Ocean and Coastal Research

ORIGINAL ARTICLE

http://doi.org/10.1590/2675-2824072.23120
ISSN 2675-2824

Exploring ecoacoustic indices in response to soundscapes in a marine protected area exposed to coastal upwelling

Murilo Minello[1,2*], Leandro Calado[2], Ubirajara Gonçalves de Melo-Júnior[2], Fabio C. Xavier[2]

[1] Instituto Federal de Educação Ciência e Tecnologia do Rio de Janeiro (Campus Arraial do Cabo – 28930-000 – Rio de Janeiro – Brazil).
[2] Programa de Biotecnologia Marítima – Instituto de Estudos do Mar Almirante Paulo Moreira – Universidade Federal Fluminense (Arraial do Cabo – 28930-000 – Rio de Janeiro – Brazil).

* Corresponding author: murilo.minello@ifrj.edu.br

ABSTRACT

Ecoacoustic indices may become an important tool to monitor 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 yet to be fully understood. This study evaluated the Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Bioacoustic Index (H), and Normalized Difference Sound Index (NDSI) in a marine protected area (MPA) named Resex mar Arraial do Cabo in a coastal upwelling in Rio de Janeiro, Brazil. All considered variables, such as water temperature, wind direction, solar radiation, and vessel traffic were monitored from September to December 2018. Principal component analysis showed that the ACI index was negatively correlated with the number of vessels, whereas the ADI and H indices were correlated with water temperature. After categorizing specific moments, the ACI configured the best index for differentiating specific times of day, whereas the ADI was ideal for distinguishing between moments with and without vessel presence. Thus, 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.

Keywords: Soundscape ecology, Passive acoustic monitoring; Biophony, Geophony; Anthropophony.

INTRODUCTION

Soundscape ecology studies the sounds produced by living organisms and their interactions with the environment (Pijanowski et al., 2011). The soundscape (the sum of all sounds 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

Submitted: 16-Aug-2023
Approved: 04-Jun-2024

Editor: Rubens Lopes

a comprehensive understanding of ecological patterns and processes (Sueur and Farina, 2015).

The use of acoustic indices in ecology offers several advantages, reducing data complexity, enabling comparisons between different environments, and facilitating the integration of acoustic data with other types of information, 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 streamline the understanding of soundscapes. However, the use of indices also has limitations. Acoustic indices are sensitive to the quantity and quality of the collected data, which must be carefully examined to ensure accurate analysis (Bradfer-Lawrence et al., 2019). Otherwise, the indices may fail to 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 (Williams et al., 2022).

The use of acoustic indices is a relatively recent development in 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 impacts (e.g., vessel traffic) (Rice, 2003). The Resex mar 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 distinctive 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: The Arraial do Cabo marine coastal region

This researched was carried out in Arraial do Cabo, a coastal municipality in the state of Rio de Janeiro, Brazil (Figure 1). Its modern history is intrinsically linked to the salt industry and alkali production (Carvalho et al., 2021), artisanal fishing, and tourism. The small local port occasionally 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 refers to 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 decrease light availability in the water column for days (Coelho-Souza et al., 2012), in a coastal region known for their water transparency.

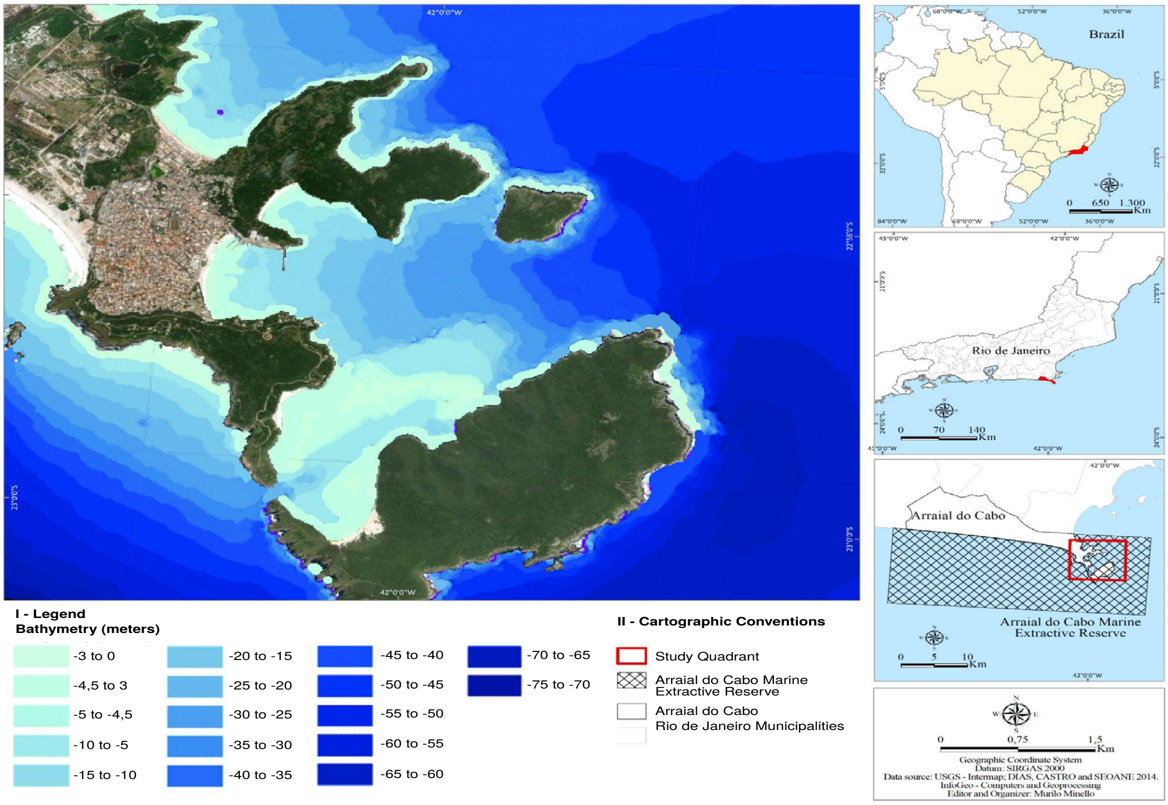

Figure 1. Coastal bathymetric map indicating the location of the acoustic acquisition system in the study area: Arraial do Cabo, Rio de Janeiro, Brazil.

Data processing and analysis

The recording system consisted of a stainless-steel pyramid structure with four hydrophones installed approximately eight meters below the waterline and about seven meters away from the rocky shore (Figure 1). 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 were collected using a fixed acquisition system equipped with hydrophones (a four-channel Marsensing Ltda's digital model Hyd TP-1). The system was configured with a sampling frequency of 52.7 kHz, a 24-bit resolution, a sensitivity of −174.9 dB re $1V(1\mu Pa)^{-1}$ and a flat response from 0.10 to 26.35 kHz. Acoustic recordings were conducted at a duty cycle of 20%, i.e., for one minute every five minutes. To calculate the Sound Pressure Level (SPL), each one-minute audio file (wav file) was divided into 60 one-second blocks. For each such block, 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 (50^{th} SPL percentile or median) was estimated for each 60s.

To examine the behavior of the acoustic indices, we recorded the number of vessels per day circulating in the region and water temperature, obtained by communication with the team at the Admiral Paulo Moreira Sea Studies Institute. Solar radiation (kJ/m^2), wind intensity (m/s), and wind direction (°(gr)) data were obtained from the National Institute of Meteorology. 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 (Table 1). At first, sound pressure level (SPL) data were collected considering 1/3-octave bands, following the structure of Descriptor 11 of the European Marine Strategy Framework Directive 2008/56/EC for marine noise monitoring (Zampoukas et al., 2012). In total, the SPL was calculated for 23 bands, considering the following central frequencies: 125 Hz (112 - 141 Hz), 160 Hz (141 - 178 Hz), 200 Hz (178 - 224 Hz), 250 Hz (224 - 282 Hz), 315 Hz (282 - 355 Hz), 400 Hz (355 - 447 Hz), 500 Hz (447 - 562 Hz), 630 Hz (562 - 708 Hz), 800 Hz (708 - 891 Hz), 1 kHz (892 Hz - 1.1 kHz), 1.3 kHz (1.1 - 1.4 kHz), 1.6 kHz (1.4 - 1.8 kHz), 2 kHz (1.8 - 2.2 kHz), 2.5 kHz (2.2 - 2.8 kHz), 3.2 kHz (2.8 - 3.6 kHz), 4 kHz (3.6 - 4.5 kHz), 5 kHz (4.5 - 5.6 kHz), 6.3 kHz (5.6 - 7.1 kHz), 8 kHz (7.1 - 8.9 kHz), 10 kHz (8.9 - 11.2 kHz), 12.5 kHz (11.2 - 14.1 kHz), 16 kHz (14.1 - 17.8 kHz), and 20 kHz (17.8 - 22.4 kHz). To facilitate the comparison of how ecoacoustic indices interpret different frequency bands, we grouped them based on the observations proposed by Buscaino et al. (2016). This study identified three bands with distinct behaviors for the ACI index response. Buscaino et al. (2016) categorizes them as low-frequency bands, referred to here as G1 (112 to 891 Hz); silence or intermediate band, labeled as G2 (892 Hz to 2.23 kHz); and high-frequency bands, designated as G3 (2.24 to 22.4 kHz).

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

Numerous ecoacoustic indices can be tested (Sueur and Farina, 2015). This study chose to test the most commonly used indices according to Minello et al. (2021): 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); and Acoustic Diversity Index (ADI) (Villanueva-Rivera et al., 2011). The ecoacoustic indices were calculated using the *Soundecology* package on *R*.

Other analysis

Following PCA analysis, the dataset for all environmental variables was examined to identify specific instances in which all potential combinations were present. Subsequently, we applied acoustic indices during these specific moments to assess their ability to distinguish all identified categories.

The ACI, ADI, H, and NDSI for each analyzed category were compared separately within their respective sets. These comparisons included that of reference categories to assess differences between the following time periods: dawn, day, dusk, and night. Pairwise comparisons were made between moments with cold and warm water, those with and without vessels, and those with a predominance of north/northeast and south/southeast winds. These findings were compared by the Kruskal-Wallis test. The *post hoc* Dunn analysis highlighted the variations observed for each category and index. The statistical analyses were conducted on the *Past* 4.03 software (Hammer and Hasper, 2001).

RESULTS

The environmental variables showed clear correlations to specific sound pressure levels and acoustic indices according to principal component analysis (PCA) (Figure 2A). Solar radiation, time of day, and number of vessels overlap, show strong correlation, and are closely associated with SPL G1, indicating their significant influence on the lower frequency range of the soundscape. The acoustic complexity index (ACI) showed a negative correlation to number of vessels. Higher water temperature showed a stronger correlation with wind intensity and direction, which have a stronger influence on SPL G3, i.e., higher frequencies. The eigenvalues and eigenvectors were derived from a correlation matrix. Component 1 explained 32% of the variation (Figure 2B), with H (loading 0.40) and ACI (loading -0.41) (Figure 2C); whereas Component 2, 22% (Figure 2B), involving solar radiation (loading 0.40) and vessels (loading 0.40) (Figure 2D).

PCA analysis showed the influence of key environmental variables and their correlations with sound pressure level (SPL) values and ecoacoustic indices. After this analysis, we searched the obtained data of the environmental variables for moments in which all possible combinations could be found to apply the acoustic indices in these specific moments and find 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 2 m s^{-1}, during dawn “DW” (5 to 7 am)
2	Reference_DY	60	Water temperature between 21 and 23°C, wind under 2 m s^{-1}, during daytime “DY” (8 am to 5 pm)
3	Reference_DU	24	Water temperature between 21 and 23°C, wind under 2 m s^{-1}), during dusk “DU” (6 to 7 pm)
4	Reference_NI	120	Water temperature between 21 and 23°C, wind under 2m s^{-1}), during nighttime “NI” (after 8 pm)
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 3 m s^{-1}s and direction between 0-90º(gr)
10	Wind S/SE	108	When wind intensity was above 3 m s^{-1} and direction between 180-270º(gr)

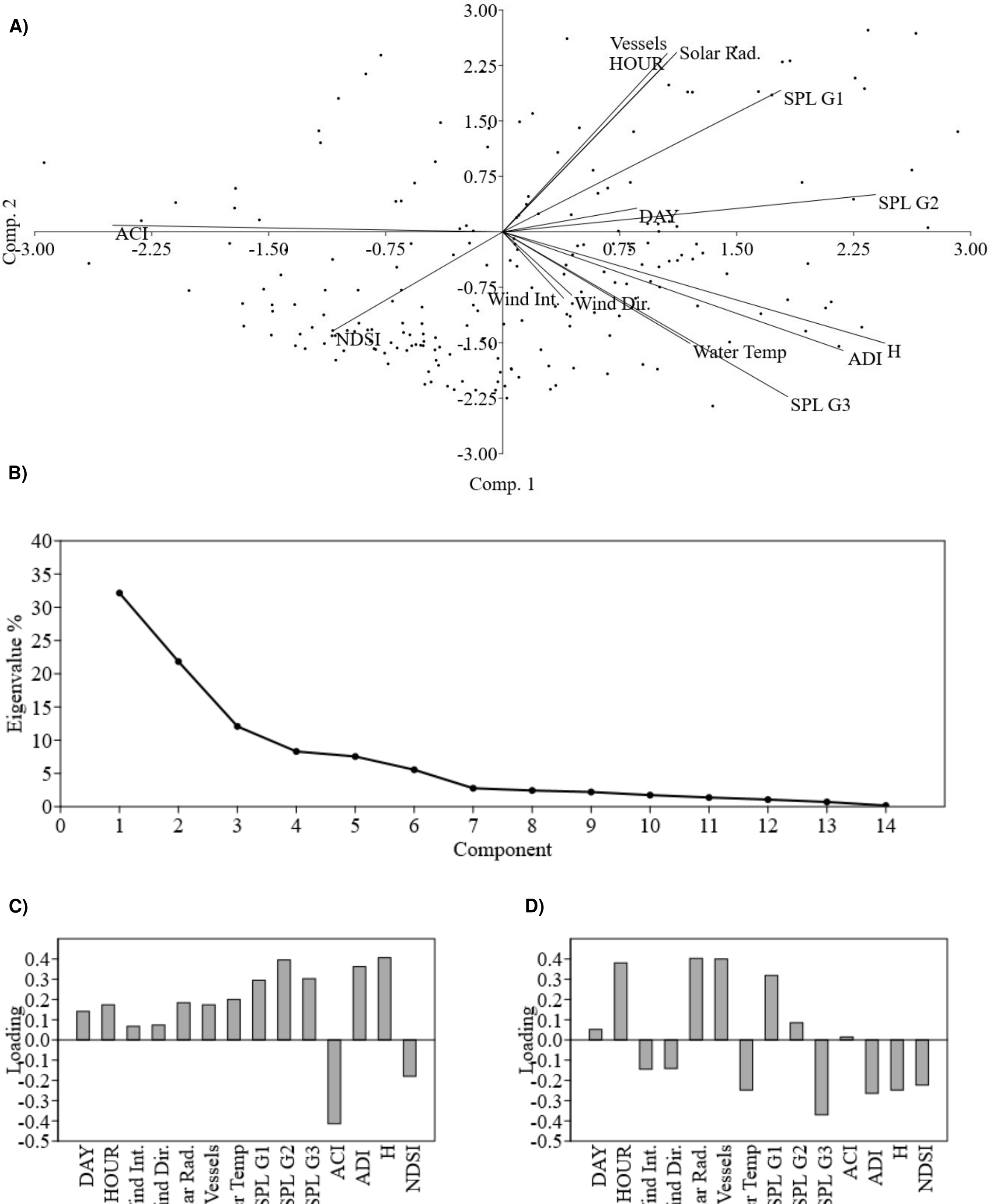

Figure 2. A) Principal component analysis of environmental variables, ecoacoustic indices, and sound pressure level, conducted on a dataset comprising 10 randomly selected complete days between September and December 2018. The analyzed variables include day, hour, solar radiation, wind intensity and direction, water temperature, number of vessels, sound pressure level divided into three frequency bands: G1, G2, and G3, as well as the Acoustic Complexity Index (ACI), the Acoustic Diversity Index (ADI), the Bioacoustic Index (H), and Normalized Difference Sound Index (NDSI); **B)** Eigenvalue (%) of all 14 components; **C)** Loading plot component 1; **D)** Loading plot component 2.

ACI

The Acoustic Complexity Index (ACI) performed better than the other indices when comparing categories (Figure 3). It could significantly differentiate ($p < 0.05$) the hours of the day, except for dawn and night. It also could differentiate all other categories, with moments of cold water showing significantly higher values than those of hot water ($p < 0.05$); moments with intense vessel traffic showing significantly lower values than those without vessels; and moments of south/southeast winds showing significantly higher values than those of north/northeast winds.

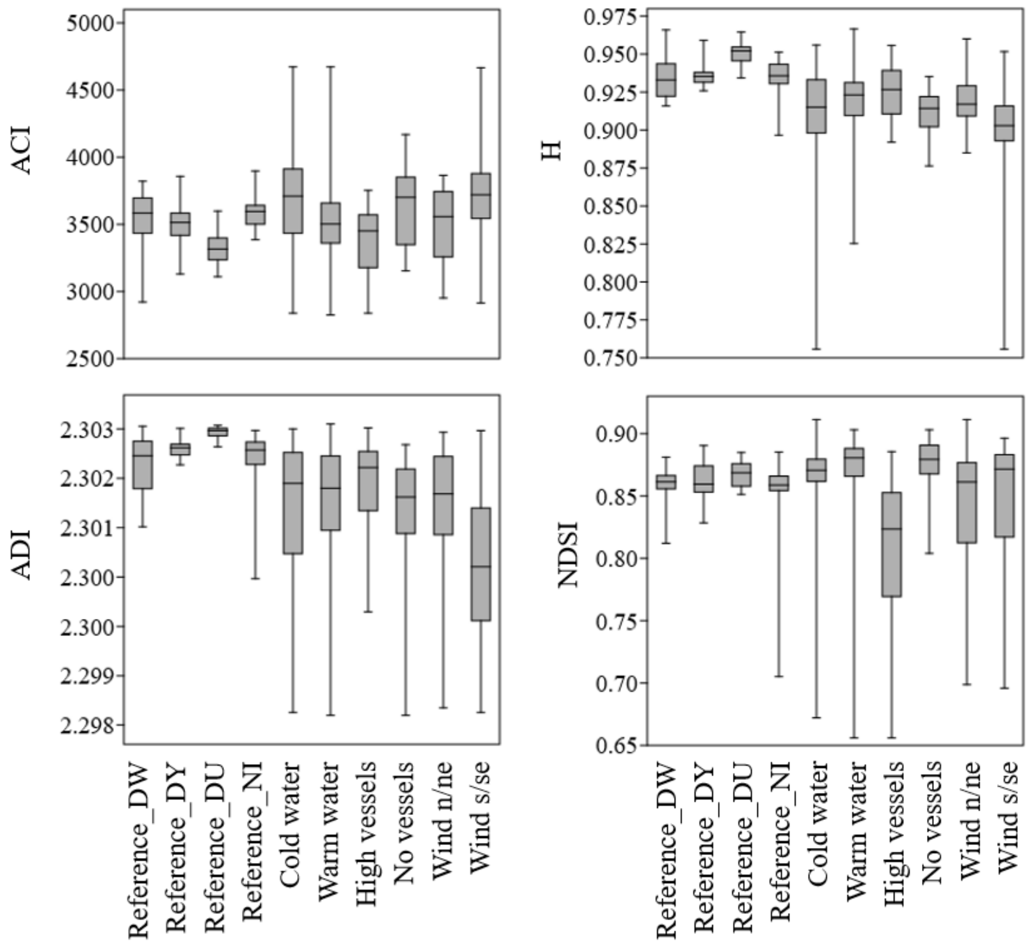

Figure 3. Box plots with the data collected from the categories created and shown in the table above. The data correspond to the values of the ecoacoustic indices ACI, ADI, H, and NDSI, calculated using the *Soundecology* package on *R*, based on the found categories (Table 2).

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 dusk (Figure 3). The night period also showed significantly lower values than the dusk period, but with no significant difference between dawn, daytime, and night. These indices failed to significantly differentiate ($p > 0.05$) moments of cold/warm water. Moments with a vessel showed significantly higher values ($p < 0.05$) than those without a vessel. The moments with north/northeast winds showed significantly higher values ($p<0.05$) than those with south/southeast winds.

NDSI

The Normalized Difference Sound Index (NDSI) significantly differentiated ($p>0.05$) neither the categories comparing different times of day, 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 (Figure 3).

DISCUSSION

The applicability of acoustic indices may vary according to each environment due to specific spatial, temporal, and seasonal characteristics affecting 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 to assess soundscapes and the factors that contribute to their composition. The key categories identified were divided between two groups: indicators of human activity at 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, whereas 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, in which more vessel noise affects the interpretation of acoustic indices. Strong winds, cold water, and rain decrease boat activity, therefore, reducing underwater noise pollution.

The acoustic influence of human activity on the marine soundscape in Arraial do Cabo is greater during the day, whereas the biological community produces more sound during the night. The soundscape in Arraial do Cabo indicated higher biological activity during the nighttime, with notable peaks of activity at dawn and dusk (Campbell et al. 2019), which has also found 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, in which nighttime, dawn, and dusk showed 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 acoustic landscapes 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 of three types of vessels: tourist vessels, fishing vessels, and cargo transport or oil platform service vessels, which utilize the Porto do Forno structure (Gurgel et al., 2019). The latter occurs occasionally, despite the 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, proving to more effectively identify moments with vessel presence. The significance of sound emitted by vessels in interpreting specific ecoacoustic indices is evident. However, further studies are required to further develop our understanding of factors related to vessel types and their distance from the hydrophone. Do different types of vessels result in distinct interpretations of these indices? Additionally, determining the appropriate distance certain vessels should maintain from conservation areas to mitigate sound impacts is an important aspect requiring investigation.

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 food supply for filter-feeding organisms, consequently enhancing 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 best distinguished the values between the categories of N/NE 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 N/NE winds 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 is where the hydrophone installed. Therefore, exposure of the hydrophone to wave action could be influencing acoustic interpretation and must be further investigated.

The marine soundscape of Arraial do Cabo: future directions

Many other variables influence the marine soundscape. They should be studied in the soundscape of Arraial do Cabo. They include seasonality (Bittencourt et al., 2016), lunar cycles (Staaterman et al., 2014), circadian rhythms (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, some dolphins species 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 tides (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 with decreased sound propagation (Gottesman et al., 2020). Anthropogenic sounds may cause serious environmental harm to marine soundscapes. Seismic airguns, which are used in oil and gas exploration, cause significant noise pollution and hearing loss in marine mammals

(Kyhn et al., 2019). Moreover, noise pollution from wind turbines disrupt the feeding and breeding behavior of fish (Mooney et al., 2022).

In summary, it is important to identify variables that affect analyses 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 enables 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. Overall, 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 differentiated moments with cold or warm water, with and without vessel presence, and 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 are 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.

ACKNOWLEDGMENTS

The authors would like to thank Instituto de Estudos do Mar Almirante Paulo Moreira (IEAPM) and the Federal Fluminense University (UFF) for their logistic support. The authors are grateful to the Brazilian Navy and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)/Ciência Sem Fronteiras (Contract No. 401407/2014-4) for all the support given to BIOCOM Project. Special thanks to Dra. Laís Farias Oliveira Lima for helping translating and reviewing the final manuscript. We would like to express our gratitude to the reviewers for their insightful comments and valuable suggestions, which significantly contributed to the improvement of this manuscript.

AUTHOR CONTRIBUTIONS

M.M.: Conceptualization; Investigation; Data Analysis; Writing – original draft; Writing – review & editing.

L.C.: Supervision; Formal Analysis; Writing – review & editing.

U.G.M.J.: Data Analysis; Methodology; Writing – review & editing.

F.C.X.: Investigation; Data Analysis; Supervision; Methodology; Writing – review & editing.

REFERENCES

Alcocer, I., Lima, H., Sugai, L. S. M. & Llusia, D. 2022. Acoustic indices as proxies for biodiversity: a meta-analysis. *Biological Reviews*, 97(6), 2209–2236.

Benocci, R., Brambilla, G., Bisceglie, A. & Zambon, G. 2020. Eco-acoustic indices to evaluate soundscape degradation due to human intrusion. *Sustainability*, 12(24), 10455.

Bittencourt, L., Barbosa, M., Secchi, E., Lailson-Brito Jr, J. & Azevedo, A. 2016. Acoustic habitat of an oceanic archipelago in the Southwestern Atlantic. Deep Sea Research Part I: *Oceanographic Research Papers*, 115, 103–111.

Boelman, N. T., Asner, G. P., Hart, P. J. & Martin, R. E. 2007. Multi-trophic invasion resistance in Hawaii: bioacoustics, field surveys and airborne remote sensing. *Ecological Applications*, 17, 2137–2144.

Bradfer-Lawrence, T., Gardner, N., Bunnefeld, L., Bunnefeld, N., Willis, S. G. & Dent, D. H. 2019. Guidelines for the use of acoustic indices in environmental research. *Methods in Ecology and Evolution*, 10(10), 1796–1807.

Braga, H. O., Pardal, M., Azeiteiro, U. M., Oliveira, H. F. & Cruz, R. M. 2016. Fishers' local ecological knowledge about the Brazilian sardine (*Sardinella brasiliensis*, Steindachner, 1879) in ResexMar Arraial do Cabo, RJ, Brazil. In: XIX Iberian Symposium on Marine Biology Studies. DOI: https://doi.org/10.3389/conf.FMARS.2016.05.00072

Brasil. 1997. Decreto de 3 de janeiro de 1997. Dispõe sobre a criação da Reserva Extrativista Marinha do Arraial do Cabo, no Município de Arraial do Cabo, Estado do Rio de Janeiro, e dá outras providências. Brasília, DF: Presidência da República. Available from: http://www.planalto.gov.br/ccivil_03/DNN/Anterior%20a%202000/1997/Dnn5025.htm. Acess date 2024 june 3.

Brockington, S. & Clarke, A. 2001. The relative influence of temperature and food on the metabolism of a marine invertebrate. *Journal of Experimental Marine Biology and Ecology*, 258(1), 87–99.

Buscaino, G., Ceraulo, M., Pieretti, N., Corrias, V., Farina, A., Filiciotto, F., Maccarrone V., Grammauta R., Caruso F., Giuseppe A. & Mazzola, S. 2016. Temporal patterns in the soundscape of the shallow waters of a Mediterranean marine protected area. *Scientific reports*, 6(1), 34230.

Calado, L., Camargo Rodríguez, O., Codato, G. & Contrera Xavier, F. 2018. Upwelling regime off the Cabo Frio region in Brazil and impact on acoustic propagation. *The Journal of the Acoustical Society of America*, 143(3), 174–180.

Campbell, D., Xavier, F. C., Melo Júnior, U. G., Silveira, N. G., Versiani, L. L. & Netto, E. B. F. 2019. Underwater soundscape pattern during high season of nautical tourism in Cabo Frio Island, Brazil. In: *5th International Conference on the Effects of Noise on Aquatic Life*.

Carvalho, J. G. da S., Minello, M., da Silva, A. P., Bastos, R. S. & Brizzi, R. R. 2021. Rejeitos e rejeitados da Companhia Nacional de Álcalis, Arraial do Cabo-RJ: apontamentos para um estudo interdisciplinar. *GEOgraphia*, 23(50).

Coelho-Souza, S. A., López, M. S., Guimarães, J. R. D., Coutinho, R. & Candella, R. N. 2012. Biophysical interactions in the Cabo Frio upwelling system, Southeastern Brazil. *Brazilian Journal of Oceanography*, 60, 353–365.

Dale, V. H. & Beyeler, S. C. 2001. Challenges in the development and use of ecological indicators. *Ecological indicators*, 1(1), 3–10.

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., Harding, H.R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., Slabbekoorn, H., Staaterman, E., Opzeeland, I. C. V., Winderen, J., Zhang, X. & Juanes, F. 2021. The soundscape of the Anthropocene ocean. *Science*, 371(6529).

Farina, A. & Li, P. 2021. *Methods in Ecoacoustics: The Acoustic Complexity Indices* (Vol. 1). Cham, Springer Nature.

Fisher-Pool, P. I., Lammers, M. O., Gove, J. & Wong, K. B. 2016. Does primary productivity turn up the volume? Exploring the relationship between chlorophyll a and the soundscape of coral reefs in the Pacific. In: POPPER, Arthur N. & HAWKINS, Anthony. (ed.). *The Effects of Noise on Aquatic Life II* (pp. 289-293). New York: Springer.

Freeman, S. E., Rohwer, F. L., D'spain, G. L., Friedlander, A. M., Gregg, A. K., Sandin, S. A. & Buckingham, M. J. 2014. The origins of ambient biological sound from coral reef ecosystems in the Line Islands archipelago. *The Journal of the Acoustical Society of America*, 135(4), 1775–1788.

Garrett, J. K., Blondel, P., Godley, B. J., Pikesley, S. K., Witt, M. J. & Johanning, L. 2016. Long-term underwater sound measurements in the shipping noise indicator bands 63 Hz and 125 Hz from the port of Falmouth Bay, UK. *Marine pollution bulletin*, 110(1), 438–448.

Gottesman, B. L., Francomano, D., Zhao, Z., Bellisario, K., Ghadiri, M., Broadhead, T., Gasc, A. & Pijanowski, B. C. 2020. Acoustic monitoring reveals diversity and surprising dynamics in tropical freshwater soundscapes. *Freshwater Biology*, 65(1), 117–132.

Gurgel, F. O. M. J., Rosman, P. C. & Dos Santos, M. 2019. Evaluation of Oil Spill in the Environment of Forno Port, Municipality of Arraial do Cabo, Brazil. *Modern Environmental Science and Engineering*, 5(7), 596–601.

Hammer, Ø. & Harper, D. A. 2001. Past: paleontological statistics software package for educaton and data analysis. *Palaeontologia electronica*, 4(1).

Haver, S. M., Rand, Z., Hatch, L. T., Lipski, D., Dziak, R. P., Gedamke, J., Haxel, J., Heppell, S. A., Jahncke, J., Mckenna, M. F., Mellinger, D. K., Oestreich, W. K., Roche, L., Ryan, J. & Van Parijs, S. M. 2020. Seasonal trends and primary contributors to the low-frequency soundscape of the Cordell Bank National marine sanctuary. *The Journal of the Acoustical Society of America*, 148(2), 845–858.

Jesus, S. M., Xavier, F. C., Vio, R. P., Osowsky, J., Simões, M. V. S. & Netto, E. B. F. 2020. Particle motion measurements near a rocky shore off Cabo Frio Island. *The Journal of the Acoustical Society of America*, 147(6), 4009–4019.

Kaplan, M. B., Lammers, M. O., Zang, E. & Mooney, T. A. 2018. Acoustic and biological trends on coral reefs off Maui, Hawaii. *Coral Reefs*, 37, 121–133.

Kasten, E. P., Gage, S. H., Fox, J. & Joo, W. 2012. The remote environmental assessment laboratory's acoustic library: An archive for studying soundscape ecology. *Ecological informatics*, 12, 50–67.

Kim, J., Kim, H., Paeng, D. G., Bok, T. H. & Lee, J. 2015. Low-salinity-induced surface sound channel in the western sea of Jeju Island during summer. *The Journal of the Acoustical Society of America*, 137(3), 1576–1585.

Korneliussen, R. J., Heggelund, Y., Macaulay, G. J., Patel, D., Johnsen, E. & Eliassen, I. K. 2016. Acoustic identification of marine species using a feature library. *Methods in Oceanography*, 17, 187–205.

Krause, B. & Farina, A. 2016. Using ecoacoustic methods to survey the impacts of climate change on biodiversity. *Biological conservation*, 195, 245–254.

Kyhn, L. A., Wisniewska, D. M., Beedholm, K., Tougaard, J., Simon, M., Mosbech, A. & Madsen, P. T. 2019. Basin-wide contributions to the underwater soundscape by multiple seismic surveys with implications for marine mammals in Baffin Bay, Greenland. *Marine pollution bulletin*, 138, 474–490.

Ladich, F. 2022. Shut up or shout loudly: Predation threat and sound production in fishes. *Fish and Fisheries*, 23(1), 227-238.

Lima, L. F. O. & Coutinho, R. 2016. The reef coral Siderastrea stellata thriving at its range limit: population structure in Arraial do Cabo, southeastern Brazil. *Bulletin of Marine Science*, 92(1), 107–121.

Lin, T. H., Akamatsu, T., Sinniger, F. & Hari, S. 2021. Exploring coral reef biodiversity via underwater soundscapes. *Biological Conservation*, 253, 108901.

Louza, F. B., Osowsky, J., Xavier, F. C., Vale, E. E., Maia, L. P., Vio, R. P., Simões M. V. S., Barroso, V. & Jesus, S. M. 2019. Communications and biological monitoring experiment in an upwelling environment at Cabo Frio island bay. In: *OCEANS 2019-Marseille* (pp. 1-7).

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., Harris, D. & Tyack, P. L. 2013. Estimating animal population density using passive acoustics. *Biological reviews*, 88(2), 287–309.

Mcwilliam, J. N., Mccauley, R. D., Erbe, C. & Parsons, M. J. 2017. Patterns of biophonic periodicity on coral reefs in the Great Barrier Reef. *Scientific Reports*, 7(1), 1–13.

Minello, M., Calado, L. & Xavier, F. C. 2021. Ecoacoustic indices in marine ecosystems: a review on recent developments, challenges, and future directions. *ICES Journal of Marine Science*, 78(9), 3066–3074.

Mooney, T. A., Andersson, M. H. & Stanley, J. 2020. Acoustic impacts of offshore wind energy on fishery resources. *Oceanography*, 33(4), 82–95.

Niemi, G. J. & Mcdonald, M. E. 2004. Application of ecological indicators. *Annual Review of Ecology, Evolution, and Systematics*, 35, 89–111.

Pereira, W. L. C. M. 2014. A indústria química de álcalis e o “Projeto Cabo Frio”. *Cadernos do Desenvolvimento Fluminense*, 4, 42–64.

Pieretti, N., Farina, A. & Morri, D. 2011. A new methodology to infer the singing activity of an avian community: the Acoustic Complexity Index (ACI). *Ecological Indicators*, 11(3), 868–873.

Pijanowski, B. C., Farina, A., Gage, S. H., Dumyahn, S. L. & Krause, B. L. 2011. What is soundscape ecology? An introduction and overview of an emerging new science. *Landscape ecology*, 26, 1213–1232.

Qi, J., Gage, S. H., Joo, W., Napoletano, B. & Biswas, S. 2008. Soundscape characteristics of an environment: a new ecological indicator of ecosystem health. *Wetland and water resource modeling and assessment*, 201–211.

Radford, C., Jeffs, A., Tindle, C. & Montgomery, J. C. 2008. Resonating sea urchin skeletons create coastal choruses. *Marine Ecology Progress Series*, 362, 37–43.

Rajan, S. C., Athira, K., Jaishanker, R., Sooraj, N. P. & Sarojkumar, V. 2019. Rapid assessment of biodiversity using acoustic indices. *Biodiversity and Conservation*, 28, 2371–2383.

Rice, J. 2003. Environmental health indicators. *Ocean & Coastal Management*, 46(3-4), 235–259.

Ricci, S. W., Eggleston, D. B., Bohnenstiehl, D. R. & Lillis, A. 2016. Temporal soundscape patterns and processes in an estuarine reserve. *Marine Ecology Progress Series*, 550, 25–38.

Rogers, R., Correal, G. O., Oliveira, T.C., Carvalho, L. L., Mazurek, P., Barbosa, J. E., Chequer, L., Domingos, T. F., Jandre, K.A., Leão, L. S., Moura, L.A., Occhioni, G. E., Oliveira, V. M., Silva, E. S., Cardoso, A. M., Costa, A. C. & Ferreira, C. E. L. 2014. Coral health rapid assessment in marginal reef sites. *Marine Biology Research*, 10, 612–624.

Romano, T. A., Keogh, M. J., Kelly, C., Feng, P., Berk, L., Schlundt, C. E., Carder, D. A. & Finneran, J. J. 2004. Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(7), 1124–1134.

Siddagangaiah, S., Chen, C. F., Hu, W. C., Danovaro, R. & Pieretti, N. 2021. Silent winters and rock-and-roll summers: The long-term effects of changing oceans on marine fish vocalization. *Ecological Indicators*, 125, 107456.

Silva, M. L., Castro, R. O., Sales, A. S. & De Araújo, F. V. 2018. Marine debris on beaches of Arraial do Cabo, RJ, Brazil: An important coastal tourist destination. *Marine pollution bulletin*, 130, 153–158.

Staaterman, E., Paris, C. B., Deferrari, H. A., Mann, D. A., Rice, A. N. & D’alessandro, E. K. 2014. Celestial patterns in marine soundscapes. *Marine Ecology Progress Series*, 508, 17–32.

Sueur, J. & Farina, A. 2015. Ecoacoustics: the ecological investigation and interpretation of environmental sound. *Biosemiotics*, 8, 493–502.

Vieira, M., Fonseca, P. J. & Amorim, M. C. P. 2021. Fish sounds and boat noise are prominent soundscape contributors in an urban European estuary. *Marine Pollution Bulletin*, 172, 112845.

Villanueva-Rivera, L. J., Pijanowski, B. C., Doucette, J. & Pekin, B. 2011. A primer of acoustic analysis for landscape ecologists. *Landscape Ecology*, 26, 1233–1246.

Wang, W., Sun, H., Guo, J., Lao, L., Wu, S. & Zhang, J. 2021. Experimental study on water pipeline leak using In-Pipe acoustic signal analysis and artificial neural network prediction. *Measurement*, 186, 110094.

Watanabe, M., Sekine, M., Hamada, E., Ukita, M. & Imai, T. 2002. Monitoring of shallow sea environment by using snapping shrimps. *Water science and technology*, 46(11-12), 419–424.

Williams, B., Lamont, T. A., Chapuis, L., Harding, H. R., May, E. B., Prasetya, M. E., Seraphim, M. J., Jompa J., Smith D. J., Janetski N., Radford A. N. & Simpson, S. D. 2022. Enhancing automated analysis of marine soundscapes using ecoacoustic indices and machine learning. *Ecological Indicators*, 140, 108986.

Zampoukas, N., Piha, H., Bigagli, E., Hoepffner, N., Hanke, G., & Cardoso, A. C. 2012. Monitoring for the Marine Strategy Framework Directive: requirements and options. *JRC Scientific and Technical Reports*, 25187.