Global Ecology and Biogeography

WILEY

Global Ecology and Biogeography — A Journal of Macroecology

RESEARCH ARTICLE OPEN ACCESS

Worldwide Soundscapes: A Synthesis of Passive Acoustic Monitoring Across Realms

Kevin F. A. Darras[1,2,3] | Rodney A. Rountree[4,5] | Steven L. Van Wilgenburg[6] | Anna F. Cord[3,7] | Frederik Pitz[3] | Youfang Chen[2] | Lijun Dong[8] | Agnès Rocquencourt[1] | Camille Desjonquères[9,10] | Patrick Mauritz Diaz[11] | Tzu-Hao Lin[12] | Théophile Turco[13] | Louise Emmerson[14] | Tom Bradfer-Lawrence[15,16] | Amandine Gasc[17] | Sarah Marley[18] | Marcus Salton[14] | Laura Schillé[19] | Paul J. Wensveen[20] | Shih-Hung Wu[21] | Adriana C. Acero-Murcia[22] | Orlando Acevedo-Charry[23,24,25,26,27] | Matyáš Adam[28] | Jacopo Aguzzi[29] | Irmak Akoglu[30] | M. Clara P. Amorim[31] | Mina Anders[32] | Michel André[33] | Alexandre Antonelli[34,35,36] | Leandro Aparecido Do Nascimento[37] | Giulliana Appel[38] | Stephanie Archer[39] | Christos Astaras[40] | Andrey Atemasov[41,42] | Jamieson Atkinson[43] | Joël Attia[13] | Emanuel Baltag[44] | Luc Barbaro[45] | Fritjof Basan[46] | Carly Batist[47] | Julio Ernesto Baumgarten[48] | Just T. Bayle Sempere[49] | Kristen Bellisario[50] | Asaf Ben David[51] | Oded Berger-Tal[52] | Frédéric Bertucci[53] | Matthew G. Betts[54] | Iqbal S. Bhalla[55] | Thiago Bicudo[56,57] | Marta Bolgan[58] | Sara Bombaci[59] | Gerard Bota[60] | Martin Boullhesen[61] | Robert A. Briers[62] | Susannah Buchan[63,64] | Michal Budka[65] | Katie Burchard[66] | Giuseppa Buscaino[67] | Alice Calvente[68] | Marconi Campos-Cerqueira[56] | Maria Isabel Carvalho Gonçalves[48] | Maria Ceraulo[67] | Maite Cerezo-Araujo[69] | Gunnar Cerwén[70] | Adams A. Chaskda[71] | Maria Chistopolova[72] | Christopher W. Clark[73] | Kieran D. Cox[74] | Benjamin Cretois[75] | Chapin Czarnecki[76] | Luis P. da Silva[77,78] | Wigna da Silva[79] | Laurence H. De Clippele[80] | David de la Haye[81] | Ana Silvia de Oliveira Tissiani[82] | Devin de Zwaan[83,84] | M. Eugenia Degano[85,86] | Jessica Deichmann[87] | Joaquin del Rio[88] | Christian Devenish[89] | Ricardo Díaz-Delgado[90] | Pedro Diniz[91] | Dorgival Diógenes Oliveira-Júnior[92,93] | Thiago Dorigo[94] | Saskia Dröge[95] | Marina Duarte[96,97] | Adam Duarte[98] | Kerry Dunleavy[99] | Robert Dziak[100] | Simon Elise[101,102] | Hiroto Enari[103] | Haruka S. Enari[103] | Florence Erbs[33] | Britas Klemens Eriksson[104] | Pınar Ertör-Akyazi[30] | Nina C. Ferrari[54] | Luane Ferreira[79] | Abram B. Fleishman[99] | Paulo J. Fonseca[105] | Bárbara Freitas[106,107,108] | Nicholas R. Friedman[109,110] | Jérémy S. P. Froidevaux[15,111] | Svetlana Gogoleva[112] | Carolina Gonzaga[97] | José Miguel González Correa[49] | Eben Goodale[113] | Benjamin Gottesman[73] | Ingo Grass[114] | Jack Greenhalgh[115] | Jocelyn Gregoire[116] | Samuel Haché[116] | Jonas Hagge[117] | William Halliday[118] | Antonia Hammer[119] | Tara Hanf-Dressler[120] | Sylvain Haupert[121] | Samara Haver[122] | Becky Heath[123,124] | Daniel Hending[125] | Jose Hernandez-Blanco[72] | Dennis Higgs[126] | Thomas Hiller[114,127] | Joe Chun-Chia Huang[128] | Katie Lois Hutchinson[129] | Carole Hyacinthe[130] | Christina Ieronymidou[131] | Iniunam A. Iniunam[71] | Janet Jackson[132] | Alain Jacot[133] | Olaf Jahn[134,135] | Francis Juanes[4] | K. S. Jasper Kanes[136] | Ellen Kenchington[137] | Sebastian Kepfer-Rojas[138] | Justin Kitzes[76] | Tharaka Kusuminda[139] | Yael Lehnardt[52] | Jialin Lei[140] | Paula Leitman[94] | José León[141] | Deng Li[140] | Cicero Simão Lima-Santos[92,93] | Kyle John Lloyd[142,143,144] | Audrey Looby[145,146] | Adrià López-Baucells[147] | David López-Bosch[147] | Tristan Louth-Robins[148] | Tatiana Maeda[149] | Franck Malige[150] | Christos Mammides[151] | Gabriel Marcacci[133] | Matthias Markolf[152,153] | Marinez Isaac Marques[82] | Charles W. Martin[145] | Dominic A. Martin[154,155] | Kathy Martin[83,156] | Ellen McArthur[128] | Matthew McKown[99] | Logan J. T. McLeod[157] | Vincent Médoc[13] | Oliver Metcalf[158] | Christoph F. J. Meyer[96] | Grzegorz Mikusinski[159] | Brian Miller[14] | João Monteiro[160] | T. Aran Mooney[161] | Sérgio Moreira[79] | Larissa Sayuri Moreira Sugai[73] | Dave Morris[132] | Sandra Müller[162] | Sebastian Muñoz-Duque[163] | Kelsie A. Murchy[164] | Ivan Nagelkerken[165] | Maria Mas[147] | Rym Nouioua[166] | Carolina Ocampo-Ariza[32,167] | Julian D. Olden[168] | Steffen Oppel[16,133] | Anna N. Osiecka[169] | Elena Papale[67] | Miles Parsons[118] | Michael Pashkevich[170] | Julie Patris[150] | João Pedro Marques[31] | Cristian Pérez-Granados[171] | Liliana Piatti[172] | Mauro Pichorim[92,93] | Matthew K. Pine[4,173] | Thiago Pinheiro[79] | Jean-Nicolas Pradervand[133] | John Quinn[174] | Bernardo Quintella[31] | Craig Radford[175] | Xavier Raick[73,176] | Ana Rainho[105] | Emiliano Ramalho[177] | Vijay Ramesh[73] | Sylvie Rétaux[178] | Laura K. Reynolds[179] | Klaus Riede[134] |

For affiliations refer to page 14.

Talen Rimmer[164] | Noelia Ríos[180,181] | Ricardo Rocha[125] | Luciana Rocha[79] | Paul Roe[182] | Samuel R. P.-J. Ross[183] | Carolyn M. Rosten[184] | John Ryan[185] | Carlos Salustio-Gomes[92,93] | Filipa I. P. Samarra[20] | Philip Samartzis[186] | José Santos[79] | Thomas Sattler[133] | Kevin Scharffenberg[187] | Renée P. Schoeman[188] | Karl-Ludwig Schuchmann[82] | Esther Sebastián-González[171] | Sebastian Seibold[189] | Sarab Sethi[190] | Fannie W. Shabangu[191,192] | Taylor Shaw[162] | Xiaoli Shen[193] | David Singer[117] | Ana Širović[194] | Matthew Slater[195] | Brittnie Spriel[164] | Jenni Stanley[196] | Jérôme Sueur[121] | Valeria da Cunha Tavares[38,197,198] | Karolin Thomisch[199] | Simon Thorn[200,201] | Jianfeng Tong[202] | Laura Torrent[147] | Juan Traba[203,204] | Junior A. Tremblay[205] | Leonardo Trevelin[38] | Sunny Tseng[206] | Mao-Ning Tuanmu[12] | Marisol Valverde[207] | Ben Vernasco[98,208] | Manuel Vieira[31] | Raiane Vital da Paz[92,93] | Matthew Ward[209] | Maryann Watson[104] | Matthew J. Weldy[54] | Julia Wiel[75] | Jacob Willie[210] | Heather Wood[211] | Jinshan Xu[137] | Wenyi Zhou[25,212,213] | Songhai Li[8] | Renata Sousa-Lima[79] | Thomas Cherico Wanger[2,214,215]

Correspondence: Kevin F. A. Darras (kevin.darras@inrae.fr) | Thomas Cherico Wanger (tomcwanger@westlake.edu.cn)

Received: 17 August 2024 | **Revised:** 6 December 2024 | **Accepted:** 15 February 2025

Handling Editor: Franziska Schrodt

Funding: We acknowledge the NFDI Consortium Earth System Sciences—NFDI4Earth, coordinated by TU Dresden, funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—project number: 460036893. This research was also funded by a Westlake University Startup Fund (Thomas C. Wanger). JGM was funded by Fundação para a Ciência e Tecnologia (FCT) under the Scientific Employment Stimulus—Institutional Call—(CEECINST/00037/2021) and Luis P. da Silva through the research contract CEECIND/02064/2017 (https://doi.org/10.54499/CEECIND/02064/2017/CP1423/CP1645/CT0009). Ana Rainho also acknowledges funding from the FCT, under the EcoPestSuppression project (DOI 10.54499/PTDC/ASP-AGR/0876/2020). BIOMON is funded by the European Union's Horizon Europe Programme under grant agreement 101090273. Christos Mammides acknowledges BirdLife Cyprus. Bárbara Freitas was funded by the Foundation for Science and Technology (FCT, Portugal) through a PhD grant (2020.04569.BD). Larissa Sayuri M. Sugai and Liiana Piatti acknowledge grant Fundect T.O.:95/2023; SIAFEM: 33112. This paper is NOAA-PMEL, contribution number 5948. Adriana C. Acero-Murcia acknowledge grand Bat Conservation International (Code SS2001), and CAPES Brasil (Finance Code 001). The OBSEA research has been carried out within the framework of the Research Unit Tecnoterra (ICM-CSIC/UPC) of the Spanish Government, developing the EU Project 'SUstainable Nature and inclusive offshore energy with the parallel BIOdiversity flourishing, protection and monitoring (SUN-BIO-101157493-GAP-101157493)'. Songhai Li acknowledges the National Natural Science Foundation of China (Grant numbers 42225604). Jeremy Froidevaux acknowledges funding from the Leverhulme Trust (ECF-2020-571). Kevin Darras and Sylvain Haupert thank the Sounds of Life Huma-Num consortium for training support. Anna F. Cord was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2070-390732324. Ivan Nagelkerken acknowledges funding from the Australian Research Council. M. Eugenia Degano acknowledges the Deutsche Forschungsgemeinschaft (DFG, Project Number: 428658210). Renata Sousa-Lima and her collaborators have received funding from The Canon National Parks Science Scholars Program, CNPq (grants 312763/2019-0 and 311533/2022-1) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001. The Asian Soundscape Monitoring Network is funded by Asi@Connect (Asi@Connect-17-100) and the Biodiversity Research Center and the Grid-Computing Centre at Academia Sinica. This work was also supported by Portuguese Funds through FCT—Foundation for Science and Technology through MARE's base funding (UIDB/04292/2020, https://doi.org/10.54499/UIDB/04292/2020) and MARE's strategic program (UIDP/04292/2020, https://doi.org/10.54499/UIDP/04292/2020), through project LA/P/0069/2020 granted to the Associate Laboratory ARNET (https://doi.org/10.54499/LA/P/0069/2020); and the CoastNet Research Infrastructure, funded by FCT and the European Regional Development Fund (FEDER) until 2021 (PINFRA/22128/2016), through LISBOA2020 and ALENTEJO2020 regional operational programs. Drs Slater and Radford recognise funding by the Royal Society of New Zealand and the German Federal Ministry of Education and Research within the Framework of the New Zealand–Germany Scientific Exchange Programme. Maria Isabel Carvalho Gonçalves has received funding from an anonymous donor, CAPES, Cetacean Society International (CSI), Rufford Foundation, Universidade Estadual de Santa Cruz (UESC) and Viva Instituto Verde Azul. Pinar Ertör-Akyazı received funding from Bogazici University BAP No: 18701. This material is partly based upon work supported by the H.J. Andrews Experimental Forest and Long Term Ecological Research (LTER) program under the NSF grant LTER8 DEB-2025755. This is from Nina Ferrari and Matthew Betts. Pedro Diniz held a CAPES postdoctoral fellowship (grant 88887.469218/2019–00) and is currently supported by a postdoctoral fellowship from the São Paulo Research Foundation (FAPESP), Brazil (Process #2024/13237-3). Tharaka Kusuminda acknowledges the Wildlife Acoustics Research Grant Program.

Keywords: ARU | automated sound recorder | biodiversity | conservation biology | ecoacoustics | IUCN GET realm | Passive Acoustic Monitoring | phenology | soundscape ecology

ABSTRACT

Aim: The urgency for remote, reliable and scalable biodiversity monitoring amidst mounting human pressures on ecosystems has sparked worldwide interest in Passive Acoustic Monitoring (PAM), which can track life underwater and on land. However, we lack a unified methodology to report this sampling effort and a comprehensive overview of PAM coverage to gauge its potential as a global research and monitoring tool. To address this gap, we created the Worldwide Soundscapes project, a collaborative network and growing database comprising metadata from 416 datasets across all realms (terrestrial, marine, freshwater and subterranean).

Location: Worldwide, 12,343 sites, all ecosystem types.

Time Period: 1991 to present.

Major Taxa Studied: All soniferous taxa.

Methods: We synthesise sampling coverage across spatial, temporal and ecological scales using metadata describing sampling locations, deployment schedules, focal taxa and audio recording parameters. We explore global trends in biological, anthropogenic and geophysical sounds based on 168 selected recordings from 12 ecosystems across all realms.

Results: Terrestrial sampling is spatially denser (46 sites per million square kilometre—Mkm^2) than aquatic sampling (0.3 and 1.8 sites/Mkm^2 in oceans and fresh water) with only two subterranean datasets. Although diel and lunar cycles are well sampled

across realms, only marine datasets (55%) comprehensively sample all seasons. Across the 12 ecosystems selected for exploring global acoustic trends, biological sounds showed contrasting diel patterns across ecosystems, declined with distance from the Equator, and were negatively correlated with anthropogenic sounds.
Main Conclusions: PAM can inform macroecological studies as well as global conservation and phenology syntheses, but representation can be improved by expanding terrestrial taxonomic scope, sampling coverage in the high seas and subterranean ecosystems, and spatio-temporal replication in freshwater habitats. Overall, this worldwide PAM network holds promise to support cross-realm biodiversity research and monitoring efforts.

1 | Introduction

Sounds permeate all realms on Earth—terrestrial, freshwater, marine and subterranean (Keith et al. 2022). Passive Acoustic Monitoring (PAM) captures soundscapes that document soniferous (i.e., sound-producing) organisms and human activities, and some geophysical events (i.e., biophony, anthropophony and geophony, respectively). In ecoacoustics and soundscape ecology (Pijanowski, Farina, et al. 2011; Sueur and Farina 2015), PAM can measure the impacts of global change (e.g., climatic shifts, urbanisation, deep-sea mining) (Kang et al. 2023; Sueur et al. 2019; Williams et al. 2022); monitor ecosystem health, recovery and restoration (Müller et al. 2023; Ross et al. 2024; Sethi et al. 2020); assess human–environment interactions (e.g., public health, cultural ecosystem services) (Alvarsson et al. 2010; Chen et al. 2022); and guide environmental management and conservation policies (e.g., protected areas, landscape planning) (Haver et al. 2019; Holgate et al. 2021).

Despite the wide-ranging and increasing soundscape sampling effort (Havlik et al. 2022; Sugai et al. 2019), global recording efforts across realms remain undescribed. Previous non-systematic qualitative reviews (Duarte et al. 2021; Lindseth and Lobel 2018) cannot describe data trends. Existing systematic reviews (Greenhalgh et al. 2020; Havlik et al. 2022; Scarpelli et al. 2020; Sugai et al. 2019) have not quantitatively addressed marine taxonomic coverage, terrestrial ecosystem coverage, nor spatio-temporal sampling distribution in fresh water, while the subterranean realm has yet to be reviewed. Notably, all reviews to date used only published data and involved only a small part of their respective communities. Indeed, practitioners of PAM are currently only networked within realms (e.g., terrestrial/marine), and often use distinct methods. Marine scientist networks using PAM exist (Boyd et al. 2015), but the freshwater community is nascent, and the terrestrial community is often fragmented by taxa. Methodological differences are also striking: acoustic calibration and sound propagation modelling are advanced in aquatic studies (Wang et al. 2014) but seldom considered in terrestrial ones (but see Haupert et al. (2022) and Sousa-Lima et al. (2013)); artificial intelligence can increasingly identify species on land (Nieto-Mora et al. 2023), whereas most aquatic sounds are still challenging to identify (Looby, Erbe et al. 2023; Parsons et al. 2023).

Overall, a global PAM network could increase knowledge transfer, resulting in more efficient and consistent methods, analyses and cross-system syntheses (Sugai et al. 2019). Cross-realm PAM studies can advance theoretical (Ross et al. 2023) and applied solutions. For instance, organisms' sound durations follow a common distribution across multiple realms (de Sousa et al. 2022). Also, soundscapes can track terrestrial and marine resilience to and recovery from disturbance (Gottesman et al. 2021). Transnational sampling could form the basis for comprehensive soniferous biodiversity monitoring, just as community-initiated telemetry databases (Kays, Davidson, et al. 2022) and collaborative camera trap surveys (Kays, Cove, et al. 2022) have advanced entire research fields. A global PAM network could complement existing biodiversity-monitoring networks, establish historical biodiversity baselines, support systematic long-term and large-scale monitoring and connect with the public through citizen science. Such information is critical to inform global biodiversity policies such as the Kunming-Montreal Global Biodiversity Framework (Moersberger et al. 2024).

We present the 'Worldwide Soundscapes' project, the first global PAM meta-database and network (https://ecosound-web.de/ecosound_web/collection/index/106). We use it to quantify the known state of PAM efforts, highlight apparent sampling gaps and biases, illustrate the potential of cross-realm PAM syntheses for research and federate PAM users. The project currently comprises 357 contributors who collated metadata from 416 passively recorded, stationary, replicated soundscape datasets. Metadata describe the exact spatio-temporal coverage, sampled ecosystems (*sensu* International Union for Conservation of Nature Global Ecosystem Typology: IUCN GET), transmission medium (air, water, or soil), focal taxa (IUCN Red list), audio recording settings, as well as data and publication availability. We inferred coverage within administrative (Global ADMinistrative Database: GADM; International Hydrographic Organisation: IHO) and protected areas (World Database on Protected Areas: WDPA) from geographic locations. We selected recordings referenced in the meta-database to quantify soundscape components (biophony, anthropophony, and geophony) across 12 ecosystems from all realms. We showcase how the soundscape components can be used to answer exemplary macroecology, conservation biology and phenology research questions and we identify opportunities to advance the global PAM network. The publicly accessible meta-database (Darras et al. 2025) continues to grow to enhance accessibility of data and remains open for metadata contributions, facilitating exchange among researchers and future syntheses.

2 | Methods

2.1 | Database Construction

The Worldwide Soundscapes project began in August 2021 using collaborative, peer-driven metadata collation (Darras et al. 2025). It represents the current state of knowledge of PAM within our network. We additionally conducted focal publication searches to plug coverage gaps by inviting the respective corresponding authors. We posted the call for contributors on specialised ecoacoustics platforms and social media, and kept the project open for any contributor owning suitable soundscape recordings. We communicated by emails in English, Spanish, French, Portuguese, German, Russian, and Chinese to federate users in our network. Of 581 contacted contributors potentially involved in PAM, 61% provided metadata. We included metadata from larger, national or international groups such as the Silent Cities project (Challéat et al. 2024), Ocean Networks Canada (Heesemann et al. 2014), and the Australian Acoustic Observatory (Roe et al. 2021). Primary contributors provided the metadata and bear the responsibility for their accuracy. Research assistants checked the coherence of the metadata input (beyond automated data format checks) and primary contributors cross-validated metadata displayed as maps and graphical timelines. The database information page and content are integrated as a project in our online collaborative ecoacoustics platform ecoSound-web (Darras et al. 2023) that also hosts the annotated soundscape recordings of the case study (https://ecosound-web.de/ecosound_web/collection/show/49).

Soundscape recording datasets needed to meet four criteria: (1) stationary—mobile recorders have variable spatial assignments, thus we excluded recordings from cars, transect walks or towed deployments; (2) passive—obtained from unattended recorders; (3) ambient—omni-directional, non-triggered recordings, under non-experimental conditions; (4) spatially or temporally replicated (Figure 1)—to disentangle spatial and temporal effects from other soundscape determinants. Datasets were defined as spatially replicated when several sites were sampled simultaneously, and temporally replicated when a site was sampled over multiple days at the same time of day. Sampling sites and days were our elemental units for defining replication; however, in other contexts, spatial replicates may, for instance, be required to be in the same habitat, and temporal replicates may be defined across multiple full moon nights. Taken together, our requirements homogenise the dataset to enable general, unified statistical analyses across datasets.

2.2 | Time and Space

Soundscapes result from geophysical phenomena as well as wildlife and human activities that are broadly determined by solar and lunar cycles and geographical positions on the planet relative to the poles or Equator or the land and water surface. We defined and calculated spatial coverage as the number of audio sampling sites ('sites' hereafter) and spatial density as the number of sites relative to each realm's areal extent (Figure 2). Spatial sampling extent could have been defined as the area bounded by sites, but calculating extents on the world sphere is conceptually challenging for large extents. Spatial coverage calculation is further hindered by the fact that the sampling area covered at each site is generally unknown: they are rarely measured in terrestrial sites but sometimes simulated in marine environments (Erbe and Thomas 2022). Detection spaces vary with sound source intensity, frequency, directivity, recording medium temperature, currents, pressure, atmospheric humidity (for air), habitat structure and ambient sound level (Darras et al. 2016; van Parijs et al. 2009). Underwater, at depths above the wavelength, detection spaces are greater than on land due to the higher density of the recording medium. Our measure of spatial sampling density using points per area is thus provisional. Temporal extent was defined as the time range from the start of the first to the end of the last recording of a site, temporal coverage as the time sampled for that site and temporal density as the proportion of time sampled within the temporal extent.

We quantified latitudinal and topographical distribution by collecting coordinates, elevation and depth data for each site. Topography values on land were either provided by the contributors or filled in automatically using the General Bathymetric Chart of the Oceans surface elevation data (GEBCO 2025). For freshwater sites, depth values below the water surface were provided by the contributors, and for subterranean sites, depth below the land surface was recorded. We assigned sampling sites to administrative areas (GADM divisions for freshwater and land, IHO for sea areas) and extracted their WDPA category. Sites' climates were geographically classified into tropical (between −23.5° and 23.5° latitude), polar (below −66.5° or above 66.5° latitude) and temperate (between polar and tropical regions).

Primary contributors coded their exact recording times for each site using deployment start and end dates and times and operation modes (or combinations thereof). Operation modes included continuous operation, which lasted from the deployment start to its end; scheduled operations that had daily start and end times; and periodical operations that used duty cycles. A temporal framework was devised to quantify sampling coverage in three solar and lunar cycles using the timing of sound recordings relative to specific events (Figure 3). Seasonal coverage was inferred only for temperate sites by splitting the year into four meteorological seasons (winter: December–February, spring: March–May, summer: June–August, fall: September–November, reversed for Southern latitude sites). The daily cycle was split into four diel windows delimiting dawn (from astronomical dawn start at −18° solar altitude until 18° solar altitude), day, dusk (from 18° solar altitude to astronomical dusk end at −18° solar altitude) and night. The lunar illumination cycle was split into two time windows centred on the full and new moon phases. Thus, extrema and ecotones in the temporal cycles define time windows, and in temperate zones, equinoxes roughly correspond to thermal ecotones. Seasonal cycles in tropical and polar regions arising from precipitation patterns were not considered in this analysis, but future frameworks should consider recent developments (Littleboy et al. 2024).

2.3 | Ecological Characterisation

We assigned sites to ecosystem types following the IUCN GET (https://global-ecosystems.org). Sites were assigned hierarchically to realms, biomes and functional groups. 'Core' realms are terrestrial, marine, freshwater and subterranean, while 'transitional' realms represent the interface between these. For example, the transitional marine–freshwater–terrestrial realm comprises the brackish tidal biome, which contains coastal river deltas as a functional group. We calculated major occurrence areas of all functional groups based on ecosystem maps (Keith, Ferrer-Paris, Nicholson, Bishop, et al. 2020) to quantify spatio-temporal extent, coverage and sampling density within realms

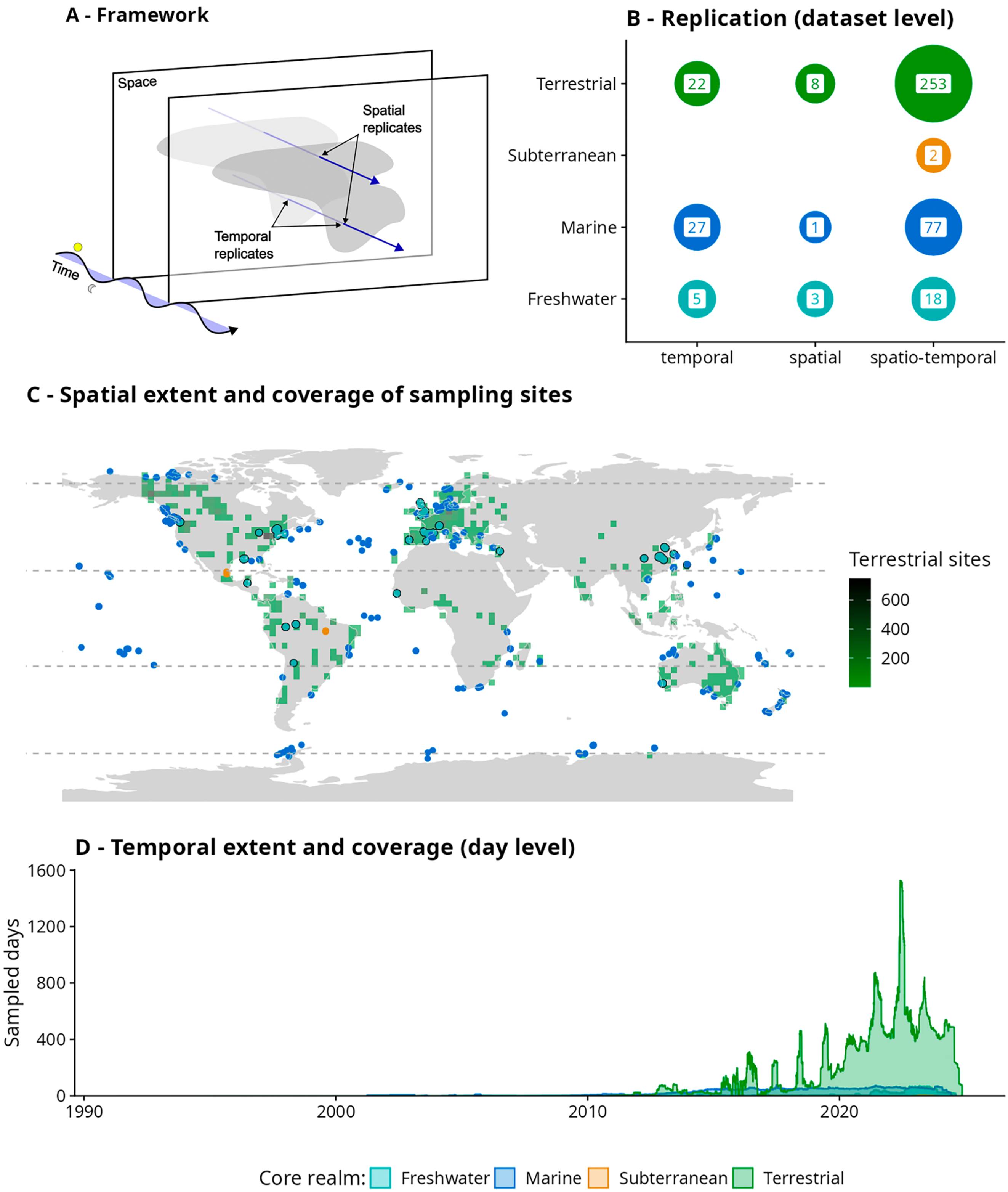

FIGURE 1 | Overview of Worldwide Soundscapes meta-database. (A) Framework used to define spatial and temporal replicates. (B) Number of datasets in each core realm for the different replication levels. (C) Spatial extent and coverage, based on sampling sites, split by core realm. Due to their higher representation and to avoid overlapping site clusters, terrestrial site densities were plotted on a 3° resolution raster (Interactive map: https://ecosound-web.de/ecosound_web/collection/index/106). (D) Temporal extent and coverage, based on recorded days, split by core realm. An enlarged version of panel D without terrestrial sites can be found in Figure S3. For panels B–D, sites from transitional realms were assigned to their parent core realm.

and biomes. For the spatial and temporal result sections, sites were assigned to their 'parent' realm (i.e., the first mentioned realm in the compound transitional realm names). The results section 'Sampling in ecosystems' separates results among core and transitional realms. Deployments were linked to IUCN Red List taxa (class, order, family or genus) when studies were designed for monitoring these taxa; other deployments could be collected without taxonomic focus.

2.4 | Acoustic Frequency Ranges

We needed to determine the spectral scope of soundscape recordings. Microphones (including hydrophones and geophones) have variable frequency responses, usually declining with frequencies above the human-audible range. Additionally, digital recorders restrict the spectral range of the recording with the sampling frequency. Contributors provided audio parameters for their deployments: sampling frequency, high-pass filters, microphone and recorder models. More recent metadata contributions include the number of channels, audio amplification and bit depth.

2.5 | Soundscape Case Studies

To illustrate how the database can be used for macroecology, conservation biology and phenology analyses, we selected 168 recordings across a variety of topographical, latitudinal and anthropisation conditions—all fundamental gradients of assembly filters in both terrestrial and marine realms (Keith et al. 2022)—belonging to 12 IUCN GET functional groups (i.e., ecosystem types): large lowland rivers, small permanent freshwater lakes, riverine estuaries, bathypelagic ocean waters, island slopes, photic coral reefs, tropical montane rainforests, tropical lowland rainforests, plantations, urban ecosystems, polar outcrops and aerobic caves. We aimed for four spatial replicates within the same functional group, with 10-min audible sound recordings (at least 44.1 kHz sampling frequency) starting at sunrise, solar noon, sunset, and solar midnight from the same date during the biologically active season. However, the available data sometimes yielded fewer replicates or a lower sampling frequency in one case (Table S3). We acknowledge that this targeted, non-systematic selection of recordings is not statistically representative of global patterns but rather illustrative of the database's potential for future studies.

In each soundscape recording, we identified the three fundamental soundscape components: biophony, anthropophony, and geophony. For example, biophony could comprise acoustic cues (vocalisations or sonant displays) from non-human vertebrates or invertebrates; anthropophony comprises human speech or noises from any human technologies (e.g., engines, explosions; sometimes termed 'technophony'); geophony comprises geophysical sounds (e.g., from wind, rain or waves). Soundscape recordings were uploaded to ecoSound-web (Darras et al. 2023) for annotation (https://ecosound-web.de/ecosound_web/collection/show/49): KD listened to them while visually inspecting spectrograms (Fast Fourier Transform window size of 1024) at a density of 1116 pixels per 10 min. Visible and audible sounds were annotated using rectangular boxes on the spectrogram, with defined coordinates in the time and frequency dimensions, bounding the corresponding sound closely. Annotations were classified into different soundscape components and could overlap if they were simultaneously visible or audible. Soundscape components above 22.05 kHz and sounds caused by microphone or recorder self-noise were excluded from the analysis. All annotations were validated by the recordists using the peer-review mode on ecoSound-web, which allowed them to view and listen to the same recording to accept, revise or reject annotations, and to check whether annotations were missing. Revised or rejected annotations were corrected by KD before a second validation. Finally, acoustic space occupancy for each soundscape component in each recording was calculated as the proportion of the sampled spectro-temporal space (Luypaert et al. 2022) (i.e., annotations area divided by total area of spectrogram; range: 0–1), and silence was the proportion of the acoustic space not covered by any soundscape component. We used the total coverage of annotations of the same soundscape component, excluding overlaps, to compute acoustic space occupancy. For instance, a windy episode covering half of the spectrogram's duration from 1 to 3000 Hz would cover ~7% of the acoustic space (300 s $\times$ 3000 Hz/(600 s $\times$ 22,050 Hz)).

We asked whether biophony occupancy increases with proximity to the equator, whether biophony is negatively correlated with anthropophony and whether phenology patterns differ across functional groups. Statistical models predicting biophony occupancy were Bayesian beta regression models (four chains of 4000 sampling iterations with 2000-warmup iterations, thinning rate of 1) fitted with the R package brms (Bürkner 2017). Models converged as determined by trace plots and R hat values smaller than 1.1. The number of data points equaled the number of recordings ($N = 168$). The models using latitude and anthropophony were mixed-effect models including the functional group as a random intercept. The phenology model used diel time windows, coded as a numeric variable with integers from 1 to 4, and functional group, as well as their interaction, as predictors. This allowed for the comparison of effects of the functional group on the phenology profile, approximated by a linear regression, by measuring statistically significant differences in the slopes of that regression depending on the functional group.

3 | Results

3.1 | Summary Dataset Statistics

To date, 416 validated soundscape meta-datasets (hereafter 'datasets') have been registered in our database from across the globe, dating back to 1991 (Figure 1D). A dataset comprises the metadata of a study or project. Based on the IUCN GET definition of four core realms, our database includes 283 terrestrial, 105 marine, 26 freshwater and 2 subterranean datasets. The transmission medium was air for terrestrial datasets (except for soil in one dataset), mostly water for aquatic datasets (eight above-water datasets, mostly fresh water). In the subterranean realm, one dataset used aerial recordings, while the other used underwater recordings. The majority of datasets (84%) included both spatial and temporal replicates (Figure 1B). Few datasets have openly accessible recordings (8%–12% excluding subterranean realm, Figure S1). Presently, few terrestrial and freshwater datasets (28% and 19%, respectively) are associated with

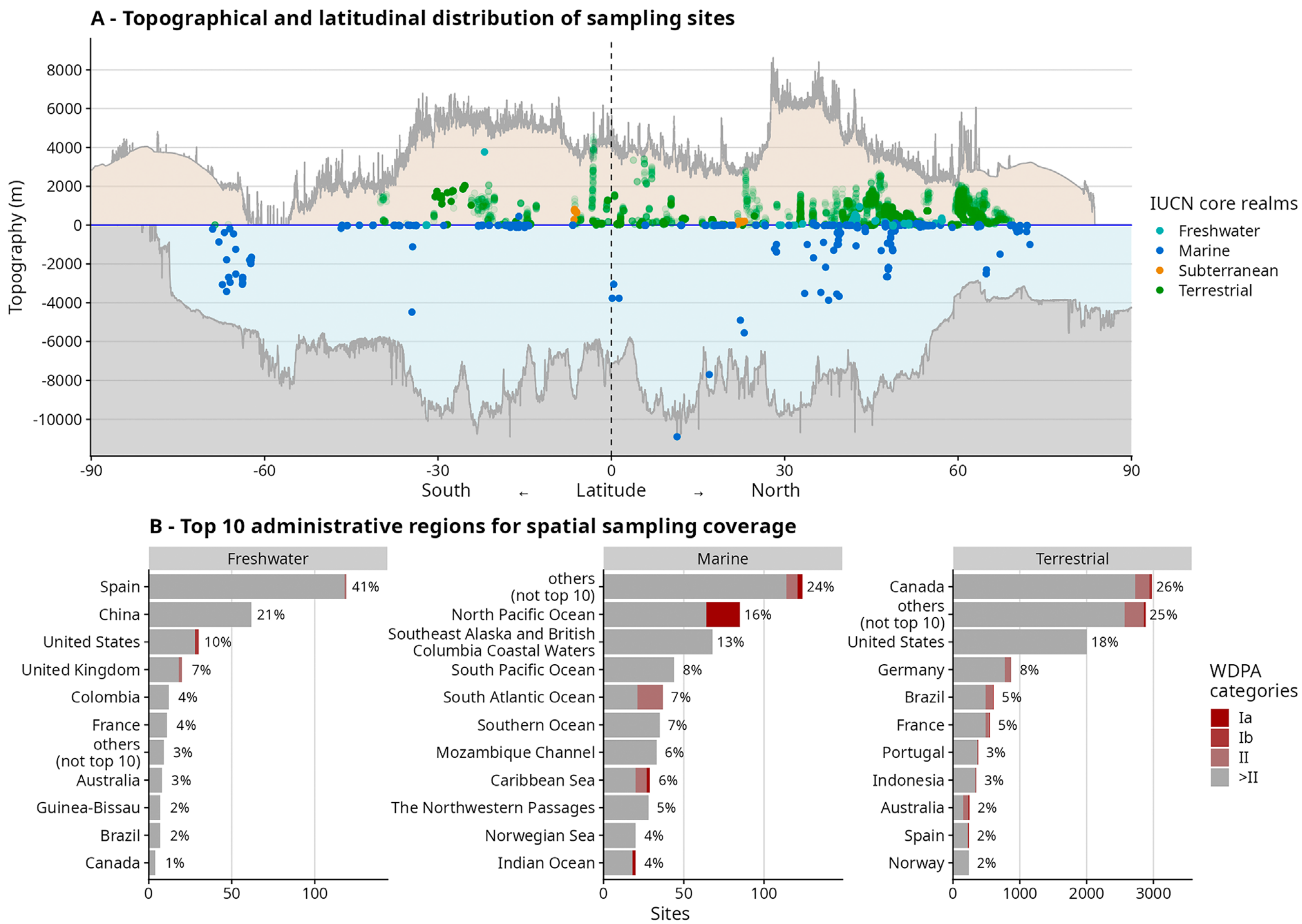

FIGURE 2 | Spatial distribution of sampling sites. (A) Latitudinal and topographic distribution of sampling sites across core realms. Due to their higher representation and to avoid overlapping site clusters, terrestrial sites are shown with transparency. The minimum (deepest seafloor) and maximum (highest elevation of land or sea level) topographical limits (dark grey lines) are shown against latitude, based on General Bathymetric Chart of the Oceans data (GEBCO 2025). Minimum topography above sea level and maximum topography below sea level were set to zero as the sea level represents the minimum and maximum in these cases. (B) Number of sampling sites within different administrative regions (GADM level 0 and IHO sea areas), split by core realm, across WDPA categories (Ia: Strict nature reserve; Ib: Wilderness area, II: National park). The areas that do not belong to the top 10 in terms of datasets have been aggregated under 'others'. The 13 subterranean sites are not shown. Sites from transitional realms were assigned to their parent core realm.

DOI-referenced publications in contrast to marine datasets (50%), excluding the subterranean realm with too few datasets (Figure S1). The decline in coverage in 2023 and onwards (Figure 1D) presumably reflects that ongoing or recent studies have not yet been reported. Overall, the recordings registered in our database would use a minimum of 5904 TB of storage space, assuming 50% losslessly compressed, single-channel recordings at the most common and lowest bit depth of 16.

3.2 | Spatial Sampling Coverage and Density

The database contains 12,343 sampling sites, including 147 polar, 9214 temperate and 2982 tropical sites (Figure 1C). On land, 11,368 sites are located within 86 (out of 263) GADM level 0 areas (i.e., countries, Figure 2B), primarily in the Northern Hemisphere (Table S1). Most terrestrial sites occur in Canada (26%), followed by the United States (18%), but a significant proportion are elsewhere in the world (25% do not belong to the top 10 GADM areas). Few terrestrial sites (8%) are located in WDPA category Ia, Ib or II areas, corresponding to the highest protection levels. Our database currently lacks data from vast areas in Russia, Greenland, Antarctica, North Africa and Central Asia. Site elevations range from sea level up to 4548 m (Figure 2A), but mountains above 4000 m in the Northern Hemisphere and above 2000 m in the Southern Hemisphere (except for Kilimanjaro), as well as the Transantarctic Mountains, are currently not represented in the database. At sea, 637 sites are located within 35 (out of 101) IHO sea areas. Administratively, most marine sites are widespread among IHO areas (24% do not belong to the top 10 IHO areas), but the North Pacific Ocean as well as the Southeast Alaskan and British Columbia Coastal Waters contain a large proportion of marine sites (16% and 13%, respectively). Many sites are situated in WDPA high-protection category Ia and II areas (12%). Our database currently lacks datasets from Arctic waters off Eurasia and Southeast Asian coastal areas. Sampling sites span ocean depths from sea water surface to depths of 10,090 m, but tropical bathypelagic and Southern benthic areas are poorly represented (Table S2). Few GADM areas (11) are represented in the 324 freshwater sites. Spain holds most

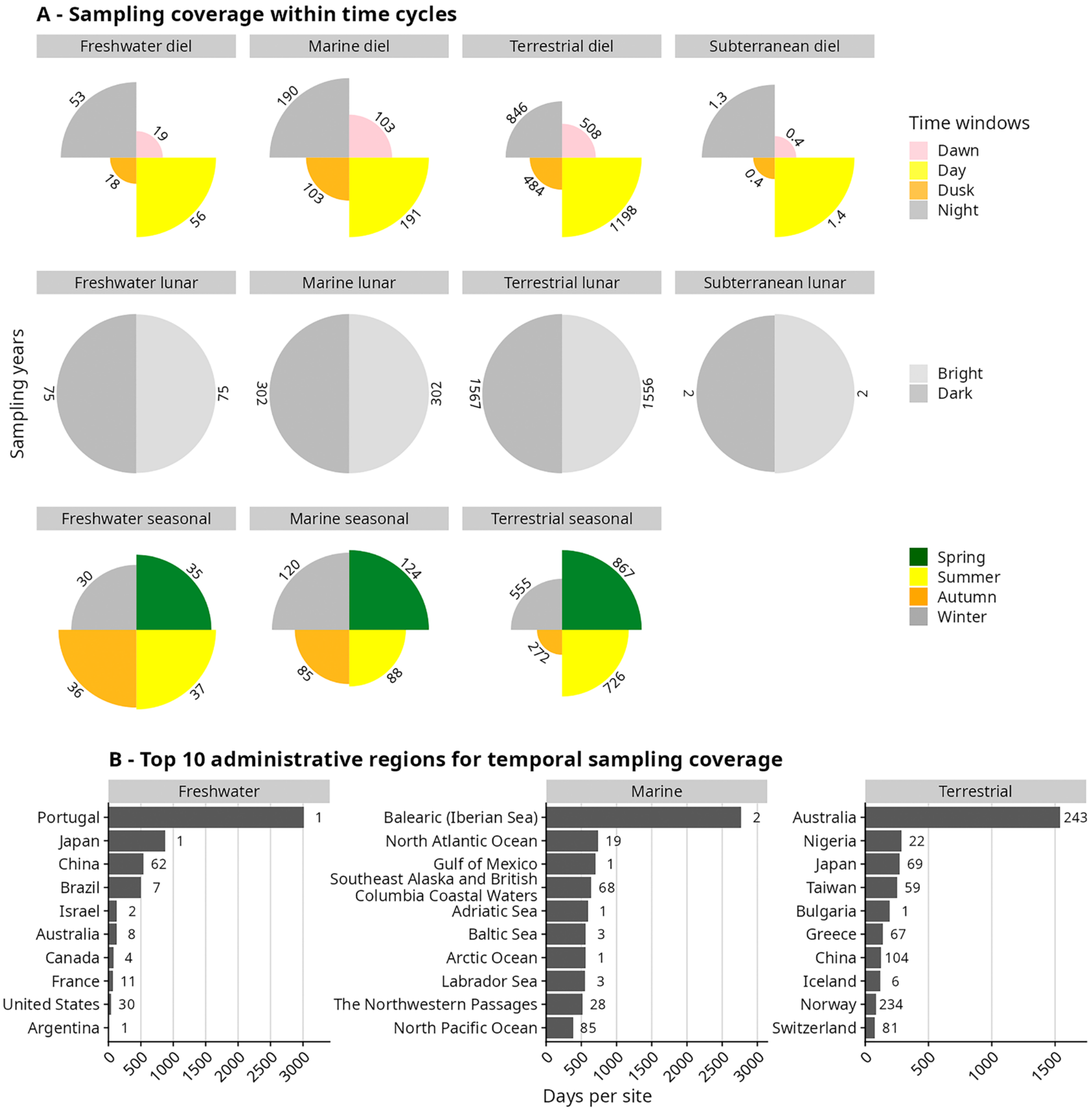

FIGURE 3 | Temporal sampling distribution. (A) Temporal sampling coverage across solar and lunar cycles for all core realms. Cycles consist of solar (daily and seasonal) and lunar time cycles (lunar phase), divided in time windows. Seasons were only analysed in temperate regions and subterranean sites were all in tropical regions. Sampling coverage is represented with sampling years in number labels. (B) Mean number of sampling days per site within administrative regions (GADM level 0, IHO areas), split by core realm. The 13 subterranean sites are not shown. Numbers to the right of bars indicate the number of sites the means were calculated from. Sites from transitional realms were assigned to their parent core realm.

freshwater sites (41%), followed by China (21%). Few freshwater sites (2%) are in WDPA category II or Ib areas. Freshwater bodies are sampled at elevations up to 3770 m and were sampled up to 25 m depth. Mountain freshwater bodies and those in Africa, Asia, and Oceania are currently poorly represented in our database (only one site at 3770 m). The database contains 14 subterranean sites situated in Brazil and Mexico between 34 and 810 m elevation and a depth of up to 20 m.

3.3 | Temporal Sampling Extent, Coverage and Density

We compare sampling coverage (in years sampled by recordings, summed over sites) across time windows of the diel cycle, the lunar phases and the seasons (Figure 3A). Dawn and dusk diel windows are shorter than day and night diel windows for most locations and correspondingly less intensively sampled. The lunar phase cycle is evenly covered across realms and comprehensively covered within datasets (Figure S2). In the terrestrial realm, daytime coverage surpasses night-time coverage (1198 vs. 846 years), while 76% of datasets sampled all diel time windows. Terrestrial temperate datasets mostly sampled spring (867 years, 36%) and summer (726 years, 30%) while 22% sampled all seasons. In conjunction with the higher sampling intensity in the northern temperate zones, this causes the observed peaks in Figure 1D. Terrestrial temporal coverage per site is highest in Australia (1541 days - Australian Acoustic Observatory). In the marine realm, diel coverage is even, as 87% of marine datasets sampled all diel time windows. Marine temperate datasets have high and similar coverage for winter and spring (120 and 124 years, combined 59% of seasonal coverage) and 55% cover the full seasonal cycle. Marine temporal coverage per site is highest in the Balearic (2771 days). In the freshwater realm, temporal coverage among diel time windows is even, and 81% of freshwater temperate datasets sampled all diel time windows. By contrast, 36% of datasets sampled all seasons. Freshwater temporal coverage per site is highest in Portugal (3009 days). The subterranean tropical sites primarily covered the day- and night-time.

3.4 | Sampling in Ecosystems

Our database includes 82 of the 107 functional groups (as per IUCN GET version 2.1.1 for spatial data). All biomes are covered except anthropogenic shorelines, the subterranean tidal biome, anthropogenic subterranean voids, and anthropogenic subterranean freshwaters (Table S2). The terrestrial realm has the second-largest extent and the highest spatial sampling density among realms (45.8 sites per million square kilometres (Mkm^2) over entire temporal extent), but temporal coverage is comparatively low (30% sampled out of 203 days of mean extent per site). The most commonly sampled terrestrial biome is the temperate-boreal forests and woodlands biome (56% of sites). The marine realm is the most extensive, but spatial sampling density is the lowest (0.3 sites per Mkm^2), while temporal sampling coverage is the highest among all realms (66% out of 377 days sampled). The most commonly sampled marine biomes are the marine shelf and pelagic ocean waters (55% and 35% of sites respectively). The freshwater realm has low spatial sampling densities (1.8 sites per Mkm^2) and high temporal sampling densities (68% out of 238 days sampled). Lakes are the most commonly sampled freshwater biome (48% of sites). The terrestrial–freshwater realm, representing 81% of the area of transitional realms, has the third-highest spatial sampling density (7.9 sites per Mkm^2) and moderate temporal sampling density (18% out of 2363 days sampled). The marine–freshwater–terrestrial realm (including 26 sites in coastal river deltas, saltmarshes and intertidal forests) has the second largest temporal extent (465 days per site). The subterranean realm, when excluding endolithic systems, is the smallest core realm and it includes seven tropical sites (all in tropical aerobic caves) sampled with a low temporal coverage (1% out of 129 days sampled). The subterranean–freshwater realm includes five sites in underground streams and pools, sampled with a low temporal coverage over the largest temporal extent (6% out of 1109 days sampled).

3.5 | Target Taxa and Frequency Ranges

Most marine datasets do not target specific taxa (66%) and record wide frequency ranges from 0.009 to 31 kHz (mean bounds of frequency ranges across datasets, Figure 4B). Marine datasets that focus on single taxa comprise fish (12%, 0.002–20 kHz) and cetaceans (6%, 0.006–7 kHz). Similarly, most freshwater datasets are taxonomically unspecific (56%) and cover frequencies from 1 to 29 kHz. Some datasets (14%) focus on ray-finned fish, covering frequencies from 0.001 to 23 kHz. By contrast, terrestrial datasets mostly target single taxa and record narrow frequency ranges. Bird-focused datasets are most common (44%), spanning frequencies from 0.056 to 21 kHz, while bat-focused datasets are next (12%) and range from 5 to 139 kHz. Taxonomically unspecific datasets account for 24% of terrestrial datasets, covering a broad range from 0.2 to 23 kHz. Generally, datasets targeting multiple taxa use wider frequency ranges than those targeting single taxa.

3.6 | Soundscape Case Studies

The selected soundscape recordings spanned latitudes from 69° South to 67° North (Table S3 and Figure 5A). Biophony dominated, with an average soundscape occupancy of 27% across all ecosystems. Notable examples include the photic coral reefs in Okinawa, Japan, with snapping shrimps and grunting fish choruses, and the tropical lowland rainforests in Jambi, Indonesia, with buzzing insects and echoing bird and primate songs, showing soundscape occupancy of 75% and 61%, respectively (Lin et al. 2023). Only marine island slopes (off Sanriku, Japan) and polar outcrops (Antarctica) contained minimal biophony (0% and 2%, respectively). Geophony was absent in most of our soundscape samples, with the exception of high wind noise in polar outcrops (14%) and some wind in montane tropical forests and urban ecosystems (both 5%). On average, anthropophony occupied 9% of the soundscapes. Cities (Jambi, Indonesia; Montreal, Canada) exhibited the highest anthropophony (43%) with prevalent engine noise and human voices, while deep-sea mining and vessel communication signals caused high anthropophony in marine island slopes (32%) (Chen et al. 2021). Silence was most prevalent in bathypelagic ocean waters (96%) and polar outcrops (82%).

The selected soundscapes revealed greater biological activity closer to the Equator, a negative relationship between biophony and anthropophony, and variable phenology patterns of soniferous organisms over the diel cycle (Figure 5). We detected a negative correlation of biophony occupancy with increasing distance from the Equator ($p_{\text{negative}} = 1$) and with anthropophony occupancy ($p_{\text{negative}} = 0.98$). The phenology model predicted a negative slope for the effect of the diel time windows in tropical montane forests, different from the positive slope in bathypelagic ocean waters ($p_{\text{different}} = 1$), and a negative slope in small permanent freshwater lakes, likely different from the one in bathypelagic ocean waters ($p_{\text{different}} = 0.94$). More complex relationships than linear regressions can be expected, which might lead to further detectable differences between functional groups, so this simple analysis on our limited dataset constitutes a minimal proof that the phenological profiles differ among functional groups. We displayed loess smooths for the biophony occupancy values for each diel time window and realm (Figure 5B), revealing their widely differing phenology patterns.

4 | Discussion

The 'Worldwide Soundscapes' project has—to our knowledge—assembled the first global meta-database of PAM datasets across realms. We analysed its current content to quantify sampling extent, coverage and density across spatiotemporal and ecological scales. We analysed soundscapes from 12 ecosystems to investigate macroecological, conservation biology and phenological

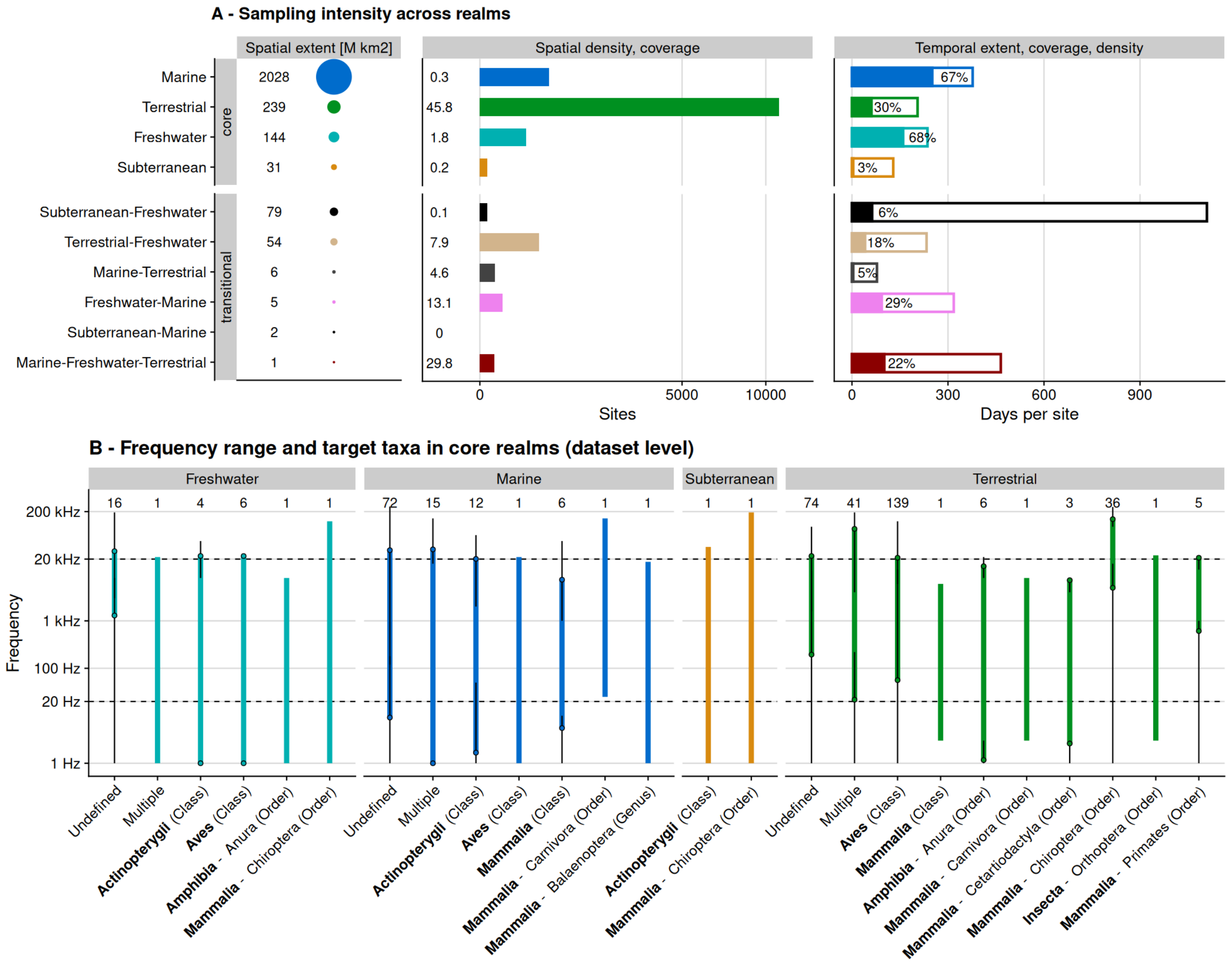

FIGURE 4 | Sampling distribution across ecological scales. (A) Sampling intensity, split between core and transitional realms: Spatial extent of realms, based on major occurrence areas according to IUCN GET (coloured disk area proportional to area); spatial sampling density (in sites per Mkm^2) and coverage (in number of sites); temporal extent (mean range between first and last recording day), coverage (days sampled per site) and density (proportion of days sampled per extent). (B) Frequency ranges of datasets across realms (using Nyquist frequency i.e., actual recorded frequencies) for the main studied taxa. The dots at the ends of coloured lines represent means of the lowest and highest recorded frequencies, and the ranges between the minimum and maximum of these values are indicated with black error bars. The limits of human hearing are indicated with dashed lines. Number of datasets indicated above lines—datasets can be counted several times if they contain deployments targeting different taxa. Data from transitional realms were assigned to their parent core realm in panel B.

trends. The database remains open for contributions, can be openly accessed to source datasets and helps initiate collaborative studies (Darras et al. 2025). Next, we discuss the state and potential of PAM globally (Table 1). While we aim for large-scale research questions here, the database can also be used to address more specific questions, for instance using the finely resolved taxonomic information that we recorded, or for within-realm syntheses.

Our results likely represent global PAM trends, even though they may be biased by the project contributors' background. Our terrestrial spatial coverage is similar to an existing systematic review (Sugai et al. 2019). Our database gaps in North Africa and Northeastern Europe correspond with the paucity of bioacoustic datasets for these regions in the Xeno-Canto bioacoustic repository (Xeno-canto Foundation 2012). Our database comprises 637 marine sampling locations, while a recent systematic review compiled 991 (Havlik et al. 2022) from published data. Although the latter review's locations are represented at the dataset level (which can comprise several sites), most overlap with our finer site-level locations (Figure S4). Marine tropical waters that are under-represented in our database reflect gaps found in the International Quiet Ocean Experiment network coverage (IQOE n.d.). Our marine and terrestrial database's spatial coverage is thus broadly comparable with published data, but it is more detailed as the exact sampling locations are known. Our database's temporal coverage is also more finely resolved with exact sampling times, and thus not directly comparable with previous work. To our knowledge, no other spatially explicit review of freshwater sampling or synthesis of subterranean PAM coverage exists for comparison. Finally, as our database originates from an active network of researchers, it represents the current availability of mostly as-yet-unpublished data (Figure S1).

Geographic coverage differs strikingly among realms: marine coverage is sparse but widespread; terrestrial coverage is

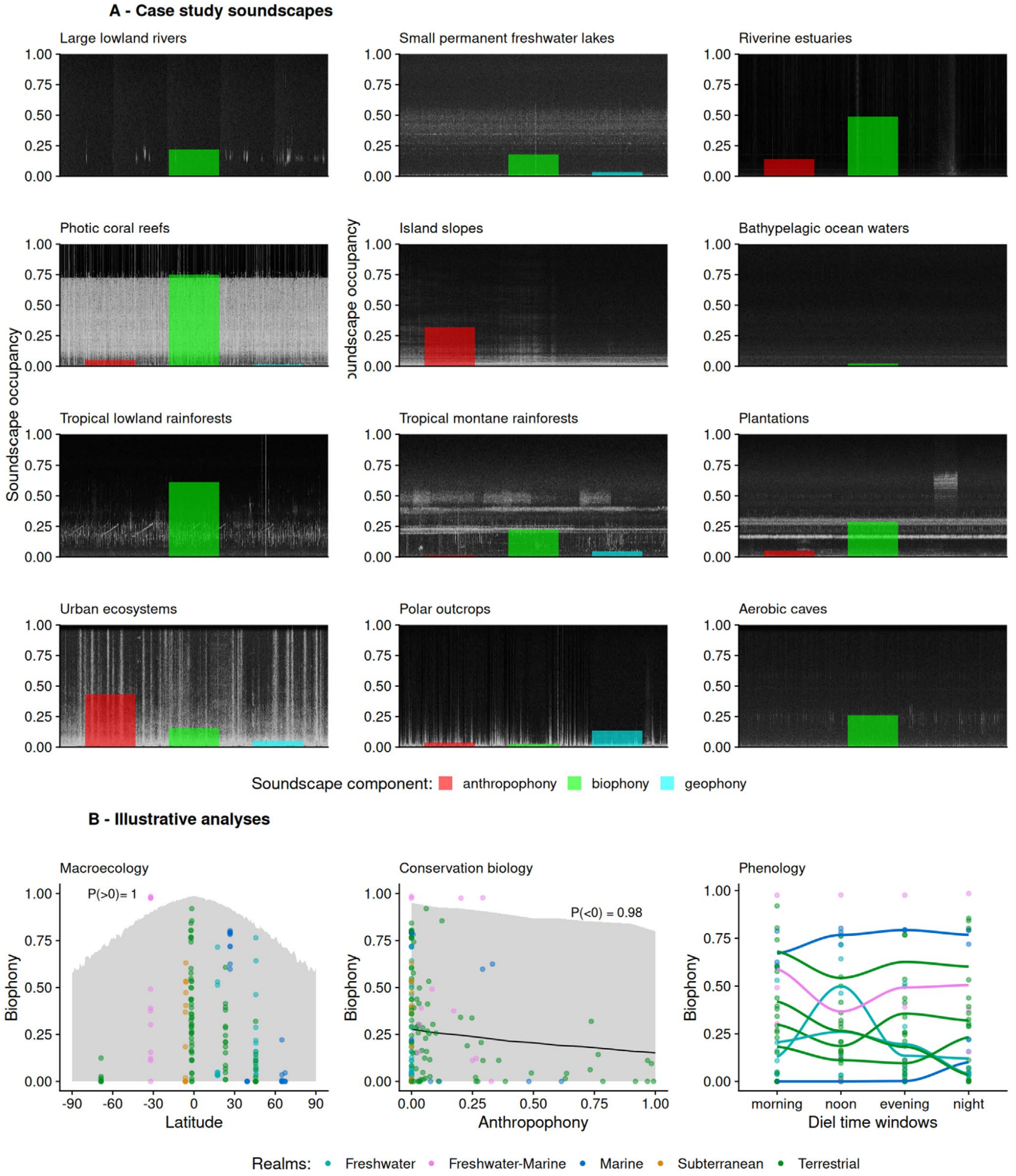

FIGURE 5 | Soundscape components analysis. (A) Mean acoustic space occupancy of soundscape components (biophony, geophony, anthropophony) shown with bar plots, as calculated from spectrogram annotations for 12 selected ecosystems, measured in proportion of spectro-temporal space used, over 168 recordings covering the time windows of the diel cycle. Annotated recordings are accessible at https://ecosound-web.de/ecosound_web/collection/show/49. Sample spectrograms are shown in the background. (B) Soundscape component occupancy data illustrate three research questions linked to macroecological patterns (i.e., biophony with distance from Equator relationship), conservation biology trade-offs (i.e., biophony with anthropophony relationship); and phenological trends (i.e., biophony loess smooths along diel time windows for each functional group). Grey ribbons indicate 95% credible intervals and numbers indicate probabilities of positive or negative relationships.

TABLE 1 | An agenda towards a global PAM coverage and network.

Aims	Opportunities
Increasing spatial and ecosystemic coverage	• Affordable shallow underwater recorders • Autonomous setups for extreme environments on land • Explore subterranean realm, dynamic freshwater bodies • Deploy at high latitude and elevation on land
Increasing temporal and taxonomic coverage	• Longer deployments with duty cycles on land • Cover all seasons in fresh water and on land • Scale up to inter-annual cycles • Higher sampling frequencies • Disabling high-pass filters and triggers
Increasing collaboration	• Work interdisciplinarily with speleologists, urban ecologists, soil and deep-sea benthic scientists • Foster international missions to work at large scales • Collaborate, invest, and fund work with under-represented countries • Disseminate results in multiple languages
Interoperability	• Calibrate equipment and measure detection ranges • Build accessible and sustainable data repositories • Design and adopt standards for deployment, reporting, and analysis • Integrate PAM into biodiversity and remote sensing databases

comparatively intensive in the Americas, Australia and Western Europe; freshwater coverage is scattered. This partly reflects the gap between high-income countries, which have the resources to carry out conservation and active ecosystem management actions, and developing countries, which are home to the majority of biodiversity hotspots (and are some of the most densely populated areas). Accessibility and technical limits in extreme environments also drive geographic patterns: high latitudes and elevations entail low temperatures that present challenges for operation and maintenance, some of which can be solved with robust power setups (solar panels, freeze-resistant batteries). Marine deployments are generally even more constrained due to costly and demanding underwater work, but some deployments reach the polar regions as water temperatures are buffered below the freezing point. Affordable underwater recorders (Lamont et al. 2022) may help to intensify sampling of marine coastal areas and close gaps in freshwater coverage. By contrast, terrestrial monitoring is relatively straightforward. Northern temperate areas outside of Northeastern Europe are comparatively better covered, while the tropics outside of Africa are better represented. Gaps in North Africa, Central Asia and Northeastern Europe may arise from unequal research means and differing priorities between countries. Addressing these gaps will help correct spatial biases (Beck et al. 2014) and identify high-priority, unique research areas that should be included in global assessments.

Currently, only marine studies achieve relatively even coverage of temporal cycles. Indeed, offshore deployments—especially in the deep sea—are expensive and limited-duration deployments are not cost-effective (Rountree, Aguzzi et al. 2020). Marine soundscapes fluctuate stochastically (Siddagangaiah et al. 2022), but the ocean buffers water temperatures so that animals are active year-round. Although lunar phases affect marine life (Hernández-León et al. 2001; Mougeot and Bretagnolle 2000; Simonis et al. 2017) and shape tidal ecosystems, we did not consider lunar tides. In the terrestrial and freshwater realms, most deployments cover the entire diel cycle, but monitoring on land often focuses either on diurnal birds or on nocturnal bats (Sugai et al. 2019). By contrast, although seasons also drive acoustic activity cycles on land (Grinfeder et al. 2022; Krause et al. 2011), spring- and summertime monitoring is disproportionately common, and we lack a complete understanding of seasonal dynamics (Figures 1D and S3). Terrestrial deployments, in particular, may be short for logistical reasons: in the cold, batteries drain faster or fail and road access is harder; in arid regions, fire hazards complicate long-term deployments; in general, recorders are at risk of theft, and limited equipment may be cycled between sites (Sugai et al. 2020). Lunar phases also influence land animals (Kronfeld-Schor et al. 2013) and should be explicitly considered in future study designs. Overall, we encourage longer duration setups with regularly spread sampling inside temporal cycles to alleviate the higher expenses for energy and storage, as well as trade-offs with spatial coverage (Van Wilgenburg et al. 2024). Global changes impact soundscapes in largely unpredictable ways through changing species distributions and phenology, necessitating higher and unbiased coverage across multiple time scales—including inter-annual ones—to successfully monitor ongoing changes (Desjonquères et al. 2022).

Re-use of soundscape datasets is restricted by their taxonomic focus. Many soundscape recordings sample particular frequencies, often in the human-audible range (Luypaert et al. 2022), although biophony ranges from infrasound to ultrasound. For instance, studies of toothed whales or bats often use triggers and high-pass filters to cope with high data storage demands by recording purely ultrasonic recordings only when signals are detected, resulting in spectrally restricted and temporally biased soundscape recordings. Less studied taxa, such as anurans and insects, could effectively be co-sampled by adjusting ongoing terrestrial deployments. We encourage terrestrial researchers to maximise frequency ranges (and to broaden diel coverage—see above) to enhance interdisciplinary collaboration. In oceans, taxonomically untargeted, long, and regular deployments, coupled to large detection ranges, concurrently sample many taxa (Lillis and Boebel 2018). Mutual sampling campaigns can share resources to mitigate potentially prohibitive equipment, power, storage, transportation and post-processing costs (Sousa-Lima et al. 2013). Emerging embedded-AI audio detectors may offer an alternative to continuous and broadband recording (Höchst et al. 2022), but whole soundscape recordings will remain essential for broader application.

In every realm, ecosystems await acoustic discovery. Except for two datasets from aerobic caves and underground streams, we currently lack data from subterranean realms (e.g., anthropogenic voids, sea caves), while endolithic systems may be the only ecosystem for which PAM is probably irrelevant. Access is usually challenging or restricted for non-specialists, but subterranean biodiversity shows high spatial turnover (Zagmajster et al. 2018). Freshwater data were less rare, but several datasets with unreplicated sampling could not be included. Temporary, dynamic water bodies (seasonal, episodic, and ephemeral ecosystems), although prevalent (Messager et al. 2021), are not yet well studied (Table S2), though accessible from land. Notably, aquatic realms feature important peculiarities: extraneous sounds from the air can be captured in so-called holo-soundscapes in freshwater and shallow coastal areas (Rountree, Juanes et al. 2020), and particle motion (that accompanies sound) impacts aquatic organisms (Popper and Hawkins 2018). Advances in soundscape research are imminent as the freshwater acoustic research community is growing rapidly (Linke et al. 2018). In the oceans, sound propagates comparatively far and multiple biomes can be sampled at once (e.g., recorders on the seafloor sample pelagic waters too) so that all ecosystems (i.e., functional groups) are covered by at least one site. On land, sampling is biased towards biodiverse forests, while rocky habitats (young rocky pavements, lava flows and screes) and some vegetated temperate ecosystems (cool temperate heathlands, temperate subhumid grasslands) appear poorly sampled. Within the IUCN GET framework, soil soundscapes also belong to the terrestrial realm, and to date only one spatiotemporally replicated dataset is in our database, despite recent efforts to record soil soundscapes (Maeder et al. 2022; Metcalf et al. 2024). Soil and benthic habitats may also be sampled with geophones to record infrasonic vibrations used to sense the environment (e.g., by insects, frogs, elephants, interstitial fauna and benthic fish) (Šturm et al. 2022).

Our database highlights well-known global sampling biases (Hughes et al. 2021) which could be resolved with collaboration and communication to remove cultural and socioeconomic barriers (Amano et al. 2016). Technological progress for more affordable equipment renders PAM more accessible in lower income countries (Hill et al. 2019; Lamont et al. 2022). However, high- and deep-sea work remains considerably more expensive, and tropical developing countries in particular often lack funding for marine programmes requiring large vessels, underwater vehicles or cabled stations on the seafloor (Rountree, Aguzzi et al. 2020). Our network currently consists of active members from 58 countries. Collaborative projects, such as data compilations, shared sea missions and equipment loans, should promote the establishment of soundscape research communities (Reboredo Segovia et al. 2020). However, equitable, collaborative efforts will also require capacity-building so that local researchers can independently process, analyse, and interpret PAM-derived data. Increased international collaboration with scientists and local stakeholders supporting citizen science (Newson et al. 2015) in heavily underrepresented regions would improve not only data coverage but also representation and dialogue within the field.

Collaborative soundscape research relies on interoperable data. We harmonised metadata with a bottom-up approach leading to our global inventory. Comprehensive standards for PAM equipment, deployment, reporting and data analysis are needed for enabling comparative, global analyses. However, such standards do not currently exist, even though initiatives for the marine realm are ongoing (Roch et al. 2016; Wall et al. 2021). Few affordable solutions exist for sharing large audio data volumes, underlining the need for distributed soundscape recording repositories (Sugai and Llusia 2019). Marine oil and gas industry projects routinely upload data as part of their efforts to mitigate noise impacts on marine animals (Southall et al. 2008), but these recordings often focus on frequencies relevant to seismic prospecting and access may be restricted (Haver et al. 2018). Furthermore, recording equipment requires calibration (Jarrett et al. 2024), sound detection spaces need to be measured (Darras et al. 2016; Haupert et al. 2022), and data privacy must be ensured on land (Cretois et al. 2022). In parallel, species sound libraries (Görföl et al. 2022; Looby, Vela et al. 2023; Parsons et al. 2022; Xeno-canto Foundation 2012) grow and continue to provide invaluable acoustic and taxonomic references, without which automated soundscape analyses for soniferous organisms would not be possible. International organisations such as the Global Biodiversity Information Facility (GBIF) will be key to roll out standards (e.g., Darwin Core) in a top-down manner. For the moment, we encourage early planning for archiving data. In the future, the Worldwide Soundscapes will interoperate with other databases to close remaining coverage gaps and enhance standardisation.

A unified approach to macroecology with PAM is now possible. More comprehensive coverage is needed to decisively answer research, conservation and management questions that PAM can address, so we encourage prospective contributors to curate their metadata and join our inclusive project. The project co-leads assist prospective members, and the project website (https://ecosound-web.de/ecosound_web/collection/index/106) provides information about metadata requirements. While metadata were previously added to the database after vetting by project managers, new features enable contributors to manage their meta-datasets (i.e., collections, sites, meta-recordings) directly online. A large portion of the PAM community is willing to collaborate across realms and form global networks. We advocate for a bolder PAM effort to inform the agenda of soundscape ecology (Pijanowski, Villanueva-Rivera, et al. 2011), reaching out to places where no sound has been recorded before. The research community may open new avenues to study environmental effects on acoustic activity (Desjonquères et al. 2022), social species interactions (Briefer et al. 2024), human-wildlife relationships (Lin et al. 2023), function and phylogeny (Gasc et al. 2013), soundscape effects on human health (Buxton et al. 2021), acoustic adaptation and niche hypotheses (Ey and Fischer 2009; Hart et al. 2021), macroecological patterns across ecosystems (Keith et al. 2022) and initiate an integrated approach to noise impacts on wildlife.

PAM is an established method that can be applied over large spatial and temporal scales. However, consistent, large-scale monitoring of the Earth's soundscapes is direly needed and essential to establish baselines for historical trends (Pilotto et al. 2020) and quantify rapid changes in biodiversity and natural systems. Funding schemes should encourage the use of PAM in large-scale biodiversity monitoring projects and require the submission of expert-vetted soniferous animal detections to platforms such as GBIF (GBIF: The Global Biodiversity Information Facility 2024). The initiation of PAM projects linked to the GEO BON (Gonzalez et al. 2023; Towards a Transnational Acoustic Biodiversity Monitoring Network (TABMON) n.d.) should further expand the use and acceptance of PAM. Integrated PAM workflows similar to the 'BON in a box' framework, which already include some marine acoustic projects, would help to generate distribution maps and to infer Essential Biodiversity Variables for soniferous wildlife, which could underpin the evaluation of progress towards threat reduction and ecosystem service provision of the Kunming-Montreal Global Biodiversity Framework (Batist and Campos-Cerqueira 2023). Soundscapes are just beginning to be recognised in legislation as an ecosystem feature to be preserved (Leiper 2020). By building collaborations around the knowledge frontiers identified here, we can aim to comprehensively describe and understand the acoustic make-up of the planet.

Author Note

The present study has involved people who carried out PAM-based studies as primary contributors. Their willingness to be informed through a mailing list, responsibility for their metadata, approval for sharing the meta-data publicly and willingness to participate in this study as co-authors were explicitly stated in an online form-based collaboration agreement. Primary contributors who became co-authors all fulfilled either data curation (e.g., as providers of structured metadata) or project administration (e.g., as principal investigators designing the corresponding study) roles and additionally a manuscript revision role. They could be corresponding authors for published studies, referred contacts for unpublished studies or principal investigators, and were asked to identify further primary and secondary contributors of their study. Primary contributors could become co-authors, and secondary contributors are acknowledged here. Some primary contributors were invited as co-leads to expand the network for particular realms or biomes and are listed in the first-tier authors list. Primary contributors who provided soundscape recordings in addition to metadata are also listed in the first-tier authors list. All primary contributors were asked to identify further contacts to reach a comprehensive coverage for the database.

Disclaimer

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Government of any product or service. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official US Government determination or policy.

Affiliations

[1]EFNO, ECODIV, INRAE, Domaine des Barres, Nogent-sur-Vernisson, France | [2]Sustainable Agricultural Systems & Engineering Lab, School of Engineering, Westlake University, Hangzhou, Zhejiang, China | [3]Chair of Computational Landscape Ecology, Faculty of Environmental Sciences, Dresden University of Technology, Dresden, Germany | [4]Biology Department, University of Victoria, Victoria, British Columbia, Canada | [5]The Fish Listener, Waguoit, Massachusetts, USA | [6]Terrestrial Unit, Prairie Region, Canadian Wildlife Service, Environment & Climate Change Canada, Prairie & Northern Wildlife Research Centre, Saskatoon, Saskatchewan, Canada | [7]Agro-ecological Modeling Group, Faculty of Agriculture, University of Bonn, Bonn, Germany | [8]Marine Mammal and Marine Bioacoustics Laboratory, Department of Deep Sea Science, Institute of Deep-sea Science and Engineering Chinese Academy of Sciences, Sanya, Hainan, China | [9]Institut de Systématique, Évolution, Biodiversité, Muséum National d'Histoire Naturelle, Paris, France | [10]Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, LECA, Grenoble, France | [11]Climate Change and Biodiversity, Hanns R. Neumann Stiftung Indonesia, Muaradua, Indonesia | [12]Biodiversity Research Center, Academia Sinica, Nankang, Taipei, Taiwan | [13]ENES Bioacoustics Research Laboratory, University of Saint-Etienne, CRNL, CNRS UMR 5292, Inserm UMR_S 1028, Saint-Etienne, France | [14]Australian Antarctic Division, Science Branch, Department of Climate Change, Energy, Environment and Water, Channel Highway, Kingston, Tasmania, Australia | [15]Biological and Environmental Sciences, University of Stirling, Stirling, Scotland | [16]Centre for Conservation Science, RSPB, Edinburgh, UK | [17]IMBE, Aix Marseille Univ, Avignon Univ, CNRS, IRD, Aix-en-Provence, France | [18]Scotland's Rural College, Craibstone Estate, Aberdeen, UK | [19]BIOGECO, INRAE, University of Bordeaux, Cestas, France | [20]Westman Islands Research Centre, University of Iceland, Vestmannaeyjar, Iceland | [21]Qigu Research Center, Taiwan Biodiversity Research Institute, Nantou County, Taiwan | [22]Programa de Pós-graduação em Ecologia e Conservação, Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Cidade Universitária, Mato Grosso do Sul, Brazil | [23]School of Natural Resources and Environment, University of Florida, Gainesville, Florida, USA | [24]Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, Florida, USA | [25]Ordway Lab of Ecosystem Conservation, Florida Museum of Natural History, University of Florida, Gainesville, Florida, USA | [26]Center for Latin American Studies and Tropical Ecology and Conservation Program, University of Florida, Gainesville, Florida, USA | [27]Colección de Sonidos Ambientales Mauricio Álvarez-Rebolledo - Colecciones Biológicas, Subdirección de Investigaciones, Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Claustro de San Agustín, Boyacá, Colombia | [28]Department of Environmental Security, Faculty of Logistics and Crisis Management, Tomas Bata University, Uherské Hradiště, Czech Republic | [29]Marine Science Institute (ICM-CSIC), Marine Renewable Resources, Barcelona, Spain | [30]Institute of Environmental Sciences, Boğaziçi University, Hisar Campus, İstanbul, Türkiye | [31]MARE – Marine and Environmental Sciences Centre/ARNET - Aquatic Research Network, Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal | [32]Functional Agrobiodiversity and Agroecology, Department of Crop Sciences, University of Göttingen, Niedersachsen, Germany | [33]Laboratory of Applied Bioacoustics, Polytechnic University of Catalonia, BarcelonaTech, Barcelona, Spain | [34]Royal Botanic Gardens, Kew, Richmond, UK | [35]Gothenburg Global Biodiversity Centre, Department of Biological and Environmental Sciences, University of Gothenburg, Göteborg, Sweden | [36]Department of Biology, University of Oxford, Oxford, UK | [37]Bioacoustics Group, Science Department, Biometrio.earth, Saarbrücken, Germany | [38]Biodiversidade e Serviços Ecossistêmicos, Instituto Tecnológico Vale, Belém, Brazil | [39]Louisiana Universities Marine Consortium, Chauvin, Louisiana, USA | [40]Wildlife Lab, Forest Research Institute, Hellenic Agricultural Organization - DIMITRA (ELGO-DIMITRA), Thessaloniki, Greece | [41]Department of Zoology and Animal Ecology, School of Biology, V.N. Karazin Kharkiv National University, Kharkiv, Ukraine | [42]Research Department, National Park 'Homilshanski Lisy', Kharkiv, Ukraine | [43]Aquatic Research and Restoration Centre, British Columbia Conservation Foundation, Surrey, British Columbia, Canada | [44]Marine Biological Station "Prof. Dr. Ioan

Borcea", Agigea, Alexandru Ioan Cuza University of Iasi, Constanta, Romania | [45]DYNAFOR, University of Toulouse, INRAE, Chemin de Borde-Rouge, Castanet-Tolosan, France | [46]Federal Maritime and Hydrographic Agency (BSH), Hamburg, Germany | [47]Department of Anthropology, Graduate Center of the City University of New York, New York, New York, USA | [48]Applied Ecology & Conservation Lab, Universidade Estadual de Santa Cruz, Ilhéus, Brazil | [49]Marine Biological Acoustic, Marine Sciences and Applied Biology, University of Alicante, Alicante, Spain | [50]HIFI Lab, John Martinson Honors College, Purdue University West Lafayette Indiana, West Lafayette, Indiana, USA | [51]Tamar Dayan's Lab, School of Zoology, Steinhardt Museum of Natural History, Tel-Aviv, Israel | [52]The Conservation Behavior Research Group, Mitrani Department of Desert Ecology, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel | [53]UMR MARBEC, University of Montpellier-CNRS-IFREMER-IRD, Sète, France | [54]Forest Landscape Ecology Lab, Department of Forest Ecosystems and Society, Oregon State University, Corvallis, Oregon, USA | [55]School of Geography and the Environment, Oxford University, Oxford, UK | [56]Science team, WildMon, Dale, Texas, USA | [57]Grupo de Pesquisa em Ecologia de Vertebrados Terrestres, Instituto de Desenvolvimento Sustentável Mamirauá, Tefé, Brazil | [58]Fugro, Edinburgh, UK | [59]Equity in Ecological Research Lab, Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, Colorado, USA | [60]Biodiversity and Animal Conservation Lab, Forest Science and Technology Center of Catalonia, Lleida, Spain | [61]Instituto de Ecorregiones Andinas (INECOA-UNJu-CONICET), Facultad de Ingeniería, Universidad Nacional de Jujuy, Jujuy, Argentina | [62]Centre for Conservation and Restoration Science, School of Applied Sciences, Edinburgh Napier University, Sighthill Campus, Edinburgh, UK | [63]COPAS-COASTAL, Centro de Investigación Oceangráfica en el Pácifico Sur-Oriental, Departamento de Oceanografía, Universidad de Concepciòn, Concepciòn, Chile | [64]CEAZA, Centro de Estudios Avanzados en Zonas Aridas, Santiago, Chile | [65]Department of Behavioural Ecology, Faculty of Biology, Adam Mickiewicz University, Poznań, Poland | [66]National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Narragansett Laboratory, Narragansett, Rhode Island, USA | [67]BioacousticsLab Capo Granitola, National Research Council, Campobello di Mazara, Italy | [68]Laboratório de Botânica Sistemática, Departamento de Botânica, Ecologia e Zoologia, Universidade Federal do Rio Grande do Norte, Rio Grande do Norte, Brazil | [69]South Iceland Research Centre, University of Iceland, Laugarvatn, Iceland | [70]Sensola SLU Multisensory Outdoor Laboratory, Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, SLU, Alnarp, Sweden | [71]Nocturnal Avian ecology Lab, A. P. Leventis Ornithological Research Institute, University of Jos, Laminga, Nigeria | [72]Behavior and Behavioral Ecology of Mammals, Servertsov Institute of Ecology and Evolution of the Russian Academy of Sciences, Moscow, Russia | [73]K. Lisa Yang Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Cornell University, New York, New York, USA | [74]The Marine Ecology Lab, Department of Biological Sciences, Simon Fraser University, Burnaby, British Columbia, Canada | [75]Miljødata, Norwegian Institute for Nature Research, Trondheim, Norway | [76]Department of Biological Sciences, University of Pittsburgh, Clapp Hall, Pittsburgh, Pennsylvania, USA | [77]CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Campus de Vairão, Universidade do Porto-InBIO, Universidade do Porto, Porto, Portugal | [78]BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, University of Porto, Porto, Portugal | [79]EcoAcoustic Research Hub (EAR Hub), Biosciences Center, Universidade Federal do Rio Grande do Norte, Natal, Brazil | [80]School of Biodiversity, One Health & Veterinary Medicine, University of Glasgow, Scotland, UK | [81]School of Arts and Cultures, Newcastle University, Newcastle upon Tyne, UK | [82]INAU Pantanal Biodata Center, National Institute of Science and Technology in Wetlands (INAU), Computational Bioacoustics Research Unit (CO.BRA), Federal University of Mato Grosso (UFMT), Mato Grosso, Brazil | [83]Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada | [84]Department of Biology, Mount Allison University, Sackville, New Brunswick, Canada | [85]Senckenberg Biodiversity and Climate Research Center, Frankfurt am Main, Germany | [86]Department of Biological Sciences, Goethe University, Frankfurt am Main, Germany | [87]Center for Conservation and Sustainability, Smithsonian's National Zoo and Conservation Biology Institute, Washington, DC, USA | [88]SARTI-MAR Research Group, UPC-Vilanova, Universitat Politecnica de Catalunya, Vilanova i la Geltru, Spain | [89]School of Geography, Geology and the Environment, Keele University, Staffordshire, UK | [90]ICTS-Doñana, Estación Biológica de Doñana-CSIC, CSIC, Sevilla, Spain | [91]Laboratório de Comportamento Animal, Departamento de Zoologia, Instituto de Ciências Biológicas, Universidade de Brasília, Brasília, Brazil | [92]Laboratório de Ornitologia, Departamento de Botânica e Zoologia, Universidade Federal do Rio Grande do Norte, Natal, Brazil | [93]Programa de Pós-Graduação em Ecologia, Centro de Biociências, Universidade Federal do Rio Grande do Norte, Natal, Brazil | [94]Lifeplan Rio de Janeiro/Araçá project, Estrada Hans Garlipp, Nova Friburgo, Brazil | [95]Forest, Nature and Landscape, KU Leuven, Leuven, Belgium | [96]Environmental Research and Innovation Centre, School of Science, Engineering and Environment, University of Salford, Manchester, UK | [97]ECOA - Laboratory of Bioacoustics, Post graduate Program in Vertebrate Biology/Museum of Natural Sciences, Pontifical Catholic University of Minas Gerais, Minas Gerais, Brazil | [98]Pacific Northwest Research Station, U.S.D.A. Forest Service, Washington, DC, USA | [99]Conservation Metrics, Inc., Santa Cruz, California, USA | [100]Acoustics Program, Pacific Marine Envrionmental Laboratory, National Oceanic and Atmospheric Administration, Newport, Oregon, USA | [101]Reef Pulse S.A.S., Reunion Island, France | [102]UMR 9220 ENTROPIE, Faculté des Sciences et Technologies, University of Reunion Island, Reunion Island, France | [103]Wildlife Ecology & Management, Faculty of Agriculture, Yamagata University, Yamagata, Japan | [104]Groningen Institute for Evolutionary Life-Sciences, GELIFES, University of Groningen, Groningen, Netherlands | [105]cE3c–Centre for Ecology, Evolution and Environmental Changes & CHANGE—Global Change and Sustainability Institute, Departamento de Biologia Animal, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal | [106]National Museum of Natural Sciences, Spanish National Research Council, Madrid, Spain | [107]Centre de Recherche sur la Biodiversité et l'Environnement (UMR 5300 CNRS-IRD-TINPT-UPS), Université Paul Sabatier, Toulouse, France | [108]Facultad de Ciencias, Universidad Autónoma de Madrid, Madrid, Spain | [109]Centre for Taxonomy and Morphology, Leibniz Institute for the Analysis of Biodiversity Change, Museum of Nature Hamburg, Hamburg, Germany | [110]Biodiversity and Biocomplexity Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan | [111]Centre d'Ecologie et des Sciences de la Conservation (CESCO, UMR 7204), Museum National d'Histoire Naturelle, Concarneau, France | [112]Laboratory of Tropical Ecology, A.N. Severtsov Institute of Ecology and Evolution of Russian Academy of Sciences, Moscow, Russia | [113]Department of Health and Environmental Sciences, Xi'an Jiaotong-Liverpool University, Suzhou, China | [114]Ecology of Tropical Agricultural Systems, Institute of Agricultural Sciences in the Tropics, University of Hohenheim, Stuttgart, Germany | [115]School of Biological Sciences, Life Sciences Building, University of Bristol, Bristol, UK | [116]Wildlife & Habitat Assessment, Northern Region, Canadian Wildlife Service, Environment and Climate Change Canada, Yellowknife, Northwest Territories, Canada | [117]Species and Habitat Conservation, Forest Nature Conservation, Northwest German Forest Research Institute, Hann. Münden, Germany | [118]Wildlife Conservation Society Canada, Whitehorse, Yukon, Canada | [119]Applied Zoology and Nature Conservation, Zoological Institute and Museum, University of Greifswald, Greifswald, Germany | [120]Bat Lab, Department of Evolutionary Ecology, Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany | [121]Institut de Systématique, Évolution, Biodiversité (ISYEB), Muséum national d'Histoire naturelle, CNRS, Sorbonne Université, Ecole Pratique des Hautes Etudes, Université des Antilles, Paris, France | [122]Cooperative Institute for Marine Ecosystem and Resources Studies, National Oceanic and Atmospheric Administration

Pacific Marine Environmental Laboratory and Oregon State University, Newport, Oregon, USA | [123]Insect Ecology Group, Department of Zoology, University of Cambridge, Cambridge, UK | [124]Kings College, University of Cambridge, Cambridge, UK | [125]Department of Biology, University of Oxford, Oxford, UK | [126]Department of Integrative Biology, University of Windsor, Windsor, Ontario, Canada | [127]Center for Biodiversity and Integrative Taxonomy (KomBioTa), University of Hohenheim, Stuttgart, Germany | [128]Department of Life Science, National Taiwan Normal University, Taipei City, Taiwan | [129]Nature based Solutions Initiative, Department of Biology, University of Oxford, Oxford, England | [130]Tabin Lab, Department of Genetics, Harvard Medical School – Boston, Boston, Massachusetts, USA | [131]BirdLife Cyprus, Nicosia, Cyprus | [132]Centre for Northern Forest Ecosystem Research, Ministry of Natural Resources, Ontario Government, Thunder Bay, Ontario, Canada | [133]Swiss Ornithological Institute, Sempach, Switzerland | [134]Zoological Research Museum Alexander Koenig, Leibniz Institute for the Analysis of Biodiversity Change, Bonn, Germany | [135]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany | [136]Ocean Networks Canada, University of Victoria, Victoria, British Columbia, Canada | [137]Ocean and Ecosystem Science Division, Department of Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada | [138]Ecology and Nature Management, Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg, Denmark | [139]Department of Agricultural Biology, Faculty of Agriculture, University of Ruhuna, Kamburupitiya, Sri Lanka | [140]Product R&D Department, Beijing, China | [141]Fundación de Conservación Jocotoco, Quito, Ecuador | [142]Landscape Conservation Programme, Conservation Division, BirdLife South Africa, Gauteng, South Africa | [143]Afromontane Research Unit, Department of Zoology and Entomology, University of the Free State, Phuthaditjhaba, South Africa | [144]Centre for Statistics in Ecology, the Environment and Conservation, Department of Statistical Sciences, University of Cape Town, Cape Town, South Africa | [145]Nature Coast Biological Station, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida, USA | [146]Fisheries and Aquatic Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida, USA | [147]BiBio Research Group, Natural Sciences Museum of Granollers, Granollers, Spain | [148]CSIRO (not affiliated with specific BU), Urrbrae, South Australia, Australia | [149]Sound Forest Lab, The Nelson Institute of Environmental Studies and The Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, Wisconsin, USA | [150]DYNI, Laboratoire Informatique et Systèmes (LIS) CNRS UMR 7020, Université de Toulon, Université d'Aix Marseille, La Garde, France | [151]Nature Conservation Unit, Frederick University, Nicosia, Cyprus | [152]Madagascar Programme, Chances for Nature, Göttingen, Germany | [153]Cologne Zoo, Köln, Germany | [154]Biodiversity, Macroecology and Biogeography, Faculty of Forest Sciences and Forest Ecology, University of Goettingen, Goettingen, Germany | [155]Department of Environmental Sciences, Wageningen University and Research, Wageningen, the Netherlands | [156]Pacific Wildlife Research Center, Environment and Climate Change Canada, Delta, British Columbia, Canada | [157]Migratory Bird Unit, Northern Region, Canadian Wildlife Service, Environment and Climate Change Canada, Whitehorse, Yukon Territory, Canada | [158]Lancaster Environment Centre, Lancaster University, Lancaster, UK | [159]School for Forest Management, Swedish University of Agricultural Sciences SLU, Skinnskatteberg, Sweden | [160]MARE – Marine and Environmental Sciences Centre/ARNET – Aquatic Research Network, Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação (ARDITI), Faculty of Life Sciences of University of Madeira, Funchal, Portugal | [161]Biology Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA | [162]Chair of Geobotany, Chair of Geobotany, University of Freiburg, Freiburg im Breisgau, Germany | [163]Fish Bioacoustics Lab, Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal | [164]Fisheries Ecology and Conservation Lab, Department of Biology, University of Victoria, Victoria, British Columbia, Canada | [165]Southern Seas Ecology Laboratories, School of Biological Sciences, The University of Adelaide, Adelaide, South Australia, Australia | [166]Department of Botany and Biodiversity Research, Faculty of Life Sciences, University of Vienna, Vienna, Austria | [167]Bioversity International, Las Américas Office, Lima, Peru | [168]School of Aquatic and Fishery Sciences, University of Washington, Seattle, Washington, USA | [169]Polar Ecology Group, Department of Vertebrate Ecology and Zoology, University of Gdańsk, Gdańsk, Poland | [170]Forest Health and Biodiversity Group, Natural Resources Institute Finland, Helsinki, Finland | [171]Department of Ecology, University of Alicante, Alicante, Spain | [172]Laboratório de Ecologia, Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil | [173]Styles Group Underwater Acoustics, Auckland, New Zealand | [174]CHESS Lab, Biology, Furman University, Greenville, South Carolina, USA | [175]Institute of Marine Science, University of Auckland, Auckland, New Zealand | [176]Freshwater and Oceanic Sciences Unit of Research, Department of Biology, Ecology, and Evolution, University of Liège, Liège, Belgium | [177]Grupo de Ecologia e Conservação de Felinos na Amazônia, Instituto de Desenvolvimento Sustentável Mamirauá, Amazonas, Brazil | [178]DECA, Neuropsi, CNRS—University Paris Saclay, Paris, France | [179]Department of Soil, Water, and Ecosystem Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida, USA | [180]MARE—Marine and Environmental Sciences Centre/ARNET—Aquatic Research Network, ISPA, Instituto Universitário, Lisbon, Portugal | [181]Ecological behaviour, ISPA Instituto Universitario, Lisbon, Portugal | [182]Queensland University of Technology, Brisbane, Queensland, Australia | [183]Integrative Community Ecology Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan | [184]Salmonid Fishes, Norwegian Institute for Nature Research, Trondheim, Norway | [185]Ocean Soundscape Team, Research, Monterey Bay Aquarium Research Institute, Moss Landing, California, USA | [186]Cold Climate Research Lab, School of Art, RMIT University, Melbourne, Victoria, Australia | [187]Fisheries and Oceans Canada, Freshwater Institute, Winnipeg, Manitoba, Canada | [188]Centre for Marine Science and Technology, Curtin University, Perth, Western Australia, Australia | [189]Forest Zoology, TUD Dresden University of Technology, Tharandt, Germany | [190]Ecosystem Sensing group, Department of Life Sciences, Imperial College London, London, UK | [191]Fisheries Management Branch, Department of Forestry, Fisheries and the Environment, Cape Town, South Africa | [192]Mammal Research Institute Whale Unit, Department of Zoology and Entomology, University of Pretoria, Pretoria, South Africa | [193]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing, China | [194]Trondhjem Biological Station, Department of Biology, Norwegian University of Science and Technology, Trondheim, Norway | [195]Aquaculture Research, Sustainable Marine Bioeconomy, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany | [196]Coastal Marine Field Station, School of Science, University of Waikato, Tauranga, New Zealand | [197]Museu Paraense Emílio Goeldi, Belém, Brazil | [198]Universidade Federal da Paraíba, João Pessoa, Brazil | [199]Ocean Acoustics Group, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany | [200]Biodiversity Center, State Institute for the Protection of Birds, Hessian Agency for Nature Conservation, Environment and Geology, Giessen, Germany | [201]AG Spezielle Tierökologie, Univeristy of Marburg, Marburg, Germany | [202]College of Marine Living Resource Sciences and Management, Shanghai Ocean University, Shanghai, China | [203]Department of Ecology, Universidad Autónoma de Madrid, Madrid, Spain | [204]Centro de Investigación en Biodiversidad y Cambio Global, Universidad Autónoma de Madrid, Madrid, Spain | [205]Wildlife Research Division, Environment and Climate Change Canada, Quebec, Québec, Canada | [206]Natural Resources & Environmental Studies, University of Northern British Columbia, Prince George, British Columbia, Canada | [207]Department of Ecology and Evolutionary Biology & K. Lisa Yang Center for Conservation Bioacoustics, Cornell University, Ithaca, New York, USA | [208]Department of Biology, Whitman College, Walla Walla, Washington, USA | [209]Talarak Foundation, Inc., Negros Forest Park, Bacolod City, Philippines | [210]Centre for Research and Conservation, Royal Zoological Society of Antwerp, Antwerpen, Belgium | [211]Department of Physical Geography, Stockholm University, Stockholm, Sweden | [212]Department of Biology, University of Florida, Gainesville, Florida, USA | [213]State Key Laboratory of Biocontrol, School of Ecology, Sun Yat-sen University, Shenzhen, China | [214]Academy of Global Food Economics and Policy, China Agricultural University, Beijing, China | [215]Production Technology & Cropping Systems, Department of Plant Production, Agroscope, Nyon, Switzerland

Acknowledgements

We are thankful to our colleagues who supported our work: Abigail Seybert, Adrien Charbonneau, Agung Aryawan, Alain Paquette, Albert García, Alexander Alvarez Rosario, Alexander C. Lees, Alexandra Buitrago-Cardona, Alfonso Zúñiga, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Allan G. Oliveira, Almo Farina, Alpheous, Ambroise N. Zongo, Amy Oden, Ana Filipa Palmeirim, Anamaria Dal Molin, Anastasia Viricheva, Andrea Gavio, Andrew N. Gweh, Andros T. Gianuca, Annalea Beard, Anne Sourdril, Annebelle Kok, Anthony Tan, Anthony Truskinger, Anushka Rege, Arne Wenzel, Astrid Brekke Skrindo, Australian Institute of Marine Science, Base de Estudos do Pantanal - UFMS, Bastien Castagneyrol, Bea Maas, Benedictus Freeman, Bibiana Gómez-Valencia, Bobbi J. Estabrook, Borja Milá, Bridget Maher, C. Lisa Mahon, Carolline Z. Fieker, Cat Adshead, Catherine Potvin, Catrin Westphal, Chamara Amarasinghe, Chantal Huijbers, Charlie Griffiths, Charlotte Roemer, Chia-Yun Lee, Chistophe Thébaud, Chong Chen, Christine Cassin, Christine Erbe, Cicero Simao, Claire Attridge, Claudia A. Medina-Uribe, Claudia Ascencio-Elizondo, Clément Lemarchand, Colin Bates, Colin K.C. Wen, Conner Partaker, Cowichan Tribes Lulumexun department - Fisheries and Marine projects staff, Craig A Radford, Curtin University, Cássio Alencar Nunes, Cécile Albert, Cédric Gervaise, Dadang Dwi Putra, Daisy Dent, Damayanti Buchori, Dan Warren, Daniel Mihai Toma, Daniel Rieker, Danny Swainson, David Lecchini, David Tucker, David Watson, Dawit Yemane, Deanna Clement, Dedi Rahman, Denise Risch, Dennis Kühnel, Dexter Hodder, Didier Casane, Diego Alejandro Gómez-Montes, Diego Balbuena, Diego Gil, Diego Pavón Jórdan, Diogo Provete, Dustin Whalen, Ed Turner, Edho Walesa Prabowo, Eduardo Rodríguez Martinez, Elisa Schutz, Elizabeth Clingham, Eliziane Oliveira, Elma Kay, Eloy Revilla, Emilia Sokolowska, Emilio Tan, En-Hao Liu, Enoc Martinez, Eric Parmentier, Eric Rakotomalala, Erich Fischer, Erik Tedesco, Erika Berenguer, Estância Mimosa Ecoturismo, Evan Economo, Fabio De Leo Cabrera, Faisal Ali Awanrali Khan, Fang-Yee Lin, Fernando Hidalgo, Fernando Murakami, Filipe F. de Deus, Filipe F. de Deus, Flávio Rodrigues, Frederic Sinniger, Frode Fossøy, Frédéric Sèbe, Fu Huihui, George Best, Giselle Mahung, Gonzalo Pérez-Rosales, Gonçalo Silva, Greg and Lisa Morgan, Groupe Chiroptères de Guyane, Guillermo McPherson, Hailey Davies, Hajar, Hannah Reyes, Hanneline Smit-Robinson, Harris Papadopoulos, Heriniaina Randrianarison, Hervé Jourdan, Hila Shamon, Hiromi Kayama Watanabe, Holger Kreft, Héloïse Rouzé, Ian Avery Bick, Ilias Karmiris, Irfan Fitriawan, Isabelle Côté, Italo A.A. Rondon, Ivin Wilfred Raj, Jack LeBien, Jacques Keumo Kuenbou, Jakob Tougaard, Jamie Ratliff, Janice Ser Huay Lee, Jason Gedamke, Jean Pierre Castro Namuche, Jean-Yves Royer, Jeff Robinson, Jennifer Clark, Jens-Georg Fischer, Jessica Qualley, Jodanne Pereira, Johan Diepstraten, Johanna Järnegren, John Ewen, John Hildebrand, Jos Barlow, Jose A. Hernandez-Blanco, Jose Manuel Ochoa-Quintero, José Luis Mena, José W Ribeiro, João Gama Monteiro, Juan Diego Tovar, Juliana Carolina Herran García, Julie Perrot, Julio Baumgarten, Justine Magbanua, Jérémy Anso, Jérôme Sueur, Karen H. Beard, Katie Huong, Katie Innes, Ken Otter, Ken P. Findlay, Kenneth Dudley, Kevin G. Borja-Acosta, Kieran Cox, Kinga Buda, Kris Harmon, Kristopher Harmon, Laela Sayigh, Laetitia Hédouin, Laure Desutter-Grandcolas, Laurel Symes, Lauren Kuehne, Laurent Legendre, Leeann Henry, Leila Hatch, Lenka Brousset, Liana Chesini Rossi, Lin Schwarzkopf, Linilson Padovese, Lisa Loseto, Lourdes Maigua Medrano, Luca Iacobucci, Lucia Di Iorio, Luciana Nacimento, Ludovic Crochard, Lény Lego, Malika René-Trouillefou, Marc Fernandez, Marc Lammers, Marcel A. van den Berg, Marcia Maia, Marcos Vaira, Marcus Rowcliffe, Maria Cielo Bazterrica, Marilyn Beauchaud, Marina Puebla-Aparicio, Marlize Muller, Martim Melo, María Jesús García Bianco, Mathias Igulu, Matias Carandell, Mauricio Akmentins, Max Ritts, Michael Scherer-Lorenzen, Michael Towsey, Miguel Pessanha Pais, Mike van der Schaar, Milton Cezar Ribeiro, Muhammad Justi Makmun Jusrin, Nadia Pieretti, Niaina Nirina Mahefa Andriamavosoloarisoa, Nicholas Brown, Nick Gardner, Nicolas Farrugia, Nicolas Hette-Tronquart, Nicolas Pajusco, Nikos Fakotakis, Noam Leader, Nuno Faria, Nursyamin Zulkifli, Ocean Acoustics Group, Ocean Networks Canada Society, Olaf Boebel, Omar Hiram Martinez Castillo, Paul McDonald, Pedro B. Lopes, Peter Ellis, Peter Taylor, Phillip Eichinski, Pooja Choksi, Pousada Xaraés, Pshemek Zdroik, Rafael Murakami, Rainforest Connection (RFCx), Refúgio Ecológico Caiman, Refúgio da Ilha Ecolodge, Rex K. Andrew, Ricardo Duarte, Richard Fuller, Richard Kinsey, Rob Rempel, Robert John Young, Robert McCauley, Robert Spaan, Robert Young, Rodrigo Silva, Rouvah Andriafanomezantsoa, Saki Harii, Samuel Challéat, Sandra Mueller, Sara Gonçalves, Sarah Rowley, Sarika Khanwilkar, Sean Connell, Sean Martin, Shanghai Aquatic Wildlife Conservation and Research Center, Shannon MacPhee, Shinsuke Kawagucci, Sierra Hunicutt, Sierra Jarriel, Sigal Balshine, Silent cities consortium, Simon Childerhouse, Sina Weier, Sofie Van Parijs, Soledad Gaston, Stan Dosso, Stanislas Wroza, Stephanie Plön, Stephen Insley, Stuart Marsden, Stéphan Jacquet, Stéphane Père, Susanna Piovano, Talatu Tende, Tarron Lamont, Tatiana Atemasova, Tetsuya Miwa, The Hunters and Trappers Committees of Inuvik Aklavik and Tuktoyaktuk, The Inuvialuit-Canada Fisheries Joint Management Committee, Thiago M. Ventura, Todor Ganchev, Tomas Altamirano, Tomasz Stanislaw Osiejuk, Tomaz Melo, Tomaz Nascimento de Melo, Tomonari Akamatsu, Tulio Rossi, Tómas Grétar Gunnarsson, Ulf Ottoson, Under The Pole Consortium, Valentin Chevalier, Valerie Linden, Valéria Tavares, Vu Dinh Thong, Vy Tram Nguyen, Wen-Ling Tsai, Will Duguid, Yang Liu, Yenifer Herrera-Varón, Yitmwa Joel, You-Fang Chen, Yue Qiu, Yuhang Song, Zehava Sigal, Zuania Colón-Piñeiro, Zuzana Burivalova, Çağlar Akçay.

Consent

Necessary permits from landowners or environmental protection agencies, precautions to limit biological contaminations (e.g., biofilm on marine recorders), approvals for animal welfare and local ethics committee reviews were the responsibilities of the respective primary contributors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The metadata used for all analyses except the case studies are archived in Zenodo: https://zenodo.org/records/14216871. We provide the R script for reproducing the metadata analysis and graphs, as well as the R script and data for reproducing the case study analysis and graph. The demonstration collection providing all case study recordings is hosted here: https://ecosound-web.de/ecosound_web/collection/show/49.

References

Alvarsson, J. J., S. Wiens, and M. E. Nilsson. 2010. "Stress Recovery During Exposure to Nature Sound and Environmental Noise." *International Journal of Environmental Research and Public Health* 7, no. 3: 1036–1046. https://doi.org/10.3390/ijerph7031036.

Amano, T., J. P. González-Varo, and W. J. Sutherland. 2016. "Languages Are Still a Major Barrier to Global Science." *PLoS Biology* 14, no. 12: e2000933. https://doi.org/10.1371/journal.pbio.2000933.

Batist, C., and M. Campos-Cerqueira. 2023. *Harnessing the Power of Sound and AI to Track Global Biodiversity Framework (GBF) Targets* (Rainforest Connection (RFCx) White Paper Series). Rainforest Connection.

Beck, J., M. Böller, A. Erhardt, and W. Schwanghart. 2014. "Spatial Bias in the GBIF Database and Its Effect on Modeling Species' Geographic Distributions." *Ecological Informatics* 19: 10–15. https://doi.org/10.1016/j.ecoinf.2013.11.002.

Boyd, I., G. Frisk, E. Urban, et al. 2015. "An International Quiet Ocean Experiment." *Oceanography* 24, no. 2: 174–181. https://doi.org/10.5670/oceanog.2011.37.

Briefer, E. F., B. Xie, S. Engesser, C. Sueur, T. M. Freeberg, and J. B. Brask. 2024. "The Power of Sound: Unravelling How Acoustic Communication Shapes Group Dynamics." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 379, no. 1905: 20230182. https://doi.org/10.1098/rstb.2023.0182.

Bürkner, P.-C. 2017. "Brms: An R Package for Bayesian Multilevel Models Using Stan." *Journal of Statistical Software* 80, no. 1: 1–28. https://doi.org/10.18637/jss.v080.i01.

Buxton, R. T., A. L. Pearson, C. Allou, K. Fristrup, and G. Wittemyer. 2021. "A Synthesis of Health Benefits of Natural Sounds and Their Distribution in National Parks." *Proceedings of the National Academy of Sciences of the United States of America* 118, no. 14: e2013097118. https://doi.org/10.1073/pnas.2013097118.

Challéat, S., N. Farrugia, J. S. P. Froidevaux, A. Gasc, and N. Pajusco. 2024. "A Dataset of Acoustic Measurements From Soundscapes Collected Worldwide During the COVID-19 Pandemic." *Scientific Data* 11, no. 1: 928. https://doi.org/10.1038/s41597-024-03611-7.

Chen, C., T.-H. Lin, H. K. Watanabe, T. Akamatsu, and S. Kawagucci. 2021. "Baseline Soundscapes of Deep-Sea Habitats Reveal Heterogeneity Among Ecosystems and Sensitivity to Anthropogenic Impacts." *Limnology and Oceanography* 66, no. 10: 3714–3727. https://doi.org/10.1002/lno.11911.

Chen, Z., J. Hermes, J. Liu, and C. von Haaren. 2022. "How to Integrate the Soundscape Resource Into Landscape Planning? A Perspective From Ecosystem Services." *Ecological Indicators* 141: 109156. https://doi.org/10.1016/j.ecolind.2022.109156.

Cretois, B., C. M. Rosten, and S. S. Sethi. 2022. "Voice Activity Detection in Eco-Acoustic Data Enables Privacy Protection and Is a Proxy for Human Disturbance." *Methods in Ecology and Evolution* 13, no. 12: 2865–2874. https://doi.org/10.1111/2041-210X.14005.

Darras, K., P. Pütz, K. Rembold, and T. Tscharntke. 2016. "Measuring Sound Detection Spaces for Acoustic Animal Sampling and Monitoring." *Biological Conservation* 201: 29–37. https://doi.org/10.1016/j.biocon.2016.06.021.

Darras, K. F. A., N. Pérez, L. Mauladi-Dilong, T. Hanf-Dressler, M. Markolf, and T. C. Wanger. 2023. "ecoSound-web: An Open-Source, Online Platform for Ecoacoustics." *F1000Research* 9: 1224. https://f1000research.com/articles/9-1224/v3.

Darras, K. F. A., R. Rountree, S. V. Wilgenburg, et al. 2025. *Worldwide Soundscapes Project Meta-Data (Version 4.0.0)* [Dataset]. Zenodo. https://zenodo.org/records/14216871.

de Sousa, I. P., G. Z. dos Santos Lima, E. G. Oliveira, et al. 2022. "Scale-Free Distribution of Silences." *Physical Review E* 105, no. 1: 014107. https://doi.org/10.1103/PhysRevE.105.014107.

Desjonquères, C., S. Villén-Pérez, P. De Marco, R. Márquez, J. F. Beltrán, and D. Llusia. 2022. "Acoustic Species Distribution Models (aSDMs): A Framework to Forecast Shifts in Calling Behaviour Under Climate Change." *Methods in Ecology and Evolution* 13, no. 10: 2275–2288. https://doi.org/10.1111/2041-210X.13923.

Duarte, C. M., L. Chapuis, S. P. Collin, et al. 2021. "The Soundscape of the Anthropocene Ocean." *Science* 371, no. 6529: eaba4658. https://doi.org/10.1126/science.aba4658.

Erbe, C., and J. A. Thomas, eds. 2022. *Exploring Animal Behavior Through Sound: Volume 1: Methods*. Springer International Publishing. https://doi.org/10.1007/978-3-030-97540-1.

Ey, E., and J. Fischer. 2009. "The "Acoustic Adaptation Hypothesis"—A Review of the Evidence From Birds, Anurans and Mammals." *Bioacoustics* 19, no. 1–2: 21–48. https://doi.org/10.1080/09524622.2009.9753613.

Gasc, A., J. Sueur, F. Jiguet, et al. 2013. "Assessing Biodiversity With Sound: Do Acoustic Diversity Indices Reflect Phylogenetic and Functional Diversities of Bird Communities?" *Ecological Indicators* 25: 279–287. https://doi.org/10.1016/j.ecolind.2012.10.009.

GBIF: The Global Biodiversity Information Facility. 2024. *What Is GBIF?* https://www.gbif.org/what-is-gbif.

GEBCO. 2025. *Gridded Bathymetry Data (General Bathymetric Chart of the Oceans)*. GEBCO. https://www.gebco.net/data_and_products/gridded_bathymetry_data/.

Gonzalez, A., P. Vihervaara, P. Balvanera, et al. 2023. "A Global Biodiversity Observing System to Unite Monitoring and Guide Action." *Nature Ecology & Evolution* 7, no. 12: 1–5. https://doi.org/10.1038/s41559-023-02171-0.

Görföl, T., J. C.-C. Huang, G. Csorba, et al. 2022. "ChiroVox: A Public Library of Bat Calls." *PeerJ* 10: e12445. https://doi.org/10.7717/peerj.12445.

Gottesman, B. L., J. C. Olson, S. Yang, et al. 2021. "What Does Resilience Sound Like? Coral Reef and Dry Forest Acoustic Communities Respond Differently to Hurricane Maria." *Ecological Indicators* 126: 107635. https://doi.org/10.1016/j.ecolind.2021.107635.

Greenhalgh, J. A., M. J. Genner, G. Jones, and C. Desjonquères. 2020. "The Role of Freshwater Bioacoustics in Ecological Research." *WIREs Water* 7, no. 3: e1416. https://doi.org/10.1002/wat2.1416.

Grinfeder, E., S. Haupert, M. Ducrettet, et al. 2022. "Soundscape Dynamics of a Cold Protected Forest: Dominance of Aircraft Noise." *Landscape Ecology* 37, no. 2: 567–582. https://doi.org/10.1007/s10980-021-01360-1.

Hart, P. J., T. Ibanez, K. Paxton, G. Tredinnick, E. Sebastián-González, and A. Tanimoto-Johnson. 2021. "Timing Is Everything: Acoustic Niche Partitioning in Two Tropical Wet Forest Bird Communities." *Frontiers in Ecology and Evolution* 9: 753363. https://doi.org/10.3389/fevo.2021.753363.

Haupert, S., F. Sèbe, and J. Sueur. 2022. "Physics-Based Model to Predict the Acoustic Detection Distance of Terrestrial Autonomous Recording Units Over the Diel Cycle and Across Seasons: Insights From an Alpine and a Neotropical Forest." *Methods in Ecology and Evolution* 14, no. 2: 614–630. https://doi.org/10.1111/2041-210X.14020.

Haver, S. M., M. E. H. Fournet, R. P. Dziak, et al. 2019. "Comparing the Underwater Soundscapes of Four U.S. National Parks and Marine Sanctuaries." *Frontiers in Marine Science* 6: 500. https://doi.org/10.3389/fmars.2019.00500.

Haver, S. M., J. Gedamke, L. T. Hatch, et al. 2018. "Monitoring Long-Term Soundscape Trends in U.S. Waters: The NOAA/NPS Ocean Noise Reference Station Network." *Marine Policy* 90: 6–13. https://doi.org/10.1016/j.marpol.2018.01.023.

Havlik, M.-N., M. Predragovic, and C. M. Duarte. 2022. "State of Play in Marine Soundscape Assessments." *Frontiers in Marine Science* 9: 919418. https://doi.org/10.3389/fmars.2022.91941810.3389/fmars.2022.919418.

Heesemann, M., T. L. Insua, M. Scherwath, K. S. Juniper, and K. Moran. 2014. "Ocean Networks Canada: From Geohazards Research Laboratories to Smart Ocean Systems." *Oceanography* 27, no. 2: 151–153.

Hernández-León, S., C. Almeida, L. Yebra, J. Arístegui, M. L. F. de Puelles, and J. García-Braun. 2001. "Zooplankton Abundance in Subtropical Waters: Is There a Lunar Cycle?" *Scientia Marina* 65, no. S1: 59–64. https://doi.org/10.3989/scimar.2001.65s159.

Hill, A. P., P. Prince, J. L. Snaddon, C. P. Doncaster, and A. Rogers. 2019. “AudioMoth: A Low-Cost Acoustic Device for Monitoring Biodiversity and the Environment.” *HardwareX* 6: e00073. https://doi.org/10.1016/j.ohx.2019.e00073.

Höchst, J., H. Bellafkir, P. Lampe, et al. 2022. “Bird@Edge: Bird Species Recognition at the Edge.” In *Networked Systems: 10th International Conference, NETYS 2022, Virtual Event, May 17–19, 2022, Proceedings*, 69–86. https://doi.org/10.1007/978-3-031-17436-0_6.

Holgate, B., R. Maggini, and S. Fuller. 2021. “Mapping Ecoacoustic Hot Spots and Moments of Biodiversity to Inform Conservation and Urban Planning.” *Ecological Indicators* 126: 107627. https://doi.org/10.1016/j.ecolind.2021.107627.

Hughes, A. C., M. C. Orr, K. Ma, et al. 2021. “Sampling Biases Shape Our View of the Natural World.” *Ecography* 44, no. 9: 1259–1269. https://doi.org/10.1111/ecog.05926.

IQOE. n.d. *Acoustic Capabilities of Existing Observing Systems*, March 15, 2023. https://www.iqoe.org/systems.

Jarrett, D., R. Barnett, T. Bradfer-Lawrence, et al. 2024. “Mitigating Bias in Long-Term Terrestrial Ecoacoustic Studies.” *Journal of Applied Ecology* n/a. https://doi.org/10.1111/1365-2664.70000.

Kang, J., F. Aletta, T. Oberman, et al. 2023. “Supportive Soundscapes Are Crucial for Sustainable Environments.” *Science of the Total Environment* 855: 158868. https://doi.org/10.1016/j.scitotenv.2022.158868.

Kays, R., M. V. Cove, J. Diaz, et al. 2022a. “SNAPSHOT USA 2020: A Second Coordinated National Camera Trap Survey of the United States During the COVID-19 Pandemic.” *Ecology* 103, no. 10: e3775. https://doi.org/10.1002/ecy.3775.

Kays, R., S. C. Davidson, M. Berger, et al. 2022b. “The Movebank System for Studying Global Animal Movement and Demography.” *Methods in Ecology and Evolution* 13, no. 2: 419–431. https://doi.org/10.1111/2041-210X.13767.

Keith, D. A., J. R. Ferrer-Paris, E. Nicholson, et al. 2022. “A Function-Based Typology for Earth's Ecosystems.” *Nature* 610, no. 7932: 1–6. https://doi.org/10.1038/s41586-022-05318-4.

Keith, D. A., J. R. Ferrer-Paris, E. Nicholson, et al. 2020. *Indicative Distribution Maps for Ecosystem Functional Groups—Level 3 of IUCN Global Ecosystem Typology* [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.4018314.

Krause, B., S. H. Gage, and W. Joo. 2011. “Measuring and Interpreting the Temporal Variability in the Soundscape at Four Places in Sequoia National Park.” *Landscape Ecology* 26, no. 9: 1247–1256. https://doi.org/10.1007/s10980-011-9639-6.

Kronfeld-Schor, N., D. Dominoni, H. de la Iglesia, et al. 2013. “Chronobiology by Moonlight.” *Proceedings of the Royal Society B: Biological Sciences* 280, no. 1765: 20123088. https://doi.org/10.1098/rspb.2012.3088.

Lamont, T. A. C., L. Chapuis, B. Williams, et al. 2022. “HydroMoth: Testing a Prototype Low-Cost Acoustic Recorder for Aquatic Environments.” *Remote Sensing in Ecology and Conservation* 8, no. 3: 362–378. https://doi.org/10.1002/rse2.249.

Leiper, A. 2020. “What Does the Consultancy Industry Need From Academia? A Soundscape and Planning Perspective.” *Acoustics 2020, Virtual*. https://doi.org/10.25144/13347.

Lillis, I. V., and O. Boebel. 2018. “Marine Soundscape Planning: Seeking Acoustic Niches for Anthropogenic Sound.” *Journal of Ecoacoustics* 2, no. 1. https://doi.org/10.22261/JEA.5GSNT8.

Lin, T.-H., F. Sinniger, S. Harii, and T. Akamatsu. 2023. “Using Soundscapes to Assess Changes in Coral Reef Social-Ecological Systems.” *Oceanography*. https://doi.org/10.5670/oceanog.2023.s1.7.

Lindseth, A. V., and P. S. Lobel. 2018. “Underwater Soundscape Monitoring and Fish Bioacoustics: A Review.” *Fishes* 3, no. 3: 36. https://doi.org/10.3390/fishes3030036.

Linke, S., T. Gifford, C. Desjonquères, et al. 2018. “Freshwater Ecoacoustics as a Tool for Continuous Ecosystem Monitoring.” *Frontiers in Ecology and the Environment* 16, no. 4: 231–238. https://doi.org/10.1002/fee.1779.

Littleboy, C., J.-A. Subke, N. Bunnefeld, and I. L. Jones. 2024. “WorldSeasons: A Seasonal Classification System Interpolating Biome Classifications Within the Year for Better Temporal Aggregation in Climate Science.” *Scientific Data* 11, no. 1: 927. https://doi.org/10.1038/s41597-024-03732-z.

Looby, A., C. Erbe, S. Bravo, et al. 2023. “Global Inventory of Species Categorized by Known Underwater Sonifery.” *Scientific Data* 10, no. 1: 892. https://doi.org/10.1038/s41597-023-02745-4.

Looby, A., S. Vela, K. Cox, et al. 2023. “FishSounds Version 1.0: A Website for the Compilation of Fish Sound Production Information and Recordings.” *Ecological Informatics* 74: 101953. https://doi.org/10.1016/j.ecoinf.2022.101953.

Luypaert, T., A. S. Bueno, G. S. Masseli, et al. 2022. “A Framework for Quantifying Soundscape Diversity Using Hill Numbers.” *Methods in Ecology and Evolution* 13, no. 10: 2262–2274. https://doi.org/10.1111/2041-210X.13924.

Maeder, M., X. Guo, F. Neff, D. S. Mathis, and M. M. Gossner. 2022. “Temporal and Spatial Dynamics in Soil Acoustics and Their Relation to Soil Animal Diversity.” *PLoS One* 17, no. 3: e0263618. https://doi.org/10.1371/journal.pone.0263618.

Messager, M. L., B. Lehner, C. Cockburn, et al. 2021. “Global Prevalence of Non-Perennial Rivers and Streams.” *Nature* 594, no. 7863: 391–397. https://doi.org/10.1038/s41586-021-03565-5.

Metcalf, O. C., F. Baccaro, J. Barlow, et al. 2024. “Listening to Tropical Forest Soils.” *Ecological Indicators* 158: 111566. https://doi.org/10.1016/j.ecolind.2024.111566.

Moersberger, H., J. Valdez, J. G. C. Martin, et al. 2024. “Biodiversity Monitoring in Europe: User and Policy Needs.” *Conservation Letters* 17, no. 5: e13038. https://doi.org/10.1111/conl.13038.

Mougeot, F., and V. Bretagnolle. 2000. “Predation Risk and Moonlight Avoidance in Nocturnal Seabirds.” *Journal of Avian Biology* 31, no. 3: 376–386. https://doi.org/10.1034/j.1600-048X.2000.310314.x.

Müller, J., O. Mitesser, H. M. Schaefer, et al. 2023. “Soundscapes and Deep Learning Enable Tracking Biodiversity Recovery in Tropical Forests.” *Nature Communications* 14, no. 1: 6191. https://doi.org/10.1038/s41467-023-41693-w.

Newson, S. E., H. E. Evans, and S. Gillings. 2015. “A Novel Citizen Science Approach for Large-Scale Standardised Monitoring of Bat Activity and Distribution, Evaluated in Eastern England.” *Biological Conservation* 191: 38–49. https://doi.org/10.1016/j.biocon.2015.06.009.

Nieto-Mora, D. A., S. Rodríguez-Buritica, P. Rodríguez-Marín, J. D. Martínez-Vargaz, and C. Isaza-Narváez. 2023. “Systematic Review of Machine Learning Methods Applied to Ecoacoustics and Soundscape Monitoring.” *Heliyon* 9, no. 10: e20275. https://doi.org/10.1016/j.heliyon.2023.e20275.

Parsons, M. J. G., T.-H. Lin, T. A. Mooney, et al. 2022. “Sounding the Call for a Global Library of Underwater Biological Sounds.” *Frontiers in Ecology and Evolution* 10: 810156. https://doi.org/10.3389/fevo.2022.810156.

Parsons, M. J. G., A. Looby, K. Chanda, et al. 2023. “A Global Library of Underwater Biological Sounds (GLUBS): An Online Platform With Multiple Passive Acoustic Monitoring Applications.” In *The Effects of Noise on Aquatic Life: Principles and Practical Considerations*, edited by A. N. Popper, J. Sisneros, A. D. Hawkins, and F. Thomsen, 1–25. Springer International Publishing. https://doi.org/10.1007/978-3-031-10417-6_123-1.

Pijanowski, B. C., A. Farina, S. H. Gage, S. L. Dumyahn, and B. L. Krause. 2011. “What Is Soundscape Ecology? An Introduction and

Overview of an Emerging New Science." *Landscape Ecology* 26, no. 9: 1213–1232. https://doi.org/10.1007/s10980-011-9600-8.

Pijanowski, B. C., L. J. Villanueva-Rivera, S. L. Dumyahn, et al. 2011. "Soundscape Ecology: The Science of Sound in the Landscape." *Bioscience* 61, no. 3: 203–216. https://doi.org/10.1525/bio.2011.61.3.6.

Pilotto, F., I. Kühn, R. Adrian, et al. 2020. "Meta-Analysis of Multidecadal Biodiversity Trends in Europe." *Nature Communications* 11, no. 1: 3486. https://doi.org/10.1038/s41467-020-17171-y.

Popper, A. N., and A. D. Hawkins. 2018. "The Importance of Particle Motion to Fishes and Invertebrates." *Journal of the Acoustical Society of America* 143, no. 1: 470–488. https://doi.org/10.1121/1.5021594.

Reboredo Segovia, A. L., D. Romano, and P. R. Armsworth. 2020. "Who Studies Where? Boosting Tropical Conservation Research Where It Is Most Needed." *Frontiers in Ecology and the Environment* 18, no. 3: 159–166. https://doi.org/10.1002/fee.2146.

Roch, M. A., H. Batchelor, S. Baumann-Pickering, et al. 2016. "Management of Acoustic Metadata for Bioacoustics." *Ecological Informatics* 31: 122–136. https://doi.org/10.1016/j.ecoinf.2015.12.002.

Roe, P., P. Eichinski, R. A. Fuller, et al. 2021. "The Australian Acoustic Observatory." *Methods in Ecology and Evolution* 12, no. 10: 1802–1808. https://doi.org/10.1111/2041-210X.13660.

Ross, S. R. P.-J., N. R. Friedman, K. L. Dudley, et al. 2024. "Divergent Ecological Responses to Typhoon Disturbance Revealed via Landscape-Scale Acoustic Monitoring." *Global Change Biology* 30, no. 1: e17067. https://doi.org/10.1111/gcb.17067.

Ross, S. R. P.-J., D. P. O'Connell, J. L. Deichmann, et al. 2023. "Passive Acoustic Monitoring Provides a Fresh Perspective on Fundamental Ecological Questions." *Functional Ecology* 37, no. 4: 959–975. https://doi.org/10.1111/1365-2435.14275.

Rountree, R., J. Aguzzi, S. Marini, et al. 2020. *Towards an Optimal Design for Ecosystem-Level Ocean Observatories*, 79–106. Taylor & Francis. https://doi.org/10.1201/9780429351495-2.

Rountree, R. A., F. Juanes, and M. Bolgan. 2020. "Temperate Freshwater Soundscapes: A Cacophony of Undescribed Biological Sounds Now Threatened by Anthropogenic Noise." *PLoS One* 15, no. 3: e0221842. https://doi.org/10.1371/journal.pone.0221842.

Scarpelli, M. D. A., M. C. Ribeiro, F. Z. Teixeira, R. J. Young, and C. P. Teixeira. 2020. "Gaps in Terrestrial Soundscape Research: It's Time to Focus on Tropical Wildlife." *Science of the Total Environment* 707: 135403. https://doi.org/10.1016/j.scitotenv.2019.135403.

Sethi, S. S., N. S. Jones, B. D. Fulcher, et al. 2020. "Characterizing Soundscapes Across Diverse Ecosystems Using a Universal Acoustic Feature Set." *National Academy of Sciences of the United States of America* 117: 17049–17055. https://doi.org/10.1073/pnas.2004702117.

Siddagangaiah, S., C.-F. Chen, W.-C. Hu, and A. Farina. 2022. "The Dynamical Complexity of Seasonal Soundscapes Is Governed by Fish Chorusing." *Communications Earth & Environment* 3, no. 1: 109. https://doi.org/10.1038/s43247-022-00442-5.

Simonis, A. E., M. A. Roch, B. Bailey, et al. 2017. "Lunar Cycles Affect Common Dolphin *Delphinus delphis* Foraging in the Southern California Bight." *Marine Ecology Progress Series* 577: 221–235. https://doi.org/10.3354/meps12247.

Sousa-Lima, R. S., T. F. Norris, J. N. Oswald, and D. P. Fernandes. 2013. "A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals." *Aquatic Mammals* 39, no. 1: 23–53. https://doi.org/10.1578/AM.39.1.2013.23.

Southall, B. L., A. E. Bowles, W. T. Ellison, et al. 2008. "Marine Mammal Noise-Exposure Criteria: Initial Scientific Recommendations." *Bioacoustics* 17, no. 1–3: 273–275. https://doi.org/10.1080/09524622.2008.9753846.

Šturm, R., J. J. López Díez, J. Polajnar, J. Sueur, and M. Virant-Doberlet. 2022. "Is It Time for Ecotremology?" *Frontiers in Ecology and Evolution* 10: 828503. https://www.frontiersin.org/articles/10.3389/fevo.2022.828503.

Sueur, J., and A. Farina. 2015. "Ecoacoustics: The Ecological Investigation and Interpretation of Environmental Sound." *Biosemiotics* 8, no. 3: 493–502. https://doi.org/10.1007/s12304-015-9248-x.

Sueur, J., B. Krause, and A. Farina. 2019. "Climate Change Is Breaking Earth's Beat." *Trends in Ecology & Evolution* 34, no. 11: 971–973. https://doi.org/10.1016/j.tree.2019.07.014.

Sugai, L. S. M., C. Desjonquères, T. S. F. Silva, and D. Llusia. 2020. "A Roadmap for Survey Designs in Terrestrial Acoustic Monitoring." *Remote Sensing in Ecology and Conservation* 6, no. 3: 220–235. https://doi.org/10.1002/rse2.131.

Sugai, L. S. M., and D. Llusia. 2019. "Bioacoustic Time Capsules: Using Acoustic Monitoring to Document Biodiversity." *Ecological Indicators* 99: 149–152. https://doi.org/10.1016/j.ecolind.2018.12.021.

Sugai, L. S. M., T. S. F. Silva, J. W. Ribeiro, and D. Llusia. 2019. "Terrestrial Passive Acoustic Monitoring: Review and Perspectives." *Bioscience* 69, no. 1: 15–25. https://doi.org/10.1093/biosci/biy147.

Towards a Transnational Acoustic Biodiversity Monitoring Network (TABMON). n.d. https://www.nina.no/english/TABMON.

Van Parijs, S. M., C. W. Clark, R. S. Sousa-Lima, et al. 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.

Van Wilgenburg, S. L., D. A. W. Miller, D. T. Iles, et al. 2024. "Evaluating Trade-Offs in Spatial Versus Temporal Replication When Estimating Avian Community Composition and Predicting Species Distributions." *Avian Conservation and Ecology* 19, no. 1. https://doi.org/10.5751/ACE-02604-190111.

Wall, C. C., S. M. Haver, L. T. Hatch, et al. 2021. "The Next Wave of Passive Acoustic Data Management: How Centralized Access Can Enhance Science." *Frontiers in Marine Science* 8: 703682. https://doi.org/10.3389/fmars.2021.703682.

Wang, L. S., K. Heaney, T. Pangerc, P. Theobald, S. P. Robinson, and M. Ainslie. 2014. *Review of Underwater Acoustic Propagation Models*. Report/Guide No. NPL Report No. AC 12. https://eprintspublications.npl.co.uk/6340/.

Williams, R., C. Erbe, A. Duncan, K. Nielsen, T. Washburn, and C. Smith. 2022. "Noise From Deep-Sea Mining May Span Vast Ocean Areas." *Science* 377, no. 6602: 157–158. https://doi.org/10.1126/science.abo2804.

Xeno-canto Foundation. 2012. *Xeno-Canto: Sharing Bird Sounds From Around the World*. Xeno-canto Foundation.

Zagmajster, M., F. Malard, D. Eme, and D. C. Culver. 2018. "Subterranean Biodiversity Patterns From Global to Regional Scales." In *Cave Ecology*, edited by O. T. Moldovan, Ľ. Kováč, and S. Halse, 195–227. Springer International Publishing. https://doi.org/10.1007/978-3-319-98852-8_9.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.