UNIVERSIDADE ESTADUAL DE SANTA CRUZ

PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA E CONSERVAÇÃO DA BIODIVERSIDADE

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APLICAÇÕES DO MONITORAMENTO ACÚSTICO PASSIVO EM CETÁCEOS E O CANTO DA BALEIA-JUBARTE (*Megaptera novaeangliae*) COMO MODELO EM ESTIMATIVAS DE ABUNDÂNCIA

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Tese apresentada à Universidade Estadual de Santa Cruz como parte das exigências para obtenção do título de Doutora em Ecologia e Conservação da Biodiversidade.

Área de concentração: Ecologia e Conservação de Populações

Orientadora: Profa. Dra. Deborah M. de Faria

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ILHÉUS – BAHIA
2025

C193 Campelo, Mariana Silva.
Aplicações do monitoramento acústico passivo em cetáceos e o canto da baleia-jubarte (Megaptera novaeangliae) como modelo em estimativas de abundância / Mariana Silva Campelo. – Ilhéus, BA: UESC, 2025.
. 176 f.:il.; anexos.

Orientadora: Deborah M. de Faria.
Tese (doutorado) – Universidade Estadual de Santa Cruz. Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade.
Inclui referências.

1. Cetáceos. 2. Baleia-jubarte – Monitorização. 3. Aninais aquáticos – Populações. 4. Biodiversidade – Conservação. I. Título.

CDD 599.5

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Ilhéus, 30 de julho de 2025

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Dedico este trabalho ao professor Julio E. Baumgarten,

Por ter confiado em mim, aceitado me orientar e por ter sido um grande incentivador.

AGRADECIMENTOS

Aos meus pais, Ilcléa de Sá Silva e José Costa Campêlo, que me deram a base necessária para que eu pudesse seguir meus objetivos. À minha mãe, por nunca ter medido esforços para apoiar minha formação; e ao meu pai, por ter direcionado meu olhar ao mar com mais cuidado e atenção. Vocês foram essenciais nessa caminhada.

Meus sinceros agradecimentos e reconhecimento ao meu orientador inicial, Julio E. Baumgarten, por suas contribuições na minha formação desde o mestrado. Obrigada pelas palavras positivas e de incentivo. Ser orientada por alguém assim trouxe leveza ao processo e o tornou mais gratificante.

À minha orientadora Deborah M. de Faria, deixo aqui meu reconhecimento e minha imensa gratidão. Obrigada por sua generosidade ao assumir minha orientação em um momento tão delicado da sua vida.

À minha coorientadora Maria Isabel, minha imensa gratidão por ter me acolhido como aluna ainda na graduação e por seguir presente até hoje, no doutorado. Não tenho palavras para agradecer o suporte que você me ofereceu ao longo desses anos. Obrigada pelos ensinamentos que levo comigo e por ter me apresentado ao universo científico das baleias-jubarte.

À minha coorientadora Renata S. Sousa-Lima, por ter aceitado me orientar. Suas contribuições à minha trajetória acadêmica também antecedem o doutorado. Foi um privilégio poder aprender com uma profissional cujo trabalho sempre admirei. Obrigada pela oportunidade e pelos ensinamentos ao longo desse percurso.

A toda a equipe do Projeto Baleias na Serra:

Ao professor Niel Teixeira, pela colaboração nas atividades do ponto fixo; e ao professor Linilson Padovese, pela parceria que tornou possível a gravação do canto das jubartes, além da constante disponibilidade para esclarecer dúvidas sobre os equipamentos.

A Lara Lopes, cuja colaboração foi essencial na etapa das análises acústicas, que entre períodos embarcada e em terra, compartilhou com paciência e generosidade seus conhecimentos comigo.

Ao Giulio Lombardi, por ter disponibilizado o espaço para o ponto fixo; e ao Davi Santiago, Sr. Nelson Cangirana e Sr. Raimundo Gomes, por todo o auxílio prestado.

Ao Rafael Murakami e Fernando Murakami, da Água Viva Sub, e a Erik Tedesco, pelo planejamento, organização e realização do trabalho de campo.

Ao pessoal do ponto fixo, meu muito obrigada pela contribuição na coleta de dados: Andrea Tribulado, Bianca Righi, Érica Lopes, Evelyn Froés, Fernanda Tonolli, Juliede Nonato, Luana Pini, Naiane Silva, Rayane Tomaselli, Stella Tomás, Tamires Fernandes e Winnie Silva.

Ao Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade (PPGECB) e à Universidade Estadual de Santa Cruz (UESC), por toda a estrutura e apoio acadêmico.

À Amábille e à Mayra, da secretaria da pós-graduação, expresso meu agradecimento especial pela eficiência na resolução das demandas burocráticas e pela gentileza no atendimento.

Ao suporte oferecido pela CAPES – "O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001. "

À Fundação de Amparo à Pesquisa do Estado da Bahia – FAPESB, pela bolsa de doutorado; e aos demais apoios financeiros que tornaram possível a realização deste trabalho: CAPES, CNPq, UESC, Viva Instituto Verde Azul, Rufford Foundation, Cetacean Society International e aos patrocinadores anônimos.

À minha família: meus avós, em especial Cleonice de Sá, por todas as orações a meu favor; minhas tias, minha irmã Maiana e minha prima Jocinéa, obrigada por serem um ponto de apoio no qual eu sempre pude confiar e a Joilson pelos almoços preparados como demonstração de cuidado e preocupação nos momentos de correia.

Ao meu amor e companheiro, Pedro Campos. Meus agradecimentos vão muito além da ajuda direta ao meu trabalho, com seu toque gráfico nas figuras; incluem também o fato de você ter sido um verdadeiro ponto de apoio, sempre disponível para ajudar e presente em cada etapa desta fase da minha vida.

Aos colegas de graduação — Bianca Farias, Carla Araújo, Emily Bronze, Geiseane Velozo, Jemile Viana, Julyanna Castro, Rebeca Quinto, Thayná Barreto e Thomas Vieira — e aos parceiros que a pós-graduação me deu — Arthur Gomes, Bianca Righi e Lidiane Gomes — agradeço pela parceria e pela ajuda constante ao longo desse caminho.

Também agradeço às minhas amigas da vida, em especial Carol Botelho, Jamile Bahia e Yasmim Mendes, pela torcida constante.

Às baleias-jubarte, pela graciosidade que me encantou desde o primeiro encontro e me guiou a esta área de conhecimento, moldando minha trajetória acadêmica e fortalecendo vínculos que levarei para toda a vida.

E, por fim, a todos aqueles que, mesmo não citados nominalmente, contribuíram de alguma forma, deixo aqui o meu sincero agradecimento.

“Feche os olhos, aguce os ouvidos, e da mais leve respiração ao mais selvagem ruído, do mais simples som à mais sublime harmonia, do mais violento e apaixonante grito às mais suaves palavras da doce razão, é somente a Natureza que fala, revelando sua existência, seu poder, sua vida e suas relações e estruturas, de tal modo que um cego, a quem é vedado o mundo infinitamente visível, é capaz de aprender no audível tudo o que é infinitamente vivo”

Johann Wolfgang von Goethe

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RESUMO

O monitoramento acústico passivo (MAP) tem se consolidado como uma ferramenta valiosa e em constante expansão no estudo dos cetáceos. Por meio de diferentes abordagens, esse método tem viabilizado a obtenção de informações ecológicas relevantes em regiões-chave de ocorrência do grupo, como áreas de alimentação, corredores migratórios e áreas reprodutivas. A capacidade dos cetáceos de permanecerem submersos por longos períodos, aliada à intensa atividade acústica exibida por muitas espécies, torna o MAP uma abordagem especialmente eficaz para registros contínuos e não invasivos, inclusive em locais remotos onde a aplicação de métodos tradicionais baseados em observação visual é limitada. Nesse contexto, esta tese teve como objetivo geral avaliar as aplicações do MAP no estudo de cetáceos, com ênfase na análise do canto da baleia-jubarte (*Megaptera novaeangliae*), como potencial indicador de abundância populacional. Na primeira etapa, foi realizada uma revisão sistemática da literatura, considerando apenas estudos que utilizaram gravadores acústicos autônomos fixos de forma exclusiva, sem integração com métodos visuais. Foram analisados 138 artigos publicados em periódicos revisados por pares entre 2007 e 2024. A análise destacou as regiões acessadas, as espécies-alvo e os tipos de informação biológica obtida. Observou-se uma predominância de estudos no Hemisfério Norte, mas com crescimento expressivo no Hemisfério Sul a partir de 2014. Entre os misticetos, destacaram-se a baleia-fin (*Balaenoptera physalus*) e a baleia-jubarte; entre os odontocetos, o cachalote (*Physeter macrocephalus*) e a orca (*Orcinus orca*). A maioria dos estudos abordou padrões de ocorrência e uso do habitat, enquanto parâmetros populacionais ainda são menos explorados. Fatores como a distribuição global das espécies, as características de suas vocalizações e as desigualdades no acesso à tecnologia e financiamento científico entre regiões parecem influenciar a representatividade das espécies nos estudos analisados. Na segunda etapa, foram avaliadas métricas acústicas extraídas do canto dos machos de baleias-jubarte pertencentes ao Estoque Reprodutivo A. Os registros acústicos foram realizados na região sul da Bahia, Brasil, nos anos de 2014, 2015, 2018 e 2019. As métricas incluíram o nível de pressão sonora quadrático médio (SPL RMS), os níveis de banda de 1/3 de oitava (TOL), o índice de complexidade acústica (ACI) e o número de cantores (em uma escala de 0 a 4). Esses dados acústicos foram comparados a estimativas visuais de abundância relativa. Os resultados mostraram que o SPL RMS e o número de cantores foram os indicadores mais consistentes em refletir os padrões sazonais e interanuais de abundância, embora cada métrica apresente limitações específicas. O ACI mostrou-se instável e sensível a variações estruturais no canto, enquanto o TOL permitiu identificar as faixas de frequência mais associadas à vocalização da espécie. Conclui-se que o MAP, tanto em sua aplicação isolada quanto em combinação com outros métodos, constitui uma abordagem eficaz para o monitoramento ecológico de cetáceos. Além de ampliar o acesso a áreas e espécies anteriormente subamostradas, o uso de métricas acústicas para estimar a abundância mostra-se promissor como ferramenta complementar às estratégias tradicionais de monitoramento populacional e conservação.

Palavras-chave: Cetáceo; *Megaptera novaeangliae*; Monitoramento acústico passivo; métricas acústicas; canto; abundância.

APPLICATIONS OF PASSIVE ACOUSTIC MONITORING IN CETACEANS AND THE HUMPBACK WHALE'S SONG (*Megaptera novaeangliae*) AS A MODEL FOR ESTIMATING ABUNDANCE

ABSTRACT

Passive acoustic monitoring (PAM) has become a valuable and steadily expanding tool for the study of cetaceans. Through a variety of approaches, this method enables the collection of ecologically relevant information in key areas of cetacean occurrence, including migratory corridors, feeding and breeding grounds. The ability of cetaceans to remain submerged for long periods, combined with the intense acoustic activity exhibited by many species, makes PAM an especially effective approach for continuous and non-invasive recordings, including in remote locations where the use of traditional visual observation methods is limited. In this context, the general objective of this thesis was to assess the applications of PAM in cetacean research, with an emphasis on the analysis of humpback whale (*Megaptera novaeangliae*) song as a potential indirect indicator of population abundance. In the first stage, a systematic literature review was conducted, considering only studies that used fixed autonomous acoustic recorders exclusively, without integration with visual methods. A total of 138 articles published in peer-reviewed journals between 2007 and 2024 were analyzed. The analysis focused on the accessed regions, target species, and types of biological information obtained. A predominance of studies was observed in the Northern Hemisphere, although the Southern Hemisphere showed significant growth from 2014 onward. Among mysticetes, the most frequently studied species were the fin whale (*Balaenoptera physalus*) and the humpback whale; among odontocetes, the sperm whale (*Physeter macrocephalus*) and the killer whale (*Orcinus orca*) stood out. Most studies addressed occurrence patterns and habitat use, while population parameters remain less explored. Factors such as the global distribution of species, the characteristics of their vocalizations, and inequalities in access to technology and scientific funding across regions appear to influence the representativeness of species in the analyzed studies. In the second stage, acoustic metrics extracted from the songs of male humpback whales belonging to Reproductive Stock A were evaluated. Acoustic recordings were conducted in the southern region of Bahia, Brazil, in the years 2014, 2015, 2018, and 2019. The metrics included root mean square sound pressure level (RMS SPL), 1/3 octave band levels (TOL), the Acoustic Complexity Index (ACI), and the number of singers (on a 0 to 4 scale). These acoustic data were compared with visual estimates of relative abundance. The results showed that RMS SPL and the number of singers were the most consistent indicators of seasonal and interannual abundance patterns. Although each metric had specific limitations. ACI proved unstable and sensitive to structural variations in the song, while TOL was useful in identifying the frequency bands most associated with the species' vocalizations. In conclusion, PAM—whether applied in isolation or integrated with other methods—constitutes an effective approach for the ecological monitoring of cetaceans. In addition to improving access to under-sampled areas and species, the use of acoustic metrics for estimating abundance shows promise as a complementary tool to traditional population monitoring and conservation strategies.

Keywords: Cetaceans; *Megaptera novaeangliae*; Passive acoustic monitoring; Acoustic metrics; Song; Abundance.

SUMÁRIO

1. INTRODUÇÃO GERAL

1.1. Contextualização: monitoramento acústico da paisagem

Os sons que compõem uma paisagem sonora variam tanto no espaço quanto no tempo, resultando da integração de diferentes tipos de fontes sonoras. De modo geral, esses sons são classificados em três componentes principais que estruturam o que foi definido como paisagem acústica (PIJANOWSKI *et al.*, 2011a): *i*- a biofonia, referente aos sons produzidos por animais, como por exemplo, vocalizações de aves e mamíferos; *ii*- a geofonia, relacionada aos sons de origem geofísica e metereológica, tais como vento e chuva; e *iii*- a antropofonia, associada às atividades humanas, incluindo o tráfego de veículos, embarcações, máquinas, dentre outras fontes sonoras geradas pelo homem (PIJANOWSKI *et al.*, 2011a, 2011b).

Entre os componentes da paisagem acústica, a biofonia tem se destacado como uma importante fonte de dados bioacústicos e ecológicos. Os sons emitidos pelos animais são altamente informativos e podem se propagar em múltiplas direções, atravessar obstáculos físicos e percorrer distâncias relativamente longas (BRADBURY; VEHRENCAMP, 1998; WILKINS; SEDDON; SAFRAN, 2013). Por esse motivo, levantamentos acústicos representam uma estratégia particularmente eficaz para o monitoramento de espécies com o comportamento vocal mais ativo, especialmente aquelas que são dificilmente detectadas visualmente (ROSENTHAL; RYAN, 2000; ZIMMER *et al.*, 2011; HEINICKE et al., 2015).

As observações acústicas podem ser realizadas de forma ativa ou passiva. Na acústica ativa, há a emissão de um sinal sonoro no ambiente e a subsequente análise do eco refletido, permitindo a detecção e caracterização de organismos e/ou estruturas (MELLINGER *et al.*, 2007; AU; HASTINGS, 2008). Já na acústica passiva, o equipamento apenas registra os sons presentes no ambiente (MELLINGER et al., 2007; ZIMMER, 2011). Com base nesse princípio, o monitoramento acústico passivo (MAP), consiste no registro não invasivo do ambiente sonoro, uma vez que os gravadores não adicionam ruído, permitindo documentar sua composição e variação ao longo do tempo (BROWNING *et al.*, 2017).

A possibilidade de registrar sons em campo de forma sistemática representou um avanço significativo na pesquisa científica (SUGAI *et al.*, 2019). A introdução dos gravadores digitais trouxe melhorias que vão desde a maior qualidade do registro, até a redução dos custos na aplicação do método (OBRIST *et al.*, 2010; SUGAI *et al.*, 2019). Com a introdução dos gravadores autônomos, as abordagens de pesquisa se expandiram ainda mais, pois, esses dispositivos permitem gravações contínuas ou programadas por longos períodos, aumentando a cobertura temporal e a possibilidade de monitorar diferentes aspectos ecológicos e ambientais. Os gravadores autônomos podem ser móveis ou fixos (MELLINGER et al., 2007). Os dispositivos móveis podem ser rebocados por navios (*e.g.,* YACK *et al.,* 2013) ou planadores (*e.g.,* BITTENCOURT *et al.,* 2018), dentre outras plataformas, oferecendo ampla cobertura espacial e a possibilidade de integração com levantamentos visuais (MELLINGER *et al.*, 2007). Já os gravadores fixos permanecem posicionados em um ponto específico, permitindo maior cobertura temporal e monitoramento contínuo do ambiente acústico (MELLINGER *et al.,* 2007; SOUSA-LIMA *et al.,* 2013).

Por meio dos gravadores acústicos autônomos, a paisagem sonora de diversos habitats — terrestres e marinhos, naturais e antropizados — tem sido investigada (*e.g.,* SUGAI *et al.*, 2019; DARRAS *et al.,* 2025). A possibilidade de programar a gravação para registro contínuo ou em intervalos previamente definidos, elimina a necessidade de presença constante do pesquisador, reduz custos operacionais e minimiza interferências no comportamento natural dos organismos, além de evitar a introdução de ruídos adicionais no ambiente (SOUSA-LIMA *et al.,* 2013; BROWNING *et al.,* 2017).

Os registros obtidos são processados em softwares especializados, que permitem analisar as características espectrais dos sinais acústicos e extrair informações bioacústicas, como parâmetros de frequência e energia, e ecológicas, como ocorrência, uso do habitat, riqueza e diversidade de espécies, densidade populacional e comportamento (*e.g.,* AU *et al.*, 2013; HILDEBRAND *et al.,* 2015; KALAN *et al.,* 2015; RICE *et al.*, 2021; MORALES *et al.*, 2022). Esses dados podem ser analisados em diferentes escalas temporais, possibilitando a identificação de padrões diários, sazonais e interanuais (*e.g.,* RICE *et al.*, 2021; PILKINGTON *et al.,* 2023). A continuidade da amostragem ao longo do tempo também permite detectar mudanças e tendências nos padrões sonoros, sejam elas associadas a processos naturais ou a impactos antrópicos (*e.g.,* WINN; WINN, 1978; GOMES *et al.*, 2022; MCCAULEY *et al.*, 2018).

1.2. O estudo da biofonia marinha

As paisagens sonoras terrestres têm sido foco de estudos acústicos ambientais há mais de 40 anos (*e.g.,* TRUAX, 1978). Em contrapartida, no ambiente marinho, embora o registro de sons subaquáticos já fosse realizado no âmbito da geofonia desde a década de 1960, foi apenas a partir dos anos 1990 que os gravadores acústicos autônomos passaram a ser aplicados ao estudo da biofonia (MCDONALD, HILDEBRAND, WEBB, 1995). Nesse período, diversos laboratórios começaram a desenvolver seus próprios equipamentos, o que contribuiu para a redução dos custos — até então um dos principais obstáculos à aplicação da bioacústica em ambientes marinhos (MELLINGER *et al.*, 2007; SOUSA-LIMA *et al.*, 2013). Entre os avanços tecnológicos alcançados, destacam-se as melhorias na capacidade de armazenamento de dados e na autonomia das baterias, que viabilizaram o registro de sons subaquáticos por períodos mais longos e com maior resolução temporal, além das melhorias na taxa de amostragem dos equipamentos, que permitiram a coleta de dados em faixas de frequência mais amplas (SOUSA-LIMA *et al.*, 2013; SUGAI *et al.*, 2019).

Esses avanços, no entanto, não atuam isoladamente. A aplicação do MAP no ambiente marinho também se beneficia das propriedades físicas do meio aquático, que favorecem a propagação da onda sonora. Em comparação com o ar, na água o som se propaga cerca de cinco vezes mais rápido, podendo, em determinadas condições, percorrer milhares de quilômetros (HAWKINS; MYRBERG, 1983; BRADBURY; VEHRENCAMP, 1998; RICHARDSON *et al.*, 2013). Esse potencial de propagação supera o alcance dos sinais visuais e químicos, tornando o som, nesse contexto, o meio de comunicação mais eficiente (BRADBURY; VEHRENCAMP, 1998). Como consequência, muitas espécies marinhas exibem especializações acústicas que proporcionam vantagens adaptativas ao meio e são utilizadas na realização de atividades essenciais como navegação, forrageamento e reprodução (AU, 2000).

No contexto da biofonia, os sons emitidos por crustáceos, peixes e cetáceos se destacam como os principais componentes da paisagem acústica marinha. Essas emissões variam ao longo de ciclos diários e sazonais, refletindo processos ecológicos e fornecendo informações valiosas sobre a dinâmica ambiental (*e.g.*, LAMMERS *et al.*, 2008; RADFORD *et al.*, 2008; BITTENCOURT *et al.*, 2016; BUSCAINO *et al.*, 2016; PIERETTI *et al.*, 2017; SÁNCHEZ-GENDRIZ; PADOVESE, 2017a, 2017b). Crustáceos, como camarões e lagostas, emitem sons pulsados e estalidos de banda larga, com componentes de frequência que chegam até 200 kHz (AU; BANKS, 1998). Esses organismos são fontes persistentes e predominantes no ambiente acústico de águas rasas, especialmente em regiões tropicais e subtropicais (*e.g.*, BUSCAINO *et al.*, 2016). Os peixes são conhecidos por produzirem sons impulsivos ou modulados, geralmente em baixa frequência e amplitude (AMORIM *et al.*, 2006). Suas emissões acústicas estão associadas a comunicação, reprodução, mecanismo de defesa e comportamentos agonísticos (*e.g.*, TAVOLGA, 1960; CODARIN *et al.*, 2009; SLABBEKOORN *et al.*, 2010; LADICH, 2013). Os cetáceos, por sua vez, produzem uma ampla gama de sons pulsados e tonais com diferentes finalidades, cujas características acústicas variam entre os grupos (*i.e.*, odontocetos e misticetos). De modo geral, os odontocetos vocalizam em uma faixa extensa de frequências, que vai de aproximadamente 5 kHz a mais de 135 kHz, enquanto os misticetos emitem sons predominantemente em frequências mais baixas, entre cerca de 14 Hz e 5 kHz (AU, 2000).

Dentre esses componentes da biofonia, os cetáceos apresentam características que favorecem as aplicações do MAP em seu estudo, como a diversidade de repertório vocal, a ampla mobilidade e o papel ecológico que desempenham nos ecossistemas marinhos (ZIMMER, 2011). O método acústico tem se mostrado especialmente eficaz para a detecção desses animais, pois permite o registro contínuo e não invasivo de suas vocalizações, mesmo em áreas de difícil acesso ou sob condições ambientais que comprometem a observação visual (*e.g.*, MELLINGER *et al.*, 2007; SOUSA-LIMA *et al.*, 2013).

1.3. Produção de som nos cetáceos

Os cetáceos constituem um grupo de mamíferos aquáticos incluídos na ordem Cetartiodactyla, embora sua classificação taxonômica interna (por exemplo, em subordem ou infraordem) ainda seja alvo de discussão (FORDYCE; PERRIN, 2025). Tradicionalmente, são divididos em dois grupos: Odontoceti, sendo representado pelos cetáceos que possuem dentes, como os botos e golfinhos e Mysticeti, incluindo os cetáceos que possuem barbatanas, como é o caso das grandes baleias, também chamadas de baleias verdadeiras (REEVES; FOLKENS, 2002; WILSON; REEDER, 2005; FORDYCE; PERRIN, 2025). Esses organismos ocupam desde áreas costeiras e oceânicas, até rios e estuários (LODI; BOROBIA; FOLKENS, 2013. Em linhas gerais, suas emissões acústicas podem ser divididas em sons vocais — produzidos por órgãos especializados — e sons não vocais — gerados por interações mecânicas com a água ou entre partes do corpo (CLARK, 1990; HERZING, 2006).

A produção sonora por meio de órgãos especializados tem sido amplamente investigada nos cetáceos (*e.g.*, CALDWELL; CALDWELL, 1971; PAYNE; MCVAY, 1971; HERMAN; TAVOLGA, 1980; SHARPE *et al.*, 1998; JOHNSTON *et al.*, 2008; VARGA; WIGGINS; HILDEBRAND, 2018; MADSEN; SIEBERT; ELEMANS, 2023; ELEMANS *et al.*, 2024). Sabe-se que enquanto os odontocetos produzem sons por meio de estruturas nasais (MADSEN; SIEBERT; ELEMANS, 2023), os misticetos desenvolveram estruturas laríngeas especializadas com adaptações únicas entre os mamíferos (ELEMANS *et al.*, 2024).

Nos odontocetos, as vocalizações são comumente classificadas em (*i*) sons tonais de frequência modulada, conhecidos como assobios, e (*ii*) sinais pulsados de banda larga, que englobam tanto os cliques de ecolocalização, quanto os sons pulsados explosivos (AU, 2000). Os assobios e os sons pulsados explosivos estão associados à comunicação social — sendo os assobios, também relacionados ao reconhecimento individual (HERMAN; TAVOLGA, 1980). Os cliques de ecolocalização, por sua vez, são utilizados principalmente para a navegação e forrageamento (AU, 2000).

Nos misticetos, as vocalizações dividem-se em (*i*) chamados e (*ii*) canto (CLARK, 1990; AU, 2000). Os chamados são sinais acústicos emitidos em interações sociais e apresentam ampla variação estrutural, podendo ser simples, como gemidos de baixa frequência; complexos, como gritos e rugidos de banda larga; ou ainda breves e impulsivos, como estalos e grunhidos. O canto, por outro lado, é caracterizado por uma sequência rítmica e altamente estruturada de unidades sonoras repetidas ao longo do tempo (PAYNE; MCVAY, 1971; CLARK, 1990). Documentado sobretudo em machos de baleia-jubarte, evidências sugerem que esse comportamento está associado ao sistema reprodutivo da espécie, mas até hoje sua funcionalidade exata permanece em debate (*e.g.*, WINN; WINN, 1978; HERMAN; TAVOLGA, 1980; DARLING; BÉRUBÉ, 2001; DARLING; SOUSA-LIMA, 2006; HERMAN, 2017).

Em contraste às vocalizações, os sons não vocais são produzidos por mecanismos que não envolvem estruturas anatômicas especializadas para a emissão sonora. Entre esses, destacam-se os comportamentos percussivos — ações que geram som por meio do impacto de partes do corpo com a superfície da água — como ocorre em saltos e batidas com as nadadeiras peitorais ou caudais (*e.g.*, WHITEHEAD, 1985; WELLER *et al.*, 1996; WEINRICH; BELT; MORIN, 2001). Tais comportamentos têm sido documentados em diversas espécies de odontocetos, como o golfinho-rotador (*Stenella longirostris*) (*e.g.*, NORRIS *et al.*, 1994), o boto-cinza (*Sotalia guianensis*) (*e.g.*, ANDRADE; SICILIANO; CAPISTRANO, 1987) e o cachalote (*Physeter macrocephalus*) (*e.g.*, WATERS; WHITEHEAD, 1990); bem como em misticetos, como a baleia-jubarte (*Megaptera novaeangliae*) (*e.g.*, WHITEHEAD, 1985; PACHECO *et al.*, 2013), a baleia-franca-do-sul (*Eubalaena australis*) (*e.g.*, CLARK, 1982) e a baleia-franca-da-Groelândia (*Balaena mysticetus*) (*e.g.*, WÜRSIG *et al.*, 1989). Estudos sugerem que os sons gerados durante essas atividades podem atuar como sinais eficazes de comunicação, com potencial de propagação por longas distâncias (CLARK, 1990; HERMAN; TAVOLGA, 1980). No entanto, essas manifestações também podem cumprir funções não comunicativas, como a remoção de ectoparasitas (PERRIN; GILPATRICK, 1994). Embora os sons não vocais sejam comumente associados as exibições percussivas — também chamadas de comportamento de superfície —, é importante destacar que outros mecanismos também podem gerar som e se enquadram nesta categoria. Um exemplo são os sons resultantes da emissão de bolhas pelos espiráculos, os quais produzem ruídos de banda larga (*e.g.*, PRYOR, 1986; FRIPP, 2005).

Estudos mostram que os comportamentos acústicos vocais e não vocais, quando inseridos em contextos comunicativos, podem ser ajustados em resposta a variáveis ambientais, como as variações de luminosidade e os níveis de ruído subaquático (*e.g.*, AU *et al.*, 2000; PARKS; CLARK; TYACK, 2007; DUNLOP; CATO; NOAD, 2010). Essa plasticidade no uso dos sinais sonoros destaca o papel fundamental do som na ecologia desses organismos, além de dar ênfase ao potencial informativo do MAP.

1.4. Aplicações da bioacústica no estudo dos cetáceos

A capacidade dos cetáceos de permanecerem submersos por longos períodos, aliada à intensa atividade acústica exibida por muitas espécies, torna o monitoramento acústico particularmente eficaz para o estudo do grupo (ZIMMER, 2011). Por meio da detecção de seus sinais sonoros, o MAP possibilita registrar a presença de indivíduos mesmo sem contato visual, superando limitações impostas por fatores ambientais como variações de luminosidade, chuva ou neblina (MELLINGER *et al.*, 2007; SOUSA-LIMA *et al.*, 2013). O uso de gravadores acústicos autônomos tem impulsionado avanços no conhecimento ecológico dos cetáceos permitindo o monitoramento contínuo de regiões remotas ou de difícil acesso — como áreas polares em determinadas épocas do ano (*e.g.*, MOORE *et al.*, 2012) —, além da detecção de espécies crípticas ou com baixa densidade populacional, que raramente são observadas por métodos visuais (*e.g.*, OSWALD; AU; DUENNEBIER, 2011; RAYMENT *et al.*, 2011; MILLER *et al.*, 2015).

O reconhecimento de padrões acústicos específicos e a identificação de espécies com base em suas vocalizações (*e.g.*, BAUMGARTNER *et al.*, 2008; HELBLE *et al.*, 2020) têm viabilizado a obtenção de informações sobre ocorrência, uso do habitat e impactos antrópicos em escalas temporais e espaciais refinadas. Em alguns casos, os dados acústicos, por si só, têm se mostrado suficientes para alcançar esses objetivos, dispensando a necessidade de observações visuais complementares (*e.g.*, SOUSA-LIMA; CLARK, 2008; ACKLEH *et al.*, 2012; STANISTREET *et al.*, 2018; AHONEN *et al.*, 2021). Uma aplicação mais recente do MAP e com resultados promissores é sua aplicação em estimativas de densidade populacional (*e.g.*, MARQUES *et al.*, 2009; ACKLEH *et al.*, 2012; MARTIN *et al.*, 2013; MARQUES *et al.*, 2013; NOAD; DUNLOP; MARCK, 2017; KÜGLER *et al.*, 2021). No entanto, sua aplicação depende de variáveis biológicas e comportamentais específicas da espécie-alvo. Fatores como a taxa de vocalização, a estrutura dos sinais sonoros, bem como o contexto comportamental em que são emitidos, influenciam diretamente a precisão e acurácia das estimativas. Assim, não existe um protocolo único aplicável a todas as espécies.

Nos odontocetos, os cliques de ecolocalização têm se mostrado uma ferramenta eficaz em estimativas de abundância, uma vez que apresentam características espectrais e temporais altamente regulares e específicas, permitindo sua identificação em nível de espécie (*e.g.*, HILDEBRAND *et al.*, 2015). Essa regularidade é observada em diferentes grupos, como o cachalote, a toninha e as baleias bicudas (*e.g.*, ACKLEH *et al.*, 2012; HILDEBRAND *et al.*, 2015; OWEN; SKÖLD; CARLSTRÖM, 2021; LI *et al.*, 2021). Um estudo conduzido no Golfo do México utilizou essas informações para identificar acusticamente diferentes espécies de baleias-bicudas (família *Ziphiidae*) e, com base no conhecimento prévio sobre o intervalo entre cliques, estimar suas densidades. Para isso, foram aplicadas duas abordagens complementares: (*i*) a contagem de cliques individuais, baseada na taxa média de emissão por animal e na probabilidade de detecção dos sinais; e (*ii*) a contagem de grupos, baseada na presença de cliques em janelas de tempo fixas, incorporando estimativas de tamanho de grupo, grau de sobreposição vocal e proporção de tempo em que os animais vocalizam durante os ciclos de mergulho (HILDEBRAND *et al.*, 2015). Esse tipo de análise só é possível porque os cliques dessas espécies são bem definidos, curtos e regulares.

Em contraste, para espécies que produzem vocalizações mais complexas e prolongadas — como o canto da baleia-jubarte — esse tipo de individualização dos sinais pode não ser viável. Durante o período reprodutivo, o coro dos machos domina a paisagem acústica (BITTENCOURT *et al.*, 2016), dificultando a separação de cantores individualmente (DUNLOP; FRERE, 2023). Nesses contextos, têm sido propostas abordagens alternativas, como a análise dos níveis de pressão sonora (SPL) da paisagem acústica. AU *et al.* (2000) propuseram que medidas calibradas da intensidade do coro poderiam refletir variações na abundância, hipótese posteriormente explorada por estudos que associaram níveis de SPL à densidade de baleias (*e.g.*, KÜGLER *et al.*, 2021).

De todo modo, há consenso na literatura de que, para que estimativas de abundância sejam obtidas a partir de dados acústicos, é fundamental um conhecimento prévio detalhado sobre a bioacústica da espécie-alvo, incluindo seus padrões de emissão e comportamento vocal (MARQUES *et al.*, 2013; NOAD; DUNLOP; MACK, 2017).

1.5. OBJETIVO GERAL

Diante do potencial exploratório do MAP, esta tese buscou avaliar suas diferentes aplicabilidades no estudo dos cetáceos, com ênfase na análise do canto da baleia-jubarte, como potencial indicador de densidade populacional.

1.5.1. OBJETIVOS ESPECÍFICOS

Capítulo I: Avaliar as diferentes aplicabilidades do MAP no estudo dos cetáceos por meio do uso exclusivo de gravadores acústicos autônomos fixos, identificando as regiões ao redor do mundo onde cetáceos estão sendo acusticamente monitorados com o uso destes gravadores; quais espécies têm sido alvo desses estudos; e quais informações ecológicas têm sido obtidas a partir de dados exclusivamente acústicos.

Capítulo II: Avaliar o potencial de diferentes métricas acústicas como preditoras da densidade relativa de baleias-jubarte em uma área reprodutiva no nordeste do Brasil, a partir da correlação com dados do monitoramento visual; investigar se o canto dos machos pode ser utilizado como proxy para estimativas de densidade populacional; verificar se as métricas acústicas derivadas do canto diferem em sua capacidade explicativa; e analisar se há variação na capacidade explicativa das métricas entre os períodos diurno e crepuscular/noturno.

1.6. HIPÓTESES

Capítulo I: O MAP possui potencial para ampla aplicação geográfica, acompanhando a extensa distribuição dos cetáceos. Contudo, supõe-se que os registros se concentrem em áreas de uso estratégico, como áreas de reprodução e alimentação, onde ocorrem maiores agregações. Também se hipotetiza que as espécies mais representadas sejam aquelas com repertórios vocais já descritos e bem conhecidos, condição que favorece a identificação acústica, dado que a metodologia se baseia exclusivamente em registros sonoros. Por fim, espera-se que as informações ecológicas mais recorrentes estejam relacionadas à ocorrência e ao uso do habitat, pois tais inferências dependem apenas da identificação confiável da espécie, o que está associado ao conhecimento prévio de suas vocalizações.

Capítulo II: Hipotetiza-se que todas as métricas acústicas apresentem correlação consistente com a densidade relativa de baleias registrada visualmente, embora a magnitude dessa correlação varie conforme a sensibilidade de cada métrica às características do sinal acústico. Em particular, espera-se que os níveis de pressão sonora (SPL) apresentem a associação mais robusta com a densidade relativa de baleias, devido à predominância do coro de machos como principal fonte sonora em áreas reprodutivas e à escala contínua da métrica, que potencializa sua sensibilidade a variações na densidade de indivíduos. Adicionalmente, prevê-se que a análise por bandas de frequência (TOL) permita identificar intervalos específicos da faixa selecionada mais diretamente associados à atividade vocal da espécie. Por fim, sugere-se que o desempenho das métricas seja superior durante o período noturno, quando a atividade vocal é mais intensa, de modo que as métricas acústicas reflitam com maior precisão a abundância de baleias observadas durante o dia.

1.7. REFERÊNCIAS

ACKLEH, Azmy S. et al. Assessing the Deepwater Horizon oil spill impact on marine mammal population through acoustics: endangered sperm whales. **The Journal of the Acoustical Society of America**, v. 131, n. 3, p. 2306–2314, 2012. https://doi.org/10.1121/1.3682042

AHONEN, Heidi et al. Interannual variability in acoustic detection of blue and fin whale calls in the Northeast Atlantic High Arctic between 2008 and 2018. **Endangered Species Research**, v. 45, p. 209–224, 2021. https://doi.org/10.3354/esr01132

AMORIM, M. Clara P. et al. Diversity of sound production in fish. **Communication in fishes**, v. 1, p. 71–104, 2006.

ANDRADE, L.; SICILIANO, S.; CAPISTRANO, L. Movimentos e atividades do boto Sotalia guianensis (Cetácea: Delphinidade) na Baía de Guanabara–Rio de Janeiro. (pp. 49-56). **Anais da II Reunião de Trabalho de Especialistas em Mamíferos Aquáticos da América do Sul**, 1987.

AU, Whitlow W. L. et al. Nighttime foraging by deep diving echolocating odontocetes off the Hawaiian Islands of Kauai and Ni'ihau as determined by passive acoustic monitors. **The Journal of the Acoustical Society of America**, v. 133, n. 5, p. 3119–3127, 2013. https://doi.org/10.1121/1.4798360

AU, Whitlow W. L et al. Seasonal and diurnal trends of chorusing humpback whales wintering in waters off western Maui. **Marine mammal science**, v. 16, n. 3, p. 530–544, 2000. https://doi.org/10.1111/j.1748-7692.2000.tb00949.x

AU, Whitlow W. L. Hearing in whales and dolphins: An overview. **Hearing by whales and dolphins**, p. 1–42, 2000. https://doi.org/10.1007/978-1-4612-1150-1_1

AU, Whitlow W. L; BANKS, Kiara. The acoustics of the snapping shrimp Synalpheus parneomeris in Kaneohe Bay. **The Journal of the Acoustical Society of America**, v. 103, n. 1, p. 41–47, 1998. https://doi.org/10.1121/1.423234

AU, Whitlow W. L; HASTINGS, Mardi C. **Principles of marine bioacoustics**. New York: Springer, 2008.

BAUMGARTNER, Mark F. et al. Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*). **The Journal of the Acoustical Society of America**, v. 124, n. 2, p. 1339–1349, 2008. https://doi.org/10.1121/1.2945155

BITTENCOURT, Lis et al. Acoustic habitat of an oceanic archipelago in the Southwestern Atlantic. **Deep Sea Research Part I: Oceanographic Research Papers**, v. 115, p. 103–111, 2016. https://doi.org/10.1016/j.dsr.2016.06.001

BITTENCOURT, Lis et al. Mapping cetacean sounds using a passive acoustic monitoring system towed by an autonomous Wave Glider in the Southwestern Atlantic Ocean. **Deep Sea Research Part I: Oceanographic Research Papers**, v. 142, p. 58-68, 2018. https://doi.org/10.1016/j.dsr.2018.10.006

BRADBURY, Jack W.; VEHRENCAMP, Sandra L. **Principles of animal communication**. Sunderland, MA: Sinauer Associates, 1998.

BROWNING, Ella et al. Passive acoustic monitoring in ecology and conservation. **WWF Conservation Series**, v. 1, n. 2. WWF-UK, 2017. https://doi.org/10.25607/OBP-876

BUSCAINO, Giuseppa et al. Temporal patterns in the soundscape of the shallow waters of a Mediterranean marine protected area. **Scientific reports**, v. 6, n. 1, p. 34230, 2016. https://doi.org/10.1038/srep34230

CALDWELL, M. C.; CALDWELL, D. K. Statistical evidence for individual signature whistles in Pacific whitesided dolphins, *Lagenorhynchus obliquidens*. **Cetology,** v. 3, p. 1–9, 1971. https://doi.org/10.1016/B978-0-12-373553-9.00235-2.

CLARK, Christopher W. Acoustic behavior of mysticete whales. In: **Sensory abilities of cetaceans: Laboratory and field evidence**. Boston, MA: Springer US, 1990. p. 571–583. https://doi.org/10.1007/978-1-4899-0858-2_40

CLARK, Christopher W. Acoustic communication and behavior of the southern right whale. 1982.

CODARIN, Antonio et al. Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). **Marine pollution bulletin**, v. 58, n. 12, p. 1880–1887, 2009. https://doi.org/10.1016/j.marpolbul.2009.07.011

DARLING, James D.; BÉRUBÉ, Martine. Interactions of singing humpback whales with other males. **Marine Mammal Science**, v. 17, n. 3, p. 570–584, 2001. https://doi.org/10.1111/j.1748-7692.2001.tb01005.x

DARLING, James D.; SOUSA-LIMA, Renata S. Songs indicate interaction between humpback whale (*Megaptera novaeangliae*) populations in the western and eastern South Atlantic Ocean. **Marine Mammal Science**, v. 21, n 3, p. 557–566, 2006. https://doi.org/10.1111/j.1748-7692.2005.tb01249.x

DARRAS, Kevin F. A. et al. Worldwide Soundscapes: a synthesis of passive acoustic monitoring across realms. **Global Ecology and Biogeography**, v. 34, n. 5, p. e70021, 2025. https://doi.org/10.1111/geb.70021

DUNLOP, Rebecca A.; CATO, Douglas H.; NOAD, Michael J. Your attention please: increasing ambient noise levels elicits a change in communication behaviour in humpback whales (*Megaptera novaeangliae*). **Proceedings of the Royal Society B: Biological Sciences**, v. 277, n. 1693, p. 2521–2529, 2010. https://doi.org/10.1098/rspb.2009.2319

DUNLOP, Rebecca; FRERE, Celine. Post-whaling shift in mating tactics in male humpback whales. **Communications Biology**, v. 6, n. 1, p. 162, 2023. https://doi.org/10.1038/s42003-023-04509-7

ELEMANS, Coen P. H. et al. Evolutionary novelties underlie sound production in baleen whales. **Nature**, v. 627, n. 8002, p. 123–129, 2024. https://doi.org/10.1038/s41586-024-07080-1

FORDYCE, E.; PERRIN, W. F. **World Cetacea Database**. 2025. Disponível em: https://www.marinespecies.org/cetacea. Acesso em: 29 jun. 2025.

FRIPP, Deborah. Bubblestream whistles are not representative of a bottlenose dolphin's vocal repertoire. **Marine Mammal Science**, v. 21, n. 1, p. 29–44, 2005. https://doi.org/10.1111/j.1748-7692.2005.tb01206.x

GOMES, Lidiane et al. Influence of anthropogenic sounds on insect, anuran and bird acoustic signals: A meta-analysis. **Frontiers in Ecology and Evolution**, v. 10, p. 827440, 2022. https://doi.org/10.3389/fevo.2022.827440

HAWKINS, A. D.; MYRBERG, A. A. Hearing and sound communication under water. Bioacoustics, a comparative approach. **Academic Press, London**, p. 347–405, 1983.

HEINICKE, Stefanie et al. Assessing the performance of a semi-automated acoustic monitoring system for primates. **Methods in Ecology and Evolution**, v. 6, n. 7, p. 753–763, 2015. https://doi.org/10.1111/2041-210X.12384

HELBLE, Tyler A. et al. Fin whale song patterns shift over time in the central North Pacific. **Frontiers in Marine Science**, v. 7, p. 587110, 2020. https://doi.org/10.3389/fmars.2020.587110

HERMAN, L. M.; TAVOLGA, W. N. **The communication systems of cetaceans.** In: HERMAN, L. M. (Ed.). Cetacean Behavior: Mechanisms and Functions. New York: Wiley Interscience, 1980. p. 149–209.

HERMAN, Louis M. The multiple functions of male song within the humpback whale (*Megaptera novaeangliae*) mating system: review, evaluation, and synthesis. **Biological Reviews**, v. 92, n. 3, p. 1795–1818, 2017. https://doi.org/doi:10.1111/brv.12309

HERZING, D. L. Acoustics and social behaviour of wild dolphins: implications for a sound society. In: AU, W. L.; POPPER, A. N.; FAY, R. R. (eds.). **Hearing by whales and dolphins**. New York: Springer, 2000. p. 225–272.

HILDEBRAND, John A. et al. Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. **Scientific reports**, v. 5, n. 1, p. 16343, 2015. https://doi.org/10.1038/srep16343

JOHNSTON, D. W. et al. Temporal patterns in the acoustic signals of beaked whales at Cross Seamount. **Biology Letters**, v. 4, n. 2, p. 208–211, 2008. https://doi.org/10.1098/rsbl.2007.0614

KALAN, Ammie K. et al. Towards the automated detection and occupancy estimation of primates using passive acoustic monitoring. **Ecological Indicators**, v. 54, p. 217–a226, 2015. https://doi.org/10.1016/j.ecolind.2015.02.023

KÜGLER, Anke et al. Male humpback whale chorusing in Hawai ‘i and its relationship with whale abundance and density. **Frontiers in Marine Science**, v. 8, p. 735664, 2021.https://doi.org/10.3389/fmars.2021.735664.

LADICH, Friedrich. Effects of noise on sound detection and acoustic communication in fishes. In: **Animal communication and noise**. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013. p. 65–90. http://doi.org/10.1007/978-3-642-41494-7

LAMMERS, Marc O. et al. An ecological acoustic recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. **The Journal of the Acoustical Society of America**, v. 123, n. 3, p. 1720–1728, 2008. https://doi.org/10.1121/1.2836780

LI, Kun et al. Decadal assessment of sperm whale site-specific abundance trends in the northern Gulf of Mexico using passive acoustic data. **Journal of Marine Science and Engineering**, v. 9, n. 5, p. 454, 2021. https://doi.org/10.3390/jmse9050454

LODI, Liliane; BOROBIA, Monica; FOLKENS, Pieter A. **Baleias, botos e golfinhos do Brasil: guia de identificação**. Technical books editora, 2013.

MADSEN, Peter T.; SIEBERT, Ursula; ELEMANS, Coen P. H. Toothed whales use distinct vocal registers for echolocation and communication. **Science**, v. 379, n. 6635, p. 928–933, 2023. https://doi.org/10.1126/science.adc9570

MARQUES, Tiago A. et al. Estimating animal population density using passive acoustics. **Biological reviews**, v. 88, n. 2, p. 287–309, 2013. https://doi.org/10.1111/brv.12001

MARQUES, Tiago A. et al. Estimating cetacean population density using fixed passive acoustic sensors: An example with Blainville’s beaked whales. **The Journal of the Acoustical Society of America**, v. 125, n. 4, p. 1982–1994, 2009. https://doi.org/10.1121/1.3089590

MARTIN, Stephen W. et al. Estimating minke whale (*Balaenoptera acutorostrata*) boing sound density using passive acoustic sensors. **Marine Mammal Science**, v. 29, n. 1, p. 142–158, 2013. https://doi.org/10.1111/j.1748-7692.2011.00561.x

MCCAULEY, Robert D. et al. Pygmy blue and Antarctic blue whale presence, distribution and population parameters in southern Australia based on passive acoustics. **Deep Sea Research Part II: Topical Studies in Oceanography**, v. 157, p. 154–168, 2018. https://doi.org/10.1016/j.dsr2.2018.09.006

MCDONALD, Mark A.; HILDEBRAND, John A.; WEBB, Spahr C. Blue and fin whales observed on a seafloor array in the Northeast Pacific. **The Journal of the Acoustical Society of America**, v. 98, n. 2, p. 712–721, 1995. https://doi.org/10.1121/1.413565

MELLINGER, David K. et al. An overview of fixed passive acoustic observation methods for cetaceans. **Oceanography**, v. 20, n. 4, p. 36–45, 2007. https://doi.org/10.5670/oceanog.2007.03

MILLER, Brian S. et al. Validating the reliability of passive acoustic localisation: a novel method for encountering rare and remote Antarctic blue whales. **Endangered Species Research**, v. 26, n. 3, p. 257–269, 2015. https://doi.org/10.3354/esr00642

MOORE, Sue E. et al. Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: year-long records from Fram Strait and the Chukchi Plateau. **Polar Biology**, v. 35, p. 475–480, 2012. https://doi.org/10.1007/s00300-011-1086-y

MORALES, Gabriel et al. Method for passive acoustic monitoring of bird communities using UMAP and a deep neural network. **Ecological Informatics**, v. 72, p. 101909, 2022. https://doi.org/10.1016/j.ecoinf.2022.101909

NOAD, Michael J.; DUNLOP, Rebecca A.; MACK, Amelia K. Changes in humpback whale singing behavior with abundance: implications for the development of acoustic surveys of cetaceans. **The Journal of the Acoustical Society of America**, v. 142, n. 3, p. 1611–1618, 2017. https://doi.org/10.1121/1.5001502

NORRIS, Kenneth S. et al. **The Hawaiian spinner dolphin**. Univ of California Press, 1994.

OBRIST, Martin K. et al. Bioacoustics approaches in biodiversity inventories. **Abc Taxa**, v. 8, n. 2010, p. 68–99, 2010.

OSWALD, Julie N.; AU, Whitlow WL; DUENNEBIER, Fred. Minke whale (*Balaenoptera acutorostrata*) boings detected at the Station ALOHA Cabled Observatory. **The Journal of the Acoustical Society of America**, v. 129, n. 5, p. 3353–3360, 2011. https://doi.org/10.1121/1.3575555

OWEN, Kylie; SKÖLD, Martin; CARLSTRÖM, Julia. An increase in detection rates of the critically endangered Baltic Proper harbor porpoise in Swedish waters in recent years. **Conservation Science and Practice**, v. 3, n. 8, p. e468, 2021. https://doi.org/10.1111/csp2.468

PACHECO, Aldo S. et al. Aerial behavior of humpback whales *Megaptera novaeangliae* at the southern limit of the southeast Pacific breeding area. **Revista de biología marina y oceanografía**, v. 48, n. 1, p. 185–191, 2013.

PARKS, Susan E.; CLARK, Christopher W.; TYACK, Peter L. Short-and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. **The Journal of the Acoustical Society of America**, v. 122, n. 6, p. 3725-3731, 2007. https://doi.org/10.1121/1.2799904

PAYNE, Roger S.; MCVAY, Scott. Songs of Humpback Whales: Humpbacks emit sounds in long, predictable patterns ranging over frequencies audible to humans. **Science**, v. 173, n. 3997, p. 585–597, 1971. https://doi.org/10.1126/science.173.3997.585

PERRIN, William F.; GILPATRICK JR, James W. Spinner dolphin *Stenella longirostris* (Gray, 1828). **Handbook of marine mammals**, v. 5, p. 99–128, 1994.

PIERETTI, N. et al. Marine soundscape as an additional biodiversity monitoring tool: a case study from the Adriatic Sea (Mediterranean Sea). **Ecological Indicators**, v. 83, p. 13–20, 2017.https://doi.org/10.1016/j.ecolind.2017.07.011

PIJANOWSKI, Bryan C. et al. What is soundscape ecology? An introduction and overview of an emerging new science**. Landscape Ecology**, v. 26, n. 9, p. 1213–1232, nov. 2011a. https://doi.org/10.1007/s10980-011-9600-8

PIJANOWSKI, Bryan C. et al. Soundscape ecology: the science of sound in the landscape. **BioScience**, v. 61, n. 3, p. 203–216, 2011b. https://doi.org/10.1525/bio.2011.61.3.6

PILKINGTON, James F. et al. Patterns of winter occurrence of three sympatric killer whale populations off eastern Vancouver Island, Canada, based on passive acoustic monitoring. **Frontiers in Marine Science**, v. 10, p. 1204908, 2023. https://doi.org/10.3389/fmars.2023.1204908

PRYOR, K. Non-acoustic communicative behavior of the great whales: Origins, comparisons, and implications for management. **Reports of the International Whaling Commission**, v. 8, p. 89–96, 1986.

RADFORD, Craig A. et al. Temporal patterns in ambient noise of biological origin from a shallow water temperate reef. **Oecologia,** v. 156, p. 921–929, 2008. https://doi.org/10.1007/s00442-008-1041-y

RAYMENT, William et al. Listening for a needle in a haystack: passive acoustic detection of dolphins at very low densities. **Endangered Species Research**, v. 14, n. 2, p. 149–156, 2011. https://doi.org/10.3354/esr00356

RICE, Ally et al. Cetacean occurrence in the Gulf of Alaska from long-term passive acoustic monitoring. **Marine Biology**, v. 168, n. 5, p. 72, 2021. https://doi.org/10.1007/s00227-021-03884-1

RICHARDSON, W. John et al. **Marine mammals and noise**. Academic press, 2013. https://doi.org/10.1016/B978-0-08-057303-8.50006-9

ROSENTHAL, Gil G.; RYAN, Michael J. Visual and acoustic communication in non-human animals: a comparison. **Journal of biosciences**, v. 25, p. 285–290, 2000. https://doi.org/10.1007/BF02703937

SÁNCHEZ-GENDRIZ, Ignacio; PADOVESE, Linilson R. Temporal and spectral patterns of fish choruses in two protected areas in southern Atlantic. **Ecological Informatics**, v. 38, p. 31–38, 2017a. https://doi.org/10.1016/j.ecoinf.2017.01.003

SÁNCHEZ-GENDRIZ, Ignacio; PADOVESE, Linilson R. A methodology for analyzing biological choruses from long-term passive acoustic monitoring in natural areas. **Ecological Informatics**, v. 41, p. 1–10, 2017b. https://doi.org/10.1016/j.ecoinf.2017.07.001

SHARPE, F. A. et al. Killing me softly: Feeding calls of the Alaskan humpback whale. In: **Abstracts of the World Marine Mammal Science Conference**. 1998. p. 20–24.

SLABBEKOORN, Hans et al. A noisy spring: the impact of globally rising underwater sound levels on fish. **Trends in ecology & evolution**, v. 25, n. 7, p. 419–427, 2010. http://dx.doi.org/10.1016/j

SOUSA-LIMA, Renata S. et al. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. **Aquatic Mammals**, v. 39, n. 1, p. 23–53, 2013. https://doi.org/10.1578/AM.39.1.2013.23

SOUSA-LIMA, Renata S.; CLARK, Christopher W. Modeling the effect of boat traffic on the fluctuation of humpback whale singing activity in the Abrolhos National Marine Park, Brazil. **Canadian Acoustics**, v. 36, n. 1, p. 174–181, 2008.

STANISTREET, Joy E. et al. Spatial and seasonal patterns in acoustic detections of sperm whales *Physeter macrocephalus* along the continental slope in the western North Atlantic Ocean. **Endangered Species Research**, v. 35, p. 1–13, 2018.https://doi.org/10.3354/esr00867

SUGAI, Larissa S. M. et al. Terrestrial passive acoustic monitoring: review and perspectives. **BioScience**, v. 69, n. 1, p. 15–25, 2019. https://doi.org/10.1093/biosci/biy147

TAVOLGA, William N. Sound production and underwater communication in fishes. **Animal Sounds and Communication**, v. 62, p. 93–136, 1960.

TRUAX, Barry. **Handbook for acoustic ecology**. Cambridge Street Publishing, 1999.

VARGA, Leah M.; WIGGINS, Sean M.; HILDEBRAND, John A. Behavior of singing fin whales *Balaenoptera physalus* tracked acoustically offshore of Southern California. **Endangered Species Research**, v. 35, p. 113–124, 2018. https://doi.org/10.3354/esr00881

WATERS, Susan; WHITEHEAD, Hal. Aerial behaviour in sperm whales. **Canadian Journal of Zoology**, v. 68, n. 10, p. 2076–2082, 1990. https://doi.org/10.1139/z90-289

WELLER, David W. et al. Observations of an interaction between sperm whales and short-finned pilot whales in the Gulf of Mexico. **Marine Mammal Science**, v. 12, n. 4, p. 588–594, 1996. https://doi.org/10.1111/j.1748-7692.1996.tb00071.x

WHITEHEAD, H. Humpback whale breaching. **Investigations on cetacea**, v. 17, p. 117–155, 1985.

WILKINS, Matthew R.; SEDDON, Nathalie; SAFRAN, Rebecca J. Evolutionary divergence in acoustic signals: causes and consequences. **Trends in ecology & evolution**, v. 28, n. 3, p. 156–166, 2013. https://doi.org/10.1016/j.tree.2012.10.002

WINN, H. E.; WINN, L. K. The song of the humpback whale *Megaptera novaeangliae* in the West Indies. **Marine Biology**, v. 47, n. 2, p. 97–114, 1978. https://doi.org/10.1007/Bf00395631

WÜRSIG, B. et al. Feeding, aerial and play behaviour of the bowhead whale, *Balaena mysticetus*, summering in the Beaufort Sea. **Aquatic Mammals**, v. 15, n. 1, p. 27–37, 1989.

YACK, Tina M. et al. Passive acoustic monitoring using a towed hydrophone array results in identification of a previously unknown beaked whale habitat. **The Journal of the Acoustical Society of America**, v. 134, n. 3, p. 2589-2595, 2013. https://doi.org/10.1121/1.4816585

ZIMMER, Walter M. X. **Passive acoustic monitoring of cetaceans**. Cambridge University Press, 2011. https://doi.org/10.1017/CBO9780511977107

CAPÍTULO I:

LISTENING PORPOISES, DOLPHINS AND WHALES AROUND THE WORLD:

WHAT DOES PASSIVE ACOUSTIC MONITORING HAVE TO TELL US?

** Article to be submitted to Marine Mammal Science*

Listening porpoises, dolphins and whales around the world: what does passive acoustic monitoring have to tell us?

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Abstract

Passive acoustic monitoring (PAM) is an effective approach for studying cetaceans, especially in areas where visual methods are limited. This study compiles information on the use PAM based exclusively on fixed autonomous recorders, in the absence of complementary visual data, identifying the species targeted, the regions where this technology has been applied, and the types of biological information that can be solely derived from this method. A total of 138 studies published between 2007 and 2024 were analyzed. The majority were conducted in the Northern Hemisphere, but those in the Southern Hemisphere showed significant growth starting in 2014, contributing to the global increase in PAM-based research. The main hotspots included the Hawaiian Islands, coastal regions of the USA, Australia, and New Zealand. The suborder Mysticeti was the most studied (51.4%), with a focus on *Balaenoptera physalus*. Information on habitat use and temporal variation was most commonly reported for both mysticetes and Odontocetes, whereas population parameters were the least addressed. We observed that species representation was influenced by factors such as their global distribution, vocal characteristics, and the geographic distribution of acoustic research efforts. Despite advances in bioacoustics, regional gaps were observed, likely influenced by disparities in national GDP and investment in scientific research. In terms of biological data, passive acoustic monitoring proved to be an effective method, capable of generating valuable information for several species.

Keywords: fixed autonomous acoustic recorders, cetaceans, Mysticeti; Odontoceti, global distribution.

Introduction

Passive Acoustic Monitoring (PAM) consists of the non-invasive recording of environmental or wildlife sounds (Browning et al., 2017). The recorders can be automated and programmed to operate for predetermined periods, eliminating the need for constant researcher presence and thus avoiding interference with the natural behavior of organisms or adding acoustic energy to the environment (Browning et al., 2017; Sousa-Lima et al., 2013). In this method, different deployment strategies are possible, ranging from fixed recorders with single or multiple hydrophones, to towed or drifting systems, or even devices attached to individual animals (Van Parijs et al., 2009). Each of these approaches can influence the spatial scale and coverage of acoustically active marine animals (Van Parijs et al., 2009). To ensure the effectiveness of this method, the recorder used must be suited to the study environment and configured with a sampling rate that encompasses the frequencies of interest (Browning et al., 2017).

The physical properties of the environment influence sound propagation and, consequently, acoustic monitoring (Hawkins & Myrberg, 1983; Richardson et al., 1995). The higher density of water compared to air allows sound to travel greater distances in the aquatic environment, making it particularly advantageous for the application of this type of monitoring (Hawkins & Myrberg, 1983; Richardson et al., 1995). Additionally, the choice of the target species is crucial, as species with well known vocalizations are easier to identify, facilitate identification during acoustic analyses (*e.g.,* Andreas et al., 2022; Cholewiak et al., 2013).

PAM has been widely used in aquatic environments to characterize different components of the soundscape, including biophony, geophony, and anthropophony, which correspond, respectively, to sounds of biological, hydro-geo-meteorological, and anthropogenic origins (Krause, 2008; Pijanowski et al., 2011). In the context of biophony, cetaceans are acoustic specialists known for producing frequent and varied sounds (Zimmer, 2011). For this reason, they are commonly detected in studies characterizing the marine soundscape (*e.g.*, Bittencourt et al., 2016; Halliday et al., 2020; Haver et al., 2020). In some cases, their vocalizations dominate the biological component of the acoustic soundscape (*e.g.,* Bittencourt et al., 2016).

Cetaceans are aquatic mammals currently classified within the order Cetartiodactyla, although their exact taxonomic rank (*e.g.,* suborder or infraorder) remains under debate (Fordyce & Perrin, 2025). Traditionally, cetaceans have been divided into two main groups: Odontocetes, which include toothed whales, porpoises, and dolphins; and mysticetes, which encompass baleen whales. Both groups use sound production for communication, foraging, and navigation, but they differ in the way they produce sounds and in the acoustic characteristics of their vocalizations (Richardson et al., 2013; Zimmer, 2011). Odontocetes emit sounds across a broad frequency range, mostly from 5 kHz to over 135 kHz, whereas mysticetes produce vocalizations concentrated at lower frequencies, between 14 Hz and approximately 5 kHz (Au, 2000).

The vocal diversity of cetaceans is not limited to physical differences in sound signals between the groups, but also includes intra and interspecific, temporal, and geographic variations (Bittle & Duncan, 2013; McGaughey et al., 2010; Usman et al., 2020). Additionally, there are different levels of complexity in vocalizations, ranging from simple emissions, such as call, those documented in fin whales (*Balaenoptera physalus*) (*e.g.,* Clark, 1990) and beluga whales (*Delphinapterus leucas*) (*e.g.,* Sjare & Smith, 1986), to highly structured and stereotyped vocal sequences, such as the song of the humpback whale (*Megaptera novaeangliae*) (*e.g.,* Payne & McVay, 1971) and the pulsed calls that make up the dialectal repertoires of killer whales (*Orcinus orca*) (*e.g.,* Miller, 2002). These acoustic signals provide important clues for identifying species, populations, groups, and even individuals (*e.g.,* Caldwell & Caldwell, 1971; Guidi et al., 2021; Kremers et al., 2012; Lin & Chou, 2013; Yurk et al., 2002).

With automation and continuous data storage, PAM has emerged a valuable tool for large-scale spatiotemporal studies, while also offering relatively low costs (*e.g.*, Mellinger et al., 2007; Pijanowski et al., 2011; Sousa-Lima et al., 2013). Compared to visual monitoring, PAM is less affected by adverse weather conditions that reduce visibility, such as rain, fog, and darkness (*e.g.*, Dalpaz et al., 2021; Mellinger et al., 2007; Zimmer, 2011). This advantage allows data collection at night and the detection of animals whenever they are acoustically active, whereas visual monitoring is restricted to the moments when individuals surface (*e.g.*, Dalpaz et al., 2021; Mellinger et al., 2007; Zimmer, 2011). Given these limitations, many studies have increasingly adopted acoustic approaches to study cetaceans (*e.g.*, Aulich et al., 2019; Guidi et al., 2021; Van Parijs et al., 2009). As a result of this growing demand, recording equipment and analytical methods have been continuously improving, leading to an increase in both the quantity and quality of generated data (Kowarski & Moors-Murphy, 2021). However, it is important to note that acoustic methods also have limitations. Among these, detection efficiency depends on the signal-to-noise ratio, which can be influenced by equipment characteristics, hydrophone motion, and environmental factors such as wind, rain, and sea state (Verfuss et al., 2018). Moreover, the wide variability in vocalization types and vocal behaviors across species requires that acoustic approaches be carefully tailored to the target species or group (Dalpaz et al., 2021).

In this context, studies that have combined visual and acoustic monitoring reported substantial improvements in individual detection rates, highlighting the complementarity between these methods and recommending their joint application whenever possible (*e.g.*, Dalpaz et al., 2021; Mellinger et al., 2007; Oswald et al., 2003). However, many areas used by cetaceans are remote and difficult to access, especially during certain times of the year, such as in polar regions (*e.g.*, Moore et al., 2012). In such cases, PAM represents a viable solution to reduce seasonal and regional biases in obtaining cetacean data, particularly when visual surveys are challenging. The literature demonstrates that PAM has been widely used for a variety of purposes, including species identification (*e.g.*, Baumgartner et al., 2008), characterization of acoustic parameters and vocalization patterns (*e.g.*, Helble et al., 2020), assessment of occurrence and habitat use (*e.g.*, Ahonen et al., 2021; Stanistreet et al., 2018), and investigation of the impacts of anthropogenic noise on animal behavior (*e.g.*, Sousa-Lima & Clark, 2008, 2009).

To better understand which types of biological information can be obtained exclusively from acoustic data, the present study focuses on the use of fixed autonomous acoustic recorders, given that visual observations are generally not directly linked to the recorded sounds (Mellinger et al., 2007). This feature facilitates evaluating information that can be inferred solely from acoustic recordings. Specifically, we aim to determine which cetacean species have been surveyed using PAM, in which regions of the world, and what types of biological information can be extracted exclusively through this method, without relying on complementary visual approaches—whether fixed, vessel-based, or aerial.

Methods

Search Strategy

We conducted a literature search up to July 3rd, 2024, including peer-reviewed articles that applied PAM in cetacean research, with no restrictions on the initial publication data. The search encompassed all available articles, from the earliest record identified to the most recent publication on the specified date. We used the Scopus and Web of Science databases, applying the following search strategy for titles or keywords: *Passive AND acoustic AND (monito* OR* *record* OR sampl* OR automat* OR sound) AND (cetacean* OR whale* OR dolphin* OR odontocet* OR mysticet**). The initial search presented 520 studies. After removing duplicates, 344 studies were screened based on predefined criteria.

Inclusion Criteria

We included studies that met the following criteria: *(i)* Data were collected through PAM using fixed autonomous acoustic recorders; *(ii)* the study provided information at any taxonomic or ecological level within cetaceans; *(iii)* it included at least minimal information for georeferencing the acoustically monitored area; *(iv)* the response variable was directly related to the target group.

Exclusion Criteria

Of the 344 articles identified in our search, 206 were excluded based on the following criteria: *(i)* studies that used visual monitoring, whether from a land-based observation station, vessel (including autonomous towed systems), or aircraft; *(ii)* studies that used acoustic data obtained from databases without clear information about the origin or method of sound collection; *(iii)* studies in which the response variable was related to the recording equipment or analysis method rather than the target group, such as calibration or evaluation of recorder sensitivity; *(iv)* experimental studies involving playback or simulations of cetacean sounds; *(v)* review articles, that may have included data based on collection methods that did not meet the inclusion criteria; *(vi)* studies that addressed marine mammals as a whole, without a specific focus on cetaceans.

Analyzed Factors

A total of 138 studies was analyzed. The chronological sequence of publications was subdivided between the Northern and Southern Hemispheres to assess how article production varied across regions over time. Extracted information included the taxonomic classification of the cetacean group evaluated, either Mysticeti or Odontoceti, down to species level identification when available; georeferencing information of the acoustic recorders, and biological information related to the most detailed taxonomic level investigated.

Georeferenced recorder locations were used to generate a kernel density map in QGIS 3.28.11 (QGIS Development Team, 2023) providing an overview of global regions where cetaceans are monitored using fixed autonomous recording units. The map was created in the WGS 84 reference system, using a 500 km radius. There is an inherent bias in the map's accuracy due to the variability and completeness of the geographic information provided in the reviewed studies. Some studies included precise geographic coordinates for each recorder, allowing accurate localization. Others, however, only indicated the location of the hydrophone array, represented by a single point. Additionally, some studies did not provide detailed coordinates, only study area maps indicating where recorders were deployed. Based on these visual references, we estimated the recorder's location using Google Earth, resulting in an approximate rather than exact location. Despite this accuracy bias, the map provides a general overview of monitored areas, offering broad insight into the regions where fixed autonomous acoustic recorders are being applied for cetacean studies.

We assessed the occurrence of Mysticete and Odontocete species separately through frequency charts, considering species-level identification. Percentages were calculated based on the total number of studies (n = 138), without separating the data by group. This allowed us to identify the most frequently studied species overall. Additionally, we examined which oceans were most frequently studied to determine whether the predominance of certain species resulted from sampling bias due to a higher concentration of research in specific regions or reflected a global trend.

Biological information on cetaceans was categorized into nine categories: *Acoustic parameter*: Included studies that analyzed the acoustic content of vocalizations, such as describing and characterizing parameters or acoustic repertoires; *Anthropogenic impact*: Included studies that used acoustic recordings to assess the effects of anthropogenic activities on cetacean behavior and habitat use; *Behavior*: Included studies that used acoustic recordings to assess cetacean behavior, such as diving, swimming, foraging, migration, and other activities. Behavioral responses to anthropogenic activities were also included in this category; *Classification*: Included studies that achieved species-level identification through the acoustic content of vocalizations, regardless of the method used; *Diel occurrence*: Included studies that evaluated diel vocal patterns in cetaceans (*e.g.*, over a 24-hour period or between light and dark phases); *Habitat use*: Included studies that obtained information on how cetacean species used the study area, involving data on detection, presence, occurrence, distribution, and movement, as well as their association with the area's physical and ecological characteristics; *Population parameter*: Included studies that used acoustic emissions produced by cetaceans to estimate or infer population abundance and/or density; *Spatial variation*: Included studies that compared two or more areas concerning any ecological and behavioral aspects of the animals, as well as differences in their acoustic repertoire; *Temporal variation*: Included studies that used acoustic recordings to assess seasonal and/or interannual patterns in cetacean acoustic emissions (*e.g.*, occurrence, detection, vocal activity).

To evaluate how frequently each biological information category appeared in studies on mysticetes and odontocetes, we calculated percentages separately for each group. In cases where a study included both groups, it was counted once in each corresponding total (*i.e.*, added to both Mysticete and Odontocete totals).

It is important to note that a single study could be assigned to more than one category, as the types of biological information extracted are often interrelated. For instance, studies assessing habitat use frequently also addressed temporal variation. To explore potential co-occurrence patterns among categories, we applied a correlation matrix based on binary variables (presence = 1; absence = 0), which allowed us to identify how often these categories appeared together in the same study.

Results

The 138 studies identified as eligible for this review span the period from 2007 to 2024. Until 2011, the number of publications ranged from 0 to 5 per year, totaling eight studies (Figure 1). Despite fluctuations over the years, an increase in publication output was observed starting in 2012 in the Northern Hemisphere and 2014 in the Southern Hemisphere (Figure 1). In both hemispheres, the number of publications rose from 2019, peaking in 2021, followed by a downward trend (Figure 1). Notably, 84.4% of the articles were published in the last 10 years, with 54% of this total published from 2019 onward.

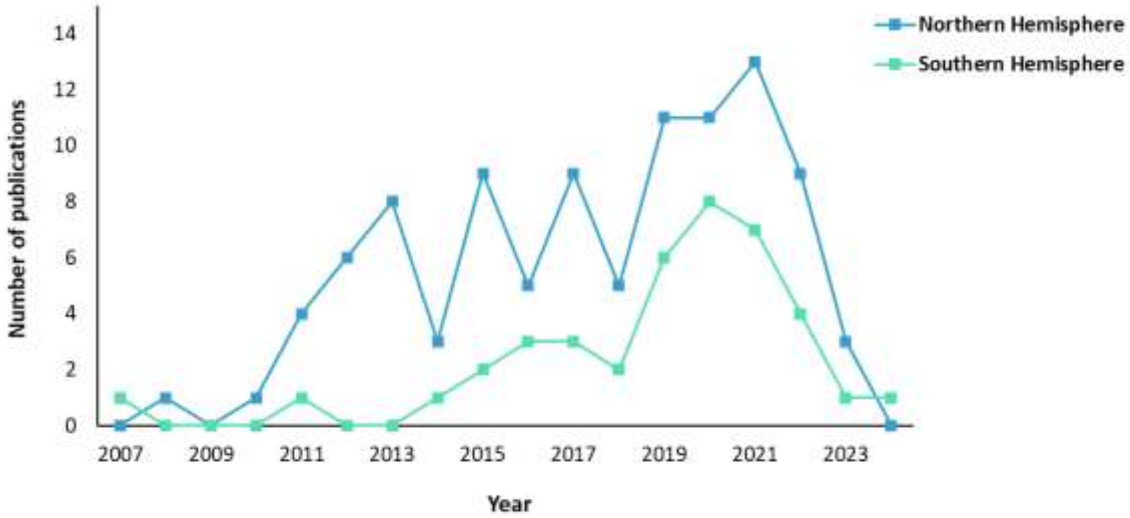

FIGURE 1. Number of eligible studies published per year that assessed cetaceans' issues using exclusively fixed autonomous acoustic recorders in the Northern Hemisphere (blue line) and Southern Hemisphere (green line). **Note:** Kowarski et al. (2023) was first published online in 2022 and officially assigned to a journal volume and issue in 2023. Therefore, the citation and reference use the year 2023. However, for the purpose of counting the number of annual publications, the year 2022 was considered, corresponding to the online publication date.

Global distribution and density of fixed autonomous acoustic recorders

The geographical areas monitored by fixed autonomous acoustic recorders were broad and diverse, covering all the world's oceans as well as inland seas, bays, gulfs, rivers, and lakes (Figure 2). The main hotspots for recorder deployment were identified in the Hawaiian Islands and along the coastal regions of the United States (Figure 2). Among the 14 studies conducted in Hawaii, eight were concentrated on the island of Kauai (see Table S1). In the United States, the coastal regions extend from the Southwest, in the Gulf of Mexico, to the Northeast, in the Gulf of Maine (Figure 2). Some of the most concentrated locations include Florida, Georgia, Virginia, New York Bight, and within the Gulf of Maine, Massachusetts Bay (Figure 2). On the West Coast, the key hotspots were found in the Northwest, in the state of Washington, and along the eastern shore of the Baja California Peninsula in the Gulf of California (Figure 2).

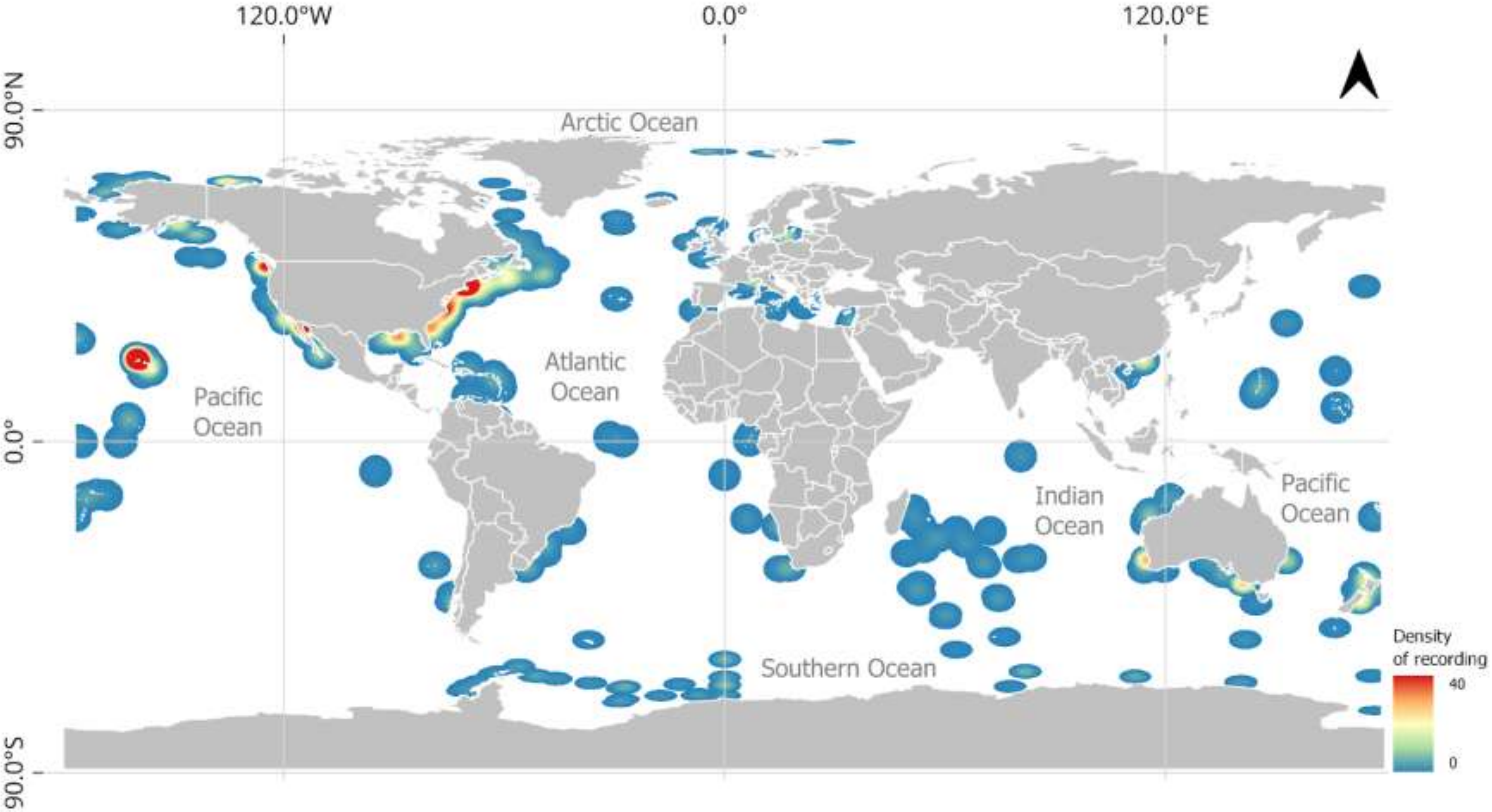
120.0°W
0.0°
120.0°E
90.0°N
0.0°
90.0°S
Arctic Ocean
Atlantic Ocean
Pacific Ocean
Pacific Ocean
Indian Ocean
Southern Ocean
Density of recording
40
0

FIGURE 2. Kernel density map showing areas of concentration of fixed autonomous acoustic recorders deployed for cetacean acoustic monitoring. The map scale is 1:140,000,000.

Fixed autonomous acoustic recorders were widely used to monitor island regions, such as New Zealand and Australia (Figure 2). These devices were used both on islands near the mainland – such as Hainan and Lantau, in the southern and southeastern coasts of China – and on more remote oceanic islands, like the Line Islands in the Pacific and South Georgia in the Atlantic (Figure 2). In addition to island areas, inland seas, bays, gulfs, rivers, and lakes were also surveyed, with studies conducted in the Mediterranean Sea, Massachusetts Bay, Gulf of Mexico, Pearl River, and Laguna San Ignacio (see table S1). Notably, this method was applied in polar regions, such as the Arctic and Southern Oceans, demonstrating its feasibility even in extreme climatic conditions (Figure 2).

Regarding ocean representativeness, the highest concentration of studies was found in the Northern Hemisphere, particularly in the Atlantic Ocean (n = 21 for mysticetes; n = 26 for odontocetes) and the Pacific Ocean (n = 18 for mysticetes; n = 28 for odontocetes) (Figure 3). In the Arctic Ocean, 6 studies with mysticetes and 3 with odontocetes were identified (Figure 3). In the Southern Hemisphere, the Pacific Ocean was the most representative for mysticetes (n = 14), while the Atlantic Ocean had the highest number of studies with odontocetes (n = 7) (Figure 3). No studies on odontocetes were identified in the North Indian Ocean, South Indian Ocean, or Southern Ocean (Figure 3).

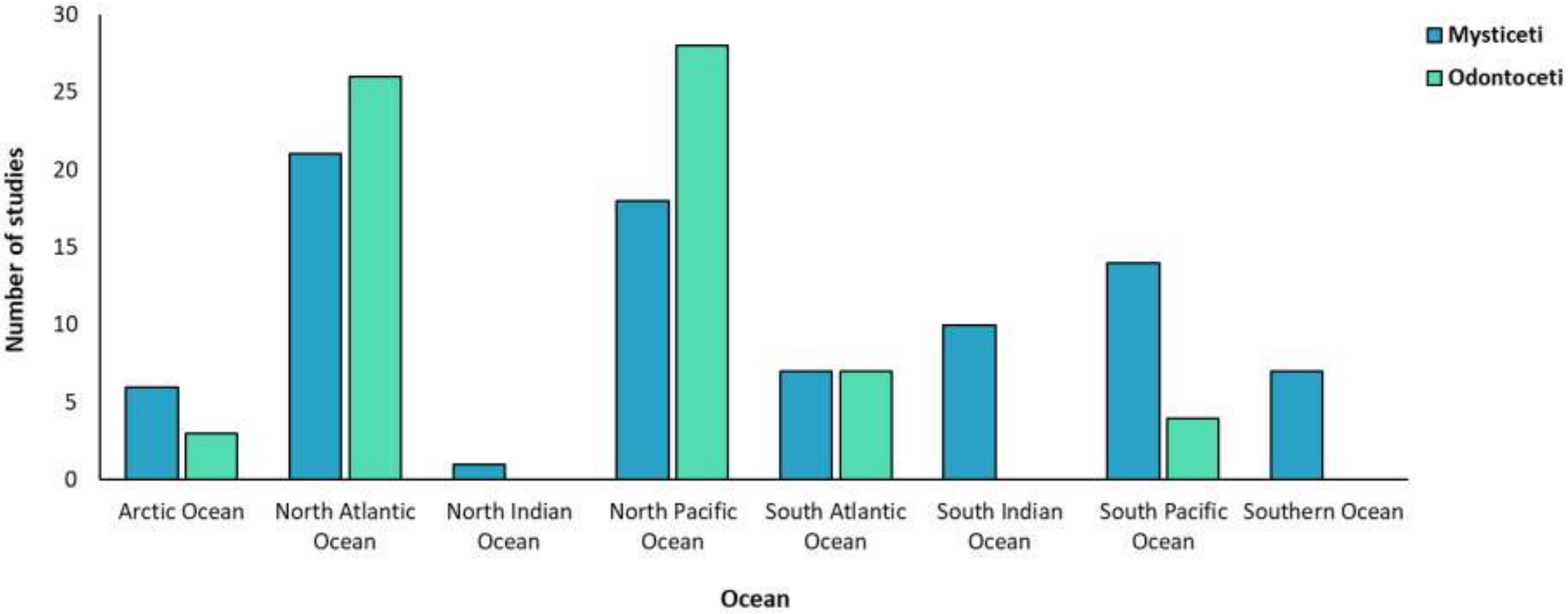

FIGURE 3. Number of studies published until July 2024, conducted using exclusively fixed autonomous acoustic recorders in each ocean considering the Mysticeti (blue bars) and Odontoceti (green bars) groups.

Representativeness of cetacean species in the studies

Mysticetes was the most studied, representing 51.4% (n = 71) of the total, while the odontocetes accounted for 45.7% (n = 63). Additionally, 2.9% (n = 4) of the studies analyzed both groups. Among the 15 Mysticete species currently recognized by the Taxonomy Committee (2024), only the pygmy right whale (*Caperea marginata*) was not recorded, as well as 5 subspecies (Table 1). Regarding odontocetes, of the 79 recognized species, 26 were recorded, along with 2 subspecies (Table 2).

TABLE 1. Mysticete species and subspecies monitored exclusively using fixed autonomous acoustic recorders worldwide.

MYSTICETI	
Scientific name	**Common name**
Balaena mysticetus	Bowhead whale
Balaenoptera acutorostrata	Minke whale
Balaenoptera bonaerensis	Antarctic minke whale
Balaenoptera borealis	Sei whale
Balaenoptera brydei	Brydes whale
Balaenoptera musculus	Blue whale
*Balaenoptera musculus brevicauda**	Pygmy blue whale
*Balaenoptera musculus chilensis**	Chilean blue whale
*Balaenoptera musculus intermedia**	Antarctic blue whale
*Balaenoptera musculus musculus**	Northeast pacific blue whale
Balaenoptera omurai	Omura’s whale
Balaenoptera physalus	Fin whale
*Balaenoptera physalus quoyi**	Southern fin whale

Balaenoptera ricei	Rice’s whale
Eschrichtius robustus	Grey whale
Eubalaena australis	Southern right whale
Eubalaena glacialis	North Atlantic right whale
Eubalaena japonica	North Pacific right whale
Megaptera novaeangliae	Humpback whale

**=subspecies*

TABLE 2. Odontocete species and subspecies monitored exclusively using fixed autonomous acoustic recorders worldwide.

ODONTOCETI	
Scientific name	**Common name**
Berardius bairdii	Baird’s beaked whale
*Cephalorhynchus hectori hectori**	Hector's dolphins
*Cephalorhynchus hectori maui**	Maui dolphin
Delphinapterus leucas	Beluga whale
Delphinus delphis	Common dolphin
Globicephala macrorhynchus	Short-finned pilot whale
Globicephala melas	Long-finned pilot whale
Grampus griseus	Risso’s dolphin
Hyperoodon ampullatus	Northern bottlenose whale
Kogia breviceps	Pygmy sperm whale
Kogia sima	Dwarf sperm whale
Lagenorhynchus obliquidens	Pacific white-sided dolphin
Mesoplodon densirostris	Blainville's beaked whale

Mesoplodon europaeus	Gervais's beaked whale
Mesoplodon stejnegeri	Stejneger beaked whale
Neophocaena asiaeorientalis	Yangtze finless porpoise
Orcinus orca	Killer Whale
Phocoena phocoena	Harbour porpoise
Phocoena sinus	Vaquita porpoise
Physeter macrocephalus	Sperm whale
Pontoporia blainvillei	Franciscana dolphin
Pseudorca crassidens	False killer whale
Sousa chinensis	Indo-Pacific humpback dolphin
Stenella attenuata	Pantropical spotted dolphin
Stenella longirostris	Spinner dolphin
Steno bredanensis	Rough-toothed dolphin
Tursiops truncatus	Bottlenose dolphin
Ziphius cavirostris	Cuvier’s beaked whale

**=subspecies*

Some species stood out in terms of the number of studies in which they were assessed. Among mysticetes, the fin whale was the most studied, appearing in 17.4% (n = 24) of the analyzed studies (Figure 4). Next, the humpback whale stood out, appearing in 10.9% (n = 15) of the studies, and the blue whale in 9.4% (n = 13) of the studies (Figure 4).

Among odontocetes, the most studied species was the sperm whale, mentioned in 13% (n = 18) of the studies (Figure 5). In second place was the killer whale, with 6.5% (n = 9), followed by Cuvier’s beaked whale, with 5.1% (n = 7) (Figure 5).

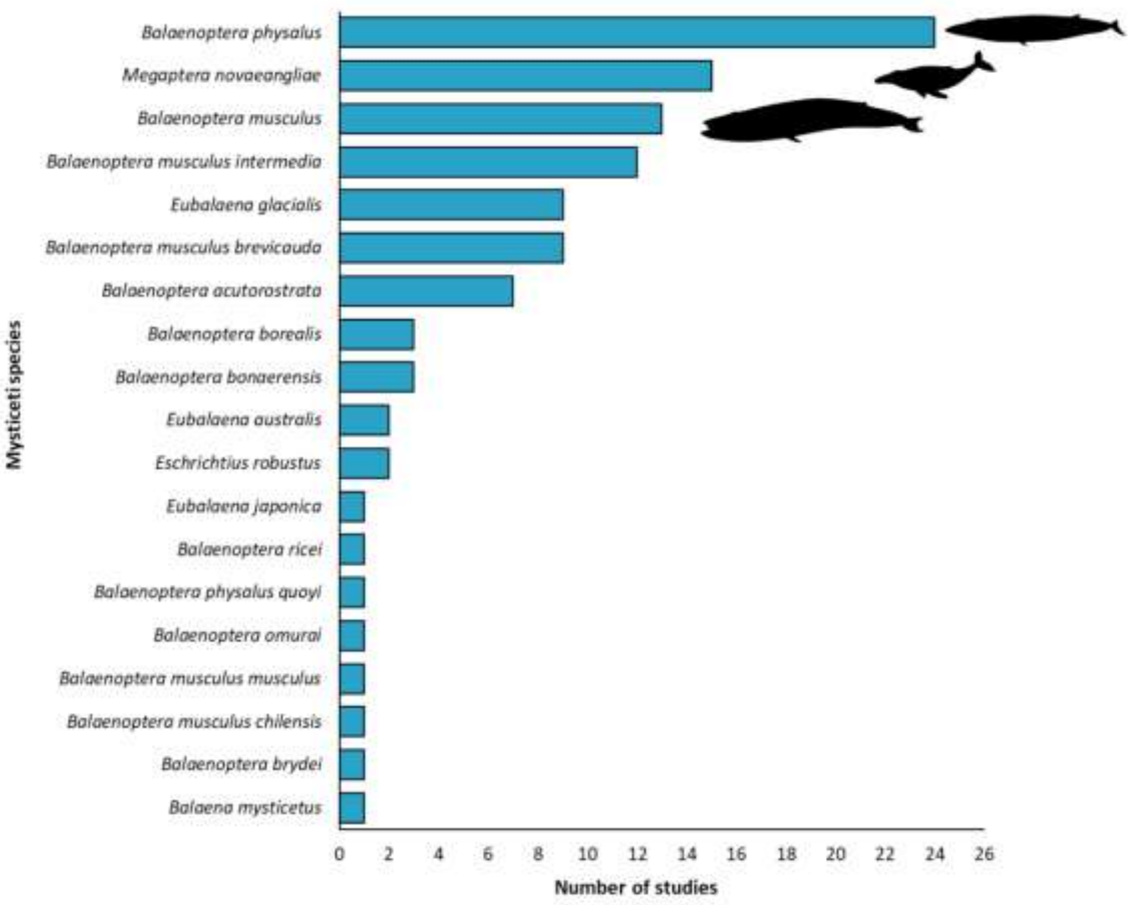

FIGURE 4. Frequency of occurrence of Mysticeti species in studies using exclusively fixed autonomous acoustic recorders.

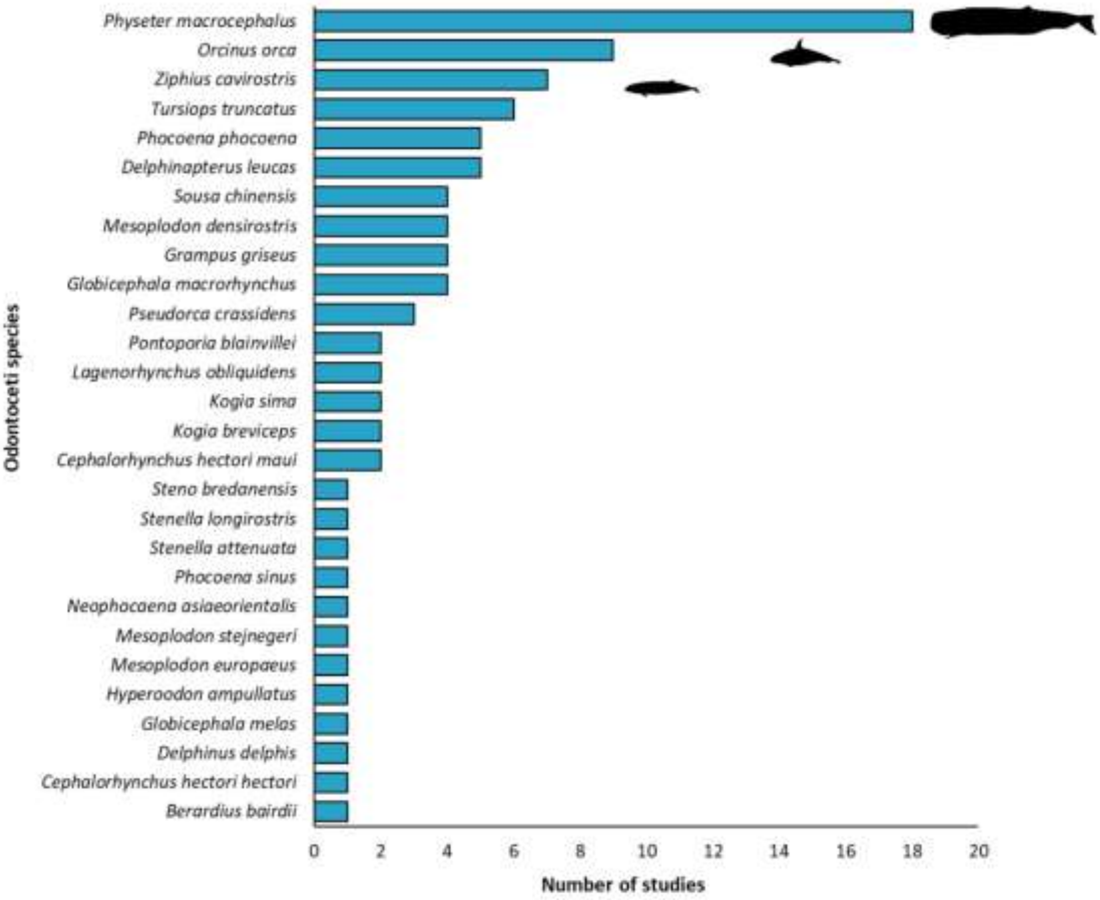

FIGURE 5. Frequency of occurrence of Odontoceti species in studies using exclusively fixed autonomous acoustic recorders.

Biological information

In evaluating the biological information, we observed that 93.5% of the studies classified cetaceans at the species level. Due to its high representativeness, we chose to remove this category from the occurrence frequency analysis. Among the eight categories analyzed, habitat use was the most representative in both groups, appearing in 80.3% of studies with mysticetes (n = 61) and 79.1% with odontocetes (n = 53) (Figure 6). Next, temporal variation stood out as the second most frequent category, present in 77.6% of studies with mysticetes (n = 59) and 70.1% of studies with odontocetes (n = 47) (Figure 6). The third position varied between the groups: for mysticetes, spatial variation was observed in 51.3% of the studies (n =

39), while for odontocetes, diel occurrence was recorded in 59.7% of the studies (n = 40) (Figure 6). Population parameter was the least representative category, present in only 5.3% of studies with mysticetes (n = 4) and 9.0% with odontocetes (n = 6) (Figure 6).

It is worth noting that most of the studies categorized under habitat use focused on the detection and occurrence of individuals within the study area, often incorporating a temporal perspective. Consequently, habitat use and temporal variation frequently co-occurred across studies. The results of the correlation matrix reveal a moderate positive correlation (r = 0.34) between habitat use and temporal variation, indicating that these aspects are commonly considered together (see figure S2).

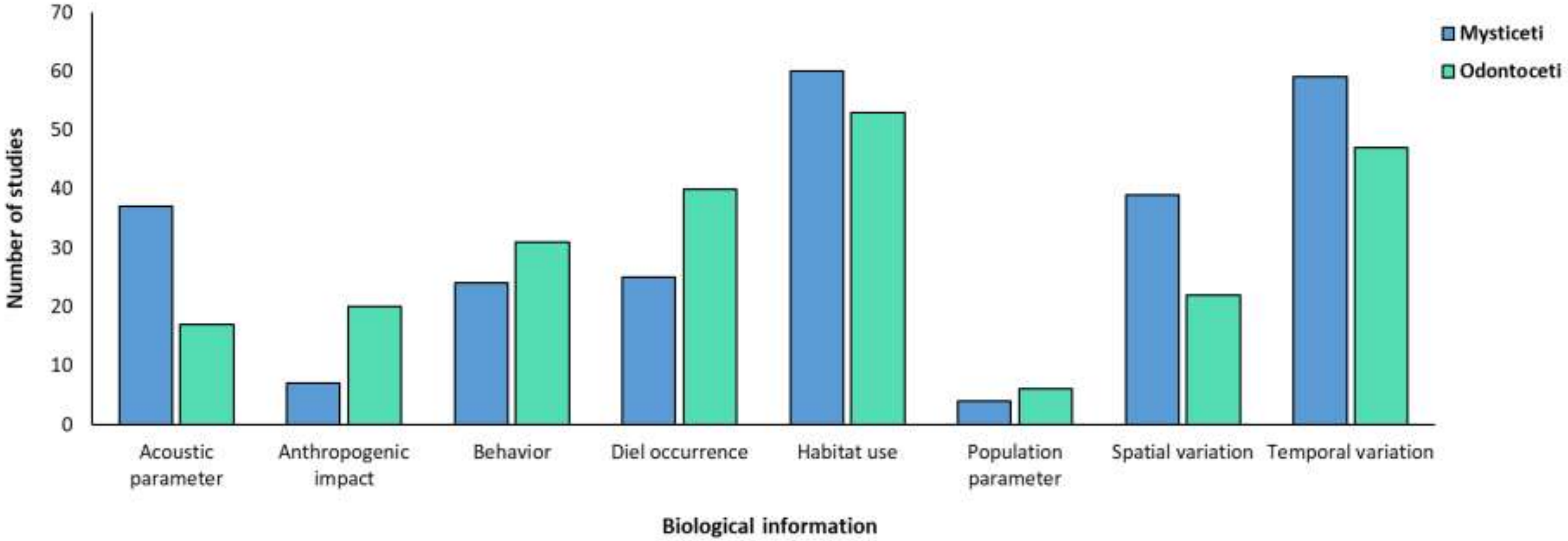

FIGURE 6. Number of studies using exclusively fixed autonomous acoustic recorders that included each category of biological information for the Mysticeti (blue bars) and Odontoceti (green bars) groups.

Discussion

The publications included in this review highlight the potential of PAM using fixed autonomous acoustic recorders to enhance our understanding of cetaceans, beginning with the earliest identified studies. Between 2007 and 2011 — a period marked by a low number of annual publications — the studies conducted provided valuable contributions for species conservation, including the characterization of acoustic content and vocal repertoire (*e.g.,* Širović et al., 2007; Stimpert et al., 2011), as well as the description of temporal patterns of acoustic activity (*e.g.,* Soldevilla et al., 2010). This information is particularly relevant for understanding the potential impacts of anthropogenic activities on cetacean behavior, as it serves as a reference point for assessing changes in known patterns, and consequently expected patterns (*e.g.,* La Manna et al., 2014; Munger et al., 2016). Furthermore, the analysis of these patterns supports the identification of seasonal trends in occurrence and habitat use, which is particularly important in hard-to-reach areas subject to seasonal biases due to winter climate conditions. In such contexts, conventional visual surveys from vessels may be unfeasible, rendering acoustic monitoring an essential tool (*e.g.,* Moore et al., 2012; Williams et al., 2014).

The Northern Hemisphere exhibited a higher number of studies compared to the Southern Hemisphere. However, a substantial increase in the number of publications since the past decade occurred in both hemispheres, possibly driven by technological advancements and the development of passive acoustic equipment, although this upward trend is also common in scientific publications in general (Bornmann & Mutz, 2015). In 2012, more than 40 fixed autonomous acoustic recording devices were reviewed by Sousa-Lima et al. (2013), who highlighted advances in the temporal operating capacity and frequency range coverage of these devices. Among the main factors cited were increased data storage capacity, longer battery life, and improvements in sampling rate. In addition to technological advancements, the study also emphasized the strengthening of cooperation between institutions in the collection of bioacoustics data for the study of marine mammals. Some examples are Cornell University and Peter Worcester's group at the Scripps Institution of Oceanography (SIO), located on the east and west coasts of the United States, respectively, coinciding with regions where we identified recorder deployments hotspots.

The decrease in the number of publications from 2021 onward may reflect natural fluctuations in scientific output or shifts in research and publication priorities influenced by external factors. During the COVID-19 pandemic, for instance, a surge in publications related to SARS-CoV-2 was accompanied by a temporary reallocation of scientific resources in various fields. Although this effect has been more clearly documented in medical research (Aviv-Reuven & Rosenfeld, 2021), its broader impact across disciplines, including ecology and bioacoustics, remains unclear.

Global distribution and density of fixed autonomous acoustic recorders used for cetacean monitoring

Recording hotspots were most clearly identified in North America and Oceania, but were also observed in Asia and Europe. This pattern reflects a well-documented trend in global scientific output, which is closely associated with countries´s level of socioeconomic development. More developed nations tend to invest more in scientific research and, consequently, produce a greater number of articles (*e.g.,* Di Marco et al., 2017; Gálvez et al., 2000). Another relevant factor is the representation of ecologically strategic areas for cetaceans, including feeding areas (*e.g.,* Durette-Morin et al., 2022; Howe & Lammers, 2021), breeding grounds (*e.g.,* Buchan et al., 2019; Thomisch et al., 2019), and migratory corridors (*e.g.,* Pearson et al., 2023; Warren et al., 2020), as well as marine protected areas such as the Stellwagen Bank National Marine Sanctuary in the Gulf of Maine (*e.g.,* Stanistreet et al., 2013; Stimpert et al., 2011).

The Chukchi Sea and the Weddell Sea — located in the Arctic and Southern Oceans, respectively — are examples of important feeding areas for Mysticeti identified in this review (*e.g.,* Filun et al., 2020; Garland et al., 2015). These regions are characterized by their high primary productivity and dense concentrations of euphausiids (krill) (Atkinson et al., 2008; 2009; Hill et al., 2006), a key food resource supporting numerous species, including baleen whales, as well as other marine mammals and fish (Hill et al., 2006). Additional regions sharing these ecological characteristics include the Bering Sea and South Georgia. The Bering Sea presents favorable conditions for PAM due its relatively flat seafloor and shallow depths (<200 m) (Munger et al., 2011; Wiggins et al., 2004). South Georgia, on the other hand, is considered a critical feeding area for one of the seven recognized humpback whale populations in the Southern Hemisphere (IWC, 1998; Zerbini et al., 2006).

In addition to humpback whales, other baleen whales are also known to undertake annual migrations between feeding and breeding grounds (Stone et al., 1990; Jonsgård, 1966). Hotspots identified at low latitudes along the western and eastern coasts of North and South America, as well as Africa and Australia, appear to effectively represent these reproductive nurseries (*e.g.,* Aulich et al., 2019; Burnham et al., 2018; Dombroski et al., 2016; Dréo et al., 2019; Salisbury et al., 2016; Thomisch et al., 2019). Understanding habitat use and behavior across different life stages is fundamental for species conservation, as it enables the identification of potential threats and the development of effective mitigation strategies. The more we understand these processes, the more informed and targeted conservation measures can be. Owing to its ability to cover vast areas and detect the presence of multiple cetacean species, PAM plays a crucial role in advancing knowledge about these organisms and their habitat use patterns.

Cetacean Species Representation in Studies

Most of the publications identified in this review assessed odontocetes and mysticetes separately. The low representation of studies addressing both groups simultaneously may be related to their distinct vocal characteristics, which consequently require different acoustic methodologies. Odontocetes produce mid- to high-frequency sounds, which propagate less effectively in the aquatic environment compared to the low-frequency sounds emitted by mysticetes (Richardson et al., 1995). As a result, although the same recorder may be capable of detecting both groups, data collection and analysis approaches often vary depending on the frequency range of interest. For example, Heenehan et al. (2019) and Kowarski et al. (2023) employed different sampling rates during data acquisition, while Bittencourt et al. (2018) and Rice et al. (2021) differentiated signals during the acoustic analysis phase. In both methodologies, the frequency ranges used by odontocetes and mysticetes were covered. Within each group, species representation in passive acoustic studies were influenced not only by biological factors — such as global distribution and vocal characteristics — but also by the geographical distribution of acoustic research efforts.

The sperm whale was the most studied Odontocete species and is also one of the most widely distributed cetaceans in the world's oceans (Whitehead, 2002). In the studies analyzed in this review, the species was recorded in both the Atlantic and Pacific Oceans (*e.g.*, Ackleh et al., 2012; Baumann-Pickering et al., 2016; Diogou et al., 2019a, 2019b; Shabangu & Andrew, 2020). However, the majority of the research identifying this species was conducted in the Northern Hemisphere, particularly in the North Atlantic. The sperm whale is currently classified as Vulnerable on the IUCN Red List (Taylor et al., 2019), and demographic assessment indicated slow population growth (Chiquet et al., 2013). However, population estimates are typically obtained through visual surveys, which has limitations in low-density areas (*e.g.,* Kaschner et al., 2012). Conversely, sperm whale vocalizations are well documented, facilitating their detection in acoustic surveys (*e.g.,* Backus & Schevill, 1966; Madsen et al., 2002; Weilgart & Whitehead, 1988). Consequently, studies have increasingly investigated acoustic techniques to improve population estimates for this species (*e.g.,* Ackleh et al., 2012; Westell et al., 2022).

Besides the sperm whale, two other frequently studied odontocetes were the killer whale and Cuvier’s beaked whale — both widely distributed globally (Allen et al., 2012; Ford, 2009). Their vocalizations are also well characterized and extensively documented (*e.g.,* Baumann-Pickering et al., 2013; Ford, 1989; Holt et al., 2013), which supports the use of acoustic monitoring in ecological and behavioral studies (*e.g.,* Giorli et al., 2016; Myers et al., 2021; Riera et al., 2019; Pierpoint et al., 2021).

Among mysticetes, the three most frequently studied species in the analyzed publications are all considered cosmopolitan (Clapham & Mead, 1999; Edwards et al., 2015; Sears & Perrin, 2009), suggesting that their broad distribution directly influences their representation in acoustic studies. In contrast, species with more restricted ranges tend to be underrepresented — for example, the bowhead whale, which is found exclusively in the Arctic Ocean (Moore & Reeves, 1993). However, the predominance of research conducted in the Northern Hemisphere, particularly in the Atlantic and Pacific Oceans, raises questions about potential biases in this interpretation. The frequency of species occurrence may have been influenced not only by their global distribution but also by the higher concentration of acoustic recorders deployed in specific regions.

The data synthesis conducted by Edwards et al. (2015) revealed that, when considering only acoustic surveys, the fin whale exhibited a higher occurrence density in the Northern Hemisphere. However, when these data were combined with visual survey information, the estimated distribution became more balanced between the Northern and Southern Hemispheres, despite the identification of an "equatorial gap" (between approximately 20°N and 20°S) in the species' global distribution (Edwards et al., 2015). This discrepancy suggests that the greater availability of acoustic data from the Northern Hemisphere may influence the perception of the species' distribution. Although this review did not directly assess the global distribution of the analyzed species, the findings highlight the need of expanding acoustic monitoring efforts to other geographic regions, particularly in the Southern Hemisphere. Despite the gradual growth of these studies — evidenced by annual fluctuations in the number of publications — the dominance of research in the Northern Hemisphere may still bias the global understanding of fin whale distribution and other species.

From an acoustic perspective, the vocal characteristics of the most studied species may have contributed to their broad representation in acoustic research. For example, blue and fin whales produce some of the most intense vocalizations among mysticetes, which propagate exceptionally well in the aquatic environment, thereby facilitating their detection in acoustic surveys (Širović et al., 2007). In the case of the humpback whale, its frequent representation in studies may be associated with the complexity of one of its most well-known vocal behaviors—song (Payne & McVay, 1971). The extensive knowledge of this vocalization has facilitated its use across a range of research approaches, including studies of seasonal variations (*e.g.*, Munger et al., 2012), movement patterns (*e.g.*, Stanistreet et al., 2013) and even abundance estimation (*e.g.*, Kügler et al., 2020). The latter remains one of the least common categories of biological information in the reviewed studies, as it requires a deep understanding of the species' vocal patterns to ensure robust and reliable estimates.

Biological Information

Most of the biological information identified in the analyzed studies was related to habitat use and seasonality, particularly the characterization of seasonal occupancy patterns in monitored areas. As a result, these categories were widely represented in the reviewed literature (*e.g.,* Castellote et al., 2020; Dréo et al., 2019; Giorli & Au, 2017; Murray et al., 2014; Stanistreet et al., 2018). This pattern was observed for both mysticetes and odontocetes, and can be attributed to the advantages of passive acoustic monitoring in reducing regional and seasonal biases associated with visual methods (Mellinger et al., 2007). While direct observations are limited to moments when individuals surface and depend on weather conditions favorable for visibility, acoustics methods enable continuous monitoring regardless of these constraints (Mellinger et al., 2007).

Most of the analyzed studies performed species-level identification, made possible by fundamentals that characterized species-specific vocalizations. These advances have enabled the widespread use of sound as a tool for detecting and monitoring a variety of species (*e.g.,* Aulich et al., 2022; Barlow et al., 2023; Pilkington et al., 2023; Valdés Hernández et al., 2024).

We observed that, beyond documenting species presence over time, bioacoustics has supported more in-depth analyses. These include assessments of movement patterns in breeding and feeding areas and along migratory routes, which require broader geographic coverage (*e.g.,* Aulich et al., 2019, 2022; Bittencourt et al., 2018; Davis et al., 2017; Oestreich et al., 2020; Stanistreet et al., 2013), as well as behavioral studies such as foraging (*e.g.,* Giorli et al., 2016, 2017) and diving patterns (*e.g.,* Hildebrand et al., 2015). Another relevant application involves assessing responses to anthropogenic activities, ranging from vessel interactions (*e.g.*, La Manna et al., 2014) to the impacts of naval exercises involving underwater explosives (*e.g.,* Lammers et al., 2017).

Studies on acoustic parameters and spatial variation were particularly notable among mysticetes. Many of these focused on characterizing species' acoustic repertoires (*e.g.,* Dombroski et al., 2016; Magnúsdóttir et al., 2015; Stimpert et al., 2011), and this high representation likely contributed to the large number of studies aimed at comparing vocalizations across different geographic regions — another prominent category within this group (*e.g.,* Helble et al., 2020; Furumaki et al., 2021; Morano et al., 2012). In contrast, the population parameters category was underrepresented for both mysticetes and odontocetes. Nonetheless, this field appears to be growing, using different methods depending on the level of knowledge available about the behavior and vocalizations of the species studied (*e.g.*, Hildebrand et al., 2015, 2019; Martin et al., 2013; Kügler et al., 2020).

It is worth noting that biological information, although less represented, was also recorded in historically under-sampled regions, where factors such as adverse climatic conditions (*e.g.,* Lammers et al., 2013), limited accessibility (*e.g.,* Munger et al., 2011), and lack of research investment (*e.g.,* Shabangu & Andrew, 2020) hinder data collection through traditional methods. Tracking individuals using acoustic records can provide more detailed and continuous information with higher spatial and temporal resolution than data obtained through visual surveys (Sousa-Lima et al., 2018), making it particularly valuable for studying cryptic species (*e.g.,* Warren et al., 2021). The reviewed studies clearly demonstrate the significant potential of PAM to address ecological and behavioral questions about cetaceans, helping to overcome limitations imposed by temporal and regional constraints.

Conclusion

In this review, we present an overview of the biological information obtained exclusively through PAM using fixed autonomous acoustic recorders applied in the study of cetaceans. In addition to evaluating mysticetes and odontocetes separately, we analyzed species representation in acoustic studies, and offered a global perspective on monitoring efforts, highlighting both well-sampled regions and those that remain underrepresented. The findings obtained here can guide future research by encouraging the expansion of bioacoustics application to access new areas and species, as well as improvements in data collection and analysis strategies.

By mapping the types of biological information accessed through PAM, this review contributes to a better understanding of how different biological themes have been addressed across species and regions. Although we do not assess methodological effectiveness directly, identifying which types of information have been most frequently explored can help inform future studies, especially in choosing target species or defining monitoring priorities. Despite the predominance of studies conducted in the Northern Hemisphere, we observed a growing number of publications reporting research in the Southern Hemisphere. However, a more in-depth analysis of author affiliations would be necessary to fully understand the geographic distribution of research leadership and institutional capacity.

This overall trend reflects not only the technological advancements in acoustic equipment but also the increasing investments in the field and the collaboration between institutions dedicated to bioacoustics. These improvements have enabled the long-term acoustic monitoring of cetaceans, granting access to previously limited information, particularly for species with restricted distributions and in remote areas. Despite geographical gaps remaining, passive acoustic monitoring proves to be an essential tool in bridging these deficiencies, enhancing ecological, behavioral, and conservation research while enabling data collection in remote and environmentally challenging regions.

Reference

Ackleh, A. S., Ioup, G. E., Ioup, J. W., Ma, B., Newcomb, J. J., Pal, N., Sidorovskaia, N. A., & Tiemann, C. (2012). Assessing the Deepwater Horizon oil spill impact on marine mammal population through acoustics: endangered sperm whales. *The Journal of the Acoustical Society of America*, *131*(3), 2306–2314. https://doi.org/10.1121/1.3682042

Ahonen, H., Stafford, K. M., Lydersen, C., Berchok, C. L., Moore, S. E., & Kovacs, K. M. (2021). Interannual variability in acoustic detection of blue and fin whale calls in the Northeast Atlantic High Arctic between 2008 and 2018. *Endangered Species Research*, *45*, 209–224. https://doi.org/10.3354/esr01132

Allen, B. M., Brownell, R. L., & Mead, J. G. (2012). Species review of Cuvier's beaked whale, *Ziphius cavirostris*. *Reports of International Whaling Commission*.

Andreas, J., Beguš, G., Bronstein, M. M., Diamant, R., Delaney, D., Gero, S., Goldwasser, S., Gruber, D. F., de Haas, S., Malkin, P., Pavlov, N., Payne, R., Petri, G., Rus, D., Sharma, P., Tchernov, D., Tønnesen, P., Torralba, A., Vogt, D.,

& Wood, R. J. (2022). Toward understanding the communication in sperm whales. *Iscience*, *25*(6). Article 104393. https://doi.org/10.1016/j.isci.2022.104393

Atkinson, A., Siegel, V., Pakhomov, E. A., Jessopp, M. J., & Loeb, V. (2009). A re-appraisal of the total biomass and annual production of Antarctic krill. *Deep Sea Research Part I: Oceanographic Research Papers*, *56*(5), 727–740. https://doi.org/10.1016/j.dsr.2008.12.007

Atkinson, A., Siegel, V., Pakhomov, E. A., Rothery, P., Loeb, V., Ross, R. M., ... & Fleming, A. H. (2008). Oceanic circumpolar habitats of Antarctic krill. *Marine Ecology Progress Series*, *362*, 1–23. https://doi.org/10.3354/meps07498

Au, W. W. (2000). Hearing in whales and dolphins: An overview. *Hearing by whales and dolphins*, 1–42. https://doi.org/10.1007/978-1-4612-1150-1

Aulich, M. G., Mccauley, R. D., Miller, B. S., Samaran, F., Giorli, G., Saunders, B. J., & Erbe, C. (2022). Seasonal distribution of the fin whale (*Balaenoptera physalus*) in Antarctic and Australian waters based on passive acoustics. *Frontiers in Marine Science*, *9*, Article 864153. https://doi.org/10.3389/fmars.2022.864153

Aulich, M. G., McCauley, R. D., Saunders, B. J., & Parsons, M. J. (2019). Fin whale (*Balaenoptera physalus*) migration in Australian waters using passive acoustic monitoring. *Scientific reports*, *9*(1), 8840. https://doi.org/10.1038/s41598-019-45321-w

Aviv-Reuven, S., & Rosenfeld, A. (2021). Publication patterns' changes due to the COVID-19 pandemic: a longitudinal and short-term scientometric analysis. *Scientometrics*, *126*(8), 6761–6784. https://doi.org/10.1007/s11192-021-04059-x

Backus, R. H., & Schevill, W. E. (1966). Physeter clicks. *Whales, dolphins and porpoises*, 510–527. https://doi.org/10.1525/9780520321373-030

Barlow, D. R., Klinck, H., Ponirakis, D., Holt Colberg, M., & Torres, L. G. (2023). Temporal occurrence of three blue whale populations in New Zealand waters from passive acoustic monitoring. *Journal of Mammalogy*, *104*(1), 29–38. https://doi.org/10.1093/jmammal/gyac106

Baumann-Pickering, S., McDonald, M. A., Simonis, A. E., Solsona Berga, A., Merkens, K. P., Oleson, E. M., Roch, M. A., Wiggins, S. M., Rankin, S., Yack, T. M., & Hildebrand, J. A. (2013). Species-specific beaked whale echolocation signals. *The Journal of the Acoustical Society of America*, *134*(3), 2293–2301. https://doi.org/10.1121/1.4817832

Baumann-Pickering, S., Trickey, J. S., Wiggins, S. M., & Oleson, E. M. (2016). Odontocete occurrence in relation to changes in oceanography at a remote equatorial Pacific seamount. *Marine Mammal Science*, *32*(3), 805–825. https://doi.org/10.1111/mms.12299

Baumgartner, M. F., Van Parijs, S. M., Wenzel, F. W., Tremblay, C. J., Carter Esch, H., & Warde, A. M. (2008). Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*). *The Journal of the Acoustical Society of America*, *124*(2), 1339–1349. https://doi.org/10.1121/1.2945155

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. https://doi.org/10.1016/j.dsr.2016.06.001

Bittencourt, L., Soares-Filho, W., de Lima, I. M. S., Pai, S., Lailson-Brito Jr, J., Barreira, L. M., ... & Guerra, L. A. A. (2018). Mapping cetacean sounds using a passive acoustic monitoring system towed by an autonomous Wave Glider in the Southwestern Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers, 142*, 58–68. https://doi.org/10.1016/j.dsr.2018.10.006

Bittle, M., & Duncan, A. (2013). A review of current marine mammal detection and classification algorithms for use in automated passive acoustic monitoring. *Proceedings of Acoustics*, *8,* 1–8.

Bornmann, L., & Mutz, R. (2015). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the association for information science and technology, 66*(11), 2215–2222. https://doi.org/10.1002/asi.23329

Browning, E., Gibb, R., Glover-Kapfer, P., & Jones, K. E. (2017). *Passive acoustic monitoring in ecology and conservation*. WWF Conservation Technology Series, *1*(2). WWF-UK. http://dx.doi.org/10.25607/OBP-876

Buchan, S. J., Gutierrez, L., Balcazar-Cabrera, N., & Stafford, K. M. (2019). Seasonal occurrence of fin whale song off Juan Fernandez, Chile. *Endangered Species Research*, *39*, 135–145. https://doi.org/10.3354/esr00956

Burnham, R., Duffus, D., & Mouy, X. (2018). Gray whale (*Eschrictius robustus*) call types recorded during migration off the west coast of Vancouver Island. *Frontiers in Marine Science*, *5*, 329. https://doi.org/10.3389/fmars.2018.00329

Caldwell, M. C., & Caldwell, D. K. (1971). Statistical evidence for individual signature whistles in Pacific whitesided dolphins, *Lagenorhynchus obliquidens*. *Cetology, 3*, 1–9. https://doi.org/10.1016/B978-0-12-373553-9.00235-2

Castellote, M., Small, R. J., Lammers, M., Jenniges, J., Mondragon, J., Garner, C. D., Atkinson, S., Delevaux, J., Graham, R., & Westerholt, D. (2020). Seasonal distribution and foraging occurrence of Cook Inlet beluga whales based on passive acoustic monitoring. *Endangered Species Research, 41,* 225–243. https://doi.org/10.3354/esr01023

Chiquet, R. A., Ma, B., Ackleh, A. S., Pal, N., & Sidorovskaia, N. (2013). Demographic analysis of sperm whales using matrix population models. *Ecological modelling, 248,* 71–79. https://doi.org/10.1016/j.ecolmodel.2012.09.023

Cholewiak, D. M., Sousa-Lima, R. S., & Cerchio, S. (2013). Humpback whale song hierarchical structure: Historical context and discussion of current classification issues. *Marine Mammal Science, 29*(3), E312–E332. https://doi.org/10.1111/mms.12005

Clapham, P. J., & Mead, J. G. (1999). Mammalian species: *Megaptera novaeangliae. American Society of Mammalogists, 604,* 5. https://doi.org/10.2307/3504352

Clark, C. W. (1990). Acoustic behavior of mysticete whales. In *Sensory abilities of cetaceans: Laboratory and field evidence* (pp. 571–583). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4899-0858-2_40

Dalpaz, L., Paro, A. D., Daura-Jorge, F. G., Rossi-Santos, M., Norris, T. F., Ingram, S. N., & Wedekin, L. L. (2021). Better together: analysis of integrated acoustic and visual methods when surveying a cetacean community. *Marine Ecology Progress Series, 678*, 197–209. https://doi.org/10.3354/meps13898

Davis, G. E., Baumgartner, M. F., Bonnell, J. M., Bell, J., Berchok, C., Bort Thornton, J., Brault, S., Buchanan, G., Charif, R. A., Cholewiak, D., Clark, C. W., Corkeron, P., Delarue, J., Dudzinski, K., Hatch, L., Hildebrand, J., Hodge, L., Klinck, H., ... & Van, S. M. (2017). Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific reports, 7*(1), Article 13460. https://doi.org/10.1038/s41598-017-13359-3

Di Marco, M., Chapman, S., Althor, G., Kearney, S., Besancon, C., Butt, N., ... & Watson, J. E. (2017). Changing trends and persisting biases in three decades of conservation science. *Global Ecology and Conservation, 10,* 32–42. https://doi.org/10.1016/j.gecco.2017.01.008

Diogou, N., Palacios, D. M., Nieukirk, S. L., Nystuen, J. A., Papathanassiou, E., Katsanevakis, S., & Klinck, H. (2019a). Sperm whale (*Physeter macrocephalus*) acoustic ecology at Ocean Station PAPA in the Gulf of Alaska–Part 1: Detectability and seasonality. Deep Sea Research Part I: *Oceanographic Research Papers, 150*, Article 103047. https://doi.org/10.1016/j.dsr.2019.05.007

Diogou, N., Palacios, D. M., Nystuen, J. A., Papathanassiou, E., Katsanevakis, S., & Klinck, H. (2019b). Sperm whale (*Physeter macrocephalus*) acoustic ecology at Ocean Station PAPA in the Gulf of Alaska–Part 2: Oceanographic drivers of interannual variability. Deep Sea Research Part I: *Oceanographic Research Papers, 150*, Article 103044. https://doi.org/10.1016/j.dsr.2019.05.004

Dombroski, J. R., Parks, S. E., Groch, K. R., Flores, P. A., & Sousa-Lima, R. S. (2016). Vocalizations produced by southern right whale (*Eubalaena australis*) mother-calf pairs in a calving ground off Brazil. *The Journal of the Acoustical Society of America*, *140*(3), 1850–1857. https://doi.org/10.1121/1.4962231

Dréo, R., Bouffaut, L., Leroy, E., Barruol, G., & Samaran, F. (2019). Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, *161*, 132–144. https://doi.org/10.1016/j.dsr2.2018.04.005

Durette-Morin, D., Evers, C., Johnson, H. D., Kowarski, K., Delarue, J., Moors-Murphy, H., Maxner, E., Lawson, J. W., & Davies, K. T. (2022). The distribution of North Atlantic right whales in Canadian waters from 2015-2017 revealed by passive acoustic monitoring. *Frontiers in Marine Science*, *9*, Article 976044. https://doi.org/10.3389/fmars.2022.976044

Edwards, E. F., Hall, C., Moore, T. J., Sheredy, C., & Redfern, J. V. (2015). Global distribution of fin whales *Balaenoptera physalus* in the post-whaling era (1980–2012). *Mammal Review*, *45*(4), 197–214. https://doi.org/10.1111/mam.12048

Filun, D., Thomisch, K., Boebel, O., Brey, T., Širović, A., Spiesecke, S., & Van Opzeeland, I. (2020). Frozen verses: Antarctic minke whales (*Balaenoptera bonaerensis*) call predominantly during austral winter. *Royal Society open science*, *7*(10), Article 192112. https://doi.org/10.1098/rsos.192112

Ford, J. K. (1989). Acoustic behaviour of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *Canadian Journal of Zoology*, *67*(3), 727–745. https://doi.org/10.1139/z89-105

Ford, J. K. (2009). Killer whale: *Orcinus orca*. In *Encyclopedia of marine mammals* (pp. 650–657). Academic Press. https://doi.org/10.1016/B978-0-12-373553-9.00150-4

Fordyce, E., & Perrin, W. F. (2025). *World Cetacea Database*. Retrieved June 29, 2025, from https://www.marinespecies.org/cetacea

Furumaki, S., Tsujii, K., & Mitani, Y. (2021). Fin whale (*Balaenoptera physalus*) song pattern in the southern Chukchi Sea. *Polar biology*, *44*, 1021–1027. https://doi.org/10.1007/s00300-021-02855-y

Galvez, A., Maqueda, M., Martinez-Bueno, M., & Valdivia, E. (2000). Scientific Publication Trends and the Developing World: What can the volume and authorship of scientific articles tell us about scientific progress in various regions?. *American scientist*, *88*(6), 526–533. https://doi.org/10.1511/2000.41.526

Garland, E. C., Berchok, C. L., & Castellote, M. (2015). Temporal peaks in beluga whale (*Delphinapterus leucas*) acoustic detections in the northern Bering, northeastern Chukchi, and western Beaufort Seas: 2010–2011. *Polar Biology*, *38*, 747–754. https://doi.org/10.1007/s00300-014-1636-1

Giorli, G., & Au, W. W. (2017). Spatio-temporal variation and seasonality of Odontocetes' foraging activity in the leeward side of the island of Hawaii. *Deep Sea Research Part I: Oceanographic Research Papers*, *121*, 202–209. https://doi.org/10.1016/j.dsr.2017.01.013

Giorli, G., Au, W. W., & Neuheimer, A. (2016). Differences in foraging activity of deep sea diving odontocetes in the Ligurian Sea as determined by passive acoustic recorders. *Deep Sea Research Part I: Oceanographic Research Papers*, *107*, 1–8. https://doi.org/10.1016/j.dsr.2015.10.002

Gonçalves, M. I. C., Sousa-Lima, R. S., Teixeira, N. N., Morete, M. E., Carvalho, G. H., Ferreira, H. M., & Baumgarten, J. E. (2018). Low latitude habitat uses patterns of a recovering population of humpback whales. *Journal of the Marine Biological Association of the United Kingdom*, *98*(5), 1087–1096. https://doi.org/10.1017/S0025315418000255

Guidi, C., Bou-Cabo, M., Lara, G., & KM3NeT Collaboration. (2021). Passive acoustic monitoring of cetaceans with KM3NeT acoustic receivers. *Journal of Instrumentation*, *16*(10), Article C10004. https://doi.org/10.1088/1748-0221/16/10/C10004

Halliday, W. D., Pine, M. K., Mouy, X., Kortsalo, P., Hilliard, R. C., & Insley, S. J. (2020). The coastal Arctic marine soundscape near Ulukhaktok, Northwest Territories, Canada. *Polar Biology*, *43*, 623–636. https://doi.org/10.1007/s00300-020-02665-8

Haver, S. M., Rand, Z., Hatch, L. T., Lipski, D., Dziak, R. P., Gedamke, 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. https://doi.org/10.1121/10.0001726

Hawkins, A. D., & Myrberg, A. A. (1983). Hearing and sound communication under water. *Bioacoustics, a comparative approach. Academic Press, London*, 347–405.

Heenehan, H., Stanistreet, J. E., Corkeron, P. J., Bouveret, L., Chalifour, J., Davis, G. E., Henriquez, A., Kiszka, J. J., Kline, L., Reed, C., Shamir-Reynoso, O., Védie, F., De Wolf, W., Hoetjes, P., & Van Parijs, S. M. (2019). Caribbean Sea soundscapes: monitoring humpback whales, biological sounds, geological events, and anthropogenic impacts of vessel noise. *Frontiers in Marine Science, 6*, 347. https://doi.org/10.3389/fmars.2019.00347

Helble, T. A., Guazzo, R. A., Alongi, G. C., Martin, C. R., Martin, S. W., & Henderson, E. E. (2020). Fin whale song patterns shift over time in the central North Pacific. *Frontiers in Marine Science*, *7,* Article 587110. https://doi.org/10.3389/fmars.2020.587110

Hildebrand, J. A., Baumann-Pickering, S., Frasier, K. E., Trickey, J. S., Merkens, K. P., Wiggins, S. M., McDonald, M. A., Garrison, L. P., Harris, D., Marques, T. A. & Thomas, L. (2015). Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. *Scientific reports, 5*(1), Article 16343. https://doi.org/10.1038/srep16343

Hildebrand, J. A., Frasier, K. E., Baumann-Pickering, S., Wiggins, S. M., Merkens, K. P., Garrison, L. P., Soldevilla, M. S., & McDonald, M. A. (2019). Assessing seasonality and density from passive acoustic monitoring of signals presumed to be from pygmy and dwarf sperm whales in the Gulf of Mexico. *Frontiers in Marine Science, 6*, 66. https://doi.org/10.3389/fmars.2019.00066

Hill, S. L., Murphy, E. J., Reid, K., Trathan, P. N., & Constable, A. J. (2006). Modelling Southern Ocean ecosystems: krill, the food-web, and the impacts of harvesting. *Biological Reviews, 81*(4), 581–608. https://doi.org/10.1017/S1464793106007123

Holt, M. M., Noren, D. P., & Emmons, C. K. (2013). An investigation of sound use and behavior in a killer whale (*Orcinus orca*) population to inform passive acoustic monitoring studies. *Marine Mammal Science, 29*(2), 1–10. https://doi.org/10.1111/j.1748-7692.2012.00599.x

Howe, M., & Lammers, M. O. (2021). Investigating the diel occurrence of Odontocetes around the Maui Nui Region using passive acoustic techniques. *Pacific Science, 75*(1), 147–161. https://doi.org/10.2984/75.1.7

International Whaling Commission [IWC]. (1998). Report of the Sub-Committee on other Southern Hemisphere whale stocks. *Report of the International Whaling Commission, 48*, 170–182.

Jonsgård, Å. (1966). The distribution of Balaenopteridae in the north Atlantic Ocean. *Whales, dolphins and porpoises*, 114–124. https://doi.org/10.1525/9780520321373-009

Kaschner, K., Quick, N. J., Jewell, R., Williams, R., & Harris, C. M. (2012). Global coverage of cetacean line-transect surveys: Status quo, data gaps and future challenges. *PLOS ONE, 7*(9), Article e44075. https://doi.org/10.1371/journal.pone.0044075

Kowarski, K. A., & Moors-Murphy, H. (2021). A review of big data analysis methods for baleen whale passive acoustic monitoring. *Marine Mammal Science, 37*(2), 652–673. https://doi.org/10.1111/mms.12758

Kowarski, K. A., Martin, S. B., Maxner, E. E., Lawrence, C. B., Delarue, J. J. Y., & Miksis-Olds, J. L. (2023). Cetacean acoustic occurrence on the US Atlantic Outer

Continental Shelf from 2017 to 2020. *Marine Mammal Science, 39*(1), 175–199. https://doi.org/10.1111/mms.12962

Krause, B. (2008). Anatomy of the soundscape: evolving perspectives. *The Journal of the Audio Engineering Society, 56*, 73–80.

Kremers, D., Lemasson, A., Almunia, J., & Wanker, R. (2012). Vocal sharing and individual acoustic distinctiveness within a group of captive orcas (*Orcinus orca*). *Journal of Comparative Psychology, 126*(4), 433. https://doi.org/10.1037/a0028858

Kügler, A., Lammers, M. O., Zang, E. J., Kaplan, M. B., & Mooney, T. A. (2020). Fluctuations in Hawaii's humpback whale *Megaptera novaeangliae* population inferred from male song chorusing off Maui. *Endangered Species Research, 43*, 421–434. https://doi.org/10.3354/esr01080

La Manna, G., Manghi, M., & Sara, G. (2014). Monitoring the habitat use of common Bottlenose Dolphins (*Tursiops truncatus*) using passive acoustics in a Mediterranean marine protected area. *Mediterranean Marine Science, 15*(2), 327–337. https://doi.org/10.12681/mms.561

Lammers, M. O., Castellote, M., Small, R. J., Atkinson, S., Jenniges, J., Rosinski, A., Oswald, J. N., & Garner, C. (2013). Passive acoustic monitoring of Cook Inlet beluga whales (*Delphinapterus leucas*). *The Journal of the Acoustical Society of America, 134*(3), 2497–2504. https://doi.org/10.1121/1.4816575

Lammers, M. O., Howe, M., Zang, E., McElligott, M., Engelhaupt, A., & Munger, L. (2017). Acoustic monitoring of coastal dolphins and their response to naval mine neutralization exercises. *Royal Society open science, 4(12),* 170558. https://doi.org/10.1098/rsos.170558

Lin, T. H., & Chou, L. S. (2015). Automatic classification of delphinids based on the representative frequencies of whistles. *The Journal of the Acoustical Society of America, 138*(2), 1003–1011. https://doi.org/10.1121/1.4927695

Madsen, P. T., Payne, R., Kristiansen, N. U., Wahlberg, M., Kerr, I., & Møhl, B. (2002). Sperm whale sound production studied with ultrasound time/depth-recording tags. *Journal of Experimental Biology, 205*(13), 1899–1906. https://doi.org/10.1242/jeb.205.13.1899

Magnúsdóttir, E. E., Miller, P. J., Lim, R., Rasmussen, M. H., Lammers, M. O., & Svavarsson, J. (2015). Humpback whale (*Megaptera novaeangliae*) song unit and phrase repertoire progression on a subarctic feeding ground. *The Journal of the Acoustical Society of America, 138*(5), 3362–3374. https://doi.org/10.1121/1.4935517

Martin, S. W., Marques, T. A., Thomas, L., Morrissey, R. P., Jarvis, S., DiMarzio, N., ... & Mellinger, D. K. (2013). Estimating minke whale (*Balaenoptera acutorostrata*) boing sound density using passive acoustic sensors. *Marine Mammal Science, 29*(1), 142–158. https://doi.org/10.1111/j.1748-7692.2011.00561.x

McGaughey, D. R., Marcotte, D., Korenberg, M. J., & Theriault, J. A. (2010, September). Detection and classification of marine mammal clicks. In *OCEANS 2010 MTS/IEEE SEATTLE* (pp. 1–10). IEEE. https://doi.org/10.1109/OCEANS.2010.5664576

Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., & Matsumoto, H. (2007). An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography*, *20*(4), 36–45. https://doi.org/10.5670/oceanog.2007.03

Miller, P. J. O. (2002). Mixed-directionality of killer whale stereotyped calls: A direction of movement cue? *Behavioral Ecology and Sociobiology*, *52*, 262–270. https://doi.org/10.1007/s00265-002-0508-9

Moore, S. E., & Reeves, R. R. (1993). Distribution and movements. In J. J. Burns, J. J. Montague, & C. J. Cowles (Eds.), *The bowhead whale* (Special Publication No. 2, pp. 313–386). The Society of Marine Mammalogy.

Moore, S. E., Stafford, K. M., Melling, H., Berchok, C., Wiig, Ø., Kovacs, K. M., Kovacs, K. M., Lydersen, C., & Richter-Menge, J. (2012). Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: year-long records from Fram Strait and the Chukchi Plateau. *Polar Biology*, *35*, 475–480. https://doi.org/10.1007/s00300-011-1086-y

Morano, J. L., Salisbury, D. P., Rice, A. N., Conklin, K. L., Falk, K. L., & Clark, C. W. (2012). Seasonal and geographical patterns of fin whale song in the western North Atlantic Ocean. *The Journal of the Acoustical Society of America*, *132*(2), 1207–1212. https://doi.org/10.1121/1.4730890

Munger, L. M., Lammers, M. O., Fisher-Pool, P., & Wong, K. (2012). Humpback whale (*Megaptera novaeangliae*) song occurrence at American Samoa in long-term passive acoustic recordings, 2008–2009. *The Journal of the Acoustical Society of America*, *132*(4), 2265–2272. https://doi.org/10.1121/1.4747014

Munger, L. M., Wiggins, S. M., & Hildebrand, J. A. (2011). North Pacific right whale up-call source levels and propagation distance on the southeastern Bering Sea shelf. *The Journal of the Acoustical Society of America*, *129(6)*, 4047–4054. https://doi.org/10.1121/1.3557060

Munger, L., Lammers, M. O., Cifuentes, M., Würsig, B., Jefferson, T. A., & Hung, S. K. (2016). Indo-Pacific humpback dolphin occurrence north of Lantau Island, Hong Kong, based on year-round passive acoustic monitoring. *The Journal of the Acoustical Society of America*, *140*(4), 2754–2765. https://doi.org/10.1121/1.4963874

Murray, A., Rice, A. N., & Clark, C. W. (2014). Extended seasonal occurrence of humpback whales in Massachusetts Bay. *Journal of the Marine Biological Association of the United Kingdom*, *94*(6), 1117–1125. https://doi.org/10.1017/S0025315412001968

Myers, H. J., Olsen, D. W., Matkin, C. O., Horstmann, L. A., & Konar, B. (2021). Passive acoustic monitoring of killer whales (*Orcinus orca*) reveals year-round distribution and residency patterns in the Gulf of Alaska. *Scientific Reports*, *11*(1), Article 20284. https://doi.org/10.1038/s41598-021-99668-0

Oestreich, W. K., Fahlbusch, J. A., Cade, D. E., Calambokidis, J., Margolina, T., Joseph, J., Friedlaender, A. S., McKenna, M. F., Stimpert, A. K., Southall, B. L., Goldbogen, J. A., & Ryan, J. P. (2020). Animal-borne metrics enable acoustic detection of blue whale migration. *Current Biology*, *30*(23), 4773–4779. https://doi.org/10.1016/j.cub.2020.08.105

Oswald, J. N., Barlow, J., & Norris, T. F. (2003). Acoustic identification of nine delphinid species in the eastern tropical Pacific Ocean. *Marine mammal science, 19*(1), 20–37. https://doi.org/10.1111/j.1748-7692.2003.tb01090.x

Payne, R. S., & McVay, S. (1971). Songs of humpback whales. *Science, 173*(3397), 585–597. https://doi.org/10.1126/science.173.3997.585

Pearson, E. J., Oestreich, W. K., Ryan, J. P., Haver, S. M., Gedamke, J., Dziak, R. P., & Wall, C. C. (2023). Widespread passive acoustic monitoring reveals spatio-temporal patterns of blue and fin whale song vocalizations in the Northeast Pacific Ocean. *Frontiers in Remote Sensing, 4,* Article 994518. https://doi.org/10.3389/frsen.2023.994518

Pierpoint, C., Oliver, E., Scala, L., & Hedgeland, D. (2021). An acoustic survey of beaked whale distribution at São Tomé and Príncipe, Gulf of Guinea, using an unmanned surface vessel. *African Journal of Marine Science, 43(4),* 443–454. https://doi.org/10.2989/1814232X.2021.1982769

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. https://doi.org/10.1007/s10980-011-9600-8

Pilkington, J. F., Stredulinsky, E. H., Gavrilchuk, K., Thornton, S. J., Ford, J. K., & Doniol-Valcroze, T. (2023). Patterns of winter occurrence of three sympatric killer whale populations off eastern Vancouver Island, Canada, based on passive acoustic monitoring. *Frontiers in Marine Science, 10,* Article 1204908. https://doi.org/10.3389/fmars.2023.1204908

QGIS Development Team. (2023). *QGIS Geographic Information System* (Version 3.28.11). Open Source Geospatial Foundation. http://qgis.osgeo.org

Rice, A., Širović, A., Trickey, J. S., Debich, A. J., Gottlieb, R. S., Wiggins, S. M., Hildebrand, J. A., & Baumann-Pickering, S. (2021). Cetacean occurrence in the Gulf of Alaska from long-term passive acoustic monitoring. *Marine Biology, 168*(5), 72. https://doi.org/10.1007/s00227-021-03884-1

Richardson, W. J., Greene Jr, C. R., Malme, C. I., & Thomson, D. H. (2013). *Marine mammals and noise*. Academic press.

Richardson, W. J., Greene, C. R. Jr., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. Academic Press.

Riera, A., Pilkington, J. F., Ford, J. K. B., Stredulinsky, E. H., & Chapman, N. R. (2019). Passive acoustic monitoring off Vancouver Island reveals extensive use by at-risk Resident killer whale (*Orcinus orca*) populations. *Endangered Species Research, 39*, 221–234. https://doi.org/10.3354/esr00966

Salisbury, D. P., Guid, C. W., & Rice, A. N. (2016). Right whale occurrence in the coastal waters of Virginia, USA: Endangered species presence in a rapidly developing energy market. *Marine Mammal Science, 32*(2), 508-519. https://doi/10.1111/mms.12276

Sears, R., & Perrin, W. F. (2009). Blue whale: *Balaenoptera musculus*. In *Encyclopedia of marine mammals* (pp. 120–124). Academic Press. https://doi.org/10.1016/B978-0-12-373553-9.00033-X

Shabangu, F. W., & Andrew, R. K. (2020). Clicking throughout the year: sperm whale clicks in relation to environmental conditions off the west coast of South Africa. *Endangered Species Research*, *43*, 475–494. https://doi.org/10.3354/esr01089

Širović, A., Hildebrand, J. A., & Wiggins, S. M. (2007). Blue and fin whale call source levels and propagation range in the Southern Ocean. *The Journal of the Acoustical Society of America*, *122*(2), 1208–1215. https://doi.org/10.1121/1.2749452

Society for Marine Mammalogy, Committee on Taxonomy. (2023). *List of marine mammal species and subspecies.* Retrieved from https://marinemammalscience.org/science-and-publications/list-marine-mammal-species-subspecies/

Sjare, B. L., & Smith, T. G. (1986). The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. *Canadian Journal of Zoology*, *64*(2), 407–415. https://doi.org/10.1139/z86-063

Soldevilla, M. S., Wiggins, S. M., & Hildebrand, J. A. (2010). Spatio-temporal comparison of Pacific white-sided dolphin echolocation click types. *Aquatic Biology*, *9*(1), 49–62. https://doi.org/10.3354/ab00224

Sousa-Lima, R. S., & Clark, C. W. (2008). Modeling the effect of boat traffic on the fluctuation of humpback whale singing activity in the Abrolhos National Marine Park, Brazil. *Canadian Acoustics*, *36*(1), 174–181.

Sousa-Lima, R. S., & Clark, C. W. (2009). Whale sound recording technology as a tool for assessing the effects of boat noise in a Brazilian marine park. *Park Science*, *26*(1), 59–63.

Sousa-Lima, R. S., Engel, M. H., Sábato, V., Lima, B. R., Queiróz, T. S., Brito, M. R., Fernandes, D. P., Martins, C. A. C., Hatum, O. S., Casagrande, T., Honda, R. K., Gonçalves, M. I. C., Baumgarten, J. E., Andriolo, A., Ribeiro, M. C., & Clark, C. W. (2018). Acoustic ecology of humpback whales in Brazilian waters investigated with basic and sophisticated passive acoustic technologies over 17 years. *Western Indian Ocean Journal of Marine Science, 23–40.*

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P. (2013). A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquatic Mammals, 39*(1), 23–53. https://doi.org/10.1578/AM.39.1.2013.23

Stanistreet, J. E., Nowacek, D. P., Bell, J. T., Cholewiak, D. M., Hildebrand, J. A., Hodge, L. E. W., Van Parijs, S. M., & Read, A. J. (2018). Spatial and seasonal patterns in acoustic detections of sperm whales *Physeter macrocephalus* along the continental slope in the western North Atlantic Ocean. *Endangered Species Research*, *35*, 1–13. https://doi.org/10.3354/esr00867

Stanistreet, J. E., Risch, D., & Van Parijs, S. M. (2013). Passive acoustic tracking of singing humpback whales (*Megaptera novaeangliae*) on a Northwest Atlantic feeding ground. *PLoS One, 8*(4), Article e61263. https://doi.org/10.1371/journal.pone.0061263

Stimpert, A. K., Au, W. W., Parks, S. E., Hurst, T., & Wiley, D. N. (2011). Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring. *The Journal of the Acoustical Society of America*, *129*(1), 476–482. https://doi.org/10.1121/1.3504708

Stone, G., Flórez-González, L., & Katona, S. (1990). Whale migration record. *Nature, 346*(6286), 705. https://doi.org/10.1038/346705a0

Taylor, B. L., Baird, R., Barlow, J., Dawson, S. M., Ford, J., Mead, J. G., Notarbartolo di Sciara, G., Wade, P., & Pitman, R. L. (2019). *Physeter macrocephalus* (amended version of 2008 assessment). *The IUCN Red List of Threatened Species 2019*, e.T41755A160983555. https://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T41755A160983555.en. Accessed on 11 March 2025.

Thomisch, K., Boebel, O., Bachmann, J., Filun, D., Neumann, S., Spiesecke, S., & Van Opzeeland, I. (2019). Temporal patterns in the acoustic presence of baleen whale species in a presumed breeding area off Namibia. *Marine Ecology Progress Series, 620*, 201–214. https://doi.org/10.3354/meps12952

Usman, A. M., Ogundile, O. O., & Versfeld, D. J. (2020). Review of automatic detection and classification techniques for cetacean vocalization. *Ieee Access, 8*, 105181–105206. https://doi.org/10.1109/ACCESS.2020.3000477

Valdés Hernández, M. J., Dawson, S., Pavanato, H., Leunissen, E., & Rayment, W. (2024). Using passive acoustic monitoring to assess the overlap between endemic endangered Hector's dolphin (*Cephalorhynchus hectori hectori*) and mussel farms in the Banks Peninsula Marine Mammal Sanctuary, New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems, 34*(6), Article e4207. https://doi.org/10.1002/aqc.4207

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., & Van Opzeeland, I. C. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series*, *395*, 21–36. https://doi.org/10.3354/meps08123

Verfuss, U. K., Gillespie, D., Gordon, J., Marques, T. A., Miller, B., Plunkett, R., ... & Thomas, L. (2018). Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Marine Pollution Bulletin, 126, 1-18. https://doi.org/10.1016/j.marpolbul.2017.10.034

Warren, V. E., Constantine, R., Noad, M., Garrigue, C., & Garland, E. C. (2020). Migratory insights from singing humpback whales recorded around central New Zealand. *Royal Society Open Science*, *7*(11), Article 201084. https://doi.org/10.1098/rsos.201084

Warren, V. E., Širović, A., McPherson, C., Goetz, K. T., Radford, C. A., & Constantine, R. (2021). Passive acoustic monitoring reveals spatio-temporal distributions of Antarctic and pygmy blue whales around central New Zealand. *Frontiers in Marine Science*, *7*, Article 575257. https://doi.org/10.3389/fmars.2020.575257

Weilgart, L. S., & Whitehead, H. (1988). Distinctive vocalizations from mature male sperm whales (*Physeter macrocephalus*). *Canadian Journal of Zoology*, *66*(9), 1931–1937. https://doi.org/10.1139/z88-282

Westell, A., Sakai, T., Valtierra, R., Van Parijs, S. M., Cholewiak, D., & DeAngelis, A. (2022). Sperm whale acoustic abundance and dive behaviour in the western North Atlantic. *Scientific Reports*, *12*(1), 16821. https://doi.org/10.1038/s41598-022-20868-3

Whitehead, H. (2002). Estimates of the current global population size and historical trajectory for sperm whales. *Marine Ecology Progress Series*, *242*, 295–304. https://doi.org/10.3354/meps242295

Wiggins, S. M., McDonald, M. A., Munger, L. M., Moore, S. E., & Hildebrand, J. A. (2004). Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. *Canadian acoustics*, *32*(2), 146–154.

Williams, R., Kelly, N., Boebel, O., Friedlaender, A. S., Herr, H., Kock, K. H., ... & Brierley, A. S. (2014). Counting whales in a challenging, changing environment. *Scientific reports*, *4(1)*, Article 4170. https://doi.org/10.1038/srep04170

Yurk, H., Barrett-Lennard, L., Ford, J. K. B., & Matkin, C. O. (2002). Cultural transmission within maternal lineages: Vocal clans in resident killer whales in southern Alaska. *Animal Behaviour*, *63*(6), 1103–1119. https://doi.org/10.1006/anbe.2002.3012

Zerbini, A. N., Andriolo, A., Heide-Jørgensen, M. P., Pizzorno, J. L., Maia, Y. G., VanBlaricom, G. R., DeMaster, D. P., Simões-Lopes, P. C., Moreira, S., & Bethlem, C. (2006). Satellite-monitored movements of humpback whales *Megaptera novaeangliae* in the Southwest Atlantic Ocean. *Marine Ecology Progress Series*, *313*, 295-304. https://doi.org/10.3354/meps313295

Zimmer, W. M. (2011). *Passive acoustic monitoring of cetaceans*. Cambridge University Press. https://doi.org/10.1017/CBO9780511977107

CAPÍTULO II:

ASSESSMENT OF ACOUSTIC METRICS FOR MONITORING HUMPBACK WHALE LOCAL POPULATION ABUNDANCE

** Article to be submitted to Bioacoustic journal.*

Assessment of acoustic metrics for monitoring humpback whale local population abundance

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Abstract

Male humpback whales produce complex acoustic signals known as songs, which dominate the underwater soundscape during the breeding season. The vocal activity of these singers has the potential to serve as an indicator of population abundance patterns. A coastal reoccupation area of humpback whales in southern Bahia in Brazil was monitored visually and acoustically during the 2014, 2015, 2018, and 2019 seasons. The objective of this study was to assess whether acoustic metrics extracted from the song chorus reflect patterns of species abundance. Sound pressure level (RMS SPL), 1/3 octave band levels (TOL), acoustic complexity index (ACI), and the number of singers (on a 0 to 4 scale) were measured and visual estimates of relative whale abundance were used as reference. The ACI presented as the most unstable metric, being more influenced by interannual variations in song structure than by population density. In contrast, RMS SPL and the number of singers more consistently reflected seasonal and annual density patterns. The number of singers presented consistency with visual estimates, although its limited scale may reduce statistical sensitivity in contexts of high vocal activity. RMS SPL showed higher sensitivity but may include sounds from other biological sources, requiring cautious interpretation, especially during low-density periods. We conclude that the combined use of these metrics represents a promising complementary approach for passive monitoring of humpback whale populations.

Keywords: acoustic index, breeding ground, *Megaptera novaeangliae*, passive acoustic monitoring, song chorusing, sound pressure level.

Introduction

Estimating population size and monitoring its variation over time are fundamental for species conservation, as they allow assessing the current status, the effectiveness of conservation efforts and projecting future trends (*e.g.*, Hare et al., 2011; Mohammed & Mohd-Sah, 2024; Turco et al., 2025). This information is essential to understand the factors influencing population viability and, consequently, to more accurately guide the adoption of management strategies and mitigation measures when necessary (*e.g.*, Fantle-Lepczyk et al., 2018; Zambrano et al., 2007). Traditionally, population abundance estimates are obtained through direct counts of individuals in a given sampling area (*e.g.*, Gonçalves et al., 2018a; Munari et al., 2011; Thresher & Gunn, 1986). From these data, statistical and mathematical models can be employed to extrapolate results to larger areas or to make temporal projections about population dynamics (*e.g.*, Conn et al., 2015; Zerbini et al., 2019). This type of approach is widely used in terrestrial environments (*e.g.*, Fantle-Lepczyk et al., 2018; Mohammed & Mohd-Sah, 2024; Munari et al., 2011), where direct observation is more feasible, but it has also been adapted to aquatic environments, being an applicable and valuable alternative (*e.g.*, Gonçalves et al., 2018a; Mobley et al., 1999; Thresher & Gunn, 1986).

Monitoring changes in animal populations over time often requires systematic long-term monitoring programs, which are not always simple to implement in aquatic environments (*e.g.*, Hayes & Schradin, 2017; Kaschner et al., 2012). Factors such as variations in light, sea state, rain, and other weather conditions can compromise animal visibility (Mellinger et al., 2007; Pieretti et al., 2015). Furthermore, visual surveys generally demand high logistical effort and significant operational costs, especially when conducted in hard-to-access areas (*e.g.*, Barlow & Taylor, 2005; Sousa-Lima et al., 2013). In this context, passive acoustic monitoring (PAM) emerges as an effective alternative, as it allows continuous and automated detection of acoustic signals regardless of lighting and weather conditions (Mellinger et al., 2007; Sousa-Lima et al., 2013). The possibility of prolonged data collection without the need for constant field presence helps reduce costs, making this approach particularly advantageous in remote regions (*e.g.,* Barlow & Taylor, 2005; Mellinger et al., 2007; Sousa-Lima et al., 2013).

Cetaceans—mammals exclusively aquatic—have been extensively studied using PAM, mainly due to their ecological and behavioral characteristics (*e.g.,* Bittencourt et al., 2018; Johnston et al., 2008; Martin et al., 2013; Todd et al., 2020; Valdés-Hernández et al., 2024). These species produce sounds in social, navigational, and foraging contexts, making them easily detectable through acoustic methods (*e.g.,* Richardson et al., 2013; Zimmer, 2011). Additionally, they spend long periods submerged, out of visual range, which reinforces PAM's applicability (Zimmer, 2011). Based on these advantages, PAM has been used to investigate factors such as occurrence patterns (*e.g.,* Johnston et al., 2008; Myers et al., 2021), vocal activity (*e.g.,* Howe & Lammers, 2021; Webster et al., 2019), responses to anthropogenic disturbances (*e.g.,* Papale et al., 2020; Poupard et al., 2022), and even population abundance estimates (*e.g.,* Kügler et al., 2021; Martin et al., 2013). However, for these last estimates to be reliable, it is essential to understand the vocal behavior of the target species and its relationship with population density (*e.g.,* Au et al., 2000; Kügler et al., 2021).

In this context, the humpback whale (*Megaptera novaeangliae*) stands out as a model species, given its well-documented song repertoire (*e.g.,* Gonçalves et al., 2023; Kügler et al., 2021; Noad et al., 2000; Payne & McVay, 1971; Winn et al., 1981) and the standardized hierarchical structure of its song, which facilitates identification in acoustic analyses (Cholewiak et al., 2013; Payne & McVay, 1971). It is widely accepted that only males sing (Darling et al., 2006; Glockner, 1983; Smith et al., 2008), particularly on breeding grounds (*e.g.,* Darling & Sousa-Lima, 2006; Mercado et al., 2005; Payne & McVay, 1971; Payne et al., 1983) and along migratory routes (*e.g.,* Clapham & Mattila, 1990; Noad & Cato, 2007; Warren et al., 2020). Although this behavior is associated with the species' mating system, its precise function remains debated (*e.g.,* Darling et al., 2006; Herman, 2017; Herman & Tavolga, 1980; Winn & Winn, 1978).

Several studies indicate a positive correlation between the vocal activity of singing males and individual abundance (*e.g.,* Au et al., 2000; Homfeldt et al., 2022; Kobayashi et al., 2021; Noad et al., 2017), although this pattern is not universal (*e.g.,* Sousa-Lima et al., 2018). Nonetheless, acoustic metrics can work as proxies for abundance, particularly in breeding grounds where song dominates the soundscape (*e.g.,* Au et al., 2000; Bittencourt et al., 2016; Kügler et al., 2021; Seger et al., 2016). Among the metrics used to estimate humpback whale vocal activity, the root mean square sound pressure level (RMS SPL) and 1/3 octave band levels (TOL) are the most commonly applied (*e.g.,* Au et al., 2000; Bittencourt et al., 2016; Kügler et al., 2021).

Other approaches have also been explored to characterize vocalization patterns in other species, such as the Acoustic Complexity Index (ACI) (Pieretti et al., 2011). This index is based on the premise that biological sounds, such as whale songs, exhibit greater temporal variability in intensity than anthropogenic noise, which is generally more constant (Pieretti et al., 2011). ACI values are thus expected to increase with the number of individuals vocalizing simultaneously. Another potentially informative metric is the number of singers. Although absolute individual counts are not feasible with a single recorder, studies suggest it is possible to obtain relative estimates, which typically range from four to five individuals based on the analysis of the song chorus (*e.g.,* Campelo, 2020; Homfeldt et al., 2022; Sousa-Lima et al., 2018). These values were positively correlated with adult humpback whale abundance, as evidenced in Serra Grande on the Brazilian coast (Campelo et al., 2020).

The Serra Grande region, in southern Bahia, was recognized as a humpback whale reoccupation area (Gonçalves et al., 2018a). The region benefits from simultaneous acoustic and visual monitoring efforts conducted over four breeding seasons. This data set offers a unique opportunity to evaluate the performance of different acoustic metrics in estimating humpback whale population abundance. In this study, we assessed the feasibility of applying RMS SPL, TOL, ACI, and number of singers as potential acoustic abundance indicators, using direct counts from visual monitoring as a baseline for comparison. We hypothesized that: (*i*) acoustic metrics would positively correlate with visual estimates of relative whale abundance; (*ii*) this correlation would be stronger during dusk and nighttime periods due to increased vocal activity during these periods; and (*iii*) frequency band analysis (TOL) would help identify which frequency intervals are most associated with the species' vocal activity.

Materials and Methods

Study area

This study was conducted in Serra Grande, located on the southern coast of Bahia, in northeastern Brazil (Figure 1). The area is notable for its geographical and ecological features and is considered a strategic area for humpback whale research. Serra Grande is located over the narrowest stretch of the Brazilian continental shelf (IBGE, 2011), where the bathymetry presents a steep slope shortly after the shelf break. This configuration facilitates the coastal approach of cetaceans, making the region particularly relevant for acoustic and visual studies of the species during the breeding season (Gonçalves et al., 2018a, b).

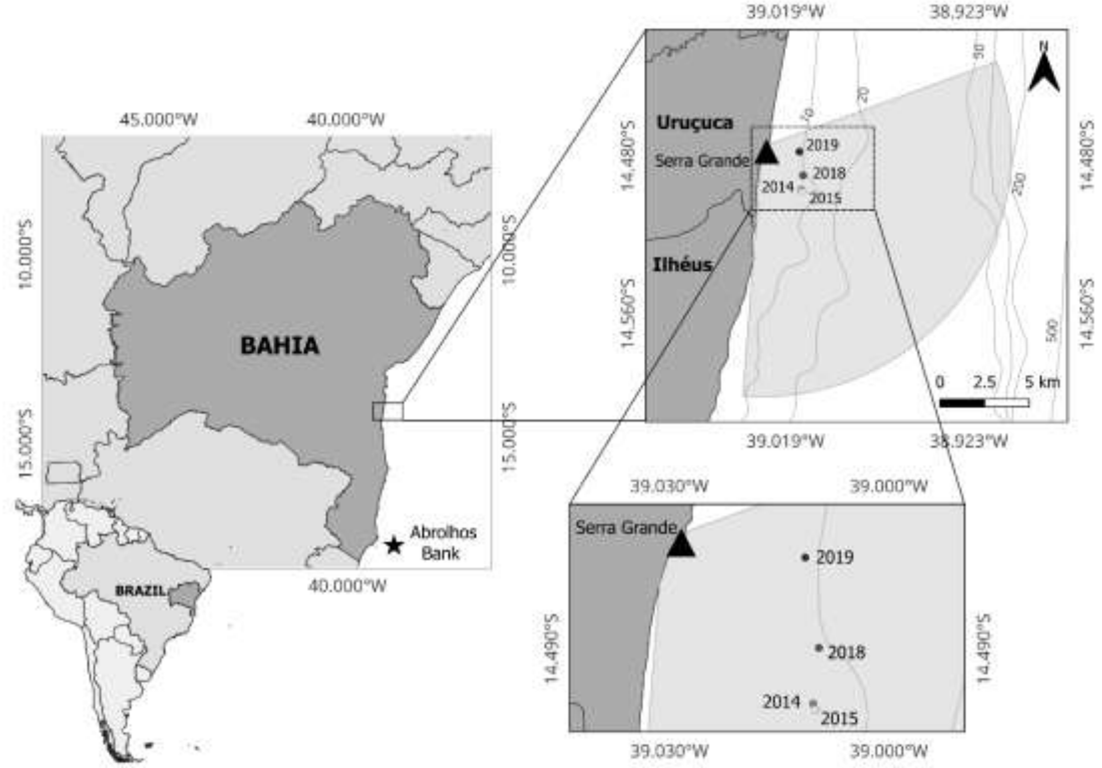


FIGURE 1. Location of the study area in Serra Grande, Bahia state, northeastern Brazil. The triangle identifies the land-based observation platform, at an elevation of 93 m. The lighter gray area corresponds to the region covered by visual monitoring, with 224.5 km^2, where autonomous underwater acoustic recording units (Oceanpods) were deployed on the seabed, with their respective locations marked by a circle indicating the corresponding year.

The land-based observation station is located 315 m from the coastline and elevated 93 m above sea level (14°28'30" S, 39°01'50" W). The visual sampling area was defined within a 15 km radius, between azimuths 70° and 184°, totaling an area of 224.5 km² (Figure 1).

Data collection

Visual monitoring

Visual monitoring was conducted between 7:21 a.m. and 3:00 p.m., generally twice a week, from July to October in 2014, 2015, 2018, and 2019 (see Table S1). We applied the scan sampling method with 1-hour sessions (Gonçalves et al., 2018a; Righi et al., 2024), carried out either in the morning (until 12:00 p.m.) or in the afternoon (after 12:00 p.m.). The objective of this monitoring was to assess fluctuations in the relative abundance of individuals based on the number of humpback whales observed per hour.

Data collection only occurred when sea state was ≤ 4 on the Beaufort scale, with satisfactory visibility of the area (including the horizon) and no rainfall, allowing for clear observation of whale groups throughout the sampling area.

Whales were sighted both with the naked eye and with 7x50 binoculars by 3 to 4 observers, one of whom operated a total station. The total station was used to track group size, composition, behavioral state, and bearing angles. In 2014 and 2015, we used a TOPCON ES105 total station, and in 2018 and 2019, a SPECTRA PRECISION Focus 2, both with 30x magnification and 5' accuracy.

Acoustic monitoring

Acoustic data were collected using different versions of an autonomous underwater recording unit (Oceanpod), developed by the Laboratory of Acoustics and the Environment of the University of São Paulo (LACMAM – USP) (Caldas-Morgan et al., 2015; Sánchez-Gendriz & Padovese, 2017). Passive acoustic monitoring was conducted in 2014, 2015, 2018, and 2019. The Oceanpod was deployed 2.0 to 2.5 km offshore, anchored to the seafloor at depths of approximately 10 m (Figure 1). Data collection took place between July 11 and November 25 (see Table S1). In 2014, recordings were performed only during the daylight hours, with continuous recordings from 7:00 a.m. to

5:00 p.m., conducted in two separate deployments (see Table S1). In the following seasons, the Oceanpod was programmed to record continuously 24 hours per day without interruption (see Table S1).

The sampling rate varied by year: in 2014 and 2015, recordings were made at 11,025 Hz using Oceanpod 1.0, with a system sensitivity of -150 dB re 1 V/µPa (WAV format); in 2018 and 2019, recordings were made at 16,000 Hz using Oceanpod 3.0, with a system sensitivity of -146 dB re 1 V/µPa (WAV format) (see Table S2).

Overlap of monitored areas

The visual and acoustic monitoring areas overlapped, as demonstrated by calculations described in (Campelo et al., manuscript submitted for publication), using the basic sonar equation (SL = RL + TL; Au et al., 2006), where SL is the source level, RL is the received level, and TL is the transmission loss. Although acoustic recorders can register humpback whale singers beyond the 15 km radius used in visual monitoring, this does not compromise the compatibility between methods, as the 15 km area serves as a representative sample of whale number fluctuations in the broader region. The critical aspect for ensuring compatibility is that the acoustic detection range is not significantly smaller than the visual range.

Considering that the Oceanpods were deployed 2 km offshore, the songs needed to be detectable up to at least 13 km. For this evaluation, we used source level (SL) values from the literature (*e.g.,* Au et al., 2006; Girola et al., 2019), received level (RL) estimates based on our dataset, and transmission loss (TL) calculations assuming cylindrical spreading, appropriate for the 10 to 50-meter depths of the study area. The results indicated that the estimated source levels are consistent with published values, confirming that the acoustic detection range is compatible with the visual monitoring area.

Acoustic Analysis

Acoustic Sampling

To evaluate the acoustic metrics—RMS SPL, TOL, ACI, and number of singers—only the days with simultaneous visual and acoustic monitoring were considered. On each of these days, up to two acoustic samples were used: one between 7:00 a.m. and 3:05 p.m., corresponding to the time window of the daytime visual scans, and an additional one between 6:00 p.m. and 6:00 a.m., corresponding to the dusk/night period, which is the peak vocal activity window for singers in the region (Campelo et al., 2020).

The acoustic metrics were derived from the soundscape recorded during the selected segments, which is predominantly composed of the male chorus during the breeding season (Au et al., 2000; Bittencourt et al., 2016; Seger et al., 2016). The chorus is defined as the asynchronous overlap of songs produced by multiple singing males (Figure 2).

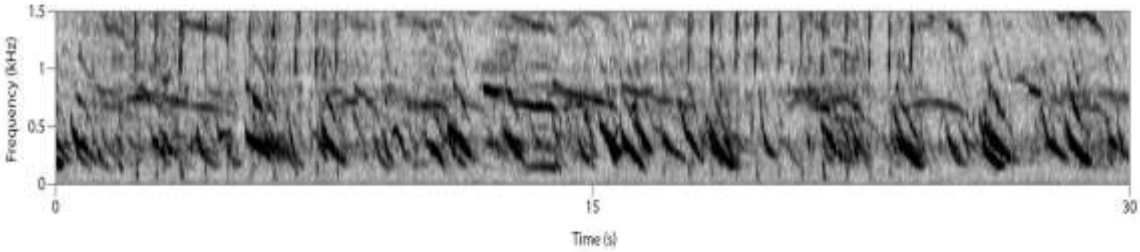


FIGURE 2. Example spectrogram of a humpback whale song chorus recorded in 2018 in Serra Grande, Bahia state (Brazil), ranging from 0 to 1,500 Hz.

With the exception of the estimate of the number of singers, all acoustic metrics were obtained from 10-minute audio segments. During data collection, the recorders were programmed to split recordings into continuous 15-minute files. Therefore, we selected the first 10 minutes of each file, as close as possible to the start time of the visual scan, always matching the visual monitoring schedule. For the dusk or nighttime period, the 10-minute window was defined based on a randomly selected time within that interval.

Data regarding the number of singers were obtained from the study by Campelo (2020), in which the samples were analyzed using Raven Pro 1.6 software, following this configuration: spectrograms with FFT and a Hann window with 1,024 points and 50% overlap. In that study, aural and visual inspections were performed systematically every 30 minutes using 2-second windows, in which the number of singers was counted on a scale from 0 to 4, with 4 representing four or more singers. In the present study, we only used the first two sample windows that coincided with the visual survey schedule. For the dusk or nighttime period, a random time was selected between 6:00 p.m. and 6:00 a.m., and the second window was defined immediately after that starting point.

During these estimations, the signal-to-noise ratio (SNR) was set to a minimum threshold of 10 dB (Charif et al., 2010), and, in some cases, a visual assessment of background noise interference was used as a criterion to exclude sample windows in which a reliable estimate of the number of singers was not possible (Campelo, 2020). Following the same principle, the remaining acoustic metrics were not calculated for time intervals in which the SNR was below the 10 dB threshold, particularly because the SPL values in these segments were likely to be heavily influenced by background noise. This exclusion is justified by the increased likelihood that, during these periods, background noise affected sound pressure levels, compromising the reliability of these metrics as indicators of whale acoustic activity.

Acoustic Data Processing

All audio segments were processed in the R statistical software (R Core Team, 2023). The PAMGuide package was used to calculate RMS SPL and TOL (Merchant et al., 2015), and the Seewave package was used to calculate ACI (Sueur et al., 2008a, b).

For the acoustic analyses, the data were downsampled to a frequency range of 50 to 3,000 Hz, resulting in an analysis bandwidth of 50 to 1,500 Hz. The lower limit was defined to minimize the intrinsic noise of the recording system. This choice was not based on the equipment's self-noise curve, as such information was not provided (Caldas-Morgan et al., 2015). Instead, it was based on the frequency response of the preamplifier, as described by Caldas-Morgan et al. (2015), along with the prior characterization of song units present in our dataset (Gonçalves, 2017). These factors also guided the selection of the upper limit, following the methodological approach adopted by Kügler et al. (2021).

RMS SPL and TOL analyses were performed using the Fast Fourier Transform (FFT), with Hann windows of 1 second and 50% overlap. This setup yielded a temporal resolution of 1 second and a time step of 0.5 seconds. During processing, end-to-end calibration was applied, using the system sensitivity corresponding to the recorder version used in each sampling year (see Table S2). To optimize processing, audio files were split into 10 blocks of 60 seconds each, using the chunksize = 60 function from the PAMGuide package (Merchant et al., 2015). For TOL estimates, we selected the frequency bands from 50 to 1,000 Hz, which best represented the dominant frequencies of the song units described for this population (Gonçalves, 2017). This selection also aimed to minimize the interference from other signals in the Serra Grande soundscape, such as fish choruses (Oliveira, 2021).

For ACI calculations, a Hanning window with 512 points and no overlap was used. This configuration resulted in a temporal resolution of approximately 46 ms for data sampled at 11,025 Hz and 32 ms for data sampled at 16,000 Hz. During processing, data were grouped into 10 blocks of 60 seconds (clusters), and the final ACI value corresponded to the mean of the values obtained for each block.

The acoustic metrics—RMS SPL, TOL, and ACI—were calculated based on formulas established in the literature (*e.g.*, Kügler et al., 2021; Merchant et al., 2015; Pieretti & Morri, 2011).

Statistical Analyses

RMS SPL and TOL metrics were calculated as the median of values obtained from 10-minute samples, following the methodology proposed by Merchant et al. (2015). The median for each sample was considered representative of the sound pressure level during the respective time period. The daytime period is hereafter referred to as daytime, and the dusk/nighttime period is referred to as nighttime. The number of singers was calculated as the mean of the two samples analyzed within each one-hour interval covered by the visual monitoring.

All analyses were conducted in the R statistical software (R Core Team, 2023). The annual mean of relative whale abundance and acoustic metrics (except TOL) were calculated using the dplyr package (Wickham et al., 2023). For data visualization, boxplots were generated using the ggplot2 package (Wickham, 2016). Data normality, stratified by time period, was tested using the Shapiro-Wilk test from base R. Due to the non-normal distribution, differences between time periods were assessed using the non-parametric Wilcoxon test.

The central aim of this study was to investigate whether acoustic metrics could explain the relative abundance of whales. To this end, visual abundance estimates were used as the response variable, while RMS SPL, ACI, and the number of singers were included as predictors in statistical models. The corresponding visual abundance value was then assigned to that day and paired with both the daytime and nighttime estimates.

Sampling effort varied substantially between years (see Figure S3). Due to the unbalanced sampling design, we chose not to include the effect of year in the model, aggregating all years in the analysis.

Models were fitted using the negative binomial distribution to account for overdispersion, identified via the Pearson dispersion test using the check_overdispersion() function from the performance package (Lüdecke et al., 2021). An initial model was fitted including time period (shift) as a fixed effect interacting with the acoustic metrics. The goal was to assess whether the relationship between acoustic metrics and relative abundance of whales varied between daytime and nighttime. Given that humpback whale song can extend across multiple consecutive audio files, potentially compromising sample independence, we performed a temporal autocorrelation test on the model residuals using the acf() function from base R. The test indicated positive autocorrelation, and as a solution, we chose to fit separate models for each time period. This approach allowed us to maintain the analysis by time of day while minimizing the effects of temporal dependence between samples. The models were then compared using AIC, R^2, and p-values. As there were no nighttime data in 2014, this season was excluded from the model.

TOL bands were initially considered as potential predictors of relative whale abundance, with the aim of investigating whether specific frequency ranges were more strongly associated with whale presence. However, due to strong collinearity between bands (see Figure S4), evaluated using the cor.test() function from base R (stats) with Pearson correlation, we chose not to include them in the predictive models. As an alternative, TOL bands were analyzed using time series to identify seasonal patterns in sound pressure levels across frequency bands throughout the monitoring period. In parallel, relative abundance data were plotted over time to enable visual comparison between whale presence patterns and acoustic environment changes across different frequency bands.

Results

Sampling effort

In total, 71 days of simultaneous visual and acoustic monitoring were conducted, and the corresponding data were included in our final dataset (see Table S1 and Figure S3). Of these, 18, 10, 20, and 23 days correspond to the years 2014, 2015, 2018, and 2019, respectively (see Figure S3).

Relative Abundance and acoustic metrics across periods and years

The whale relative abundance registered during the study period ranged from 0 to 19 individuals per hour. A gradual increase was observed over the years, with mean values of 3.4 (SD = 2.8) in 2014, 4.6 (SD = 3.5) in 2015, 7.5 (SD = 5.7) in 2018, and 7.4 (SD = 4.4) in 2019, slightly lower than the previous year (Figure 3).

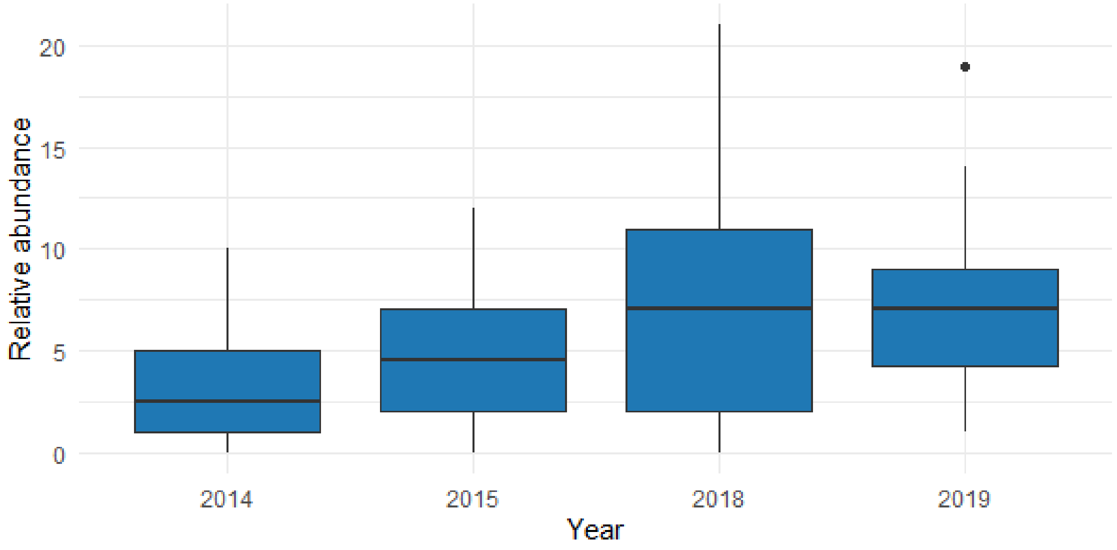


FIGURE 3. Average relative abundance of adults sighted along with their associated standard deviation, in the Serra Grande region, Bahia state, Brazil, during the breeding seasons of 2014, 2015, 2018, and 2019.

Regarding acoustic metrics, 2014 showed the highest mean RMS SPL (ẋ = 108.0; SD = 8.4) (Table 1). However, comparisons between time periods were not possible for that year due to the exclusively daytime sampling effort (see Table S1). In 2015, mean sound pressure levels were higher during the daytime (Figure 4a); however, the Wilcoxon test did not indicate a statistically significant difference between time periods (Table 1). In the subsequent seasons (2018 and 2019), RMS SPL was significantly higher during the nighttime (Table 1). Similar to the pattern observed for relative whale abundance, the mean RMS SPL in 2019 was slightly lower than that recorded in the previous year (Table 1, Figure 4a).

TABLE 1. Wilcoxon test results for differences between time of day in acoustic metrics. The mean (M) and standard deviation (SD) of each acoustic metric (SPL RMS, ACI, and number of singers) by year and time of day (daytime and nighttime) are presented. Significance levels for the p-values are indicated as follows: p ≤ .05 (*), p ≤ .01 (**), and p ≤ .001 (***).

		Daytime		**Nighttime**		**p-value**	
	Acoustic metrics	**M**	**SD**	**M**	**SD**		
2014	RMS SPL (dB re 1 V/µPa)	108	8.37	-	-	-	-
	ACI	86.5	4.15	-	-	-	-
	Number of singers	0.83	0.95	-	-	-	-
2015	RMS SPL (dB re 1 V/µPa)	97.2	11.6	94.3	8.01	.85	
	ACI	82.9	3.2	79.8	3.12	≤ .05	*

	Number of singers	0.9	0.77	1.65	0.85	.06	
2018	RMS SPL (dB re 1 V/µPa)	91.8	5.42	98.7	7.54	≤ .01	**
	ACI	60.6	2.39	58.9	3.15	≤ .01	**
	Number of singers	1.79	1	2.98	0.84	≤ .001	***
2019	RMS SPL (dB re 1 V/µPa)	89.8	8.34	95.7	6.79	≤ .01	**
	ACI	57.3	1.18	57.6	3.21	.26	
	Number of singers	1.17	0.93	1.96	0.99	≤ .01	**

ACI values were higher in the 2014 and 2015 seasons, with a marked decrease in 2018 and 2019 (Figure 4b). In 2015 and 2018, ACI was significantly lower during the nighttime ($p \leq .05$ and $p \leq .01$, respectively) (Table 1), which may suggest a possible negative relationship with whale abundance, given the simultaneous declines observed over the years (Figure 4b). This pattern contrasts with RMS SPL and relative whale abundance, as well as with the number of singers, which increased up to 2018, followed by a decline in 2019 (Figure 4c). For the number of singers, nighttime estimates were significantly higher compared to the daytime in both 2018 ($p \leq .001$) and 2019 ($p \leq .01$), with a marginally significant difference in 2015 ($p = 0.06$).

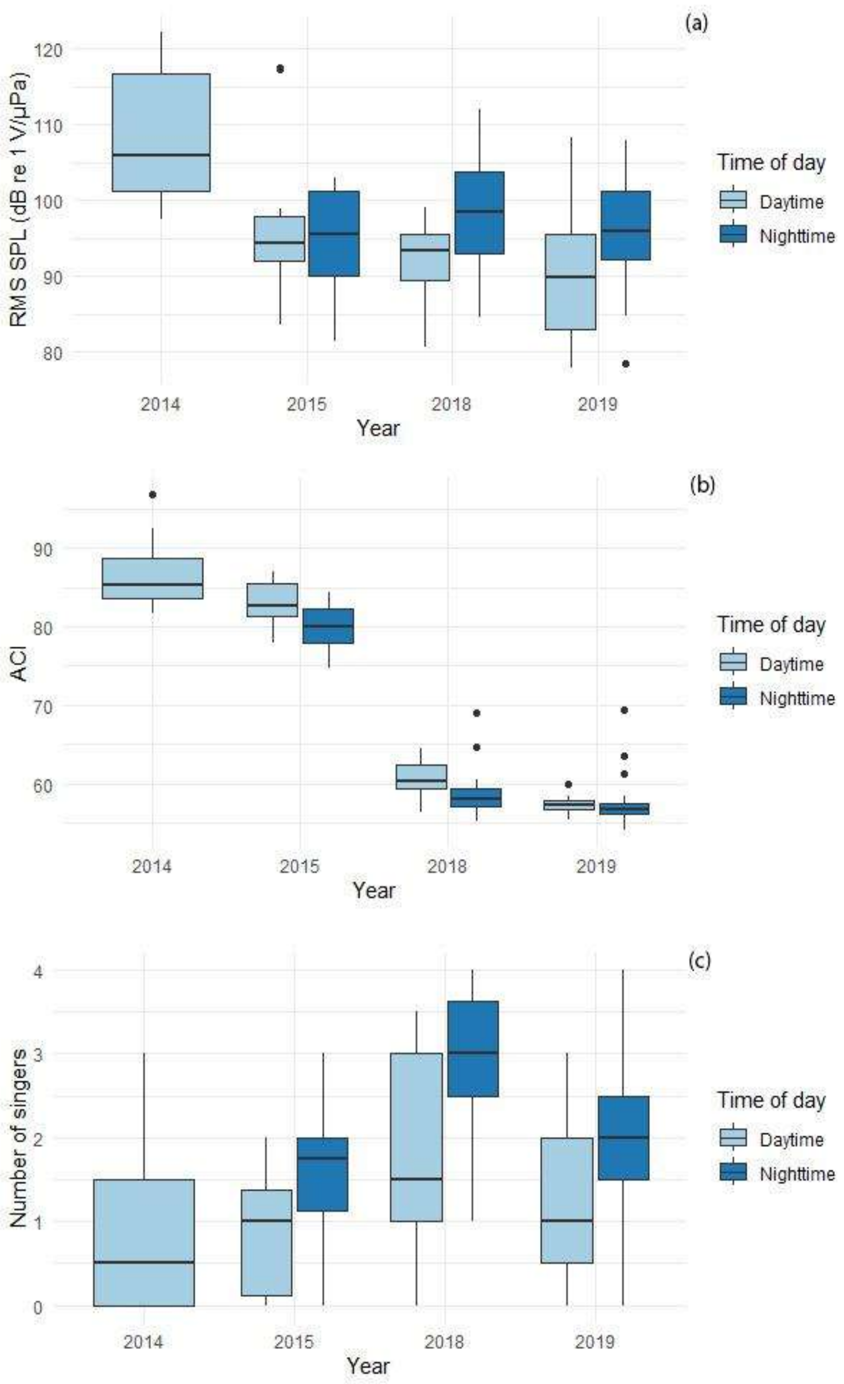


FIGURE 4. Mean values and standard deviations of (a) RMS SPL, (b) ACI, and (c) number of singers in Serra Grande, Bahia, Brazil, during the breeding seasons of 2014, 2015, 2018, and 2019. Data are grouped by time of day: daytime (light blue boxes) and nighttime (dark blue boxes).

Acoustic metrics as predictors of abundance

The daytime model showed better performance (AIC = 282.3) compared to the nighttime model (AIC = 307.2), as well as higher explanatory power ($R^2 = 0.28$) (Table 2). In the daytime model, RMS SPL had a positive and significant effect on whale abundance ($p \leq 0.01$) (Table 2, Figure 5a), while ACI showed a significant negative effect ($p \leq 0.05$) (Table 2, Figure 5b). The number of singers exhibited a marginally significant positive effect ($p = 0.06$) (Table 2, Figure 5c). In the nighttime model, none of the variables were statistically significant, although the effects showed the same pattern of positive relationships for RMS SPL and number of singers, and a negative relationship for ACI (Table 2).

TABLE 2. Summary of the models fitted for the daytime and nighttime periods, presenting AIC values, the explanatory power of the models (Nagelkerke's R^2), and the estimated coefficients for each predictor variable, along with their associated significance levels (p-values). Significance levels are indicated as follows: $p \leq .05$ (*), $p \leq .01$ (**), and $p \leq .001$ (***).

Period	**AIC**	**R^2**	**Variable**	**Estimate**	**p-value**	
Daytime	282.3	0.28	Intercept	0.087	.94	
			RMS SPL	0.032	$p \leq .01$	**
			ACI	-0.023	$p \leq .05$	*
			Number of singers	0.177	.067	
Nighttime	307.2	0.22	Intercept	0.985	.530	
			RMS SPL	0.019	.160	
			ACI	-0.020	.086	
			Number of singers	0.128	.182	

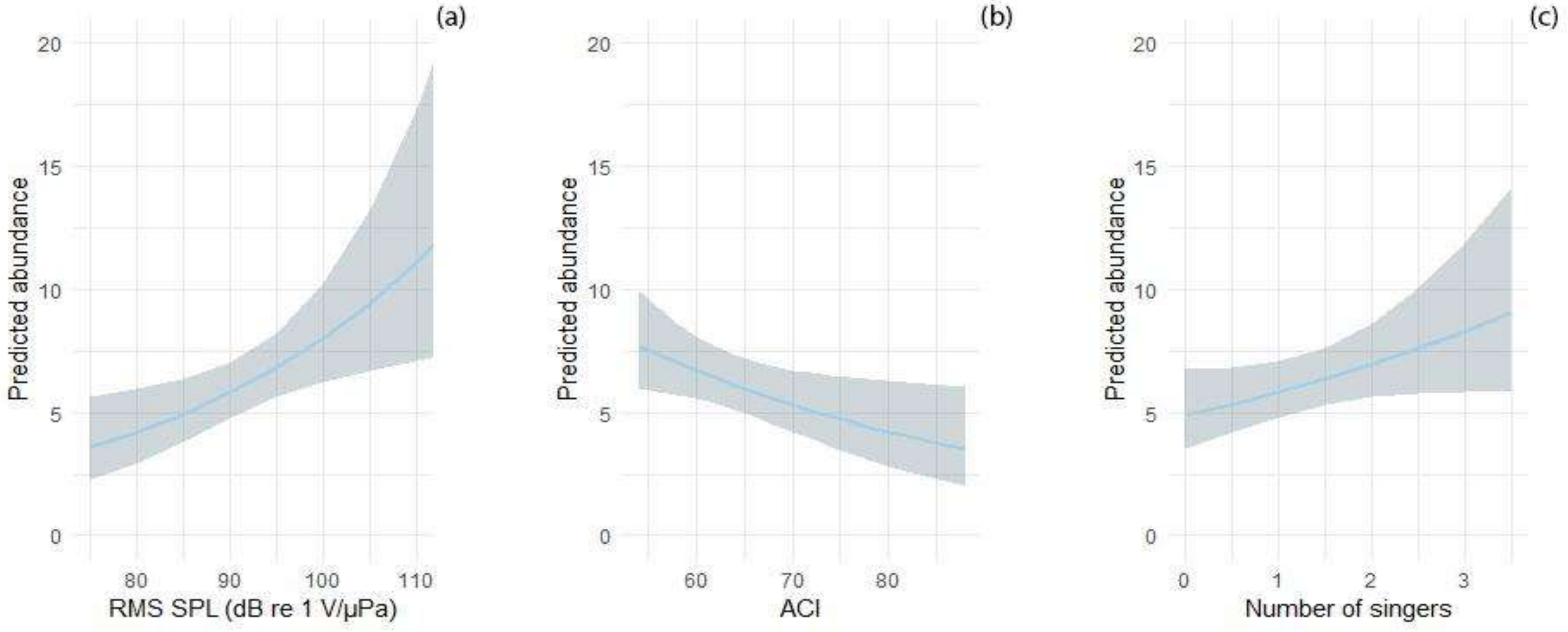


FIGURE 5. Predictions from the negative binomial model fitted for the daytime period, showing the expected humpback whale abundance as a function of (a) RMS SPL (Root Mean Square Sound Pressure Level), (b) ACI (Acoustic Complexity Index), and (c) number of singers. Only the daytime model is presented, as it was the only one with statistically significant effects. Shaded areas represent 95% confidence intervals around the predicted values.

Seasonal dynamics of sound pressure levels and relative whale abundance across years

The analysis of time series allowed for a more detailed examination of the individual contribution of each frequency band to sound pressure levels throughout the season and across different monitoring years (Figure 6). In 2014, the low-frequency bands (50 to 126 Hz) exhibited a more pronounced seasonal pattern compared to the subsequent years. Still in that season, after a decline in sound levels recorded at the end of the reproductive period, a new increasing trend was observed. In the same year, peaks in vocal activity and relative abundance did not coincide precisely: vocal activity peaked earlier than the abundance peak registered through visual scans (Figure 6).

In the following years, a trend toward stabilization was observed in the low-frequency bands (50 to 79 Hz), while seasonal variations became more pronounced in the 158 to 1,000 Hz range, generally showing a decreasing trend over the course of the season. In 2019, the year with the most completed sampling effort, there was a progressive increase in TOL levels and relative whale abundance from the beginning of the season, with peaks occurring in mid-August for sound pressure levels and early September for visual abundance. As in 2014, peaks in acoustic activity preceded the peak in visually observed abundance (Figure 6).

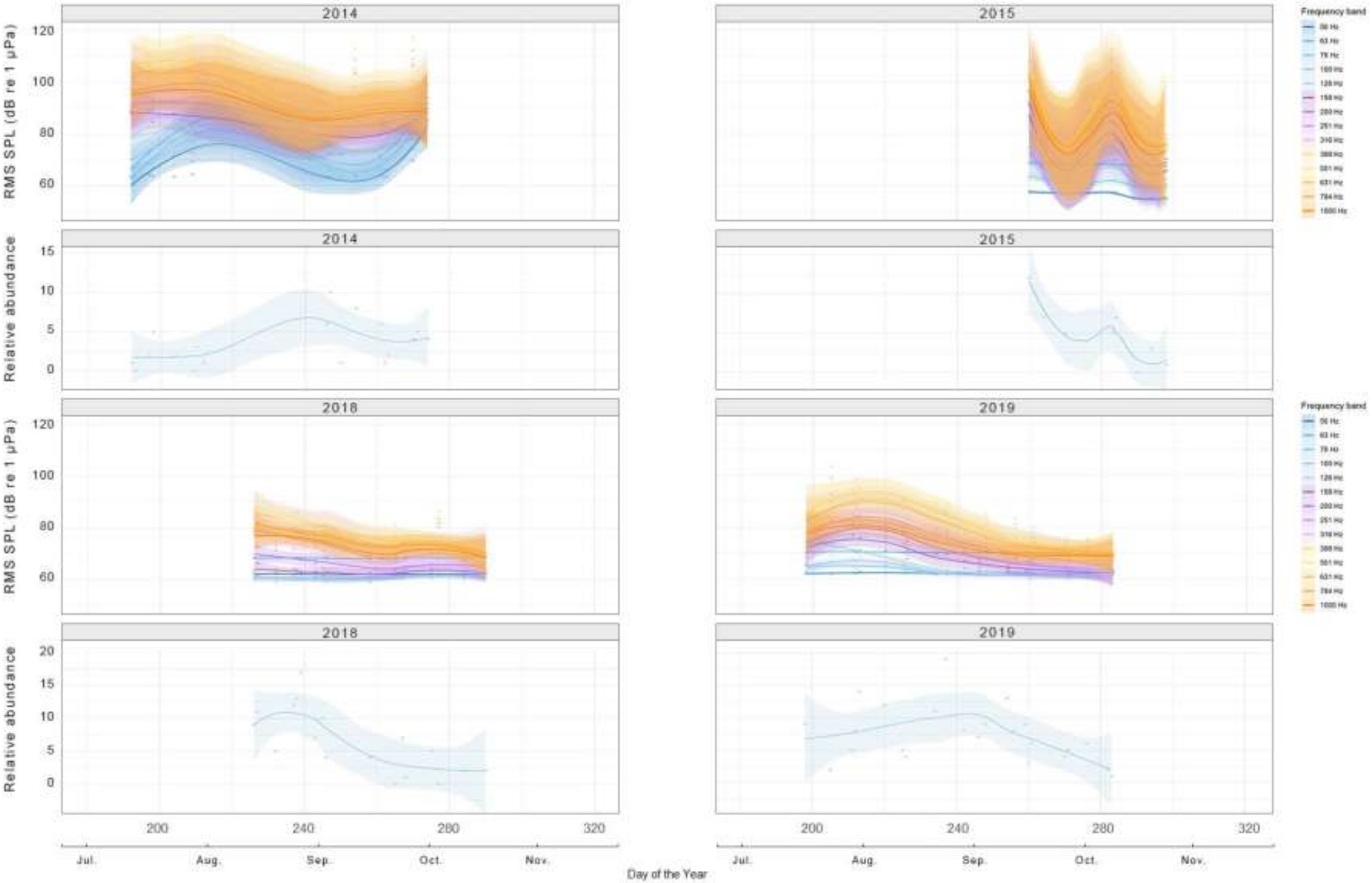

2014
2015
2018
2019
RMS SPL (dB re 1 µPa)
120
100
80
60
Relative abundance
0
5
10
15
20
200
240
280
320
Jul.
Aug.
Sep.
Oct.
Nov.
Day of the Year
Frequency band
50 Hz
63 Hz
79 Hz
100 Hz
126 Hz
158 Hz
200 Hz
251 Hz
316 Hz
398 Hz
501 Hz
631 Hz
794 Hz
1000 Hz

Fig. 6. Daily fluctuations in sound pressure levels (RMS SPL, dB re 1 μPa) across third-octave frequency bands within the range selected for TOL calculations (50–1,000 Hz), based on daytime acoustic recordings during the humpback whale breeding seasons of 2014, 2015, 2018, and 2019 in Serra Grande, Bahia. For each year, the panel is accompanied by modelled estimates of relative whale abundance obtained from visual surveys. A LOESS-smoothed curve was fitted to the acoustic data, with shaded areas representing 95% confidence intervals.

Discussion

The Serra Grande region presents geographical features that are favorable for monitoring humpback whales along the Brazilian coast. The combination of an elevated land-based observation point located near the shoreline and the narrowing of the continental shelf contributes to an extended visual range. In this area, whales tend to concentrate closer to the coast compared to other regions of occurrence in Brazil (Gonçalves et al., 2018a, b). These characteristics make Serra Grande a strategic site for the integrated application of visual and acoustic monitoring, supporting more robust comparative analyses. This is particularly relevant for the present study, which aimed to assess the potential of acoustic metrics as indicators of humpback whale presence, where a gradual increase in the number of individuals was observed over the years (Gonçalves et al., 2018a; Righi et al., 2024). This trend is consistent with the hypothesis that the population has been expanding its range of use to areas previously occupied before the whaling period. Regions where higher whale concentrations have been observed, (Rossi-Santos et al., 2008), such as the Abrolhos Bank (*e.g.*, Andriolo et al., 2010; Bortolotto et al., 2016), may be approaching their carrying capacity, leading to increased use of more northern areas, such as Serra Grande (Righi et al., 2024).

General patterns over the years

Among the acoustic metrics analyzed, the number of singers was the only one that closely followed the pattern of variation in visual abundance across annual means, showing a continuous increase from 2014 to 2018, followed by a slight decrease in 2019. Both RMS SPL and ACI exhibited their highest annual means in 2014; however, while RMS SPL increased again over the subsequent years, the ACI followed a decreasing trend throughout the study period.

The behavior of RMS SPL varied across years and time periods. In 2014 and 2015, the highest sound pressure levels were recorded during the daytime. However, only in 2015 were nighttime data available for comparison, and the difference between periods was not statistically significant. In contrast, in 2018 and 2019, both RMS SPL and the number of singers were significantly higher during the nighttime. This pattern aligns with the period of peak singing activity described for the species (*e.g.,* Au et al., 2000; Cerchio et al., 2010; Español-Jiménez & Schaar, 2018; Homfeldt et al., 2022; Kügler et al., 2024), and may reflect behavioral adjustments that emerge as population density increases, a pattern already described for this species (*e.g.,* Dunlop & Frere, 2023; Noad et al., 2017).

In a study conducted on the eastern coast of Australia, Dunlop and Frere (2023) observed that, as the population increased, the absolute number of singing males also grew. However, the proportion of singing males relative to the total population size declined over time. This suggests that singing behavior, although it increases in absolute terms with population growth, does not maintain a constant proportional relationship, which may reflect shifts in reproductive strategies over time (Dunlop & Frere, 2023).

In light of this, acoustic metrics may reflect broad trends in relative whale abundance, since vocal activity is also influenced by behavioral factors. Despite this, we do not know if this reflex can be directly proportional due to possible changes in behavioral strategies. In any case, it is important to highlight that the study by Dunlop and Frere (2023) was based on a time series of more than a decade, conducted in a migratory corridor, where the behavior of singing males may differ from that observed in breeding grounds (Kügler et al., 2021). Therefore, only long-term monitoring of our area would allow us to determine whether the proportion of singers relative to total abundance also shows a decreasing trend.

So far, our data indicate that the annual mean number of singers tracks variations in relative abundance, including the decline observed in 2019. However, the exclusion of year as a fixed effect in the models prevents a more precise evaluation of the specific effect of this variable, which may be associated with changes in population density over time.

The occurrence of higher RMS SPL levels even in years with lower whale abundance suggests a greater contribution from other biological sources to the acoustic landscape, especially given the low levels of anthropogenic noise in the region (Oliveira, 2021). In the marine environment, soundscape studies have mainly highlighted the contributions of sounds produced by crustaceans, fishes, and cetaceans, which can vary across daily and seasonal patterns and respond to changes in the sound environment (*e.g.*, Bittencourt et al., 2016; Buscaino et al., 2016; Lammers et al., 2008; Pieretti et al., 2017; Radford et al., 2008).

One possible explanation for our results is that the increasing population density of whales and the intensification of their singing may have influenced the acoustic activity of other marine species. In a soundscape study conducted in a humpback whale breeding area in the South Atlantic, Bittencourt et al. (2016) identified fish choruses as a key component of the local biophony, occurring year-round but with reduced intensity during the winter—precisely when male whale songs dominated the acoustic environment. This suggests that the presence and vocal behavior of whales may modulate the contribution of other biological sources to the soundscape.

In the case of Serra Grande, it is plausible that the progressive increase in whale occupancy and vocal activity over the years has altered the local acoustic profile. Among the possible biological contributors to RMS SPL variability, fishes emerge as the most likely candidates, especially considering that the frequency range analyzed in this study (50–1,500 Hz) excludes most crustacean-generated sounds but fully or partially encompasses the frequency bands of both fish choruses and whale songs (Oliveira, 2021). A better understanding of this interaction could be achieved through a year-round assessment of fish choruses in the study area, allowing for the identification of temporal patterns and potential shifts in their acoustic behavior in response to whale presence.

Acoustic metrics as predictors of abundance

The application of predictive models allowed us to evaluate whether the analyzed acoustic metrics can explain the variations in humpback whale abundance and to assess the effect of period of day in these comparisons. With the exception of ACI, both RMS SPL and the number of singers showed a positive relationship with abundance. Although annual means indicated greater vocal activity during the nighttime—as previously discussed—the model fitted for the daytime period presented better performance in terms of fit and explanatory power.

During the daytime period, RMS SPL and ACI were statistically significant in explaining the relative abundance of humpback whales, while the number of singers showed a positive trend, though only marginally significant. It is well established that humpback whales exhibit higher acoustic activity at night—a pattern previously described for the Serra Grande region (Campelo et al., manuscript submitted for publication) and also observed in other breeding areas (*e.g.,* Au et al., 2000; Cerchio et al., 2010; Español-Jiménez & Schaar, 2018; Homfeldt et al., 2022; Kügler et al., 2024).

The lack of statistical significance for the number of singers in the model, despite its alignment with annual abundance patterns, may be related to the limitations of its discrete scale, particularly because values equal to or greater than four singers were grouped into a single class. This likely reduced the metric’s sensitivity in contexts of high vocal density. Thus, although the number of singers generally reflects temporal variations in abundance, the statistical association between the number of singers and whale abundance may not be significant in the models. In other words, the number of singers may follow the same trend as relative abundance, but the limited resolution of the metric reduces its ability to capture quantitative nuances. As a result, modeling abundance based on this variable may not reveal a strong statistical association, even though the two are biologically related.

Finally, it is important to highlight that the structural complexity of the song may also influence the performance of acoustic metrics. The ACI was developed to represent the complexity of biological sounds in soundscapes, based on the variation in signal intensity over time within different frequency bands (Pieretti et al., 2011). Rather than quantifying absolute energy, the index accounts for short-term fluctuations in acoustic energy (Eldridge et al., 2018; Farina et al., 2011). Although ACI has been shown to correlate positively with species richness (*e.g.,* Davies et al., 2020) and acoustic activity in marine environments (*e.g.,* Buscaino et al., 2016; Pieretti et al., 2017), its performance as an ecological indicator is still considered context-dependent. A recent review focused on birds showed that ACI results can vary considerably depending on signal structure, soundscape type, and species composition (Bateman & Uzal, 2022). In benthic environments, Davies et al. (2020) found that the relationship between ACI and species richness varied across years, further highlighting the influence of seasonal and interannual changes in the soundscape on the index's performance.

In the case of humpback whales, this variability is even more relevant. The species' song has a hierarchical organization composed of three levels: sound units are grouped into phrases, repeated phrases form themes, and the succession of different themes composes the full song (Cholewiak et al., 2013; Payne & McVay, 1971). This structure is dynamic and changes over time through the addition, removal, reordering, or alteration of sound units—either individually or in combination—which can directly affect song complexity (*e.g.,* Allen et al., 2018; Garland et al., 2011; Gonçalves et al., 2023; Tougaard & Eriksen, 2006; Winn & Winn, 1978).

The influence of this dynamic context is evident in the results of the present study, particularly when considering the abrupt shift in the song of the Brazilian humpback whale population (BSA) described by Gonçalves et al. (2023) between 2017 and 2018. This transition was marked by a notable reduction in the number of sound unit types and, consequently, a simplification of vocal structure. In line with this change, we observed a significant decline in acoustic complexity in 2018, which persisted into the following year. Changes of this nature can compromise the sensitivity of the ACI to detect increases in acoustic activity, as simplified songs—even when produced by a larger number of individuals—tend to generate less signal intensity fluctuation and, therefore, lower or more stable index values. These results reinforce that structural changes in humpback whale songs directly affect ACI performance, limiting its effectiveness as an indicator of abundance.

Daily variation in sound pressure levels and their relationship with abundance

The seasonal presence of humpback whales in the region follows a consistent pattern of increasing numbers from July, peaking between late August and early September, followed by a gradual decline in sightings until the end of October (Gonçalves et al., 2018a; Righi et al., 2024). This migratory behavior is well documented in other breeding areas of the species (*e.g.,* Baker & Herman, 1981; Frankel & Clark, 2002; Martins et al., 2001; Mattila et al., 1994; Morete et al., 2008; Smultea, 1994) and reflects the gradual arrival of individuals to the breeding grounds, followed by their departure at the end of the season (Dawbin, 1997).

The analysis of time series based on the TOL (third-octave levels) allowed a more detailed assessment of the seasonal variation in sound pressure levels by decomposing signal energy across frequency bands within the 50 to 1,000 Hz range. Unlike RMS SPL, which considers the entire spectrum, TOL enables identification of specific patterns by frequency band (Merchant et al., 2015). Overall, a declining trend in TOL levels was observed as the season progressed. However, shifts in patterns between frequency bands and years were noted.

The year 2014 stood out as the only one in which the lowest frequency bands—particularly the 50 Hz band—showed a distinct seasonal pattern, with elevated levels at the beginning of the season, a peak prior to the period of highest visual abundance, and an increasing trend in October when abundance was already declining. In contrast, bands between 158 and 1,000 Hz had higher levels at the season's start followed by a gradual decrease—a pattern repeated in subsequent seasons.

Although the lower frequency bands did not exhibit seasonal variation in later years, their relevance for characterizing the species' acoustic environment should not be dismissed. Gonçalves (2017) reported, for 2014, the presence of song units with energy peaks at 50 Hz—a frequency absents in the vocal structures described for 2015, which shifted energy to higher frequency bands. This change may reflect a vocal reorganization over time, consistent with the dynamic nature of humpback whale song (*e.g.*, Allen et al., 2018; Garland et al., 2011; Gonçalves et al., 2023; Tougaard & Eriksen, 2006; Winn & Winn, 1978). Additionally, the predominance of energy in the lower bands in 2014 may indicate a greater contribution from other components of the acoustic landscape, such as the fish choruses discussed earlier.

In seasons with broader temporal coverage, such as 2019, TOL levels in the 158 to 1,000 Hz bands showed an increasing pattern until August, followed by a progressive decline toward the end of the season, reflecting trends observed in previous years. In other breeding areas, humpback whale song has been identified as the primary noise source above 200 Hz (*e.g.,* Širovic et al., 2013), and the consistency of this pattern across seasons suggests that this frequency range directly captures the species' vocal activity. However, the peak in acoustic activity preceded the peak in visual abundance, suggesting that singing intensifies soon after arrival to the breeding area and decreases as the season advances. This temporal lag reinforces that SPL—and consequently TOL—reflect not only the presence of individuals but also their behavioral state.

Overall, the frequency band analysis demonstrated that acoustic energy throughout the season is not homogeneous. Bands between 158 and 1,000 Hz were more consistent across years and more closely aligned with visual abundance patterns. Conversely, the stronger contribution of lower bands in 2014 highlights the need to consider seasonal particularities.

Conclusion

The evaluated acoustic metrics exhibited varying levels of sensitivity and explanatory power in relation to the relative abundance of humpback whales. The Acoustic Complexity Index (ACI) showed a more unstable performance, influenced by interannual variations in song structure, which limits its applicability as a direct abundance indicator. In contrast, both the number of singers and RMS SPL proved to be good predictors, albeit with specific limitations.

The number of singers consistently aligned with population patterns over the years, however, its discrete and limited scale reduced statistical sensitivity in the models. Although it reflects biologically relevant patterns, the robustness of this sensitivity requires confirmation through assessments over broader temporal scales. RMS SPL demonstrated sufficient sensitivity to correlate with abundance but should be interpreted cautiously, especially in low population density contexts, as it may also reflect acoustic activity from other species vocalizing within the humpback whale song frequency range.

In summary, combining the number of singers and RMS SPL enhances the explanatory power of these metrics, allowing the retrieval of relevant temporal information across different scales — interannual, seasonal, and daily. While they do not replace traditional population estimation methods, due to their sensitivity to behavioral variations, these metrics represent a promising complementary tool in passive acoustic monitoring. When interpreted together, they effectively compensate for each other's limitations: RMS SPL captures broader fluctuations in the soundscape, whereas the number of singers offers a direct estimate of species-specific vocal activity. In this context, visually confirmed singer counts help qualify the interpretation of SPL, assisting in distinguishing between different biological sound sources. Therefore, the combined use of these metrics, interpreted alongside ecological and behavioral information, supports a more integrated and robust understanding of humpback whale population and acoustic dynamics.

Reference

Allen, J. A., Garland, E. C., Dunlop, R. A., & Noad, M. J. (2018). Cultural revolutions reduce complexity in the songs of humpback whales. *Proceedings of the Royal Society B: Biological Sciences, 285(1891),* Article 20182088. https://doi.org/10.1098/rspb.2018.2088

Andriolo, A., Kinas, P. G., Engel, M. H., Martins, C. C. A., & Rufino, A. M. (2010). Humpback whales within the Brazilian breeding ground: distribution and population size estimate. *Endangered Species Research*, *11*(3), 233–243. https://doi.org/10.3354/esr00282

Au, W. W., Mobley, J., Burgess, W. C., Lammers, M. O., & Nachtigall, P. E. (2000). Seasonal and diurnal trends of chorusing humpback whales wintering in waters off western Maui. *Marine Mammal Science*, *16*(3), 530–544. https://doi.org/10.1111/j.1748-7692.2000.tb00949.x

Au, W. W., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H., & Andrews, K. R. (2006). Acoustic properties of humpback whale songs. *The Journal of the Acoustical Society of America*, *120*(2), 1103–1110. https://doi.org/10.1121/1.2211547

Baker, C. S., & Herman, L. M. (1981). Migration and local movement of humpback whales (*Megaptera novaeangliae*) through Hawaiian waters. *Canadian Journal of Zoology, 59*(3), 460–469. https://doi.org/10.1139/z81-067

Barlow, J., & Taylor, B. L. (2005). Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. *Marine Mammal Science, 21*(3), 429–445. https://doi.org/10.1111/j.1748-7692.2005.tb01242.x

Bateman, J., & Uzal, A. (2022). The relationship between the Acoustic Complexity Index and avian species richness and diversity: A review. *Bioacoustics, 31*(5), 614–627. https://doi.org/10.1080/09524622.2021.2010598

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. https://doi.org/10.1016/j.dsr.2016.06.001

Bittencourt, L., Soares-Filho, W., de Lima, I. M. S., Pai, S., Lailson-Brito Jr., J., Barreira, L. M., Azevedo, A. F., & Guerra, L. A. A. (2018). Mapping cetacean sounds using a passive acoustic monitoring system towed by an autonomous Wave Glider in the Southwestern Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers, 142*, 58–68. https://doi.org/10.1016/j.dsr.2018.10.006

Bortolotto, G. A., Danilewicz, D., Andriolo, A., Secchi, E. R., & Zerbini, A. N. (2016). Whale, whale, everywhere: increasing abundance of western South Atlantic humpback whales (*Megaptera novaeangliae*) in their wintering grounds. *PLoS One*, *11*(10), Article e0164596. https://doi.org/10.1371/journal.pone.0164596

Buscaino, G., Ceraulo, M., Pieretti, N., Corrias, V., Farina, A., Filiciotto, F., Maccarrone, V., Grammauta, R., Caruso, F., Alonge, G., & Mazzola, S. (2016). Temporal patterns in the soundscape of the shallow waters of a Mediterranean marine protected area. *Scientific Reports*, *6*, Article 34230. https://doi.org/10.1038/srep34230

Caldas-Morgan, M., Alvarez-Rosario, A., & Padovese, L. R. (2015). An autonomous underwater recorder based on a single board computer. *PLOS ONE*, *10*(5), Article e0130297. https://doi.org/10.1371/journal.pone.0130297

Campelo, M. S. (2020). *Atividade vocal dos cantores de baleia-jubarte (Megaptera novaeangliae) em uma área reprodutiva no sul da Bahia: construindo uma linha de base antes da instalação de um complexo portuário* (Dissertação de mestrado, Universidade Estadual de Santa Cruz). Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade. Ilhéus, Bahia, Brasil.

Campelo, M. S., Baumgarten, J. E., Sousa-Lima, R. S., Padovese, L. R., Heming, N. M., & Gonçalves, M. I. C. (manuscript submitted for publication). *Activity patterns of humpback whale singers on a coastal breeding area in northeast Brazil*. Manuscript submitted for publication.

Cerchio, S., Collins, T., Strindberg, S., Bennett, C., & Rosenbaum, H. (2010). Humpback whale singing activity off northern Angola: An indication of the migratory cycle, breeding habitat, and impact of seismic surveys on singer number in Breeding Stock B1. *International Whaling Commission Scientific Committee*, Agadir, Morocco.

Charif, R., Waack, A., & Strickman, L. (2010). *Raven Pro 1.4 user's manual*. Cornell Lab of Ornithology. https://doi.org/10.1371/journal.pone.0130297

Cholewiak, D. M., Sousa-Lima, R. S., & Cerchio, S. (2013). Humpback whale song hierarchical structure: Historical context and discussion of current classification issues. *Marine Mammal Science, 29*(3), E312–E332. https://doi.org/10.1111/mms.12005

Clapham, P. J., & Mattila, D. K. (1990). Humpback whale songs as indicators of migration routes. *Marine Mammal Science, 6*(2), 155–160. https://doi.org/10.1111/j.1748-7692.1990.tb00238.x

Conn, P. B., Johnson, D. S., & Boveng, P. L. (2015). On extrapolating past the range of observed data when making statistical predictions in ecology. *PLOS ONE, 10*(10), Article e0141416. https://doi.org/10.1371/journal.pone.0141416

Darling, J. D., & Sousa-Lima, R. S. (2006). Songs indicate interaction between humpback whale (*Megaptera novaeangliae*) populations in the western and eastern South Atlantic Ocean. *Marine Mammal Science, 21*(3), 557–566. https://doi.org/10.1111/j.1748-7692.2005.tb01249.x

Darling, J. D., Jones, M. E., & Nicklin, C. P. (2006). Humpback whale songs: Do they organize males during the breeding season? *Behaviour, 143*(9), 1051–1101. https://doi.org/10.1163/156853906778607381

Davies, B. F., Attrill, M. J., Holmes, L., Rees, A., Witt, M. J., & Sheehan, E. V. (2020). Acoustic Complexity Index to assess benthic biodiversity of a partially protected area in the southwest of the UK. *Ecological Indicators, 111*, Article 106019. https://doi.org/10.1016/j.ecolind.2019.106019

Dawbin, W. H. (1997). Temporal segregation of humpback whales during migration in southern hemisphere waters. *Memoirs of the Queensland Museum, 42*, 105–138.

Dunlop, R., & Frere, C. (2023). Post-whaling shift in mating tactics in male humpback whales. *Communications Biology, 6*(1), Article 162. https://doi.org/10.1038/s42003-023-04509-7

Eldridge, A., Guyot, P., Moscoso, P., Johnston, A., Eyre-Walker, Y., & Peck, M. (2018). Sounding out ecoacoustic metrics: Avian species richness is predicted by acoustic indices in temperate but not tropical habitats. *Ecological Indicators, 95*, 939–952. https://doi.org/10.1016/j.ecolind.2018.06.012

Español-Jiménez, S., & Vander-Schaar, M. (2018). First record of humpback whale songs in Southern Chile: Analysis of seasonal and diel variation. *Marine Mammal Science, 34*(3), 718–733. https://doi.org/10.1111/mms.12477

Fantle-Lepczyk, J., Taylor, A., Duffy, D. C., Crampton, L. H., & Conant, S. (2018). Using population viability analysis to evaluate management activities for an endangered Hawaiian endemic, the Puaiohi (*Myadestes palmeri*). *PLOS ONE, 13*(6), Article e0198952. https://doi.org/10.1371/journal.pone.0198952

Farina, A., Pieretti, N., & Piccioli, L. (2011). The soundscape methodology for long-term bird monitoring: A Mediterranean Europe case-study. *Ecological Informatics, 6*(6), 354–363. https://doi.org/10.1016/j.ecoinf.2011.07.004

Frankel, A. S., & Clark, C. W. (2002). ATOC and other factors affecting the distribution and abundance of humpback whales (*Megaptera novaeangliae*) off the North shore of Kauai. *Marine Mammal Science, 18*(3), 644–662. https://doi.org/10.1111/j.1748-7692.2002.tb01064.x

Garland, E. C., Goldizen, A. W., Rekdahl, M. L., Constantine, R., Garrigue, C., Hauser, N. D., Poole, M. M., Robbins, J. & Noad, M. J. (2011). Dynamic horizontal cultural transmission of humpback whale song at the ocean basin scale. *Current Biology*, *21*, 687–691. https://doi.org/10.1016/j.cub.2011.03.019

Girola, E., Noad, M. J., Dunlop, R. A., & Cato, D. H. (2019). Source levels of humpback whales decrease with frequency suggesting an air-filled resonator is used in sound production. *The Journal of the Acoustical Society of America*, *145*(2), Article 869. https://doi.org/10.1121/1.5090492

Glockner, D. A. (1983). Determining the sex of humpback whales (*Megaptera novaeangliae*) in their natural environment. In R. Payne (Ed.), *Communication and behavior of whales* (pp. 447–464). Westview Press.

Gonçalves, M. I. C. (2017). *Uso de habitat, comportamento e emissões acústicas das baleias-jubarte (Megaptera novaeangliae) na região de Serra Grande – Bahia* [Doctoral dissertation, Universidade Estadual de Santa Cruz]. Graduate Program in Ecology and Biodiversity Conservation, Ilhéus, Bahia, Brazil.

Gonçalves, M. I. C., Djokic, D., Baumgarten, J. E., Marcondes, M. C. C., Padovese, L. R., Eugenio, L. D. S., & Sousa-Lima, R. S. (2023). Abrupt change in humpback whale song from Brazil suggests cultural revolutions may occur in the South Atlantic. *Marine Mammal Science*, 1–13. https://doi.org/10.1111/mms.13093

Gonçalves, M. I. C., Sousa-Lima, R. S., Teixeira, N. N., Morete, M. E., Carvalho, G. H., Ferreira, H. M., & Baumgarten, J. E. (2018a). Low latitude habitat use patterns of a recovering population of humpback whales. *Journal of the Marine Biological Association of the United Kingdom*, *98*(5), 1087–1096. https://doi.org/10.1017/S0025315418000255

Gonçalves, M. I. C., Sousa-Lima, R. S., Teixeira, N. N., Carvalho, G. H., Schiavon, D. D., & Baumgarten, J. E. (2018b). Movement patterns of humpback whales (*Megaptera novaeangliae*) reoccupying a Brazilian breeding ground. *Biota Neotropica, 18*(4), Article e20180567. https://doi.org/10.1590/1676-0611-BN-2018-0567

Hare, M. P., Nunney, L., Schwartz, M. K., Ruzzante, D. E., Burford, M., Waples, R. S., Ruegg, K., & Palstra, F. (2011). Understanding and estimating effective population size for practical application in marine species management. *Conservation Biology, 25*(3), 438–449. https://doi.org/10.1111/j.1523-1739.2010.01637.x

Hayes, L. D., & Schradin, C. (2017). Long-term field studies of mammals: What the short-term study cannot tell us. *Journal of Mammalogy, 98*(3), 600–602. https://doi.org/10.1093/jmammal/gyx027

Herman, L. M. (2017). The multiple functions of male song within the humpback whale (*Megaptera novaeangliae*) mating system: Review, evaluation, and synthesis. *Biological Reviews, 92*(3), 1795–1818. https://doi.org/10.1111/brv.12309

Herman, L. M., & Tavolga, W. N. (1980). The communication systems of cetaceans. In L. M. Herman (Ed.), *Cetacean behavior: Mechanisms and functions* (pp. 149–209). Wiley Interscience.

Homfeldt, T. N., Risch, D., Stevenson, A., & Henry, L. A. (2022). Seasonal and diel patterns in singing activity of humpback whales migrating through Bermuda. *Frontiers in Marine Science, 9*, Article 941793. https://doi.org/10.3389/fmars.2022.941793

Howe, M., & Lammers, M. O. (2021). Investigating the diel occurrence of odontocetes around the Maui Nui Region using passive acoustic techniques. *Pacific Science, 75*(1), 147–161. https://doi.org/10.2984/75.1.7

Instituto Brasileiro de Geografia e Estatística – IBGE. (2011). *Atlas geográfico das zonas costeiras e oceânicas do Brasil*. IBGE.

Johnston, D. W., McDonald, M., Polovina, J., Domokos, R., Wiggins, S., & Hildebrand, J. (2008). Temporal patterns in the acoustic signals of beaked whales at Cross Seamount. *Biology Letters*, *4*(2), 208–211. https://doi.org/10.1098/rsbl.2007.0614

Kaschner, K., Quick, N. J., Jewell, R., Williams, R., & Harris, C. M. (2012). Global coverage of cetacean line-transect surveys: Status quo, data gaps and future challenges. *PLOS ONE, 7*(9), Article e44075. https://doi.org/10.1371/journal.pone.0044075

Kobayashi, N., Okabe, H., Higashi, N., Miyahara, H., & Uchida, S. (2021). Diel patterns in singing activity of humpback whales in a winter breeding area in Okinawan (Ryukyuan) waters. *Marine Mammal Science*, *37*(3), 982–992. https://doi.org/10.1111/mms.12790

Kügler, A., Lammers, M. O., Pack, A. A., Tenorio-Hallé, L., & Thode, A. M. (2024). Diel spatio-temporal patterns of humpback whale singing on a high-density breeding ground. *Royal Society Open Science*, *11*(1), Article 230279. https://doi.org/10.1098/rsos.230279

Kügler, A., Lammers, M. O., Zang, E. J., & Pack, A. A. (2021). Male humpback whale chorusing in Hawaiʻi and its relationship with whale abundance and density. *Frontiers in Marine Science*, *8*, Article 735664. https://doi.org/10.3389/fmars.2021.735664

Lammers, M. O., Brainard, R. E., Au, W. W. L., Mooney, T. A., & Wong, K. B. (2008). An ecological acoustic recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. *The Journal of the Acoustical Society of America*, *123*(3), 1720–1728. https://doi.org/10.1121/1.2836780

Lüdecke, D., Ben-Shachar, M., Patil, I., & Waggoner, P. (2021). *performance: An R package for assessment, comparison and testing of statistical models*. *Journal of Open Source Software*, *6*(60), Article 3139. https://doi.org/10.21105/joss.03139

Martin, S. W., Marques, T. A., Thomas, L., Morrissey, R. P., Jarvis, S., DiMarzio, N., Moretti, D., & Mellinger, D. K. (2013). Estimating minke whale (*Balaenoptera acutorostrata*) boing sound density using passive acoustic sensors. *Marine Mammal Science*, *29*(1), 142–158. https://doi.org/10.1111/j.1748-7692.2011.00561.x

Martins, C. C. A., Morete, M. E., Engel, M. H., Freitas, A. C., Secchi, E. R., & Kinas, P. G. (2001). Aspects of habitat use patterns of humpback whales in the Abrolhos Bank, Brazil, breeding ground. *Memoirs of the Queensland Museum*, *47*, 563–570. http://repositorio.furg.br/handle/1/1106

Mattila, D. K., Clapham, P. J., Vásquez, O., & Bowman, R. S. (1994). Occurrence, population composition, and habitat use of humpback whales in Samana Bay, Dominican Republic. *Canadian Journal of Zoology*, *72*(11), 1898–1907. https://doi.org/10.1139/z94-258

Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., & Matsumoto, H. (2007). An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography*, *20*(4), 36–45. https://doi.org/10.5670/oceanog.2007.03

Mercado, E. I., Herman, L. M., & Pack, A. A. (2005). Song copying by humpback whales: Themes and variations. *Animal Cognition*, *8*(2), 93–102. https://doi.org/10.1007/s10071-004-0238-7

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution, 6*(3), 257–265. https://doi.org/10.1111/2041-210X.12330

Mobley, J. R., Grotefendt, R. A., Forestell, P. H., & Frankel, A. S. (1999). *Results of aerial surveys of marine mammals in the major Hawaiian Islands (1993–98): Final report to the Acoustic Thermometry of Ocean Climate Marine Mammal Research Program (ATOC MMRP)* (39 pp.). Social Sciences, University of Hawaii–West Oahu.

Mohammed, U. L., & Mohd Sah, S. A. (2024). Population size and conservation status of large terrestrial mammals in a West African protected area. *African Journal of Ecology, 62*(1), Article e13241. https://doi.org/10.1111/aje.13241

Morete, M. E., Bisi, T. L., Pace, R. M., & Rosso, S. (2008). Fluctuating abundance of humpback whales (*Megaptera novaeangliae*) in a calving ground off coastal Brazil. *Journal of the Marine Biological Association of the United Kingdom, 88*(6), 1229–1235. https://doi:10.1017/s0025315408000362

Munari, D. P., Keller, C., & Venticinque, E. M. (2011). An evaluation of field techniques for monitoring terrestrial mammal populations in Amazonia. *Mammalian Biology, 76*, 401–408. https://doi.org/10.1016/j.mambio.2011.02.007

Myers, H. J., Olsen, D. W., Matkin, C. O., Horstmann, L. A., & Konar, B. (2021). Passive acoustic monitoring of killer whales (*Orcinus orca*) reveals year-round distribution and residency patterns in the Gulf of Alaska. *Scientific Reports, 11*(1), Article 20284. https://doi.org/10.1038/s41598-021-99668-0

Noad, M. J., & Cato, D. H. (2007). Swimming speeds of singing and non-singing humpback whales during migration. *Marine Mammal Science, 23*(3), 481–495. https://doi.org/10.1111/j.1748-7692.2007.02414.x

Noad, M. J., Cato, D. H., Bryden, M. M., Jenner, M. N., & Jenner, K. C. S. (2000). Cultural revolution in whale songs. *Nature*, *408*(6812), Article 537. https://doi.org/10.1038/35046199

Noad, M. J., Dunlop, R. A., & Mack, A. K. (2017). Changes in humpback whale singing behavior with abundance: Implications for the development of acoustic surveys of cetaceans. *The Journal of the Acoustical Society of America*, *142*(3), 1611–1618. https://doi.org/10.1121/1.5001502

Oliveira, T. F. de. (2021). *Paisagem acústica submarina de um sítio reprodutivo da baleia-jubarte no Brasil* [Master's thesis, Universidade Estadual de Santa Cruz]. Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Ilhéus, Bahia, Brasil.

Papale, E., Alonge, G., Grammauta, R., Ceraulo, M., Giacoma, C., Mazzola, S., & Buscaino, G. (2020). Year-round acoustic patterns of dolphins and interaction with anthropogenic activities in the Sicily Strait, central Mediterranean Sea. *Ocean & Coastal Management, 197,* Article 105320. https://doi.org/10.1016/j.ocecoaman.2020.105320

Payne, K. B., Tyack, P., & Payne, R. S. (1983). Progressive changes in the songs of humpback whales (*Megaptera novaeangliae*): A detailed analysis of two seasons in Hawaii. In R. S. Payne (Ed.), *Communication and behavior of whales* (pp. 9–57). Westview Press.

Payne, R. S., & McVay, S. (1971). Songs of humpback whales. *Science, 173*(3997), 585–597. https://doi.org/10.1126/science.173.3997.585

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. https://doi.org/10.1016/j.ecolind.2010.11.005

Pieretti, N., Duarte, M. H. L., Sousa-Lima, R. S., Rodrigues, M., Young, R. J., & Farina, A. (2015). Determining temporal sampling schemes for passive acoustic studies in different tropical ecosystems. *Tropical Conservation Science, 8*(1), 215–234. https://doi.org/10.1177/194008291500800117

Pieretti, N., Martire, M. L., Farina, A., & Danovaro, R. (2017). Marine soundscape as an additional biodiversity monitoring tool: A case study from the Adriatic Sea (Mediterranean Sea). *Ecological Indicators, 83,* 13–20. https://doi.org/10.1016/j.ecolind.2017.07.011

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*(9), 1213–1232. https://doi.org/10.1007/s10980-011-9600-8

Poupard, M., Ferrari, M., Best, P., & Glotin, H. (2022). Passive acoustic monitoring of sperm whales and anthropogenic noise using stereophonic recordings in the Mediterranean Sea, North West Pelagos Sanctuary. *Scientific Reports, 12*(1), Article 2007. https://doi.org/10.1038/s41598-022-05917-1

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Radford, C. A., Jeffs, A. G., Tindle, C. T., & Montgomery, J. C. (2008). Temporal patterns in ambient noise of biological origin from a shallow water temperate reef. *Oecologia, 156*(4), 921–929. https://doi.org/10.1007/s00442-008-1041-y

Richardson, W. J., Greene Jr, C. R., Malme, C. I., & Thomson, D. H. (2013). *Marine mammals and noise*. Academic Press.

Righi, B. M., Baumgarten, J. E., Morete, M. E., Souza, R. C. F., Marcondes, M. C. C., Sousa-Lima, R. S., Teixeira, N. N., Tonolli, F. A. S., & Gonçalves, M. I. C. (2024). Exploring habitat use and movement patterns of humpback whales in a reoccupation area off Brazil: A comparison with the Abrolhos Bank. *Marine Mammal Science, 40*(4), Article e13139. https://doi.org/10.1111/mms.13139

Rossi-Santos, M. R., Neto, E. S., Baracho, C. G., Cipolotti, S. R., Marcovaldi, E., & Engel, M. H. (2008). Occurrence and distribution of humpback whales (*Megaptera novaeangliae*) on the north coast of the State of Bahia, Brazil, 2000–2006. *ICES Journal of Marine Science, 65*(4), 667–673. https://doi.org/10.1093/icesjms/fsn034

Sánchez-Gendriz, I., & Padovese, L. R. (2017). A methodology for analyzing biological choruses from long-term passive acoustic monitoring in natural areas. *Ecological Informatics*, *41*, 1–10. https://doi.org/10.1016/j.ecoinf.2017.07.001

Seger, K. D., Thode, A. M., Martínez-Loustalot, P., Jiménez-López, M. E., & López-Arzate, D. (2016). Humpback whale-generated ambient noise levels provide insight into singers' spatial densities. *The Journal of the Acoustical Society of America, 140*(3), 1581–1597. https://doi.org/10.1121/1.4962217

Širović, A., Wiggins, S. M., & Oleson, E. M. (2013). Ocean noise in the tropical and sub-tropical Pacific Ocean. *The Journal of the Acoustical Society of America, 134*(4), 2681–2689. https://doi.org/10.1121/1.4820884

Smith, J. N., Goldizen, A. W., Dunlop, R. A., & Noad, M. J. (2008). Songs of male humpback whales (*Megaptera novaeangliae*) are involved in intersexual interactions. *Animal Behaviour, 75*(2), 467–477. https://doi.org/10.1016/j.anbehav.2008.02.013

Smultea, M. A. (1994). Segregation by humpback whale (*Megaptera novaeangliae*) cows with a calf in coastal habitat near the island of Hawaii. *Canadian Journal of Zoology, 72*(5), 805–811. https://doi.org/10.1139/z94-109

Sousa-Lima, R. S., Engel, M. H., Sábato, V., Lima, B. R., Queiróz, T. S., Brito, M. R., Fernandes, D. P., Martins, C. A. C., Hatum, O. S., Casagrande, T., Honda, R. K., Gonçalves, M. I. C., Baumgarten, J. E., Andriolo, A., Ribeiro, M. C., & Clark, C. W. (2018). Acoustic ecology of humpback whales in Brazilian waters investigated with basic and sophisticated passive acoustic technologies over 17 years. *Western Indian Ocean Journal of Marine Science*, 17(Special Issue 1), 23–40.

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P. (2013). A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquatic Mammals, 39*(1), 23–53. https://doi.org/10.1578/AM.39.1.2013.23

Sueur, J., Aubin, T., Simonis, C., 2008a. Seewave, a free modular tool for sound analysis and synthesis. *Bioacoustics, 18*(2), 213–226.

Sueur, J., Pavoine, S., Hamerlynck, O., Duvail, S., 2008b. Rapid acoustic survey for biodiversity appraisal. *PloS one, 3*(12), Article e4065.

Thresher, R. E., & Gunn, J. S. (1986). Comparative analysis of visual census techniques for highly mobile, reef-associated piscivores (Carangidae). *Environmental Biology of Fishes, 17*, 93–116. https://doi.org/10.1007/BF00001740

Todd, N. R., Cronin, M., Luck, C., Bennison, A., Jessopp, M., & Kavanagh, A. S. (2020). Using passive acoustic monitoring to investigate the occurrence of cetaceans in a protected marine area in northwest Ireland. *Estuarine, Coastal and Shelf Science, 232*, Article 106509. https://doi.org/10.1016/j.ecss.2019.106509

Tougaard, J., & Eriksen, N. (2006). Analysing Differences among animal songs quantitatively by means of the Levenshtein distance measure. *Behaviour, 143(2*), 239–252. https://doi.org/10.1163/156853906775900685

Turco, A., Wagensommer, R. P., Medagli, P., D'Emerico, S., Ippolito, F., Scordella, G., & Albano, A. (2025). *Centaurea pumilio* (Asteraceae): Conservation status, threats and population size of a critically endangered species in Italy. *Plants, 14*(7), Article 1074. https://doi.org/10.3390/plants14071074

Valdés Hernández, M. J., Dawson, S., Pavanato, H., Leunissen, E., & Rayment, W. (2024). Using passive acoustic monitoring to assess the overlap between endemic endangered Hector's dolphin (*Cephalorhynchus hectori hectori*) and mussel farms in the Banks Peninsula Marine Mammal Sanctuary, New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems, 34*(6), Article e4207. https://doi.org/10.1002/aqc.4207

Warren, V. E., Constantine, R., Noad, M., Garrigue, C., & Garland, E. C. (2020). Migratory insights from singing humpback whales recorded around central New Zealand. *Royal Society Open Science, 7*(11), Article 201084. https://doi.org/10.1098/rsos.201084

Webster, T. A., Van Parijs, S. M., Rayment, W. J., & Dawson, S. M. (2019). Temporal variation in the vocal behaviour of southern right whales in the Auckland Islands, New Zealand. *Royal Society Open Science, 6*(3), Article 181487. https://doi.org/10.1098/rsos.181487

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis* (2nd ed.). Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *dplyr: A grammar of data manipulation* (R package version 1.1.4). https://CRAN.R-project.org/package=dplyr

Winn, H. E., & Winn, L. K. (1978). The song of the humpback whale (*Megaptera novaeangliae*) in the West Indies. *Marine Biology, 47*, 97–114.

Winn, H. E., Thompson, T. J., Cummings, W. C., Hain, J., Hudnall, J., Hays, H., & Steiner, W. W. (1981). Song of the humpback whale—Population comparisons. *Behavioral Ecology and Sociobiology, 8*(1), 41–46. https://doi.org/10.1007/BF00302842

Zambrano, L., Vega, E., Herrera, M. L. G., Prado, E., & Reynoso, V. H. (2007). A population matrix model and population viability analysis to predict the fate of endangered species in highly managed water systems. *Animal Conservation, 10*(3), 297–303. https://doi.org/10.1111/j.1469-1795.2007.00105.x

Zerbini, A. N., Adams, G., Best, J., Clapham, P. J., Jackson, J. A., & Punt, A. E. (2019). Assessing the recovery of an Antarctic predator from historical exploitation. *Royal Society Open Science, 6*(10), Article 190368. https://doi.org/10.1098/rsos.190368

Zimmer, W. M. (2011). *Passive acoustic monitoring of cetaceans*. Cambridge University Press. https://doi.org/10.1017/CBO9780511977107

CONSIDERAÇÕES FINAIS

Esta tese integra o estado da arte sobre as aplicações do monitoramento acústico passivo (MAP), por meio de gravadores autônomos fixos no estudo de cetáceos, a uma investigação conduzida sobre o uso de métricas acústicas como proxies de abundância de baleias-jubarte, em Serra Grande, Bahia, uma área reprodutiva da espécie na costa brasileira.

A aplicação do MAP com gravadores autônomos tem se expandido nas últimas décadas, com maior concentração de estudos no Hemisfério Norte. No entanto, observa-se um crescimento recente da contribuição do Hemisfério Sul, ampliando o conhecimento sobre a utilização dessa abordagem em diferentes contextos geográficos, bem como em distintas espécies ou populações. Foram mapeadas as espécies mais frequentemente monitoradas acusticamente, os recortes espaciais com maior densidade de amostragem e os tipos de informação biológica acessada. A maior parte dos estudos abordou padrões sazonais de ocorrência e uso do habitat, com destaque para a aplicação do MAP em áreas de difícil acesso, o que reforça seu papel como ferramenta essencial no monitoramento em regiões remotas.

As aplicações do MAP em estimativas populacionais com base exclusivamente em dados acústicos ainda são relativamente pontuais. No entanto, apesar de estarem concentradas em um número limitado de espécies bem conhecidas, o fato de terem sido empregadas em diferentes grupos e por meio de distintas abordagens metodológicas evidencia o crescente interesse pela temática e as possibilidades emergentes dessa estratégia. Esses avanços apontam para o potencial do MAP em contribuir com análises mais robustas sobre a dinâmica populacional.

As análises conduzidas em Serra Grande demonstraram o potencial das métricas acústicas para refletir tendências de abundância relativa de baleias-jubarte. Os resultados indicaram que o número de cantores acompanhou a variação interanual no número de indivíduos registrados visualmente, enquanto os níveis de pressão sonora (SPL) apresentaram boa sensibilidade para captar variações de abundância em uma escala mais fina. No entanto, é importante destacar que o SPL não isola exclusivamente as vocalizações das baleias, podendo refletir contribuições de outras fontes sonoras presentes na paisagem acústica. Sons biológicos, como coros de peixes, por exemplo, podem influenciar os níveis de SPL em anos de menor abundância de baleias, o que exige cautela na interpretação desses dados.

A análise por bandas de 1/3 de oitava revelou que as frequências entre 158 e 1.000 Hz foram as mais consistentes ao longo dos anos, refletindo de forma robusta a atividade vocal da espécie. Um padrão similar foi observado entre as temporadas de 2015, 2018 e 2019, enquanto a temporada de 2014 apresentou variações mais expressivas. Essas diferenças estão alinhadas às particularidades da estrutura do canto descritas na literatura para aquele ano, ressaltando a importância de considerar previamente a estrutura vocal da espécie ao longo das temporadas. Outro resultado que reforça essa necessidade é o comportamento do Índice de Complexidade Acústica (ACI). A sensibilidade do ACI foi mais fortemente influenciada por alterações na estrutura do canto do que por variações na abundância de baleias. A simplificação abrupta do canto, reportada entre 2017 e 2018 para a população de baleias que migra para a costa brasileira, impactou diretamente o desempenho do ACI, tornando-o menos eficaz como preditor de abundância nesse contexto.

Conclui-se que a combinação entre métricas acústicas mostrou-se promissora para inferências sobre a presença e a atividade reprodutiva da espécie, refletindo, até o presente momento, mudanças na abundância de baleias na região. O conjunto de dados obtido para Serra Grande constitui uma linha de base valiosa sobre a atividade vocal de baleias-jubarte em uma área de baixa influência antrópica, cuja paisagem acústica ainda preserva características naturais. Os padrões de ocorrência vocal e de pressão sonora descritos neste estudo podem servir como referência para futuras comparações, sobretudo diante do empreendimento atualmente em construção na região, como o Complexo Logístico e Intermodal Porto Sul. A proximidade da costa, a plataforma continental estreita e a presença de um ponto fixo de observação tornam Serra Grande um sítio estratégico para o monitoramento de longo prazo, permitindo a associação de dados visuais e acústicos com alta resolução temporal e espacial.

MATERIAL SUPLEMENTAR CAPÍTULO I: Listening porpoises, dolphins and whales around the world: what does passive acoustic monitoring have to tell us?

TABLE S1. Description of eligible studies with the study identification (ID), authors, publication year, title, study area, corresponding ocean, target species (common and scientific names), and taxonomic group.

ID	Authors	Year	Title	Study area	Ocean	Species (Common name)	Species (Scientific name)	Group
1	Širović, Hildebrand & Wiggins	2007	Blue and fin whale call source levels and propagation range in the Southern Ocean	Antarctic Peninsula	Southern Ocean	Blue whale; Fin Whale	*Balaenoptera musculus; Balaenoptera physalus*	Mysticeti
2	Johnston et al.	2008	Temporal patterns in the acoustic signals of beaked whales at Cross Seamount	Cross Seamount	North Pacific Ocean	Beaked whale	Unidentified specie	Odontoceti
3	Soldevilla, Wiggins & Hildebrand	2010	Spatio-temporal comparison of Pacific white-sided dolphin echolocation click types	Southern California Bight	North Pacific Ocean	Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	Odontoceti

4	Munger, Wiggins & Hildebrand	2011	North Pacific right whale up-call source levels and propagation distance on the southeastern Bering Sea shelf	Bering Sea	North Pacific Ocean	North Pacific right whale	*Eubalaena japonica*	Mysticeti
5	Oswald, Au & Duennebier	2011	Minke whale (*Balaenoptera acutorostrata*) boings detected at the Station ALOHA Cabled Observatory	Oahu, Hawaii	North Pacific Ocean	Minke whale	*Balaenoptera acutorostrata*	Mysticeti
6	Rayment et al.	2011	Listening for a needle in a haystack: Passive acoustic detection of dolphins at very low densities	Manukau, Kaipara, Raglan, and Kawhia Harbours, New Zealand	South Pacific Ocean	Maui's dolphin	*Cephalorhynchus hectori maui*	Odontoceti
7	Soldevilla et al.	2011	Risso's and Pacific white-sided dolphin habitat modeling from passive acoustic monitoring	Southern California Bight	North Pacific Ocean	Risso's dolphin; Pacific white-sided dolphin	*Grampus griseus; Lagenorhynchus obliquidens*	Odontoceti

8	Stimpert et al.	2011	Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring	Stellwagen Bank National Marine Sanctuary, Gulf of Maine	North Atlantic Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
9	Ackleh et al.	2012	Assessing the Deepwater Horizon oil spill impact on marine mammal population through acoustics: Endangered sperm whales	Mississippi Coast, Gulf of Mexico	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
10	Morano et al.	2012	Acoustically Detected Year-Round Presence of Right Whales in an Urbanized Migration Corridor	Massachusetts Bay, Gulf Maine	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
11	Morano et al.	2012	Seasonal and geographical patterns of fin whale song in the western North Atlantic Ocean	Massachusetts Bay and New York Bight	North Atlantic Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
12	Mussoline et al.	2012	Seasonal and diel variation in North Atlantic right whale up-calls: Implications for management and	Stellwagen Bank National Marine Sanctuary and	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti

			conservation in the northwestern Atlantic ocean	Jeffreys Ledge, Gulf of Maine				
13	Munger et al.	2012	Humpback whale (*Megaptera novaeangliae*) song occurrence at American Samoa in long-term passive acoustic recordings, 2008-2009	American Samoa, Polynesia	North Atlantic Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
14	Newhall et al.	2012	Long distance passive localization of vocalizing sei whales using an acoustic normal mode approach	Offshore Atlantic City, New Jersey	North Atlantic Ocean	Sei whale	*Balaenoptera borealis*	Mysticeti
15	Au et al.	2013	Nighttime foraging by deep diving echolocating odontocetes off the Hawaiian islands of Kauai and Niihau as determined by passive acoustic monitors	Kauai and Niihau, Hawaii	North Pacific Ocean	Short-finned pilot whale; Risso's dolphin; Sperm whale; Small dolphin; Beaked whale	*Globicephala macrorhynchus; Grampus griseus; Physeter macrocephalus; Unidentified specie; Unidentified specie*	Odontoceti

16	Bradley et al.	2013	Assessing the coastal occurrence of endangered killer whales using autonomous passive acoustic recorders	U.S. West Coast	North Pacific Ocean	Killer Whale	*Orcinus orca*	Odontoceti
17	Charif et al.	2013	Bowhead whale acoustic activity in the southeast Beaufort Sea during late summer 2008-2010	Beaufort Sea	Arctic Ocean	Bowhead whale	*Balaena mysticetus*	Mysticeti
18	Delarue et al.	2013	Acoustic occurrence and affiliation of fin whales detected in the northeastern Chukchi Sea, July to October 2007 - 10	Northeastern Chukchi Sea, Alaska	Arctic Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
19	Lammers et al.	2013	Passive acoustic monitoring of Cook Inlet beluga whales (Delphinapterus leucas)	Cook Inlet, Alaska	North Pacific Ocean	Beluga whale; Killer whale	*Delphinapterus leucas; Orcinus orca*	Odontoceti
20	Martin et al.	2013	Estimating minke whale (*Balaenoptera acutorostrata*) boing sound	Kauai, Hawaii	North Pacific Ocean	Minke whale	*Balaenoptera acutorostrata*	Mysticeti

			density using passive acoustic sensors					
21	Risch et al.	2013	Minke whale acoustic behavior and multi-year seasonal and diel vocalization patterns in Massachusetts Bay, USA	Stellwagen Bank National Marine Sanctuary, Gulf of Maine	North Atlantic Ocean	Minke whale	*Balaenoptera acutorostrata*	Mysticeti
22	Stanistreet, Risch & Van Parijs	2013	Passive Acoustic Tracking of Singing Humpback Whales (*Megaptera novaeangliae*) on a Northwest Atlantic Feeding Ground	Stellwagen Bank National Marine Sanctuary, Gulf of Maine	North Atlantic Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
23	La Manna, Manghi & Sarà	2014	Monitoring the habitat use of common bottlenose dolphins (*Tursiops truncatus*) using passive acoustics in a Mediterranean marine protected area	Lampedusa Island, Mediterranean Sea, Italy	North Atlantic Ocean	Bottlenose Dolphin	*Tursiops truncatus*	Odontoceti

24	Murray, Rice & Clark	2014	Extended seasonal occurrence of humpback whales in Massachusetts Bay	Massachusetts Bay	North Atlantic Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
25	Risch et al.	2014	Seasonal migrations of North Atlantic minke whales: Novel insights from large-scale passive acoustic monitoring networks	Multiples sites in the North Atlantic Ocean from Nova Scotia to the Caribbean	North Atlantic Ocean	Minke whale	*Balaenoptera acutorostrata*	Mysticeti
26	Tellechea et al.	2014	Passive acoustic monitoring of bottlenose dolphins (*Tursiops truncatus*) on the uruguayan coast: Vocal characteristics and seasonal cycles	Eastern Coast of Uruguay, including the regions of Cerro Verde, Punta del Diablo, Valizas, Cabo Polonio, and La Paloma	South Atlantic Ocean	Bottlenose Dolphin	*Tursiops truncatus*	Odontoceti
27	Balcazar et al.	2015	Calls reveal population structure of blue whales	Perth Canyon, Bass Strait,	South Indian	Blue whale	*Balaenoptera musculus*	Mysticeti

			across the Southeast Indian Ocean and the Southwest Pacific Ocean	Tasman Sea, Tonga, and Samoa	Ocean and South Pacific Ocean			
28	Baumann-Pickering et al.	2015	False killer whale and short-finned pilot whale acoustic identification	Main island of Hawaii and between the islands of Kauai and Niihau	North Pacific Ocean	Short-finned pilot whale; False killer whale	*Globicephala macrorhynchus; Pseudorca crassidens*	Odontoceti
29	Bort et al.	2015	North Atlantic right whale *Eubalaena glacialis* vocalization patterns in the central Gulf of Maine from October 2009 through October 2010	Gulf of Maine	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
30	Buchan, Stafford & Hucke-Gaete	2015	Seasonal occurrence of southeast pacific blue whale songs in southern chile and the eastern tropical pacific	Coastal and insular region of southern Chile	South Pacific Ocean	Blue whale	*Balaenoptera musculus*	Mysticeti

31	Garland, Berchok & Castellote	2015	Beluga whale (Delphinapterus leucas) vocalizations and call classification from the eastern Beaufort Sea population	Icy Cape, Alaska	Arctic Ocean	Beluga whale	*Delphinapterus leucas*	Odontoceti
32	Garland, Castellote & Berchok	2015	Temporal peaks in beluga whale (*Delphinapterus leucas*) acoustic detections in the northern Bering, northeastern Chukchi, and western Beaufort Seas: 2010–2011	Alaska waters, including Bering Sea, Chukchi Sea and Beaufort Sea	Arctic Ocean and North Pacific Ocean	Beluga whale	*Delphinapterus leucas*	Odontoceti
33	Hildebrand et al.	2015	Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico	Gulf of Mexico	North Atlantic Ocean	Blainville's beaked whale; Gervais's beaked whale; Cuvier's beaked whale; Mesoplodon sp.	*Mesoplodon densirostris; Mesoplodon europaeus; Ziphius cavirostris;* Unidentified specie	Odontoceti

34	Hodge et al.	2015	North Atlantic right whale occurrence near wind energy areas along the mid-Atlantic US coast: Implications for management	North Carolina and Georgia coast, U.S.	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
35	Kyhn et al.	2015	Pingers cause temporary habitat displacement in the harbour porpoise *Phocoena phocoena*	Jammerland Bay in the Great Belt, Baltic Sea, Denmark	North Atlantic Ocean	Harbour porpoise	*Phocoena phocoena*	Odontoceti
36	Magnúsdóttir et al.	2015	Humpback whale (*Megaptera novaeangliae*) song unit and phrase repertoire progression on a subarctic feeding ground	Skjalfandi Bay, Iceland	North Atlantic Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
37	Wang et al.	2015	Passive acoustic monitoring the diel, lunar, seasonal and tidal patterns in the biosonar activity of the Indo-Pacific humpback dolphins (*Sousa chinensis*) in the Pearl River Estuary, China	Pearl River Estuary, South China Sea, China	North Pacific Ocean	Indo-Pacific humpback dolphin	*Sousa chinensis*	Odontoceti

38	Baumann-Pickering et al.	2016	Odontocete occurrence in relation to changes in oceanography at a remote equatorial Pacific seamount	Line Islands, Kiribati	South Pacific Ocean	Short-finned pilot whale; Risso's dolphin; Pygmy sperm whale; Dwarf sperm whale; Blainville's beaked whale; Sperm whale; False killer whale; Cuvier's beaked whale; Beaked whale	*Globicephala macrorhynchus; Grampus griseus; Kogia breviceps; Kogia sima; Mesoplodon densirostris; Physeter macrocephalus; Pseudorca crassidens; Ziphius cavirostris;* Unidentified specie	Odontoceti
39	Dombroski et al.	2016	Vocalizations produced by southern right whale (*Eubalaena australis*) mother-calf pairs in a calving ground off Brazil	Right Whale EPA: Gamboa and Ribanceira, Santa Catarina, Brazil	South Atlantic Ocean	Southern right whale	*Eubalaena australis*	Mysticeti

40	Giorli, Au & Neuheimer	2016	Differences in foraging activity of deep sea diving odontocetes in the Ligurian Sea as determined by passive acoustic recorders	Ligurian Sea, Mediterranean Sea	North Atlantic Ocean	Long-finned pilot whale; Risso's dolphin; Sperm whale; Cuvier's beaked whale	*Globicephala melas; Grampus griseus; Physeter macrocephalus; Ziphius cavirostris*	Odontoceti
41	Munger et al.	2016	Indo-Pacific humpback dolphin occurrence north of Lantau Island, Hong Kong, based on year-round passive acoustic monitoring	North of Lantau Island, South China Sea, Hong Kong	North Pacific Ocean	Indo-Pacific humpback dolphin	*Sousa chinensis*	Odontoceti
42	Nieukirk et al.	2016	A complex baleen whale call recorded in the Mariana Trench Marine National Monument	West Coast of Guam, Oceania	North Pacific Ocean	There wasn't identification	NA	Mysticeti
43	Salisbury, Clark & Rice	2016	Right whale occurrence in the coastal waters of Virginia, U.S.A.: Endangered species presence in a rapidly developing energy market	Chesapeake Bay, Virginia, U.S.	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti

44	Thomisch et al.	2016	Spatio-temporal patterns in acoustic presence and distribution of Antarctic blue whales Balaenoptera musculus intermedia in the Weddell Sea	Weddell Sea and Atlantic sector of the Southern Ocean	Southern Ocean	Antarctic blue whale	*Balaenoptera musculus intermedia*	Mysticeti
45	Tsujii et al.	2016	The migration of fin whales into the southern Chukchi Sea as monitored with passive acoustics	Southern Chukchi sea	Arctic Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
46	Balcazar et al.	2017	Using calls as an indicator for Antarctic blue whale occurrence and distribution across the southwest Pacific and southeast Indian Oceans	Tasman Sea, Tonga, Samoa, Bass Strait, Perth Canyon, and Dampier	North Indian Ocean and South Pacific Ocean	Antarctic blue whale	*Balaenoptera musculus intermedia*	Mysticeti
47	Benjamins et al.	2017	Harbour porpoise distribution can vary at small spatiotemporal scales in energetic habitats	Billia Croo and Scarba, Scotlan	North Atlantic Ocean	Harbour porpoise	*Phocoena phocoena*	Odontoceti

48	Davis et al.	2017	Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014	Along the eastern seaboard of North America from Florida, U.S. to Nunavut, Canada	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
49	Dong, Liu & Dong	2017	Acoustic occurrence detection of a newly recorded Indo-Pacific humpback dolphin population in waters southwest of Hainan Island, China	Southwest of Hainan island, Republic of China	North Pacific Ocean	Indo-Pacific humpback dolphin	*Sousa chinensis*	Odontoceti
50	Giorli & Au	2017	Spatio-temporal variation and seasonality of Odontocetes' foraging activity in the leeward side of the island of Hawaii	Offshore the Kona coast, Hawaii	North Pacific Ocean	There wasn't identification	NA	Odontoceti

51	Lammers et al.	2017	Acoustic monitoring of coastal dolphins and their response to naval mine neutralization exercises	US Navy training range, near Virginia Beach, U.S.	North Atlantic Ocean	There wasn't identification	NA	Odontoceti
52	Leroy et al.	2017	Identification of two potential whale calls in the southern Indian Ocean, and their geographic and seasonal occurrence	Regions across the South Indian Ocean	South Indian Ocean	Antarctic blue whale; Pygmy blue whale; Fin whale	*Balaenoptera musculus intermedia; Balaenoptera musculus brevicauda; Baleanoptera physalus*	Mysticeti
53	McDonald et al.	2017	Building time-budgets from bioacoustic signals to measure population-level changes in behavior: a case study with sperm whales in the Gulf of Mexico	Gulf of Mexico	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
54	Paniagua-Mendoza et al.	2017	Seasonal acoustic behavior of blue whales (*Balaenoptera musculus*) in	Gulf of California	North Pacific Ocean	Blue whale	*Balaenoptera musculus*	Mysticeti

			the Gulf of California, Mexico					
55	Rice et al.	2017	Spatial and temporal occurrence of killer whale ecotypes off the outer coast of Washington State, USA	Off the coast of Quinault and the continental shelf near Cape Elizabeth	North Pacific Ocean	Killer Whale	*Orcinus orca*	Odontoceti
56	Stanistreet et al.	2017	Using passive acoustic monitoring to document the distribution of beaked whale species in the western north atlantic ocean	Multiple sites from Florida, U.S. to Nova Scotia, Canada	North Atlantic Ocean	Northern bottlenose whale; Blainville's beaked whale; Cuvier's beaked whale	*Hyperoodon ampullatus; Mesoplodon densirostris; Ziphius cavirostris*	Odontoceti
57	Ward, Gavrilov & McCauley	2017	"spot" call: A common sound from an unidentified great whale in Australian temperate waters	Perth Canyon, Bremer Bay, the Great Australian Bight, Kangaroo	South Indian Ocean and Southern Ocean	There wasn't identification	NA	Mysticeti

				Island, and Portland				
58	Bittencourt et al.	2018	Mapping cetacean sounds using a passive acoustic monitoring system towed by an autonomous Wave Glider in the Southwestern Atlantic Ocean	Brazilian offshore waters of the southwestern Atlantic	South Atlantic Ocean	Brydes whale; Rough-toothed dolphin	*Balaenoptera brydei; Steno bredanensis*	Mysticeti and Odontoceti
59	Burnham, Duffus & Mouy	2018	Gray whale (*Eschrictius robustus*) call types recorded during migration off the west coast of Vancouver Island	Vancouver Island, Canada	North Pacific Ocean	Grey whale	*Eschrichtius robustus*	Mysticeti
60	Elizabeth Henderson et al.	2018	Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii	Pacific Missile Range Facility off Kauai, Hawaii	North Pacific Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
61	Leroy et al.	2018	Broad-scale study of the seasonal and geographic occurrence of blue and fin whales in the Southern Indian Ocean	Widely spaced sites near Reunion, St. Paul, Amsterdam, Kerguelen,	South Indian Ocean	Antarctic blue whale; Fin whale; Pygmy blue whale	*Balaenoptera musculus intermedia; Balaenoptera physalus; Balaenoptera*	Mysticeti

				and Crozet islands in the southern Indian Ocean			*musculus brevicauda*	
62	Pine et al.	2018	Investigating the spatiotemporal variation of fish choruses to help identify important foraging habitat for Indo-Pacific humpback dolphins, Sousa chinensis	Sanjiao Island, Qi'an Island, Lamma Island, and Lung Kwu Chau, South China Sea, China	North Pacific Ocean	Indo-Pacific humpback dolphin	*Sousa chinensis*	Odontoceti
63	Stanistreet et al.	2018	Spatial and seasonal patterns in acoustic detections of sperm whales *Physeter macrocephalus* along the continental slope in the western North Atlantic Ocean	Between Florida and New England, including Georges Bank, Norfolk Canyon, Jacksonville, Cape Hatteras,	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti

				and Onslow Bay				
64	Varga, Wiggins & Hildebrand	2018	Behavior of singing fin whales *Balaenoptera physalus* tracked acoustically offshore of Southern California	San Clemente Island, California	North Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
65	Aulich et al.	2019	Fin whale (*Balaenoptera physalus*) migration in Australian waters using passive acoustic monitoring	Marine and coastal locations around Australia, spanning the Indian Ocean and the South Pacific Ocean	South Indian Ocean and South Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
66	Bailey et al.	2019	Empirical evidence that large marine predator foraging behavior is consistent with area-restricted search theory	Ocean city, Maryland, U.S.	North Atlantic Ocean	Common dolphin; Bottlenose dolphin	*Delphinus delphis; Tursiops truncatus*	Odontoceti

67	Buchan et al.	2019	Seasonal occurrence of fin whale song off Juan Fernandez, Chile	Juan Fernandez archipelago	South Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
68	Burnham	2019	Fin Whale Call Presence and Type Used to Describe Temporal Distribution and Possible Area Use of Clayoquot Sound	Offshore from Siwash Point, Flores Island	North Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
69	Diogou et al.	2019	Sperm whale (*Physeter macrocephalus*) acoustic ecology at Ocean Station PAPA in the Gulf of Alaska – Part 1: Detectability and seasonality	Ocean Station PAPA, Gulf of Alaska	North Pacific Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
70	Diogou et al.	2019	Sperm whale (*Physeter macrocephalus*) acoustic ecology at Ocean Station PAPA in the Gulf of Alaska – Part 2: Oceanographic drivers of interannual variability	Ocean Station PAPA, Gulf of Alaska	North Pacific Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti

71	Diogou et al.	2019	Year-round acoustic presence of sperm whales (*Physeter macrocephalus*) and baseline ambient ocean sound levels in the Greek Seas	Ionian Sea and North Aegean Sea, Mediterranean Sea, Greece	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
72	Dréo et al.	2019	Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean	Southwest Indian Ridge the extensive tectonic plate boundary between Africa and Antarctica	South Indian Ocean	Antarctic blue whale; Fin whale; Pygmy blue whale	*Balaenoptera musculus intermedia; Balaenoptera physalus; Balaenoptera musculus brevicauda*	Mysticeti
73	Heenehan et al.	2019	Caribbean sea soundscapes: Monitoring humpback whales, biological sounds, geological events, and anthropogenic impacts of vessel noise	Caribbean island chain from Dominican Republic ,St. Martin, Guadeloupe east and west	North Atlantic Ocean	Minke whale; Humpback whale; Sperm whale; Delphinidae	*Balaenoptera acutorostrata; Megaptera novaeangliae; Physeter macrocephalus;* Unidentified specie	Mysticeti and Odontoceti

				and Martinique, to Bonaire and Aruba				
74	Hildebrand et al.	2019	Assessing seasonality and density from passive acoustic monitoring of signals presumed to be from pygmy and dwarf sperm whales in the gulf of Mexico	Gulf of Mexico	North Atlantic Ocean	Pygmy sperm whale; Dwarf sperm whale	*Kogia breviceps; Kogia sima*	Odontoceti
75	Merkens, Simonis & Oleson	2019	Geographic and temporal patterns in the acoustic detection of sperm whales *Physeter macrocephalus* in the central and western North Pacific Ocean	Pacific Islands and Seamounts in the Central and Western North Pacific	North Pacific Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
76	Riera et al.	2019	Passive acoustic monitoring off Vancouver Island reveals extensive use by at-risk Resident killer whale (*Orcinus orca*) populations	Vancouver Island, Canada	North Pacific Ocean	Killer Whale	*Orcinus orca*	Odontoceti

77	Silva et al.	2019	Temporal and spatial distributions of delphinid species in Massachusetts Bay (USA) using passive acoustics from ocean gliders	Stellwagen Basin in western Massachusetts Bay	North Atlantic Ocean	There wasn't identification	NA	Odontoceti
78	Simard et al.	2019	North Atlantic right whale shift to the Gulf of St. Lawrence in 2015, revealed by long-term passive acoustics	Gulf of Saint Lawrence	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
79	Thomisch et al.	2019	Temporal patterns in the acoustic presence of baleen whale species in a presumed breeding area off Namibia	Off Namibia, northwest of Walvis Ridge	South Atlantic Ocean	Antarctic minke whale; Antarctic blue whale; Fin whale; Humback whale	*Balaenoptera bonaerensis; Balaenoptera musculus intermedia; Balaenoptera physalus; Megaptera novaeangliae*	Mysticeti
80	Webster et al.	2019	Temporal variation in the vocal behaviour of southern	Auckland Island, New Zealand	South Pacific Ocean	Southern right whale	*Eubalaena australis*	Mysticeti

			right whales in the Auckland Islands, New Zealand					
81	Wright & Tregenza	2019	CPOD successful in trial for detecting Māui dolphin outside harbours	Manukau Harbour and Hamilton's Gap, New Zealand	South Pacific Ocean	Maui dolphin	*Cephalorhynchus hectori maui*	Odontoceti
82	Buchan, Balcazar-Cabrera & Stafford	2020	Seasonal acoustic presence of blue, fin, and minke whales off the Juan Fernández Archipelago, Chile (2007–2016)	Juan Fernandez Archipelago, Chile	South Pacific Ocean	Antarctic minke whale; Southeast Pacific blue whale; Pygmy blue whale; Antarctic blue whale; Fin whale	*Balaenoptera bonaerensis; Balaenoptera musculus; Balaenoptera musculus brevicauda; Balaenoptera musculus intermedia; Balaenoptera physalus*	Mysticeti
83	Castellote et al.	2020	Seasonal distribution and foraging occurrence of Cook	Cook Inlet and Adjacent	North Pacific Ocean	Cook Inlet beluga whale	*Delphinapterus leucas*	Odontoceti

			Inlet beluga whales based on passive acoustic monitoring	Coastal Regions				
84	Cauchy et al.	2020	Sperm whale presence observed using passive acoustic monitoring from gliders of opportunity	Northwestern Mediterranean, including the Gulf of Lion, Ligurian Sea, and Sea of Sardinia	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
85	Davis et al.	2020	Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data	Multiple sites between Saba in the Caribbean and the Davis Strait off western Greenland	North Atlantic Ocean	Blue whale; Sei whale; Fin whale; humpback whale	*Balaenoptera musculus; Balaenoptera borealis; Balaenoptera physalus; Megaptera novaeangliae*	Mysticeti
86	Filun et al.	2020	Frozen verses: Antarctic minke whales (*Balaenoptera bonaerensis*) call predominantly during austral winter	Multiple sites in the Weddell Sea, Antarctica	Southern Ocean	Antarctic minke whale	*Balaenoptera bonaerensis*	Mysticeti

87	Helble et al.	2020	Fin Whale Song Patterns Shift Over Time in the Central North Pacific	Northwest of the island of Kauai, Hawaii	North Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
88	Hinojosa et al.	2020	Distribution of the acoustic occurrence of dolphins during the summers 2011 to 2015 in the Upper Gulf of California, Mexico	Upper Gulf of California, Mexico	North Pacific Ocean	Vaquita porpoise	*Phocoena sinus*	Odontoceti
89	Kügler et al.	2020	Fluctuations in Hawaii'S Humpback Whale Megaptera Novaeangliae Population Inferred from Male Song Chorusing Off Maui	Maui, Hawaii	North Pacific Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
90	Longden et al.	2020	Mark-recapture of individually distinctive calls - A case study with signature whistles of bottlenose dolphins (*Tursiops truncatus*)	Walvis Bay, Namibia	South Atlantic Ocean	Bottlenose dolphin	*Tursiops truncatus*	Odontoceti

91	Morano et al.	2020	Seasonal movements of Gulf of Mexico sperm whales following the Deepwater Horizon oil spill and the limitations of impact assessments	Continental slope from Louisiana to Florida, Gulf of Mexico	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
92	Moreira et al.	2020	Occurrence of Omura's whale, *Balaenoptera omurai* (Cetacea: Balaenopteridae), in the Equatorial Atlantic Ocean based on Passive Acoustic Monitoring	São Pedro and São Paulo Archipelago	South Atlantic Ocean	Omura's whale	*Balaenoptera omurai*	Mysticeti
93	Oestreich et al.	2020	Animal-Borne Metrics Enable Acoustic Detection of Blue Whale Migration	Monterey bay, California	North Pacific Ocean	Blue whale	*Balaenoptera musculus*	Mysticeti
94	Omeyer et al.	2020	Assessing the Effects of Banana Pingers as a Bycatch Mitigation Device for Harbour Porpoises (*Phocoena phocoena*)	Coast of Mousehole, England, U.K.	North Atlantic Ocean	Harbor porpoise	*Phocoena phocoena*	Odontoceti

95	Papale et al.	2020	Year-round acoustic patterns of dolphins and interaction with anthropogenic activities in the Sicily Strait, central Mediterranean Sea	Sicily Strait, Mediterranean Sea	North Atlantic Ocean	There wasn't identification	NA	Odontoceti
96	Schall et al.	2020	Large-scale spatial variabilities in the humpback whale acoustic presence in the Atlantic sector of the Southern Ocean: Humpback whales in the Weddell Sea	Weddell Sea and Elephant Island, Antarctica	Southern Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
97	Shabangu & Andrew	2020	Clicking throughout the year: sperm whale clicks in relation to environmental conditions off the west coast of South Africa	West coast of South Africa	South Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
98	Torterotot et al.	2020	Distribution of blue whale populations in the Southern Indian Ocean based on a decade of acoustic monitoring	Multiple sites in the Southwest Indian Ocean	South Indian Ocean	Pygmy blue whale; Antarctic blue whale	*Balaenoptera musculus brevicauda; Balaenoptera musculus intermedia*	Mysticeti

99	Todd et al.	2020	Using passive acoustic monitoring to investigate the occurrence of cetaceans in a protected marine area in northwest Ireland	Broadhaven Bay, Ireland	North Atlantic Ocean	Harbor porpoise	*Phocoena phocoena*	Odontoceti
100	Warren et al.	2020	Migratory insights from singing humpback whales recorded around central New Zealand: Humpback whale song, central New Zealand	Kaikōura, Wairarapa, South Taranaki Bight, and Cook Strait, New Zealand	South Pacific Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti
101	Allen et al.	2021	A Convolutional Neural Network for Automated Detection of Humpback Whale Song in a Diverse, Long-Term Passive Acoustic Dataset	Multiple sites in the North Pacific, including islands, atolls, seamounts, reefs, and equatorial region	North Pacific Ocean	Humpback whale	*Megaptera novaeangliae*	Mysticeti

102	Ahonen et al.	2021	Interannual variability in acoustic detection of blue and fin whale calls in the Northeast Atlantic High Arctic between 2008 and 2018	Fram Strait and Atwain	Arctic Ocean	Blue whale; Fin whale	*Balaenoptera musculus; Balaenoptera physalus*	Mysticeti
103	Booy et al.	2021	Spatio-temporal summer distribution of cumberland sound beluga whales (*Delphinapterus leucas*) in clearwater fiord, nunavut, canada	Cumberland Sound, Nunavut, Canada	Arctic Ocean	Beluga whale	*Delphinapterus leucas*	Odontoceti
104	Burkhardt et al.	2021	Seasonal and diel cycles of fin whale acoustic occurrence near Elephant Island, Antarctica	Elephant Island, Antarctica	South Atlantic Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
105	Carbaugh-Rutland et al.	2021	Geographically distinct blue whale song variants in the Northeast Pacific	Palmyra Atoll, Hawaiian Islands, Southern California, Washington	North Pacific Ocean	Blue whale	*Balaenoptera musculus musculus*	Mysticeti

				state, and in the Gulf of Alaska				
106	Constaratas et al.	2021	Fin whale acoustic populations present in new zealand waters: Description of song types, occurrence and seasonality using passive acoustic monitoring	Cook Strait and Gisborn, New Zealand	South Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
107	Durbach et al.	2021	Changes in the Movement and Calling Behavior of Minke Whales (*Balaenoptera acutorostrata*) in Response to Navy Training	Pacific Missile Range Facility in Kauai, Hawaii	North Pacific Ocean	Minke Whale	*Balaenoptera acutorostrata*	Mysticeti
108	Emmons, Hanson & Lammers et al.	2021	Passive acoustic monitoring reveals spatiotemporal segregation of two fish-eating killer whale *Orcinus orca* populations in proposed critical habitat	Multiple sites along the Washington coast, U.S., spanning the continental shelf from the	North Atlantic Ocean	Killer Whale	*Orcinus orca*	Odontoceti

				Canadian border in the north to the Columbia River in the south				
109	Furumaki, Tsujii & Mitani	2021	Fin whale (*Balaenoptera physalus*) song pattern in the southern Chukchi Sea	Southern Chukchi sea	Arctic Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
110	Guazzo et al.	2021	Singing Fin Whale Swimming Behavior in the Central North Pacific	Pacific Missile Range Facility off Kauai, Hawaii	North Pacific Ocean	Fin whale	*Balaenoptera physalus*	Mysticeti
111	Howe & Lammers	2021	Investigating the Diel Occurrence of Odontocetes Around the Maui Nui Region Using Passive Acoustic Techniques	Maui Nui, Hawaii	North Pacific Ocean	Short-finned pilot whale; False killer whale; Pantropical spotted dolphin; Spinner dolphin; Bottlenose dolphin	*Globicephala macrorhynchus; Pseudorca crassidens; Stenella attenuata; Stenella longirostris;*	Odontoceti

							Tursiops truncatus	
112	Jolliffe et al.	2021	Comparing the Acoustic Behaviour of the Eastern Indian Ocean Pygmy Blue Whale on Two Australian Feeding Grounds	Portland and Perth Canyon, Australia	South Indian Ocean and Southern Ocean	Pygmy blue whale	*Balaenoptera musculus brevicauda*	Mysticeti
113	Li et al.	2021	Decadal assessment of sperm whale site-specific abundance trends in the northern gulf of mexico using passive acoustic data	Northern Gulf of Mexico	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
114	Myers et al.	2021	Passive acoustic monitoring of killer whales (*Orcinus orca*) reveals year-round distribution and residency patterns in the Gulf of Alaska	Resurrection Bay, Montague Strait, and Hinchinbrook Entrance, Gulf of Alaska	North Pacific Ocean	Killer Whale	*Orcinus orca*	Odontoceti

115	Owen, Skold & Carlstrom	2021	An increase in detection rates of the critically endangered Baltic Proper harbor porpoise in Swedish waters in recent years	Baltic Sea	North Atlantic Ocean	Harbor porpoise	*Phocoena phocoena*	Odontoceti
116	Paitach et al.	2021	Echolocation variability of franciscana dolphins (*Pontoporia blainvillei*) between estuarine and open-sea habitats, with insights into foraging patterns	Babitonga Bay and Itapirubá Beach, Brazil	South Atlantic Ocean	Franciscana dolphin	*Pontoporia blainvillei*	Odontoceti
117	Pierpoint et al.	2021	An acoustic survey of beaked whale distribution at São Tomé and Príncipe, Gulf of Guinea, using an unmanned surface vessel	Democratic Republic of São Tomé and Príncipe, Gulf of Guinea, West Africa	South Atlantic Ocean	Cuvier's beaked whale	*Ziphius cavirostris*	Odontoceti
118	Rice et al.	2021	Cetacean occurrence in the Gulf of Alaska from long-term passive acoustic monitoring	Gulf of Alaska region including Kenai Shelf, Kodiak Shelf,	North Pacific Ocean	Blue whale; Fin whale; Baird's beaked whale; Gray whale; Humpback whale; Stejneger beaked whale;	*Balaenoptera musculus; Balaenoptera physalus; Berardius*	Mysticeti and Odontoceti

				Slope, Quinn, and Pratt		Killer whale; Sperm whale; Cuvier’s beaked whale	*bairdii; Eschrichtius robustus; Megaptera novaeangliae; Mesoplodon stejnegeri; Orcinus orca; Physeter macrocephalus; Ziphius cavirostris*	
119	Truong G & Rogers	2021	Seasonal Occurrence of Sympatric Blue Whale Subspecies: the Chilean and Southeast Indian Ocean Pygmy Blue Whales With the Antarctic Blue Whale	Cape Leeuwin, Australia and Juan Fernández, Chile	South Indian Ocean and South Pacific Ocean	Pygmy blue whale; Chilean blue whale; Antarctic blue whale	*Balaenoptera musculus brevicauda; Balaenoptera musculus chilensis; Balaenoptera musculus intermedia*	Mysticeti

120	Warren et al.	2021	Passive Acoustic Monitoring Reveals Spatio-Temporal Distributions of Antarctic and Pygmy Blue Whales Around Central New Zealand	Taranaki Bight, Cook Strait, Wairarapa, Kaikoura, New Zealand	South Pacific Ocean	Pygmy blue whale; Antarctic blue whale	*Balaenoptera musculus brevicauda; Balaenoptera musculus intermedia*	Mysticeti
121	Aulich et al.	2022	Seasonal Distribution of the Fin Whale (*Balaenoptera physalus*) in Antarctic and Australian Waters Based on Passive Acoustics	Several Antarctic and Australian Marine Regions	South Indian Ocean, South Pacific Ocean and Southern Ocean	Southern fin whale	*Balaenoptera physalus quoyi*	Mysticeti
122	Bouffaut et al.	2022	Eavesdropping at the Speed of Light: Distributed Acoustic Sensing of Baleen Whales in the Arctic	Isfjorden, Svalbard, Norway	Arctic Ocean	North atlantic blue whale	*Balaenoptera musculus*	Mysticeti
123	Chen et al.	2022	Seasonal and diel activities of the Yangtze finless porpoise in natural and	Anqing Yangtze Finless	North Pacific Ocean	Yangtze finless porpoise	*Neophocaena asiaeorientalis*	Odontoceti

			highly disturbed habitats: Implications for conservation planning of freshwater cetaceans	Porpoise Natural Reserve, Anhui Province, China				
124	Durette-Morin et al.	2022	The distribution of North Atlantic right whales in Canadian waters from 2015-2017 revealed by passive acoustic monitoring	Several areas in Atlantic Canadian waters	North Atlantic Ocean	North Atlantic right whale	*Eubalaena glacialis*	Mysticeti
125	Gauger et al.	2022	Seasonal and diel influences on bottlenose dolphin acoustic detection determined by whistles in a coastal lagoon in the southwestern Gulf of California	Ensenada de La Paz, Gulf of California, Mexico	North Pacific Ocean	Bottlenose dolphin	*Tursiops truncatus*	Odontoceti
126	Kowarski et al.	2022	Cetacean acoustic occurrence on the US Atlantic Outer Continental Shelf from 2017 to 2020	Multiples sites from Florida to Virginia, U.S.	North Atlantic Ocean	Minke whale; Sei whale; Blue whale; Fin whale; North Atlantic right whale; Humpback whale;	*Balaenoptera acutorostrata; Balaenoptera borealis;*	Mysticeti and Odontoceti

	Blainville's Beaked whale; Sperm whale; Cuvier's breaked whale; Gervai's OR True's Breaked whale; Pilot OR Killer whale; Dolphins	*Balaenoptera musculus; Balaenoptera physalus; Eubalaena glacialis; Megaptera novaeangliae; Mesoplodon densirostris; Physeter macrocephalus; Ziphius cavirostris;* unidentified species; unidentified species; unidentified species

127	Letsheleha et al.	2022	Year-round acoustic monitoring of Antarctic blue and fin whales in relation to environmental conditions off the west coast of South Africa	West coast of South Africa	South Atlantic Ocean	Antarctic blue whale; Fin whale	*Balaenoptera musculus intermedia; Balaenoptera physalus*	Mysticeti
128	Leu et al.	2022	Echolocation click discrimination for three killer whale ecotypes in the Northeastern Pacific	Coast of Washington, U.S.	North Pacific Ocean	Killer whale	*Orcinus orca*	Odontoceti
129	Manzano-Roth et al.	2022	Dive characteristics of Cross Seamount beaked whales from long-term passive acoustic monitoring at the Pacific Missile Range Facility, Kaua‘i	Pacific Missile Range Facility off Kauai, Hawaii	North Pacific Ocean	Beaked whale	unidentified species	Odontoceti
130	Paitach et al.	2022	Assessing effectiveness and side effects of likely “seal safe” pinger sounds to ward off endangered franciscana dolphins (*Pontoporia blainvillei*)	Babitonga Bay, Brazil	South Atlantic Ocean	Franciscana dolphin	*Pontoporia blainvillei*	Odontoceti

131	Poupard et al.	2022	Passive acoustic monitoring of sperm whales and anthropogenic noise using stereophonic recordings in the Mediterranean Sea, North West Pelagos Sanctuary	Mediterranean Sea, near the coast of Toulon	North Atlantic Ocean	Sperm whale	*Physeter macrocephalus*	Odontoceti
132	Rojas-Cerda et al.	2022	Presence of Southeast Pacific blue whales (*Balaenoptera musculus*) off South Georgia in the South Atlantic Ocean	South Georgia and Northern Chilean Patagonia	South Atlantic Ocean and South Pacific Ocean	Southeast Pacific blue whale	*Balaenoptera musculus*	Mysticeti
133	Soldevilla et al.	2022	Rice’s whales in the northwestern Gulf of Mexico: call variation and occurrence beyond the known core habitat	Northwestern Gulf of Mexico	North Atlantic Ocean	Rice’s whale	*Balaenoptera ricei*	Mysticeti
134	Barlow et al.	2023	Temporal occurrence of three blue whale populations	South Taranaki	South Pacific Ocean	Pygmy blue whale; Antarctic blue whale	*Balaenoptera musculus brevicauda;*	Mysticeti

			in New Zealand waters from passive acoustic monitoring	Bight region, New Zealand			*Balaenoptera musculus intermedia*	
135	Pearson et al.	2023	Widespread passive acoustic monitoring reveals spatio-temporal patterns of blue and fin whale song vocalizations in the Northeast Pacific Ocean	Gulf of Alaska, Olympic Coast, Cordell Bank, and Channel Islands	North Pacific Ocean	Blue whale; Fin whale	*Balaenoptera musculus; Balaenoptera physalus*	Mysticeti
136	Pilkington et al.	2023	Patterns of winter occurrence of three sympatric killer whale populations off eastern Vancouver Island, Canada, based on passive acoustic monitoring	Strait of Georgia, Canada	North Pacific Ocean	Killer whale	*Orcinus orca*	Odontoceti
137	Zuriel et al.	2023	Multi-year passive acoustic monitoring of coastal dolphins along the Israeli Mediterranean shallow shelf reveals the impact of marine	Coastal shelf of Israel, including the Nile province, the Bay of	North Atlantic Ocean	There wasn't identification	NA	Odontoceti

			fish farms and trawling patterns on their habitat utilization	Haifa and the Levant province				
138	Valdés-Hernández et al.	2024	Using passive acoustic monitoring to assess the overlap between endemic endangered Hector's dolphin (*Cephalorhynchus hectori hectori*) and mussel farms in the Banks Peninsula Marine Mammal Sanctuary, New Zealand	Pigeon Bay, Banks Peninsula, New Zealand	South Pacific Ocean	Hector's dolphins	*Cephalorhynchus hectori hectori*	Odontoceti

FIGURE S2. Correlation Matrix of the different categories of Biological Information in the Reviewed Studies

	Acoustic parameter	Anthropogenic impact	Behavior	Spatial variation	Habitat use	Population parameter	Temporal variation	Diel occurrence
Acoustic parameter	1.00	-0.14	-0.18	0.07	-0.14	-0.04	-0.15	-0.21
Anthropogenic impact	-0.14	1.00	0.11	-0.23	-0.13	0.15	-0.07	0.09
Behavior	-0.18	0.11	1.00	0.00	0.04	-0.17	-0.09	0.11
Spatial variation	0.07	-0.23	0.00	1.00	0.11	-0.02	0.19	-0.16
Habitat use	-0.14	-0.13	0.04	0.11	1.00	-0.14	0.34	0.13
Population parameter	-0.04	0.15	-0.17	-0.02	-0.14	1.00	-0.10	-0.03
Temporal variation	-0.15	-0.07	-0.09	0.19	0.34	-0.10	1.00	0.21
Diel occurrence	-0.21	0.09	0.11	-0.16	0.13	-0.03	0.21	1.00

MATERIAL SUPLEMENTAR CAPÍTULO II: Assessment of acoustic metrics for monitoring humpback whale local population abundance

Table S1. Table S1. Sampling effort in 2014, 2015, 2018, and 2019. The start and end dates of the periods during which visual and acoustic monitoring were conducted simultaneously are presented, the total number of one-hour visual scans performed per year, and the sample size for the acoustic indicators

Sampling effort						
Year	**Start date (mm/dd)**	**End date (mm/dd)**	**Scans performed (n)**	**Daytime acoustic effort (n)**	**Nighttime acoustic effort (n)**	**Total acoustic effort (n)**
2014 - stage 1	07/11	07/31	8	8	0	8
2014 - stage 2	09/03	10/01	10	10	0	10
2015	09/17	10/25	10	10	10	20
2018	08/14	10/17	20	17	20	37
2019	07/17	10/10	23	23	23	46

Table S2. Characteristics of the acoustic recorders used in each year. This table presents the recorder version, sampling rate (Hz), system sensitivity (dB re 1 V/µPa), and the distance from the coast (km) for each year of monitoring.

Characteristics of the acoustic recorders (Pods)				
Year	**Recorder version**	**Sampling rate (Hz)**	**System sensitivity (dB re 1 V/µPa)**	**Distance from coast (km)**
2014	1	11,025	-150	2.56
2015	1	11,025	-150	2.57
2018	3	16,000	-146	2.54

2019	3	16,000	-146	2.02

Figure S3. Data collection effort during the years 2014, 2015, 2018, and 2019, with visual and acoustic monitoring conducted simultaneously. The day of the year is shown continuously, where 180 corresponds to June 29 and 320 to November 16.

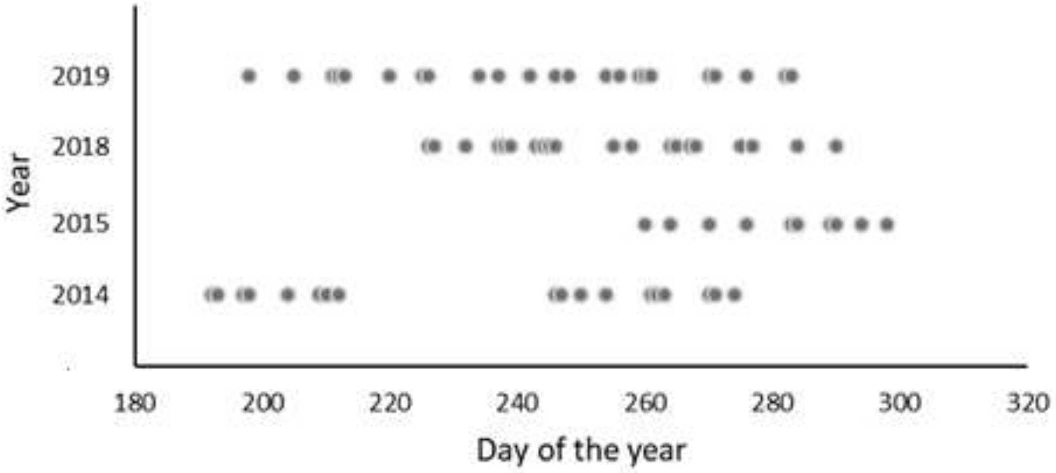
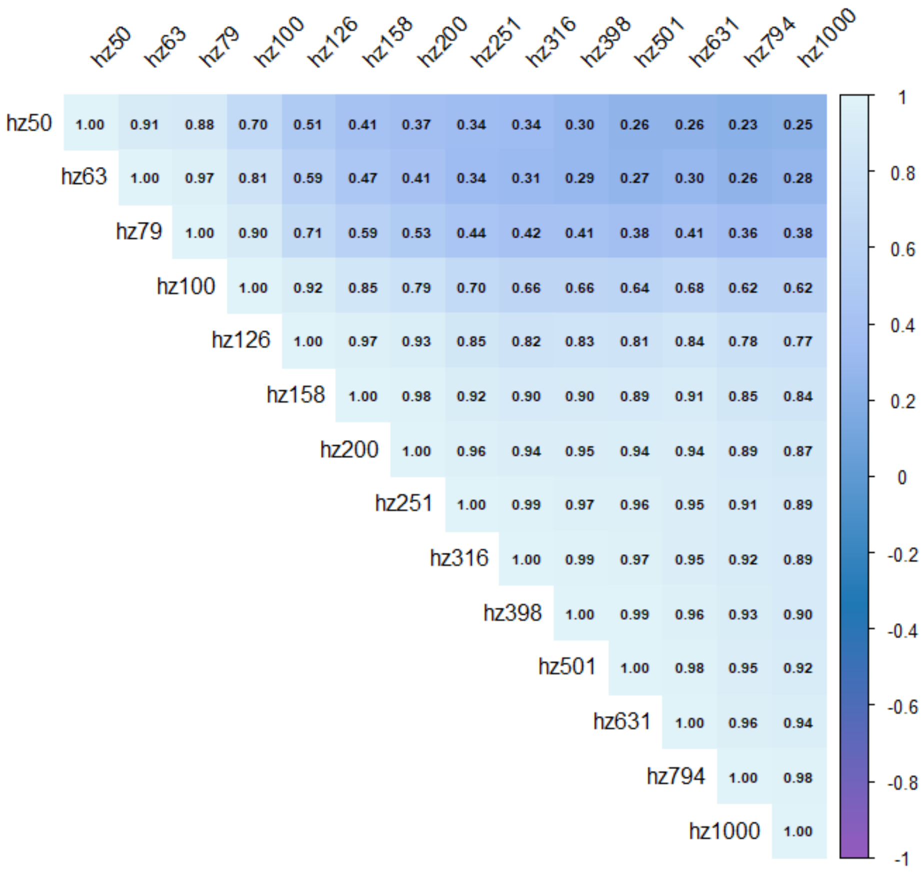


Figure S4. Pearson correlation matrix of sound pressure levels (RMS SPL) across the frequency bands used in the calculation of TOL. The strong collinearity observed among the bands led to the decision not to include them individually in the predictive models.



	hz50	hz63	hz79	hz100	hz126	hz158	hz200	hz251	hz316	hz398	hz501	hz631	hz794	hz1000
hz50	1.00	0.91	0.88	0.70	0.51	0.41	0.37	0.34	0.34	0.30	0.26	0.26	0.23	0.25
hz63		1.00	0.97	0.81	0.59	0.47	0.41	0.34	0.31	0.29	0.27	0.30	0.26	0.28
hz79			1.00	0.90	0.71	0.59	0.53	0.44	0.42	0.41	0.38	0.41	0.36	0.38
hz100				1.00	0.92	0.85	0.79	0.70	0.66	0.66	0.64	0.68	0.62	0.62
hz126					1.00	0.97	0.93	0.85	0.82	0.83	0.81	0.84	0.78	0.77
hz158						1.00	0.98	0.92	0.90	0.90	0.89	0.91	0.85	0.84
hz200							1.00	0.96	0.94	0.95	0.94	0.94	0.89	0.87
hz251								1.00	0.99	0.97	0.96	0.95	0.91	0.89
hz316									1.00	0.99	0.97	0.95	0.92	0.89
hz398										1.00	0.99	0.96	0.93	0.90
hz501											1.00	0.98	0.95	0.92
hz631												1.00	0.96	0.94
hz794													1.00	0.98
hz1000														1.00