, moments with the presence of vessels and moments without vessels, moments with a predominance of north/northeast winds, or moments with a predominance of south/southeast winds. The subsequent findings from the post hoc Dunn analysis highlight the variations observed for each category and index (Fig. 3).

Figure 3. Box plots with the data collected from the categories created and shown in the table above. The data corresponds to the values of the ecoacoustic indices ACI, ADI, H, and NDSI, calculated using the Soundecology package in R, based on the categories found (Table 2).



ACI

The Acoustic Complexity Index (ACI) performed best in comparison to the other indices when comparing the categories. It was able to significantly differentiate ($p<0.05$) the hours of the day, except for dawn and the night period. It was also able to differentiate all other categories, with moments of cold water showing significantly higher values than moments of hot water ($p<0.05$); moments with intense vessel traffic showing significantly lower values than moments without vessels; and moments of south/southeast winds showing significantly higher values than moments of north/northeast winds.

ADI AND H

The Acoustic Diversity Index and the Bioacoustic Index showed the same pattern. Regarding the time of day, dawn and daytime showed significantly lower values ($p<0.05$) than the dusk period. The night period also showed significantly lower values than the dusk period, but there was no significant difference between dawn, daytime and night. These indices did not significantly differentiate ($p>0.05$) the moments of cold/warm water. The moments with a vessel showed significantly higher values ($p<0.05$) than the moments without a vessel. The moments with north/northeast winds showed significantly higher values ($p<0.05$) than the moments with south/southeast winds.

NDSI

The Normalized Difference Sound Index (NDSI) did not significantly differentiate ($p>0.05$) any of the categories comparing different times of day, nor the categories that compared water temperatures, nor the categories that compared winds. However, the values of the index were significantly lower ($p<0.05$) in moments with large vessel traffic.

DISCUSSION

The applicability of acoustic indices may vary according to each environment, due to specific spatial, temporal, and seasonal characteristics affecting the local soundscapes. The ACI, ADI, H, and NDSI acoustic indices showed remarkably different sensitivities to environmental variables in Arraial do Cabo. Understanding these correlations helps in comprehending the soundscape and the factors that contribute to its composition. The key categories identified were divided between two groups: indicators of human activity in the MPA (i.e., boat activity correlated to time of day and solar radiation) and indicators of coastal upwelling (i.e., water temperature correlated to wind intensity and direction).

INDICATORS OF HUMAN ACTIVITY IN THE MPA: VESSEL TRAFFIC, TIME OF DAY, SOLAR RADIATION

The variables number of vessels, time of day, radiation, and SPL G1 were strongly correlated, while wind intensity and direction, cold water and acoustic indices were negatively correlated with these variables. This shows that vessels emit noise at low frequencies, directly affecting the G1 band. Besides, boat activity is strongly related to the day of the week (i.e., more tourism on weekends and holidays) and specific times during the diurnal period, when there is more vessel noise affecting the interpretation of acoustic indices. Strong winds, cold water, and rain decrease boat activity, therefore, reducing the underwater noise pollution.

The acoustic influence of human activity on the marine soundscape in Arraial do Cabo is greater during the day, while the biological community produces more sound during the night. The soundscape in Arraial do Cabo indicated higher biological activity during nighttime, with notable peaks of activity at dawn and dusk (CAMPBELL et al. 2019), which was also seen in Pacific coral reefs and Atlantic rocky shores (FREEMAN et al., 2014; KAPLAN et al., 2018). In this study, the ACI index proved to be the most effective in distinguishing categories related to time of day (i.e., dawn, day, dusk, and night), except for differentiating between dawn and nighttime. This finding reinforces the previously mentioned pattern, where nighttime, dawn, and dusk exhibited higher values. Future studies using data from multiple consecutive years would enable the examination of variations in sunrise and sunset times across different seasons and provide a more robust observation of this pattern.

Numerous studies have assessed the significance of noise pollution in the acoustic landscape and its impacts on biota (GARRETT et al., 2016; DUARTE et al., 2021; VIEIRA et al., 2021), including in the study area of this research (CAMPBELL et al., 2019). Boat activity in Arraial do Cabo is primarily comprised by three types of vessels: tourist vessels, fishing vessels, and cargo transport or oil platform service vessels that utilize the Porto do Forno structure (GURGEL et al., 2019). The latter occurs occasionally, but there is a possibility of increased demand considering the exploration of the Santos and Campos basins, which may further contribute to the noise pollution from these vessels in the extractive reserve. Among the evaluated indices, ADI was the only one to differentiate all identified categories and proved to be more effective in identifying moments with vessel presence.

INDICATORS OF COASTAL UPWELLING: WATER TEMPERATURE AND WIND PATTERN

Water temperature can interact with the underwater soundscape in distinct ways. For example, low temperatures associated with upwelling can decrease metabolic activity (BROCKINGTON and CLARKE, 2001) and consequently reduce sound production in certain species. Temperature fluctuations can create thermal layers, leading to shadow zones and hindering the transmission of underwater sound waves (CALADO et al., 2018). However, our results showed that three indices (ACI, ADI, and H) showed significantly higher values during cold water periods, contrasting with the hypothesis that cold temperature fluctuations would decrease acoustic activity. The upwelling phenomenon, which brings nutrients from the ocean floor, can promote planktonic growth, and thus increase the food supply for filter-feeding organisms, could consequently enhance their contribution to the soundscape (FISHER-POOL et al., 2016). Therefore, the increased values of acoustic indices in response to low temperatures could be related to planktonic blooms during upwelling events off Arraial do Cabo. This relationship should be further investigated given the importance of the phenomenon in the region.

Among the tested indices, the ACI was the one that best distinguished the values between the categories of N/NE winds and S/SE winds. Winds play an interesting role in the region. On one hand, S/SE winds precede the arrival of cold fronts, which typically change the weather and sometimes reduce the demand for tourist activities, resulting in a decrease in the number of boats circulating in the area. On the other hand, stronger and more constant winds from the N/NE direction favor the mentioned upwelling phenomenon. Additionally, on boat excursion days, winds exceeding 6 m/s can interrupt tourist activities for safety reasons. Consequently, stronger winds from the N/NE direction can benefit two important aspects for the region: promoting an ecologically significant phenomenon like upwelling and providing temporary respite for organisms from the noise pollution emitted by vessels. The ACI produced higher values in response to North/Northeast winds, probably because the rocky coast is facing the same direction, which where the hydrophone is installed. Therefore, exposure of the hydrophone to wave action could be influencing the acoustic interpretation and needs to be further investigated.

THE MARINE SOUNDSCAPE OF ARRAIAL DO CABO: FUTURE DIRECTIONS

There are many other variables that influence the marine soundscape that should be studied in the soundscape of Arraial do Cabo , such as: seasonality (BITTENCOURT et al., 2016), lunar cycle (STAATERMAN et al., 2014), circadian rhythm (MCWILLIAM et al., 2017), tides (RICCI et al., 2016), light (RADFORD et al., 2008), dissolved oxygen (WATANABE et al., 2002), salinity (KIM et al., 2015), weather conditions (SIDDAGANGAIAH et al., 2021), seafloor composition (WANG et al., 2021), reproductive seasons (HAVER et al., 2020), the presence of transient populations or predators (LADICH, 2022), algae growth and their influence on the soundscape (GOTTESMAN et al., 2020), seismic airguns (KYHN et al., 2019), and wind turbines MOONEY et al. (2022). Most of these factors alter the biological activities of animals. For example, dolphins are more active during the full moon (STAATERMAN et al. 2014) and daylight influences shark activity (RADFORD et al., 2008). Fish activity is higher during the day (MCWILLIAM et al., 2017), in high tide (RICCI et al., 2016), in water with high dissolved oxygen concentration (WATANABE et al. 2002), and during the summer and in low turbidity water (SIDDAGANGAIAH et al., 2021). Shrimp are more active in water with high salinity (KIM et al., 2015) and during the summer (BITTENCOURT et al., 2016). Community noise levels increased during the reproductive season (HAVER et al., 2020) and decreased in the presence of predators (LADICH et al., 2022). The soundscape of the biological community is also affected by seafloor composition (WANG et al., 2021), and algal cover, which has a muffling effect and of decreased sound propagation (GOTTESMAN et al., 2020). Anthropogenic sounds may cause serious environmental harm to marine sounscapes. Seismic airguns, which are used in oil and gas exploration, cause significant noise pollution and hearing loss in marine mammals (KYHN et al., 2019). Noise pollution from wind turbines disrupt the feeding and breeding behavior of fish, and a study by MOONEY et al. (2022).

In summary, it is important to identify variables that affect the analysis when developing an effective acoustic monitoring system. This is crucial for the precise analysis of ecoacoustic indices and for obtaining information about ecosystem functioning and the effects of human activities on the environment. Understanding these interferences allows for a more accurate and reliable interpretation of the collected data, and consequently enables the adoption of more effective management measures and conservation strategies to ensure the sustainability of the environment and its inhabiting species.

CONCLUSION

Marine ecoacoustic indices have great potential to support resource and habitat management (RAJAN et al., 2019; BENOCCI et al., 2020). By comparing four ecoacoustic indices, we have successfully identified the key variables that influence the soundscape of Arraial do Cabo. Two ecoacoustic indices (ACI and ADI) could effectively differentiate previously selected moments based on the construction of categories using environmental data. These indices distinguished moments across different times of day. Furthermore, they were differentiated moments with cold or warm water, moments with and without vessel presence, and moments with Northeast or Southeast winds.

This study shows how ecoacoustic indices can be used to monitor ecosystems and develops a standardized methodology that can be applied across different environments, enhancing the comparability and interpretability of ecoacoustic studies. Future investigations should encompass the effects of local and regional variables, including the impact of seasons, tides, rainfall, and other variables. As more data is obtained, additional patterns could be identified, providing a deeper understanding of the correlations between environmental variables and ecoacoustic indices.

In conclusion, this study sheds light on the main variables influencing the soundscape of a productive upwelling region and intensely used MPA and highlights the effectiveness of ecoacoustic indices in differentiating moments based on environmental variables. Furthermore, this research has laid the foundation for further exploration and the development of a robust, non-invasive tool for monitoring marine environments.

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5 CAPÍTULO III: *Soundscape analysis: biophony, geophony, and technophony as variables in a new ecoacoustic index*

ABSTRACT

Soundscape ecology offers environmental monitoring tools that are non-invasive, cost-effective, and cover wide spatiotemporal scales. Ecoacoustic indices are key to soundscape ecology, but many of these indices need to be properly calibrated and tested. There is an urgent need for an index that facilitates the comparison of soundscapes across different ecosystems. Soundscape classification based on the source of sounds as biophony, geophony, and technophony provides a comprehensive framework. Automatic sound source separation coud have practical applications in environmental analysis, wildlife monitoring, and ecosystem studies. This article proposes a new index based on soundscape separation into biophony, geophony, and technophony, using a ternary plot visualization. By monitoring changes in the contributions of sound sources, the proposed index would facilitate the detection of environmental changes and the effectiveness of conservation measures. This approach enables cross-environmental assessments and supports informed decision-making in the conservation and management of environmental resources.

Key-words: Soundscape Ecology, Passive Acoustic Monitoring; Acoustic Index; Ternary Plot.

Soundscape ecology is a relatively new field of study that uses sound to perform a wide variety of ecosystem analyses (PIJANOWSKI et al., 2011; GIBB et al., 2019). Acoustic tools have great potential to be used in environmental monitoring, primarily due to their capacity to cover extensive spatiotemporal scales (SERTLEK et al., 2019). Additionally, acoustic monitoring tools can be less invasive (PIERETTI et al., 2017) and more cost-effective compared to other methods (FARINA et al., 2014). Ecological acoustic indices are promising acoustic tools (SUEUR et al., 2014) that need to be further improved and tested across various scenarios as monitoring tools (FARINA and LI, 2021; MINELLO et al., 2021).

The classification of types of sounds in a soundscape is a crucial step towards an accurate calibration of ecoacoustic indices. The most widely used division is based on the categorization of sound according to its source, forming three major categories: biophony, where sounds are produced by living organisms; geophony, where sounds are generated by natural elements such as wind, water, and geological activities; and anthropophony, where sounds result from human influence, including traffic noise, construction activities, and industrial operations (PIJANOWSKI et al., 2011). Anthropophony is also referred as technophony to describe sounds originating from technologies and electronic media (CAGE et al., 2001). This classification is a comprehensive and widely accepted framework for analyzing the acoustic landscape in its various components.

Organisms process and generate sound (i.e., biophony) to interact with the environmental soundscape (i.e., geophony) and shape their behavior according to sonic perception (WEBSTER and FAY, 2012). Thus, biophony is heavily influenced by geophony and, more recently, by technophony (DUARTE et al., 2021). Additionally, biophony can influence its own soundscape. For example, the sound generated by predators can silence a coral reef area (LADICH, 2022). Therefore, biophony is a highly complex category that is shaped by multiple factors.

On evolutionary scales, geophony emerged first, followed by biophony, and, much more recently, technophony. Technophony has become a type of pollution, which can disrupt the acoustic relationships built over thousands of years between environments and living organisms (GAGE and AXEL, 2014; MULLET et al., 2016). Technophony can occupy important acoustic niches (KRAUSE, 1993; Van OPZEELAND and Boebel, 2018), possibly disturbing biological interactions (HARRIS et al., 2016; DUNLOP, 2019; DUARTE et al., 2021).

The automatic identification and separation of sound sources is a complex task (LIN and TSAO, 2020). However, recent studies have shown promising advancements in this area (LIN et al., 2021; QUINN et al., 2022) and demonstrated that satisfactory results can be achieved in sound source separation, paving the way for practical applications such as environmental analysis, wildlife monitoring, and ecosystem studies (SUN et al., 2022).

A significant gap in current ecoacoustic research is the lack of a comprehensive ecoacoustic index that proposes a unified methodology capable of facilitating comparisons across different environments (SCARPELLI et al., 2021). There are proposed practices for the calibration and standardization of acoustic signal collection and processing techniques (MERCHANDET et al., 2015), but not for the development of a standardized ecoacoustic index (HARRIS et al., 2016; SCARPELLI et al., 2021).

Here we propose a new index based on the soundscape separation into biophony, geophony, and technophony. The initial step towards implementing this proposed index involves enhancing techniques for automatic separation of sound sources. Another important aspect to consider is the occurrence of quiet moments (QUINN et al., 2022), which may indicate a decrease in sound species or noise pollution in degraded environments (NEWPORT et al., 2014; RICE et al., 2020). For example, in a hypothetical dataset of one-minute recordings (a = 1 min) replicated 60 times (n = 60), half of the recording time consisted of silence (q = 50%) and the remaining recordings were 40% biophony (B40), 25% geophony (G25), and 35% technophony (T35). This dataset can be presented as follows:

B40:G25:T35, q=50, a=1, n=60

B = biophony (%); G = geophony (%); T = technophony (%)

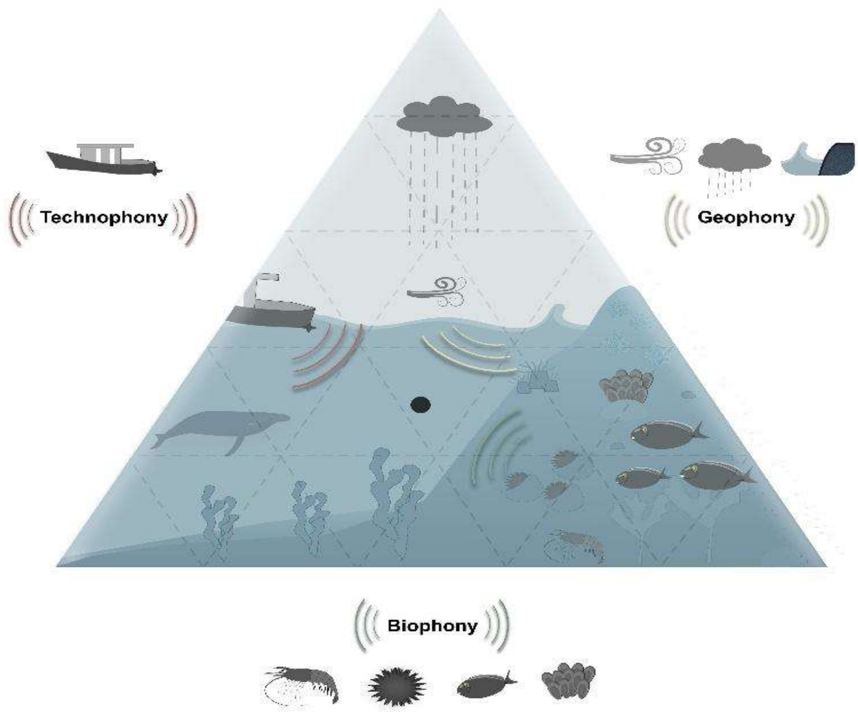
q = quiet moments (%);

a = recording time of each audio (minutes)

n = number of samples

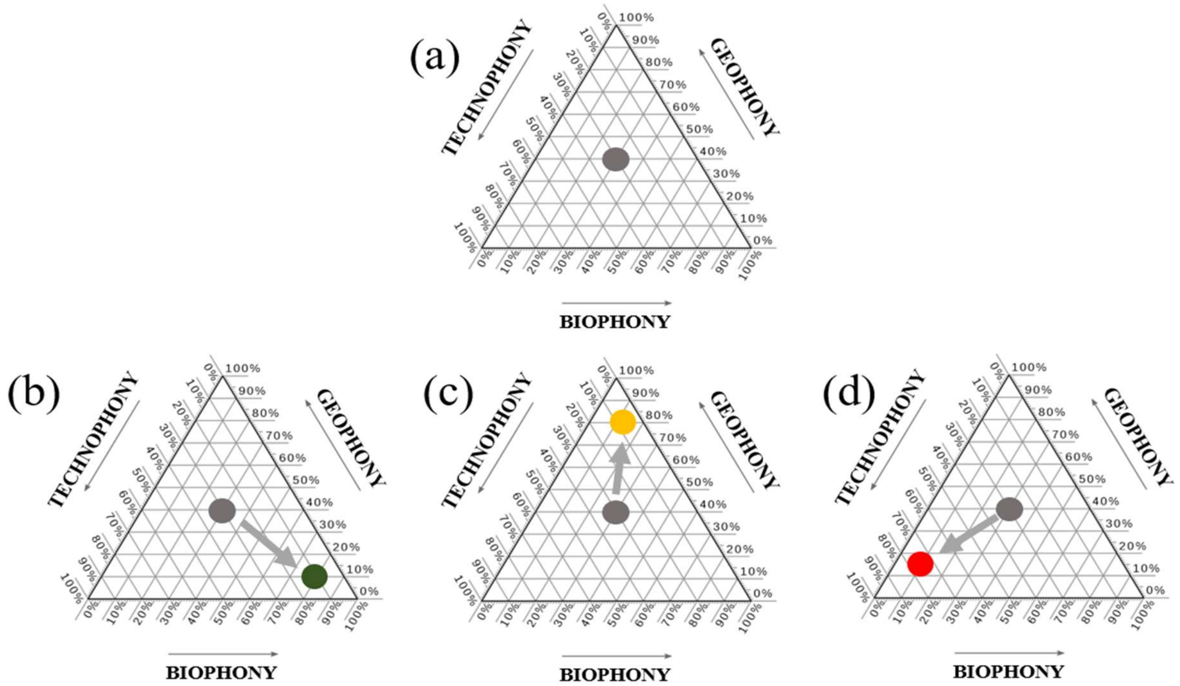
Ternary plots could be used to illustrate the contribution of each sound source that influences the analysis of the soundscape (Fig. 1). This graphical representation enhances data visualization and, consequently, becomes a valuable tool for decision-makers who require prompt and accurate analyses (ALMEIDA et al., 2007).

Figure 1: An illustrated ternary chart proposing a percentage-based division among sound sources, categorizing them into biophony, geophony, and technophony.



Four hypothetical scenarios emerge in ternary plots applied to ecoacoustic data (Fig. 2). The first scenario shows equal separation between acoustic sources, symbolized by a central circle (Fig. 2a). The second scenario represents instances when biophony becomes more prominent (Fig. 2b). This scenario finds a parallel in the observations of BORIE et al. (2021), who reveal a greater biophonic presence in protected areas as opposed to unprotected ones. The third scenario denotes moments where geophony takes on increased significance (Fig. 2c). Similar to the findings of MA et al. (2005) and RYAN et al. (2016), which demonstrate the significance of rainfall and wind in underwater soundscape. The forth scenario represents situations where technophony gains importance (Fig. 2d). Analogous patterns emerge in additional research efforts, exemplified by investigations that underscore the potential impact of vessel traffic on marine species (PUTLAND et al., 2017; WILSON et al., 2023).

Figure 2: A ternary graph presenting hypothetical data, depicting moments where (a) there is an equal separation between acoustic sources, as well as other moments where (b) biophony, (c) geophony, or (d) technophony gain importance.



This separation and visualization of acoustic data can facilitate the interpretation of environmental data. For instance, a manager of a conservation unit could see an increase in biophony in a ternary plot after implementing stricter measures to preserve an area, such as monitoring and preventing the entry of illegal boats. An augmentation of geophony in a ternary plot could indicate increased fluctuations in wind patterns, temperature, or rainfall, and support policy makers to take action in the context of managing natural disasters and climate change. City planners could monitor the the installation of a nearby development that contributes to technophony and noise pollution. This ecoacoustic approach has wide and diverse applicability.

This is a proposal for the creation of an ecoacoustic index. The index will be created to facilitate the comparison across environments and ecosystems. It is, however, an idea that needs to be improved and tested. Improvements include standardizing the methodology, and determining the minimum analysis time, and sound frequencies to be considered.

In conclusion, the integration of biophony, geophony, and technophony into a unified index enables a more holistic comprehension of the soundscape. Expressing this value as a ratio and visualizing it through a ternary plot facilitates the comparison of diverse environments.

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6 CONSIDERAÇÕES FINAIS

6.1 CONCLUSÕES

Ao percorrer os capítulos deste trabalho, observa-se como cada etapa contribuiu para as publicações subsequentes, desempenhando um papel específico na construção de cada parte deste estudo. Resumindo-os adiante, torna-se evidente como os fundamentos para o desenvolvimento de um sistema de monitoramento marinho costeiro foram progressivamente estabelecidos através da revisão temática, análise de dados locais e a proposta de um novo índice ecoacústico.

No primeiro capítulo, apresentam-se os primeiros resultados, indicando como a ecologia acústica tem ganhado destaque no monitoramento de ecossistemas marinhos devido às suas características não invasivas e eficiência espaço-temporal (SUEUR et al., 2014; DESIDERÀ et al., 2019; PIERETTI e DANOVARO, 2020). A partir da revisão de estudos mais recentes sobre o uso de índices ecoacústicos em ambientes marinhos, foi possível apontar que o desenvolvimento de índices ecoacústicos precisa enfrentar muitos desafios para cumprir seu grande potencial, especialmente no contexto do monitoramento desses ambientes (MINELLO; CALADO; XAVIER, 2021). Basicamente, foram identificadas quatro limitações principais, incluindo a dificuldade de encontrar bioindicadores acústicos adequados; a falta de um índice universal ou protocolo padronizado; a maioria dos índices acústicos aplicados em ambientes marinhos ter sido desenvolvidos para serem usados em ambientes terrestres; e a falta de estudos que tenham testado índices ecoacústicos em diferentes condições ambientais (MINELLO; CALADO; XAVIER, 2021). Estas limitações apontadas neste artigo de revisão, mencionado anteriormente, direcionaram este trabalho a testar alguns índices ecoacústicos nas diferentes condições ambientais encontradas em Arraial do Cabo (RJ) e a propor um novo índice que facilitasse a comparação entre diferentes ecossistemas.

No segundo capítulo, são apresentados dados locais onde testaram-se alguns índices ecoacústicos e foi possível perceber como estes interagiram com variáveis ambientais. A partir destes dados, constatou-se que os índices ACI e ADI foram os mais indicados, além de constatar que algumas variáveis como número de embarcações que transitam na região e a temperatura da água são variáveis importantes que devem ser mensuradas concomitante ao monitoramento acústico.

No terceiro capítulo, os esforços foram concentrados na elaboração de uma proposta de índice destinado a simplificar a comparação entre ambientes. Com esse propósito, é apresentada uma abordagem destinada a ser refinada posteriormente, consistindo em um índice fundamentado na relação entre biofonia, geofonia e tecnofonia. Antecipa-se que essa abordagem, ancorada na proporção entre as várias fontes, poderá contribuir para uma pronta identificação de possíveis anomalias que possam surgir na paisagem acústica. Espera-se que esta proposta ganhe maior usabilidade a partir da integração dos avanços apresentados na separação automática das fontes acústicas (LIN; AKAMATSU; TSAO, 2021) e do avanço sobre a recomendação de se construir um banco de dados mundial coletivo com a identificação das principais fontes acústicas submarinas (PARSONS et al., 2022).

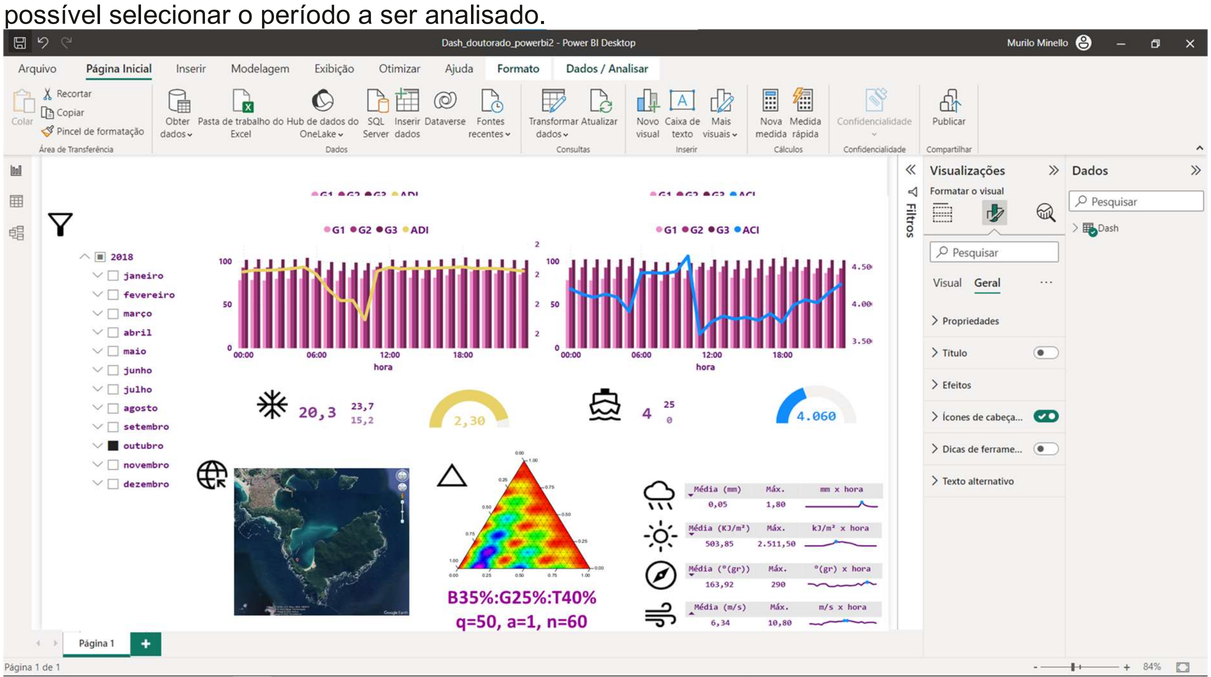
6.2 SUGESTÕES PARA TRABALHOS FUTUROS

Neste segmento conclusivo do estudo, é apresentada uma perspectiva de ferramenta que consolida todas as observações realizadas nos capítulos precedentes, proporcionando uma abordagem aprimorada para a análise dos dados, por meio da compilação dos principais índices ecoacústicos e das variáveis a serem monitoradas. A partir da integração das ideias derivadas deste estudo, emerge a viabilidade de implantar uma ferramenta de monitoramento marinho costeiro na região, por meio de um aplicativo projetado para disponibilizar um painel interativo. Essa solução tem o potencial de sincronizar tais parâmetros de maneira eficaz, oferecendo também vantagens adicionais discutidas a seguir.

O uso de tecnologias avançadas, como o emprego de painéis interativos e modelos preditivos, pode desempenhar um papel no aprimoramento dos sistemas de monitoramento marinhos costeiros. Existem muitos programas que possibilitam a criação de painéis interativos capazes de integrar diversos índices e variáveis ambientais, fornecendo análises em tempo real e a identificação imediata de desvios como por exemplo o *Tableau*, o *Qlik Sense*, *SAP Analytics* e o *Microsoft© Power Bi©* (FEINLEIB, 2014; WRIGHT; WERNECKE, 2020). Modelos preditivos, por sua vez, permitem prever impactos com base em variáveis ambientais e históricos, essenciais para tomadas de decisões fundamentadas e eficazes. Nesse contexto, a proposta de utilizar estas ferramentas de painéis interativos para criar um sistema de monitoramento marinho costeiro que integre índices ecoacústicos com variáveis ambientais emerge como uma solução com grande potencial, oferecendo benefícios substanciais para a compreensão e a tomada de decisões embasadas.

Em consonância com a abordagem de Wright e Wernecke (2020), que adaptaram um painel interativo no *Microsoft© Power Bi©* para a organização de dados relacionados ao monitoramento da qualidade do ar, foi concebida uma proposta análoga, utilizando os dados previamente apresentados no artigo discutido no Capítulo 2 (Fig. 1). Nesse cenário, as mesmas variáveis e parâmetros considerados e discutidos no Capítulo 2 foram empregados, com o intuito de avaliar as funcionalidades do aplicativo.

Figura 1: Imagem de uma proposta de painel interativo, criado no *Microsoft© Power Bi©* considerando as variáveis trabalhadas nesta tese: gráfico dividindo os dados de Sound Pressure Level (SPL) em G1 (112 a 890Hz), G2 (891 a 2239Hz) e G3 (2240 to 22390 Hz), índices ecoacústicos ADI e ACI, indicadores com os valores de temperatura da água e número de embarcações, além de mapa interativo com o ponto de coleta, *ternary plot* com a sugestão de índice baseado na razão Biofonia:Gefonia:Tecnofonia (B:G:T), valores de precipitação, radiação solar, direção e intensidade dos ventos. E todos estes parâmetros estão vinculados ao filtro mais a esquerda da imagem, com o qual é possível selecionar o período a ser analisado.



Fonte: O Autor

Um dos principais atributos observado neste exemplo é a possibilidade de incorporação de modelos matemáticos, permitindo a previsão dos índices ecoacústicos com base nas variáveis ambientais coletadas. Xavier (2021), em sua tese, apresenta um modelo matemático para descrever a assinatura bioacústica dos costões rochosos a partir de variáveis abióticas. Essa metodologia pode ser adaptada para considerar os índices acústicos. Essa habilidade de previsão viabiliza a antecipação de valores esperados, tornando possível a detecção imediata de discrepâncias entre valores medidos e previstos. Essa abordagem é fundamental para a identificação de desvios e anomalias, orientando a investigação e o desenvolvimento de estratégias de mitigação. Adicionalmente, esses programas de painéis interativos permitem a inclusão de dados coletados tanto localmente quanto de fontes externas, como estações meteorológicas, imagens de satélite ou quaisquer outras informações disponíveis *online*. Isso resulta em um fluxo contínuo de informações que alimenta o sistema de monitoramento, proporcionando uma análise abrangente das condições ambientais e reforçando a capacidade do sistema de rastrear as variações e tendências ambientais.

Outra característica interessante destes programas que disponibilizam a organização dos dados em painéis interativos é a sua capacidade de divulgação instantânea dos resultados em rede. Isso possibilita a disseminação imediata das informações para uma variedade de públicos interessados, como gestores ambientais, pesquisadores e o público em geral. Além disso, a ferramenta pode ser configurada para enviar alertas de emergência sempre que um valor fora do esperado for detectado. Esse recurso é de importância crítica em cenários onde ações rápidas são necessárias para conter impactos adversos e garantir a saúde do ambiente marinho costeiro. Ao associar técnicas de aprendizado de máquina a essa plataforma, há uma oportunidade de aprimorar ainda mais o sistema de monitoramento (KARPATNE et al., 2018; SHARMA; SATO; GAUTAM, 2023). À medida que o sistema se torna mais ativo e a experiência é acumulada, ele pode identificar e apontar padrões previamente não identificados. Essa capacidade de aprendizado contínuo permitiria que o sistema sugerisse possíveis experimentos e investigações futuras para validar esses possíveis novos padrões, tornando-se uma ferramenta não apenas eficaz para o monitoramento, mas também para a indicação de estudos que impulsionem a evolução constante desta ferramenta. O uso do painel interativo representa um passo significativo em direção à melhoria do monitoramento marinho costeiro. A integração de índices ecoacústicos com variáveis ambientais oferece uma visão completa e detalhada do estado do ambiente costeiro, permitindo a identificação de tendências, anomalias e potenciais impactos. Com a capacidade de prever índices ecoacústicos por meio de modelos matemáticos, a ferramenta proporciona uma abordagem proativa para a gestão ambiental. A combinação de previsões e análises em tempo real, juntamente com a divulgação imediata dos resultados e alertas de emergência, estabelece as bases para a conservação eficaz e a tomada de decisões informadas em prol do ambiente marinho costeiro.

Por outro lado, é possível integrar o sistema ao uso da inteligência artificial (IA) com a finalidade de buscar na literatura, experiências atuais sobre o uso dos índices ecoacústicos e suas limitações (SHIVAPRAKASH et al., 2022; STOWELL, 2022). Ao observar padrões já identificados em outros estudos é possível iniciar alguns apontamentos a serem investigados na região costeira de Arraial do Cabo. A começar pelo fenômeno oceanográfico mais importante da região, a ressurgência. CALADO et al. (2018) demonstraram que a temperatura da água pode influenciar o cenário sonoro por meio de mudanças na atividade animal e/ou propagação do som, ou seja, algo a ser investigado, buscando compreender mudanças a curto, médio e longo prazos ocorridos nestes eventos. Além disso, é necessário investigar eventos climáticos, como a chegada de frentes frias que, associados a mudanças de maré, podem causar alterações na formação de ondas na região (CANDELLA, 2009). Outro fator que pode aparecer no cenário sonoro seriam deslizamentos de terra, que ocorrem frequentemente em áreas costeiras. Nesta região entre Búzios e Arraial do Cabo, existem formações rochosas expostas que frequentemente se quebram e deslizam para o mar (MUEHE, 2006). Esses deslizamentos de terra podem aparecer como um dos componentes da geofonia assim como encontrado por VARDY et al. (2012). Eventos biológicos específicos, como temporadas reprodutivas, presença de populações transitórias ou predadores e crescimento de algas, e sua influência no cenário sonoro são pontos a serem investigados. Este ambiente costeiro possui uma biota marinha relativamente bem estudada e conhecida, especialmente após o estabelecimento do Instituto Almirante Paulo Moreira (IEAPM) (BOLTOVSKOY; VALENTIN, 2018). Entre os aspectos mais importantes relacionados à bioacústica, é possível destacar os costões rochosos colonizadas por vários organismos bentônicos

(BATISTA; GRANTOM-COSTA; COUTINHO, 2020; COUTINHO et al., 2016; PANARO et al., 2012), bem como a presença frequente de tartarugas marinhas (DI BENEDITTO; SICILIANO; MONTEIRO, 2017) e aves marinhas (RANGEL; TAVARES; ZALMON, 2020), a presença de espécies de peixes locais (FLOETER et al., 2001) e espécies de peixes migratórios ocasionais (PAES; MORAES, 2007; BRAGA; PARDAL; AZEITEIRO, 2018), baleias e golfinhos (HASSEL et al., 2003), outras espécies como pinguins e focas (DE MOURA; DI DARIO; SICILIANO, 2011) e tubarões (AXIMOFF et al., 2022). Deve-se enfatizar que a região é foco de estudos voltados para observar e monitorar a invasão de espécies invasoras exóticas (TRICARICO; JUNQUEIRA; DUDGEON, 2016). Todos esses componentes biológicos podem tanto compor quanto interagir com a paisagem acústica e devem ser levados em consideração ao propor um programa de monitoramento ecoacústico.

Outro fator importante são os ruídos gerados por embarcações (CAMPBELL et al., 2019). Na região costeira onde este trabalho foi realizado e onde os passeios de barco são comuns, além da passagem de embarcações de pesca, fontes de som antropogênico têm ganhado importância no cenário acústico (BRAGA; PARDAL; AZEITEIRO, 2018; SILVA et al., 2018; CAMPBELL et al., 2019). Apesar de relativamente simples e pequena, a estrutura do Porto do Forno (GURGEL; ROSMAN; DOS SANTOS, 2019) tem sido usada para atracação de alguns navios dedicados ao transporte de carga ou ligados à indústria do petróleo, já que esta região está próxima a duas áreas de grande importância na exploração de petróleo: a Bacia de Santos e a Bacia de Campos (ZACHARIAS; FORNARO, 2020). Entender como esta poluição acústica afeta os organismos e como ela vem ganhando importância na paisagem acústica local, torna-se um elemento importante a ser investigado e monitorado.

Considerando que nem todas as espécies são capazes de emitir sons, a escolha de estudar a paisagem acústica implica em um recorte específico das espécies presentes. Sendo assim, é de suma importância destacar a relevância da realização de estudos comparativos que abordem a comparação entre metodologias já estabelecidas e aquelas mais recentemente desenvolvidas (GADZALA-KOPCIUCH et al., 2004). Esse tipo de abordagem desempenha um papel fundamental na avaliação da capacidade das espécies sonoras em representar de maneira abrangente a totalidade da comunidade biológica. Nesse contexto, compreender o grau de representatividade de uma determinada espécie em relação ao ecossistema como um todo assume uma importância fundamental. Logo, é necessário avaliar até que ponto as espécies sonoras podem capturar de maneira precisa e abrangente os acontecimentos e dinâmicas que ocorrem na comunidade biológica, permitindo uma interpretação mais completa e precisa dos processos e interações presentes no ambiente sonoro.

É importante salientar que a implementação desses sistemas de monitoramento desempenha um papel fundamental na preservação dos ecossistemas costeiros. Essa melhoria não apenas auxilia na identificação e quantificação dos impactos costeiros, mas também fortalece a tomada de decisão em unidades de conservação. A análise precisa, rápida e eficaz dos dados coletados possibilita a implementação de medidas preventivas e corretivas de maneira oportuna, assegurando a conservação desses ambientes cruciais para a biodiversidade marinha e o bem-estar humano. O contínuo aprimoramento dos sistemas de monitoramento marinho costeiro a partir dessa aplicação de ferramenta biotecnológica (RAMOS et al., 2023) é, portanto, uma necessidade importante para garantir uma gestão ambiental mais eficiente (MINELLO et al., 2022).

Por fim, os objetivos gerais e específicos desta pesquisa foram alcançados: a avaliação do emprego de índices ecoacústicas em ecossistemas marinhos foi executada e seus resultados foram consubstanciados em forma de artigo de revisão; a análise da interação entre índices ecoacústicas e parâmetros abióticos foi aprofundada utilizando os dados obtidos na enseada da Praia da Ilha, Arraial do Cabo, RJ; a concepção de um novo índice ecoacústico emergiu, visando estabelecer uma ligação substancial entre dados sonoros de diferentes fontes em uma forma única de visualização; além disso, um protótipo de painel interativo foi apresentado como parte integrante de um sistema prospectivo de monitoramento de ecossistemas marinhos, fundado na integração de métricas ecoacústicas e variáveis ambientais. Em última análise, a sinergia entre índices ecoacústicos e variáveis ambientais evidenciou sua capacidade na interpretação de contextos ambientais, para propósitos de monitoramento marinho. Essa convergência, dessa maneira, pode ser identificada como um aprimoramento substancial de uma ferramenta destinada à aplicação da biotecnologia ambiental.

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