Worldwide soundscape ecology patterns across realms

Authors & affiliations

Kevin FA Darras[1,2]*, Rodney Rountree[3,4], Steven Van Wilgenburg[5], Lijun Dong[6], Amandine Gasc[7], Youfang Chen[2], Tzu-Hao Lin[8], Patrick Mauritz Diaz^^, Shih-Hung Wu[9], Marcus Salton[10], Sarah Marley[11], Anna F Cord^^, Leandro Aparecido Do Nascimento[12], Christos Astaras[13,14], Luc Barbaro[15], Kristen Bellisario[16], Asaf Ben David[17], Oded Berger-Tal[18], Iqbal Bhalla[19], Marta Bolgan[20], Tom Bradfer-Lawrence[21,22], Robert A Briers[23], Michal Budka[24], Maite Cerezo-Araujo[25], Gunnar Cerwén[26], Camille Desjonquères[27], Pedro Diniz[28], Adam Duarte[29], Hiroto Enari[30], Haruka S Enari[30], Bárbara Freitas[31,32], Nick Friedman[33], Jérémy Froidevaux[21,34], Svetlana Gogoleva[35], Eben Goodale[36], Jack Greenhalgh[37], Jonas Hagge[38], Alain Jacot[39], Olaf Jahn[40,41], Sebastian Kepfer Rojas[42], Kyle John Lloyd[43], Christos Mammides[44], Gabriel Marcacci[39], Matthias Markolf[45], Marinez Isaac Marques[46], Dominic A Martin[47,48], Christoph Meyer[49], Miles Parsons^^, Filipa Isabel Pereira Samarra[50], Jean-Nicolas Pradervand^^, Cristian Pérez-Granados[51], Klaus Riede[52], Samuel RP-J Ross[53], Karl-Ludwig Schuchmann[46], Esther Sebastián-González[51], David Singer[38], Juan Traba[55,56], Junior Tremblay[57], Sunny Tseng[58], Marisol Valverde[59], Ben Vernasco[29,60], Matthew Weldy[29], Paul Jacobus Wensveen[50], Heather Wood[61], Ana Silvia de Oliveira Tissiani[46], Songhai Li[6]*, Renata Sousa-Lima[54]*, Thomas Cherico Wanger[2]*

1: EFNO, ECODIV, INRAE, Domaine des Barres, Nogent-sur-Vernisson, Centre-Val de Loire, 45290, France
2: Sustainable Agricultural Systems & Engineering Lab, School of Engineering, Westlake University, No. 600 Dunyu Road, Sandun Town, Xihu District, Hangzhou, Zhejiang province, , China
3: , Biology Department, University of Victoria, Cunningham Building, Room 202, PO Box 1700 STN CSC, Victoria, BC, V8W 2Y2, Canada
4: The Fish Listener, , , 23 Joshua Lane, Waguoit, MA, 2536, USA
5: Terrestrial Unit, Prairie Region, Canadian Wildlife Service, Environment & Climate Change Canada, Prairie & Northern Wildlife Research Centre, 115 Perimeter Road, Saskatoon, Saskatchewan, S7N 0X4, Canada
6: Marine Mammal and Marine Bioacoustics Laboratory, Department of Deep Sea Science, Institute of Deep-sea Science and Engineering Chinese Academy of Sciences, 28 Luhuitou Road, Sanya, Hainan, 572000, China
7: Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale, , Aix Marseille Univ, Avignon Univ, CNRS, IRD, Campus Aix Technopôle de l'environnement Arbois Méditerranée Avenue Louis Philibert Bât Villemin, Aix-en-Provence, 13545, France
8: Marine Ecoacoustics and Informatics Lab, Biodiversity Research Center, Academia Sinica, 128 Academia Road, Section 2, Nankang, Taipei , , 11529, Taiwan
9: Biodiversity Indicator Lab, Division of Habitats and Ecosystems, Endemic Species Research Institute, 1 Minsheng East Road, Jiji Town, Nantou County, Taiwan, 552005, Taiwan
10: Australian Antarctic Division, Science Branch, Department of Climate Change, Energy, Environment and Water, Channel Highway, Kingston, Tasmania, 7050, Australia
11: , , Scotland's Rural College, Craibstone Estate, Aberdeen, AB21 9YA, UK
12: Bioacoustics Group, Science Department, Biometrio.earth, Dr. Schönemann Str. 38, Saarbrücken, 66123, Germany
13: Wildlife Lab, Forest Research Institute, Hellenic Agricultural Organization \"\"Demeter\"\" (ELGO-DIMITRA), Vasilika, Thessaloniki, TK 57006, Greece
14: Bat Lab, Department of Evolutionary Ecology, Leibnitz Institute for Zoo and Wildlife Research, Alfred-Kowalke-Straße 17, Berlin, 10315, Germany
15: DYNAFOR, University of Toulouse, INRAE, Chemin de Borde-Rouge, Castanet-Tolosan, F-31326, France
16: HIFI Lab, John Martinson Honors College, Purdue University West Lafayette Indiana, 1101 Third Street, West Lafayette, Indiana , 47906, USA

17: Tamar Dayan's Lab, School of zoology, Steinhardt Museum of Natural History, Tel-Aviv university, Klausner 12, Tel-Aviv, Tel-Aviv, 6997801, Israel
18: 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, , 8499000, Israel
19: , School of Geography and the Environment, Oxford University, South Parks Rd, Oxford, OX1 3QY, UK
20: Ocean Science Consulting Limited, , , Spott Road, Dunbar, EH42 1RR, United Kingdom
21: , Biological and Environmental Sciences, University of Stirling, Stirling, Stirlingshire, FK9 4LA, Scotland
22: , Centre for Conservation Science, RSPB, 2 Lochside View, Edinburgh Park, Edinburgh, , EH12 9DH, UK
23: Centre for Conservation and Restoration Science, School of Applied Sciences, Edinburgh Napier University, Sighthill Campus, Edinburgh, EH11 4BN, UK
24: Department of Behavioural Ecology, Faculty of Biology, Adam Mickiewicz University, Uniwersytetu Poznańskiego 6, Poznań, 61614, Poznań
25: South Iceland Research Centre, , University of Iceland, Lindarbraut 4, Laugarvatn, 840, Iceland
26: Sensola SLU Multisensory Outdoor Laboratory, Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, SLU, Sundsvägen 4-6, Alnarp, 23053, Sweden
27: Institut de Systématique, Évolution, Biodiversité, , Muséum National d'Histoire naturelle, Rue Buffon, Paris, 75005, France
28: Laboratório de Comportamento Animal, Departamento de Zoologia, Universidade de Brasília, Departamento de Zoologia – IB, Distrito Federal, 70910-900, Brazil
29: , Pacific Northwest Research Station, U.S.D.A. Forest Service, 3625 93rd Ave. SW, Olympia, Washington, 98512, U.S.A.
30: Wildlife Ecology & Management, Faculty of Agriculture, Yamagata University, 1-23 Wakabamachi, Tsuruoka, Yamagata, 9978555, Japan
31: , , National Museum of Natural Sciences, Spanish National Research Council, Calle José Gutiérrez Abascal 2, Madrid, 28006, Spain
32: , Centre de Recherche sur la Biodiversité et l'Environnement (UMR 5300 CNRS-IRD-TINPT-UPS), Université Paul Sabatier, 118 route de Narbonne, Toulouse, 31062 Toulouse Cedex 9, France
33: Centre for Taxonomy and Morphology, Leibniz Institute for the Analysis of Biodiversity Change, Museum of Nature Hamburg, Martin-Luther-King-Platz 3, Hamburg, 20146, Germany
34: , Centre d'Ecologie et des Sciences de la Conservation (CESCO, UMR 7204), Museum National d'Histoire Naturelle, Place de la Croix, Concarneau, Finistère, 29900, France
35: Laboratory of tropical ecology, , A.N. Severtsov Institute of Ecology and Evolution of Russian Academy of Sciences, Leninsky Prospect, 33, Moscow, 119071, Russia
36: Behavioral and Community Ecology, Conservation Biology, College of Forestry, Guangxi University, No. 100 Daxue Road, Nanning , Guangxi, 530004, People's Republic of China
37: School of Biological Sciences, Life Sciences Building, University of Bristol, 24 Tyndall Ave, Bristol, BS8 1TQ, UK
38: Species and Habitat Conservation, Forest Nature Conservation, Northwest German Forest Research Institute, Prof.-Oelkers-Str. 6, Hann. Münden, Lower Saxony, 34346, Germany
39: , , Swiss Ornithological Institute, Seerose 1, Sempach, 6204, Switzerland
40: , Ornithology, Zoological Research Museum Alexander Koenig (ZFMK) - Leibniz Institute for Animal Biodiversity, Adenauerallee 160, NRW, 53113, Germany
41: Tierstimmenarchiv, Evolutionary diversity dynamics, Museum für Naturkunde - Leibniz-Institut für Evolutions- und Biodiversitätsforschung, Invalidenstraße 43, Berlin, 10115, Germany
42: Ecology and Nature Management, Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, Frederiksberg, 1958,
43: Landscape Conservation Programme, Conservation Division, BirdLife South Africa, Isdell House, 17 Hume Road, Dunkeld West, Johannesburg, Gauteng, 2196, South Africa
44: Nature Conservation Unit, , Frederick University, 7, Yianni Frederickou Street, Nicosia, 1036, Cyprus
45: Madagascar Programme, , Chances for Nature, Brauweg 9a, Göttingen, 37073, Germany
46: 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), Cuiabá, 2367 Fernando Correa da Costa Ave, Mato Grosso, 78060-900, Brazil

47: Biodiversity, Macroecology and Biogeography, Faculty of Forest Sciences and Forest Ecology, University of Goettingen, Büsgenweg 1, Göttingen, Niedersachsen, 37077, Germany
48: Plant Ecology, Institute of Plant Sciences, University of Bern, Altenbergrain 21, Bern, Bern, 3013, Switzerland
49: Environmental Research and Innovation Centre, School of Science, Engineering and Environment, University of Salford, Peel Building, Salford, M5 4WT, UK
50: Westman Islands Research Centre, , University of Iceland, Ægisgata 2, Vestmannaeyjar, 900, Iceland
51: , Department of Ecology, University of Alicante, Cra. San Vicente del raspeig sn, Alicante, 3690, Spain
52: Zoological research Museum Alexander Koenig, , Leibniz Institute for the Analysis of Biodiversity Change, Adenauerallee 160, NRW, 53113, Germany
53: Integrative Community Ecology Unit, , Okinawa Institute of Science and Technology Graduate University, 1919-1 Tancha, Onna-son, Kunigami-gun, Okinawa, 904-0495, Japan
54: , Department of Ecology, Universidad Autónoma de Madrid, Darwin 2, Madrid, 28049, Spain
55: , Centro de Investigación en Biodiversidad y Cambio Global, Universidad Autónoma de Madrid, Darwin 2, Madrid, 28049, Spain
56: , Wildlife Research Division, Environment and Climate Change Canada, 801-1550, avenue d'Estimauville, Québec (Québec), G1J 0C3, CANADA
57: , Natural Resources & Environmental Studies, University of Northern British Columbia, 3333 University Way, British Columbia, V2N 4Z9, Canada
58: Department of Ecology and Evolutionary Biology & K. Lisa Yang Center for Conservation Bioacoustics, , Cornell University, Corson Mudd, 215 Tower Road, Ithaca, New York, 14853, USA
59: , Department of Biology, Whitman College, 345 Boyer AVe, Walla Walla, Washington, 99362, U.S.A.
60: , Department of Physical Geography, Stockholm University, SE-106 91 Stockholm, Stockholm, 10691, Sweden
61: EcoAcoustic Research Hub (EAR Hub), Biosciences Center, Universidade Federal do Rio Grande do Norte, Av. Sen. Salgado Filho 3000, Natal, Rio Grande do Norte, 59078-900, Brazil

*: corresponding authors

Abstract

The need for remote, reliable, and scalable monitoring of plummeting biodiversity amidst mounting human pressures on ecosystems and changing climate has sparked enormous interest in Passive Acoustic Monitoring (PAM) over multiple disciplines and ecosystems. Even though PAM could support UN Sustainable Development Goals and the Global Biodiversity Information Facility by facilitating the evaluation of management and conservation actions, global efforts have not yet been synthesised. We collated metadata from 293 soundscape datasets since 2001 describing sampling sites, deployment schedules, focal taxa, and recording parameters. We quantified biological, anthropogenic, and geophysical soundscape components across nine terrestrial and aquatic ecosystems. This is the first global, quantitative analysis of ecoacoustic sampling coverage across spatial, temporal, and ecological scales. Spatial sampling densities are two orders of magnitude higher in terrestrial realms (33 sites/Mkm^2) compared to aquatic realms, while substantial data gaps remain in subterranean realms, extreme environments, and tropical waters. Diel and lunar cycles are well-covered, but in temperate regions, a third of freshwater and

terrestrial datasets sample only one season while 57% of marine datasets cover all seasons. Opportunities arise for taxonomically broader sampling on land, for increasing spatial coverage in the high seas, and for more spatially-replicated deployments in freshwater. We illustrate the potential of soundscape ecology to address global questions related to macroecology, conservation biology, and phenology using sample soundscapes. PAM-enabled soundscape ecology has come of age to bridge different disciplines and quantify our progress towards Sustainable Development Goals on land and underwater.

Main text

Introduction

Sounds permeate all realms on Earth — terrestrial, freshwater, marine, and subterranean (Keith et al. 2022). In soundscape ecology (i.e., ecoacoustics), acoustic cues are used to study relationships between organisms and their environment (Pijanowski, Farina, et al. 2011; Sueur and Farina 2015). Much of this relies on passive acoustic monitoring (PAM) of soniferous organisms in water and on land. Since ambient soundscapes (i.e., the sounds occurring in a given space) comprise sounds of biological, human, or geophysical origin (Farina and Gage 2017; Pijanowski, Farina, et al. 2011) (i.e., biophony, anthropophony, and geophony respectively; “phonies” collectively), PAM tracks soniferous wildlife, anthropogenic activities, and geophysical phenomena (Astaras et al. 2020; Doohan et al. 2019; Duarte et al. 2021; Kuşku et al. 2018; Pensieri et al. 2015; R. A. Rountree, Juanes, and Bolgan 2020; Scarpelli et al. 2020). Soundscape recordings can be used to non-invasively document the global state of sound-producing life and the environment, and to derive metrics that measure its responses to transformations such as climate change, land use change, urbanisation, or restoration (Kang et al. 2023; Müller et al. 2023; Stowell and Sueur 2020; Sueur, Krause, and Farina 2019). PAM can thus inform conservation actions, biodiversity stewardship, protected area management (Astaras et al. 2020; Haver et al. 2019; Van Doren et al. 2023), and potentially soundscape-based policies. As such, it can support the COP15 biodiversity monitoring targets within the Global Biodiversity Framework and track progress towards UN Sustainable Development Goals.

Similar ecoacoustic concepts and methods are employed in aquatic and terrestrial systems, but their differences in application could enrich the disciplines of the respective realms. For instance, as sound travels fast and far in water, complex physics-based models of acoustic propagation were developed by marine engineers to account for great and variable detection ranges underwater. This underpins marine studies focused on signal detection, characterisation, localisation and density estimation. In contrast, terrestrial studies still

mostly ignore these aspects of sound transmission (Kevin Felix Arno Darras et al. 2016; Haupert, Sèbe, and Sueur 2022) and density estimation is in its infancy (Marques et al. 2013; Pérez-Granados and Traba 2021). In water, the identification of sound sources is challenging as sound sources cannot be intuitively identified and visual validation is rarely possible. As a result, many aquatic sound sources are unknown (Parsons et al. 2022), and while most fauna is expected to produce sound underwater, in freshwater, most animal sounds await documentation (Greenhalgh et al. 2020; Looby et al. 2022). This taxonomic haziness partly explains why, despite the terrestrial origins of the soundscape concept (Pijanowski, Farina, et al. 2011), marine ecologists pioneered studies assessing general phonies (Halliday et al. 2020; R. A. Rountree, Juanes, and Bolgan 2020). On land, species-level automated identification is relatively advanced (Nieto-Mora et al. 2023), and algorithms could potentially be re-purposed for aquatic species. Historically, underwater acoustics also benefited from technological developments in military passive surveillance and the need to evaluate and manage noise emissions in an environment that is not easily accessible to humans. It follows that aquatic standardisation efforts, especially with regard to noise level measurement (Haver et al. 2018), are relatively advanced (Abrahams, Desjonquères, and Greenhalgh 2021; ISO 2022; Roch et al. 2016), even though standards have not yet been reached (van Geel, Risch, and Wittich 2022). On land, calibrated noise measurements are performed in urban planning but rarely for soundscape ecology (Buxton et al. 2017) although bioacoustic studies more frequently analyse noise impacts on wildlife (Shannon et al. 2016). Correspondingly, terrestrial recording standards are still missing, even though general recommendations have been given (Metcalf et al. 2023; Sugai et al. 2020).

Interdisciplinary syntheses have great potential, as the state of ecoacoustic research has only been reviewed separately for each realm for now (Duarte et al. 2021; Greenhalgh et al. 2020; Havlik, Predragovic, and Duarte 2022; Lindseth and Lobel 2018; Sugai et al. 2019). What questions could be answered with such holistic approaches? PAM can help to address fundamental ecology questions (Ross et al. 2023). We could investigate the general relationship between anthropophony and biophony (Lin et al. 2023), but also specifically monitor destructive human activities (e.g., chainsaws, gunshots, bottom trawling) (Sethi et al. 2020) to model human impact on biodiversity and ecosystem services, and to support law enforcement and conservation planning. One aspect of this relationship is pervasive noise pollution effects on wildlife (Slabbekoorn et al. 2018), that have been extensively studied in the marine and terrestrial realms (Boyd et al. 2015; Buxton et al. 2017; Cox et al. 2018; Francis, Ortega, and Cruz 2009; Jerem and Mathews 2021; Solé et al. 2023) and building up for freshwater (Mickle and Higgs 2018). We could quantitatively assess the threshold at which noise levels become detrimental for biological activity to design recommendations and

designate “Quiet land, freshwater and marine” areas for conservation (but see (Bayne, Habib, and Boutin 2008)). A global PAM network could also support the identification of priority areas for conservation and restoration, in line with the goals of the Kunming-Montreal Global Biodiversity Framework, while connecting with the wider public through publicly-available, audible experiences and citizen science. Further, we could appraise the effects of different kinds of biophony and anthropophony on human health (Buxton et al. 2021; De Coensel, Sun, and Botteldooren 2017; Van Renterghem 2019). Investigating macroecological theories related to acoustic space competition, acoustic niche formation, and adaptation to noise is currently possible, and the responses of biodiversity to global ecosystem assembly filters (topography, latitude, water availability) (Keith et al. 2022) can be quantified. However, despite the wide-ranging and increasing soundscape sampling effort, the availability and distribution of datasets remain undescribed, which makes it challenging to initiate large-scale syntheses. However, the foundational role of large, inclusive data centralisation initiatives should not be overlooked: community-initiated telemetry databases (Davidson et al. 2020; Hindell et al. 2020; Kays et al. 2022; Sequeira et al. 2018), individual animal observation networks (Culina et al. 2021), and invasive species control syntheses (Spatz et al. 2022) spurred important advances for entire research fields.

Here we assembled the first global PAM meta-database in the frame of the “WorldWide SoundScapes” project and compiled a global synthesis of the ecoacoustic research state while identifying potential research fronts. We streamlined and standardised various information sources to assemble a meta-database based on 293 validated datasets comprising 8744 locations sampled over 261 000 recording days since 2000, considering only passively-recorded soundscape datasets with spatial and/or temporal replication, similar to (Alcocer et al. 2022). We gathered detailed metadata about the passive acoustic datasets identifying: 1) spatio-temporal scope and coverage; 2) sampled ecosystems and focal taxa (IUCN GET and Red list); 3) protected status (WDPA); 4) administrative status (IHO, (GADM 2022; Keith et al. 2022); 5) and audio recording settings. We used the meta-database to quantitatively assess a snapshot of the current state of sampling efforts, and highlighted gaps and sampling biases. While the meta-database will continue to grow, we identified opportunities to advance the research agenda of soundscape ecology (Pijanowski, Villanueva-Rivera, et al. 2011) on a global scale, across realms. Lastly, to demonstrate the utility and interdisciplinary potential of our database, we conducted an integrated analysis of phonies across nine ecosystems from terrestrial, marine, and freshwater realms, using actual sound recordings collated using the meta-database. We illustrate global soundscape patterns in relation to macroecology, conservation biology, and phenology disciplines. Although the database is inevitably biased by its contributing members, the project holds 259

contributors from around the world and represents the most comprehensive spatio-temporal coverage to date. The resulting publicly accessible database remains open for meta-data contributions that will facilitate future syntheses.

Results

Summary statistics

To date, 293 validated soundscape meta-datasets (hereafter "datasets") have been registered in our online database from across the globe, dating back to 2000 (Kevin F. A. Darras et al. 2024) (Fig. 1). A dataset was defined as a collection of metadata gathered by a single team on a coherent topic (generally corresponding to an individual study); subsequently added sites and yearly repetitions were coded as additional deployments within datasets. Metadata were validated by KD, YC, and FP by checking that all fields are filled and correctly formatted, and then cross-checked by their respective contributors who visualized site maps and recording timelines online on ecoSound-web (Kevin F. A. Darras et al. 2023) (https://ecosound-web.de/ecosound_web/collection/index/106). Based on the IUCN GET (Keith et al. 2022) definition of four 'core' realms, our database covers 215 terrestrial, 53 marine, 14 freshwater, and no subterranean, validated datasets. Further, sampling sites could be assigned to transitional realms, which sit at the interface between core realms. The majority of datasets were both spatially and temporally replicated for each core realm (Fig. 1). Few freshwater and terrestrial datasets had associated, openly-accessible recordings (15% for freshwater, 9% for terrestrial datasets) or peer-reviewed publications at the time of writing (21% for freshwater, 33% for terrestrial datasets) (Fig. S1), but marine datasets fared better (24% with available recordings, 58% published).

Spatial sampling extent, coverage, and density

The datasets contained 8404 terrestrial and 97 freshwater sites situated in 59 (out of 263) GADM level 0 administrative areas, and 243 marine sites situated in 27 (out of 101) IHO sea areas. Marine sites in particular were sourced from a variety of sea areas, as the bulk of sites (34) was not included in the top ten IHO areas, followed by the South Atlantic Ocean (32 sites) (Fig. 2). 32 marine sites were situated in WDPA category Ia and II areas. However, our database lacked data from Arctic waters as well as from those off the coast of South Asian and Southeast Asian countries. Canada was the top contributor for sampling sites in the terrestrial realm (2996 sites), followed by 1829 terrestrial sites again sourced from a variety of regions outside the top ten (Fig. 2). 704 terrestrial sites were situated in WDPA category Ia, Ib, or II areas. Some areas had poor sampling coverage or missing data: the database currently does not include data from Russia, Greenland, and terrestrial Australia, as well as Saharan and several Central Asian countries. Spain was the top contributor for

freshwater (20 sites), followed by the UK (16 sites). Four freshwater sites were situated in WDPA category II or Ib areas. Most GADM areas were not represented in the freshwater database subset.

The topographical analysis revealed that high-elevation mountains, polar caps, marine tropical bathypelagic and benthic areas, and high-altitude freshwater bodies constituted gaps in our database (Fig. 2). We did not receive contributions from sites above 4000 m in the Northern Hemisphere or 2000 m in the Southern Hemisphere that are, to our knowledge, currently acoustically unexplored. Terrestrial soundscape recordings from the northern polar ice caps and the Transantarctic mountains were completely missing in our database. In tropical marine areas, we compiled only scattered shallow-water soundscape datasets, and benthic recordings were missing in the Southern Hemisphere. The Northern Hemisphere was well represented in the distribution of terrestrial recordings (mean latitude across sites: 37°, Table S2).

Temporal sampling extent, coverage, and density

We analysed the diel, the seasonal cycle (only for temperate regions with four well-defined seasons) and the lunar phase cycle, and split them into time windows (Fig. 3). The temporal sampling coverage across time windows, measured in sampling years for the different solar and lunar cycles, showed unequal contributions depending on the realm. Dawn and dusk diel windows were shorter in duration than the day and night time windows, which reflects the stronger representation of lowlatitude sites, where these intermediate time windows are shorter. Daytime coverage was markedly higher than nighttime coverage in the terrestrial realm (378 vs. 279 years), while dusk and dawn were similarly covered across all realms. Terrestrial datasets had the lowest proportion of datasets that sampled all diel time windows (73%). For temperate regions, seasons were defined as equally long windows, but their coverage markedly differed across realms: in the marine realm, coverage was equal and highest in winter and spring (both 44 years, together: 70% of coverage); in freshwater, summer coverage was markedly higher (4.5 years — 38% of coverage); and in the terrestrial realm, spring and summer were covered best (respectively 324 and 260 years, accounting for 40% and 32% of coverage). Here, while 57% of the marine datasets completely covered the seasonal cycle's time windows, only respectively 29% and 19% of the temperate freshwater and terrestrial datasets sampled all seasons. The lunar phase cycle, being categorised as a simple cycle with two time windows, was evenly-covered across realms and comprehensively-covered within datasets.

Sampling in ecosystems

We quantified the extent, coverage, and density of the spatial and temporal acoustic sampling effort across ecosystems (realms, biomes, functional types, as defined by IUCN GET, Fig. 4). The terrestrial core realm has the third largest extent (239 Mkm^2), and spatial sampling density was the highest across realms (33.52 sites per Mkm^2). Temporal sampling density was relatively low (14% of the average 202 days' extent covered). The most commonly-sampled biomes were temperate-boreal forests and woodlands (4855 sites), tropical-subtropical forests (1503 sites), and the intensive land-use biome (1064 sites) (Table S1). The marine core realm, being the most extensive (2028 Mkm^2), had the lowest spatial sampling densities (0.11 sites per Mkm^2). However, it reached the highest temporal sampling extent, coverage, and density (39% of the average 625 days' extent covered). The marine shelf (107 sites) and pelagic ocean waters (68 sites) were the most-commonly sampled marine biomes. The freshwater realm's spatial and temporal sampling densities were intermediate (respectively 0.48 sites per Mkm^2 for an extent of 144 Mkm^2, and 70% of the average 179 days' extent covered). Lakes (40 sites) and artificial wetlands (19 sites) were the most commonly sampled biomes. Finally, to date there are no datasets that meet our inclusion criteria for the subterranean realm, even though it is second-largest in extent (541 Mkm^2). The terrestrial-freshwater realm was the best-studied transitional realm, and the anthropogenic shorelines biome was the only non-subterranean biome that was not included in our database. Only 24 out of the IUCN GET's 108 ecosystem functional types (i.e., 22%) are not currently represented in our database (Table S1).

Taxonomic and spectral coverage

Distinct frequency ranges were covered for the different target taxa, while taxonomically unspecific datasets tended to have a wider spectral coverage (i.e., average frequency range; Fig. 4). Most aquatic datasets were taxonomically unspecific (78%) and some focused on multiple taxa (13%), and both of them covered large frequency ranges extending below and beyond the human-audible range (14 Hz — 26 kHz). All target taxa in the marine realm were mammals, and the ones that did not target Carnivora rarely exceeded 1 kHz. Similarly, freshwater datasets were mostly taxonomically untargeted (65%), covering a range from 32 Hz to 30 kHz, or focused on Actinopterygii (4 datasets). Terrestrial datasets were dominated by bird-focused deployments (42%) from 82 Hz to 20 kHz, while taxonomically unspecific datasets made up 27% of the total, covering a frequency range of 59 Hz to 23 kHz. Datasets targeting multiple taxa (2 Hz — 45 kHz) and bat-focused datasets (6208 Hz — 119 kHz) respectively made up 13% and 9% of all datasets.

Soundscape analysis

In order to explore the soundscape patterns across different realms, we annotated the biophony, geophony, and anthropophony in 116 recordings over nine ecosystem types (Fig. 5). We used the annotation-derived phony data to illustrate the potential of soundscape data for studies about macroecology, conservation biology, and phenology. Our analysis illustrates the contributions of various sound sources to the soundscape. On the continental slopes off Sanriku (Japan), the acoustic space (i.e. the extent in frequency and time) contained no detectable biological activity over the analysed evening time intervals, but considerable human activity due to deep-sea mining and research vessel communication. Photic coral reefs in Okinawa (Japan) had the highest biological activities due to snapping shrimps and fish choruses, transient human activity due to passing vessels, and geophysical activity due to breaking waves. In river estuaries in Western Australia, passing vessels, dolphin whistles and snapping shrimp caused high levels of biophony and anthropophony, while insects formed the bulk of the biophony in French large lowland river arms. Our Asian soundscape samples from protected tropical rainforest areas were dominated by birds, primates, and insects, while the montane tropical rainforests had less biological activity but also included some human and geophysical sounds. The acoustic space of tree plantations had a lower biological activity level than the tropical lowland rainforests and also included some human activity from passing vehicles, while cities had an even higher anthropophony and slightly lower biophony. Polar screes had very low levels of biophony, but high geophony levels due to wind. Taken together, the phony data from the nine ecosystems was summarised to illustrate the increase of biological activity near the equator across large latitudinal gradients, the negative relationship between biological and anthropogenic activity across aquatic and terrestrial systems, and the variable phenology of soniferous organisms during the diel time windows (Fig. 5).

Discussion

The "WorldWide SoundScapes" project assembled the first meta-database describing soundscape datasets that cover the main realms and regions of the globe since 2001. While the database will remain open for contributions, we analysed its metadata to quantify the current state of PAM sampling extent, coverage, and density across spatiotemporal and ecological scales. We used its comprehensive information to quantify the sampling biases and gaps that may be representative of PAM on the entire globe. We further analysed 116 soundscapes across nine ecosystems to exemplify the potential use of the database for macroecology, conservation biology, and phenology studies across realms.

Previous quantitative syntheses were typically systematic reviews focusing on single realms (Greenhalgh et al. 2020; Havlik, Predragovic, and Duarte 2022; Sugai et al. 2019), freshwater syntheses were rather focused on bioacoustics, and the only cross-realm synthesis known to us was a qualitative review (Lindseth and Lobel 2018). However, recent case studies underline the potential of ecoacoustics for cross-realm syntheses: the discovery of universal distributions of sound and silence durations for freshwater, marine, and terrestrial realms (de Sousa et al. 2022) and the demonstration that soundscapes can track resilience and recovery of terrestrial and marine animals from natural disasters (Gottesman et al. 2021). Our database mainly includes yet unpublished datasets (Fig. S1), thus offering unique and novel insights into the state of ecoacoustic sampling. Spatiotemporal sampling effort was assessed using a unified framework, enabling quantitative evaluations of sampling extent, coverage, and density. More importantly, anyone can access our continuously growing, open database (CC-BY license) to source datasets and start collaborative ecoacoustic studies (https://ecosound-web.de/ecosound_web/collection/index/106) (Kevin F. A. Darras et al. 2024).

The frontiers of the current ecoacoustic spatial coverage are determined by removable technical and cultural barriers. On the one hand, our analysis reflects the technical difficulty in obtaining soundscape datasets at high latitudes and high elevations. Remoteness and extremely cold ambient temperatures present challenges for battery operation and replacement that can be solved with technical innovations. However, some marine deployments are able to reach the poles as water temperatures are buffered near the freezing point. On the other hand, large swathes of Russia, Central Asia, and Africa are still not represented in our database. This may reflect genuine disciplinary gaps as indicated by some of these regions' low bioacoustic coverage (Xeno-canto Foundation 2012) but may also result from cultural barriers (Amano, González-Varo, and Sutherland 2016) and limited hardware accessibility. Marine tropical waters are under-represented in our database, similarly to the IQOE marine networks' coverage (IQOE, n.d.). Indeed, particularly tropical countries may lack funding for setting up costly marine ecoacoustic programmes that require large vessels to reach high-sea areas, underwater vehicles or cabled stations on the seafloor (R. Rountree et al. 2020). By contrast, terrestrial monitoring is relatively inexpensive, and even tropical datasets are well-represented despite technical challenges under high humidity. Overall, while we currently miss some national programs in our database (e.g., Australian Acoustic Observatory (Roe et al. 2021)), we generally achieved a widespread distribution of terrestrial and marine datasets, and the northern hemisphere's temperate areas are well-covered. Affordable existing and future automated acoustic recorders deployed in the aquatic realm (Hill et al. 2019; Lamont et al. 2022) may close gaps

in the limited spatial coverage of freshwater PAM and help to intensify spatial sampling of marine areas. While these technical advances could make PAM more accessible in lower-income countries, collaborative projects and equipment loans should promote the establishment of soundscape research communities (Reboredo Segovia, Romano, and Armsworth 2020). An increased collaboration with scientists and supporting citizen-science projects in heavily underrepresented regions would thus improve not only the data fullness, but also the representation and dialogue within the field. We recommend targeted site selections to correct spatial biases and facilitate re-use of the data for global analyses (Beck et al. 2014), and suggest that our geographic compilation allows the identification of high-priority research areas.

Currently, only marine studies achieve a satisfactory and relatively even coverage of the major solar and lunar cycles within their datasets, while other realms are limited by specific technical constraints and taxonomic specialisation. Indeed, marine deployments offshore are so expensive, especially in the deep sea (R. Rountree et al. 2020), that it makes little sense to run them for limited durations. The ocean also buffers water temperatures so that despite seasonal variations, animals will retain a basal activity throughout the seasons, even though soundscapes may vary non-linearly and stochastically (Siddagangaiah et al. 2022). Furthermore, lunar phases have a well-recognised effect on marine life such as zooplankton and their associated predators (Hernández-León et al. 2001; Simonis et al. 2017; R. S. Sousa-Lima and Clark 2008) that is usually accounted for. However, here we do not consider more complex, ecosystem-specific cycles such as lunar tides. In the terrestrial realm, we observe a marked bias towards avian monitoring during the day, which is balanced by bat monitoring at night (Sugai et al. 2019). Often, terrestrial deployments have shorter durations due to recorders cycling between sites (Sugai et al. 2020) or because recorders can more easily be reached and are thus at risk of theft or vandalism. In temperate regions, spring soundscapes are also over-represented in contrast to winter during which birds have reduced song activity, and when batteries may fail at low temperatures. We generally don't have a good understanding of seasonal changes of vocal activities (even for birds in the most studied regions). We encourage longer-duration setups to the limits of tenable spatially representative designs: continuously-powered devices can increase temporal coverage, but their complexity and cost (large batteries and/or solar panels) represents a tradeoff against operating more recorders for greater spatial coverage. PAM offers a unique opportunity here to conduct year-round sampling (Grinfeder et al. 2022) as seasonal cycles determine activity cycles on land too (Krause, Gage, and Joo 2011; Pérez-Granados, Schuchmann, and Marques 2020; Boullhesen et al. 2021), especially for migrant birds. The lunar cycle may have a balanced coverage in terrestrial studies as its influence is

established for seabirds (Mougeot and Bretagnolle 2000), but it could also have been randomly evenly sampled. Nonetheless, the cycle should be explicitly considered for more taxa, especially for nocturnal or crepuscular ones which exhibit behavioral plasticity depending on lunar illumination (Kronfeld-Schor et al. 2013; Appel et al. 2017; Lima et al. 2021; Ferreira et al. 2020; Schaaf, Boullhesen, and Akmentins 2023). Climate and land use change will impact soundscapes in unpredictable ways through changing species distributions and phenology, thereby justifying the need for better coverage across multiple time scales — including inter-annual ones — to monitor changes in the ecosystems (Desjonquères et al. 2022).

Re-use of soundscape datasets is sometimes restricted by their focus on certain target taxa, which may hinder the analysis of other sound classes. For instance, studies focusing on toothed whales or bats often need to trigger ultrasound recordings due to higher storage demands, thereby resulting in species-focused, unrepresentative soundscape recordings. Although there is no simple solution to this problem, we encourage researchers to record audio files over frequency ranges that support potential re-use and interdisciplinary collaboration (Lin and Tsao 2020). Technical limitations for making broadband recordings are often slight, even though not all recorders offer high sampling rates and some microphones have non-removable high-pass filters or low sensitivity at higher frequencies. The downsides are higher power and memory consumption (R. Sousa-Lima 2013), as well as potential post-processing, which altogether can make such endeavors prohibitively costly. Analogously, re-use of data requires centralised soundscape repositories and species sound libraries (e.g., Xeno-Canto, ChiroVox). New repositories should be created and existing ones made interoperable (Pijanowski, Farina, et al. 2011; Parsons et al. 2022; Looby et al. 2022; Kevin F. A. Darras et al. 2023). Fundamental bioacoustics continue to be needed to establish the taxonomic base: While vocalizations of marine and freshwater mammals are rather well studied, the sounds of most other aquatic wildlife still await proper documentation (R. A. Rountree, Juanes, and Bolgan 2020). Although soundscape recording repositories present tremendous data management challenges, established hybrid commercial solutions are available to store recordings on low-cost, long-term archival media with temporary transfers on fast hard disk space for regularly-accessed data (c.f. WildTrax https://www.wildtrax.ca). Governmental and industrial marine projects from the oil and gas industry also routinely upload data, sometimes as part of mitigation efforts. However, recordings may be restricted to low frequencies (Haver et al. 2018), or be access-limited. We encourage planning soundscape data archival at an early stage to safeguard data in the long term and to enable public availability within ethical and legal boundaries.

New frontiers in soundscape research appear upon close scrutiny of the sampled ecosystem types and their soundscapes. To our knowledge, all core and transitional subterranean realms, such as aerobic caves, anthropogenic voids, underground streams or sea caves, await acoustic exploration. Although the subterranean realm is the second-largest, access is usually challenging or restricted. One may expect that subterranean soundscapes comprise substrate-borne geophony and anthropophony, while the biophony of aerobic caves would comprise social calls of cave-dwelling birds and bats. Notably, freshwater ecoacoustic studies were also too rare to draw robust conclusions from. They suffer from a lack of spatiotemporal replication arising from opportunistic sampling: several studies could not be included in our database for this very reason. Dynamic water bodies (seasonal, episodic/ephemeral, freeze/thaw, and rice paddies) are not yet well-studied (Messager et al. 2021). This underlines that the freshwater realm is relatively accessible but poorly represented, even though that realm also comprises above-water, aerial recordings. We expect geophony to increase with elevation in moving water, prevalent anthropogenic noise in large flowing lowland water bodies, and the underwater biophony to come mainly from insects and fish (R. A. Rountree, Juanes, and Bolgan 2020). Luckily the freshwater community grows rapidly (Hill et al. 2019; Linke et al. 2018).

The relatively better-explored marine and terrestrial realms also leave plenty of opportunities for acoustic exploration. Marine research is dominated by the omnipresent impact of noise on wildlife (Duarte et al. 2021), as borne out by the high prevalence of anthropophony in our case study's selected soundscapes with deep-sea mining sound and vessel noise in coral reefs. At the same time, our reef soundscapes exhibited the highest biophony occupancy in snapping shrimp aggregations. Importantly, sound in the ocean propagates so far that multiple biomes can be sampled at once, i.e., recorders on the seafloor will also record the soundscape of the pelagic waters above. Still, our database suggests coverage gaps exist in marine sessile animal and algae habitats (kelp, shellfish, seagrass, animal forests). On land, the terrestrial realm is biased towards sampling forests, which in our case study exhibited a high biophony and low geophony, with more intensively-managed systems such as plantations or cities having increasing anthropophony levels. In our case study soundscapes, biophony declined with elevation and almost disappeared in less hospitable high-latitude areas as well as arid habitats such as polar screes and deserts. Our database coverage suggested that the most challenging terrestrial functional groups were yet unsampled (lava flows, polar tundra, and sclerophyll hot deserts). Finally, as most datasets focused on single realms, transitional realms were also under-represented: these habitats are more challenging to assess, but by being at the interface between realms, potentially very dynamic and diverse. To add to this complexity, soundscapes can be recorded in aquatic realms

above the water surface — and in terrestrial systems, below the ground (Maeder et al. 2022; Inyang et al. 2019). The interactions between realms, at the boundary between recording media, are rarely considered but can be captured in holo-soundscapes (R. A. Rountree, Juanes, and Bolgan 2020; Murchy, K.A., Rountree, R.A., and Juanes, F., n.d.).

A unified, interdisciplinary approach to soundscape science is now possible. We need to come up with a consistent, broad-scale monitoring of the Earth soundscape in a period of major population increase and climate change which has the potential to cause rapid changes in biodiversity and natural systems. Sound can be used across the globe to measure fundamental qualities of the environment (Ross et al. 2023). Although more comprehensive coverage is needed to answer research questions decisively, our database grows as it remains open for future dataset inclusions. We encourage prospective contributors to archive their metadata sustainably and to join our inclusive project. We showed that a large portion of the ecoacoustic community is willing to publicly share their work across realm-specific disciplines and to collaborate. We advocate for a bolder ecoacoustic research agenda, reaching out to challenging places where no sound has been recorded before as well as to populated places — while accounting for data privacy issues. Ecoacoustic monitoring should be integrated into long-term ecosystem monitoring platforms (i.e., eLTER (Mirtl 2018)) and come to aid to support the necessary evaluation of progress towards the ambitious goals and targets of the newly established Kunming-Montreal Global Biodiversity Framework. Ideally, it should be included in the future resolutions of the next Convention on Biological Diversity's Conference Of Parties. Soundscape recording standardisation should be initiated and general soundscape repositories be created to sustainably archive data like "time capsules" (Sugai and Llusia 2019) and to make it available for citizen science. Together with more taxonomically inclusive recording practices, we would obtain a treasure of general-purpose datasets that maximise potential re-use and facilitate comparability for large-scale syntheses. Further, international collaborations should accelerate plugging the remaining coverage gaps, and future studies should be framed within a broader context by collaborating with a variety of disciplinary experts across socio-economic groups. By building collaborations around the research frontiers identified here, we can aim to comprehensively describe and understand the acoustic make-up of the planet.

Methods

Ethics & Inclusion statement

The present study has involved all local researchers who carried out the studies forming the basis for the database. Local researchers were the respective study leads — usually corresponding authors for published studies, and referred contacts for unpublished studies — who were asked to identify further primary and secondary contributors of their study. Primary contributors were invited as co-authors, and secondary contributors are acknowledged at the end of the main text. As such, the research was locally relevant as it had already been initiated and performed by the primary contributors. The responsibility of primary contributors regarding their metadata and their implication as co-authors were explicitly agreed in a collaboration agreement. Primary contributors all fulfil data curation and manuscript revision roles, and were invited to participate more actively. Selected contributors were invited as co-leads to be responsible for particular realms or biomes, and are all listed in the first-tier authors list. All contributors were asked to identify further contacts to reach a comprehensive coverage for the database.

By the nature of the study (using passive acoustic monitoring methods), the research did not suffer from restrictions or prohibitions in the setting of the researchers. Necessary permits from landowners or environmental protection agencies, precautions to limit biological contaminations (biofilm on marine recorders) or for animal welfare, and local ethics committee reviews were the responsibility of the respective dataholders. None of the passive acoustic monitoring activities resulted in personal risk to participants; neither did they involve health, safety, security or other risk to researchers; nor did they require benefit-sharing measures as nothing was transferred out of any country. Local and regional research relevant to our study were taken into account in citations throughout the main text.

Database construction

The database was constructed within the frame of the Worldwide Soundscapes project (Kevin F. A. Darras et al. 2024) using a collaborative, peer-driven metadata collation. It represents the current state of publicly accessible meta-datasets. We started contacting contributors that we personally know, and designating co-lead authors who supported contacting potential contributors in the respective ecosystem types of their expertise (i.e. terrestrial, urban, freshwater, and marine). We posted the call for contributors on specialised ecoacoustics platforms and social media and constantly keep the project open for any contributor owning suitable soundscape recordings beyond the present publication. We

communicated mostly in English but also in Spanish, French, Portuguese, German, and Chinese to gather metadata; we tracked metadata completion and cross-validated them with graphical map and timeline checks by the contributors. As a result, apart from basic coherence checks conducted by the co-leads and research assistants, the responsibility of the database content is borne by their individual contributors, who were all invited as co-authors. The database information page is integrated on our online collaborative ecoacoustics platform ecoSound-web (Kevin Felix Arno Darras et al. 2020). It already hosts selected soundscape recordings for the present phony analysis (https://ecosound-web.de/ecosound_web/collection/show/49).

At the time of writing, our database achieves a global coverage of soundscape datasets. Its scope is limited to datasets accessible over the internet, through email contact with their creators and through publications recommended by peers. Out of 420 contacted contributors potentially involved in PAM, 259 (62%) provided metadata, but the database remains open for future contributions. More datasets exist but are not accessible despite valid contact details, as reflected by the 23% percentage of contacts that have not yet responded. This may correspond to peers with limited availability to share research data. There may be further datasets that could not be obtained yet due to no longer reachable contacts. Older soundscape datasets may be stored on analog media that are inaccessible over the internet, but these are more often attended recordings (e.g. (Krause, Gage, and Joo 2011)) — thus not fulfilling our inclusion criteria (see below). The missing share of datasets could be estimated with a systematic literature search, but we posit that our dataset search was exhaustive enough and importantly, able to find gaps more effectively due to focused calls for missing datasets in our large group of contributors. Moreover, our database is open for new contributions and constantly growing to be more comprehensive.

We made sure that datasets have as little bias as possible and are clearly representative of spatiotemporal patterns. We only considered soundscape recording datasets that are: 1) stationary — mobile recorders would have constantly changing and shifting acoustic detection spaces, we excluded recordings from cars, transect walks, or towed deployments; 2) passive — obtained from automated, unattended recorders, without human presence near the acoustic sensor; 3) ambient — with no particular recording direction, as obtained from omnidirectional microphones; 4) from spatially or temporally replicated study designs (Fig. 1). Datasets with spatial and temporal replication are necessary to disentangle spatial and temporal effects from other soundscape determinants: we considered that datasets were spatially replicated when several sites were sampled simultaneously, and temporally replicated when one site was sampled over multiple days at the same daytime. We chose sampling sites and days as the most elemental units for defining replication in our unified

analysis. However, we acknowledge that replicates are defined differently in each study: sampling sites could only be spatial replicates if they belong to the same category (i.e. habitat, management type). Temporal replicates could also be defined at the scale of other solar and lunar cycles (i.e. multiple full moons). Taken together, our requirements homogenize the dataset to enable statistical analyses across datasets and future collaborative syntheses.

Time and space

Soundscapes are fundamentally determined by their time and location. Wildlife and human activity is broadly determined by events in the solar and lunar cycles (Frey et al. 2017; Gottesman et al. 2021; Grinfeder et al. 2022; Kronfeld-Schor et al. 2013), as well as geographical positions on the planet relative to the poles, equator, or the land and water surface. For both space and time, we determined the extent (area of realms or time range), coverage (number of sites or number of days per site), and density (sites per area or recorded time per time range) of the respective units under consideration (datasets, sites, deployments). Notably, the true, areal coverage of sites is unknown in the vast majority of cases and generally larger in marine environments than terrestrial ones. Our measure of spatial sampling density using points per area is thus a provisional one.

For each sampling site, we gathered numerical latitude and longitude and topography (above and below the sea level), and further assigned them to administrative areas: GADM (Global administrative areas database) divisions for freshwater and land, and IHO (International Hydrographic Organisation) for sea areas. We also extracted the WDPA protected area category each sampling site belonged to. We use these metadata to quantify the latitudinal and topographical sampling site coverage across realms.

Contributors were asked to code the timing of their deployments using start and end dates and times, operation modes (continuous, periodical, scheduled), schedules if applicable (daily starting times and end times or durations) as well as duty cycles if applicable. Deployments were assigned to single sampling sites. Temporal information was inferred from the timing of sound recordings relative to time events that structure life and meteorological events on Earth (Fig. 3): the yearly cycle was split into four seasons approximately centered on solstices and equinoxes (only temperate regions); the daily cycle was split into four 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 centered around the full and new moon phases. It follows that the extrema and ecotones in

the temporal cycles define the relevant sampling time windows, noting that in temperate zones, the equinoxes roughly correspond to thermal ecotones. However, seasonal cycles in tropical, subtropical, and arid regions that are due to precipitation variations were not considered in this analysis. The resulting temporal framework was used to quantify sampling coverage in these three solar and lunar cycles.

Ecology and frequency range

We assigned individual sampling locations to ecosystem types such as realms (core and transitional ones), biomes, and functional groups as determined by the IUCN GET (https://global-ecosystems.org), and calculated the major and minor occurrence areas of all functional groups (Keith et al. 2022; Keith, Ferrer-Paris, Nicholson, Bishop, et al. 2020; Keith, Ferrer-Paris, Nicholson, and Kingsford 2020). We used these metadata to quantify spatio-temporal extent, coverage, and sampling density within ecosystem types. Deployments were also linked to their main studied IUCN taxa (class, order, family, or genus) when applicable — some datasets were collected without taxonomic focus. We use these data to depict the sampled frequency ranges depending on the target taxon.

Sound recordings store a representation of the original soundscape. Microphones have variable frequency responses, and the spectral scope of the recording is limited by the sampling frequency of the recorder (nowadays, overwhelmingly digital). Contributors were asked to provide the audio parameters of their deployments (sampling rate, high-pass filter) as well as auxiliary metadata about the microphones' and recorders' makes and brands. The frequency range is additionally determined by microphone roll-off frequencies at the low end and their frequency response at high frequencies, but we could not gather these detailed, often unpublished data for the high number of equipment types used here. Together, the available metadata allowed us to determine the spectral scope of the soundscape recording datasets and to potentially correct for variable detection space areas.

Phony analysis case study

To illustrate how the database can be used for macroecology, conservation biology, and phenology analyses, we chose to acoustically sample a selection of ecosystems across a variety of topographical, humid, latitudinal, and anthropisation conditions — all fundamental gradients of assembly filters in both terrestrial and marine realms (Keith et al. 2022). We aimed to select datasets containing at least four spatial replicates within the same functional group, with recordings spanning all four diel time windows from the same date. Our sampling sites spanned -68 to 39 degrees of numerical latitude and were recorded during the Northern Hemisphere's summer. The recordings covered the audible frequency range with sampling

rates of 44.1 kHz in mono or stereo. We extracted 10-minute recordings starting at sunrise, solar noon, sunset, and solar midnight from the chosen datasets and sampling sites. Our selection resulted in 16 recordings for each of the functional groups (tropical-subtropical forests biome: tropical/subtropical lowland rainforests, tropical/subtropical montane rainforests; intensive land use biome: plantations). We could not find temporally replicated recordings for the deepest marine functional group (four solar noon recordings from continental and island slopes — deep sea floors biome), and only three spatial replicates for the shallowest marine functional group (12 recordings from photic coral reefs — marine shelf biome). Overall, we obtained 116 recordings.

Each recording's spectrogram (i.e., a visual representation of sound intensity along the time and frequency axes) was annotated with the three fundamental phonies: biophony, anthropophony, and geophony. KD resampled recordings to 44.1 kHz when higher sampling frequencies were used, and uploaded them on ecoSound-web (https://ecosound-web.de/ecosound_web/collection/show/49) (Kevin F. A. Darras et al. 2023), where all recordings were listened to while visually inspecting the spectrograms (FFT window size of 1024) at 15 pixels per second, and creating annotations at a visual density of 1116 pixels per 10 minutes on the left channel. Sounds caused by microphone or recorder self-noise were not annotated. Annotations were rectangular tags on the spectrogram, encompassing only the annotated sound, with defined coordinates in the time and frequency dimensions. Annotations of different phonies could overlap if they were simultaneously visible or audible. Annotations of the same phony were adjacent and non-overlapping to avoid double-counting. All annotations were reviewed by the contributors who created the recordings, using the peer-review mode on ecoSound-web, and only accepted ones were used in the analysis. The annotations were then exported and acoustic space occupancy for each phony was calculated as the proportion of the spectro-temporal space (duration multiplied by frequency range and divided by total area of spectrogram, range: 0-1. Similar to (Luypaert et al. 2022)).

Tables

Table 1: An agenda for enabling global soundscape ecology research.

Research gap or bias	Solution
Poor global coverage, acceptance, and standardisation	- Build general data repositories - Invest in low-income country cooperation, capacity building, equitable funding access - Disseminate results in local languages - Get explicit agreements for data collection
Poor spatial coverage in marine realm	- Cheaper recorders for coastal recordings (Hydromoth) - More collaboration for equipment sharing and vessel use for high seas (World Ocean Day)
Null coverage in subterranean realm	- Collaboration with speleologists, chiropterologists, urban ecologists
Biased spatial coverage in terrestrial realm	- Deploy more recorders in extreme and dynamic biomes
Biased temporal coverage and selection in terrestrial realm	- Cover all seasons and whole diel cycle - Include geophony and anthropophony periods into analysis
Biased taxonomic coverage in terrestrial realm	- Avoid taxonomic focus by covering wide frequency range: disable high-pass filters, use high sampling rates
Missing standardisation in terrestrial realms	- Calibrate equipment - Measure detection spaces - Estimate animal densities
Poor coverage in freshwater realm	- Increase collaboration with scientists from other realms - Record soundscapes linking terrestrial and freshwater realm
Poor coverage of transitional realms	- More dynamic/time-series analyses (Gottesman et al. 2021) to acknowledge temporal and spatial dynamics of complex systems
Differing workflows across realms	- Adopt common standards and increase interoperability of software tools to foster interdisciplinarity and integration into biodiversity and remote sensing databases
Unknown geophony-biophony interactions	- Collaboration with meteorological networks to include acoustic monitoring

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Competing interests

The authors declare to have no competing interests. All authors have seen and approved the manuscript; it hasn't been accepted or published elsewhere.

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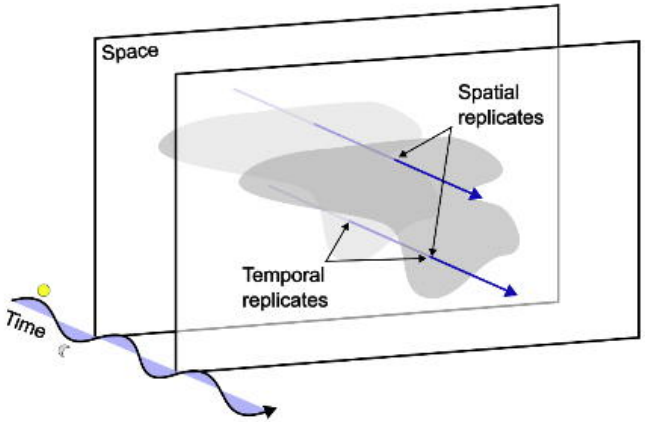
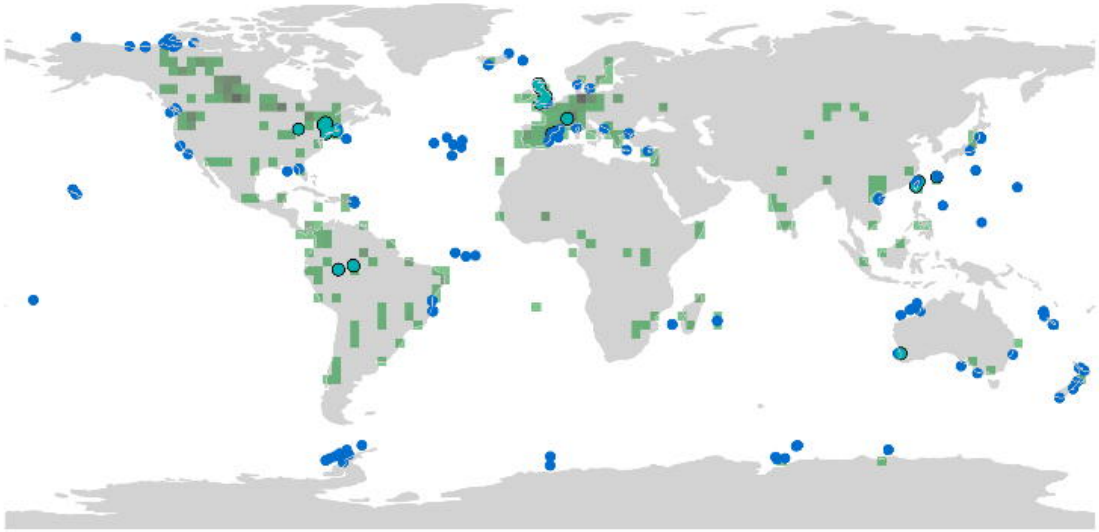
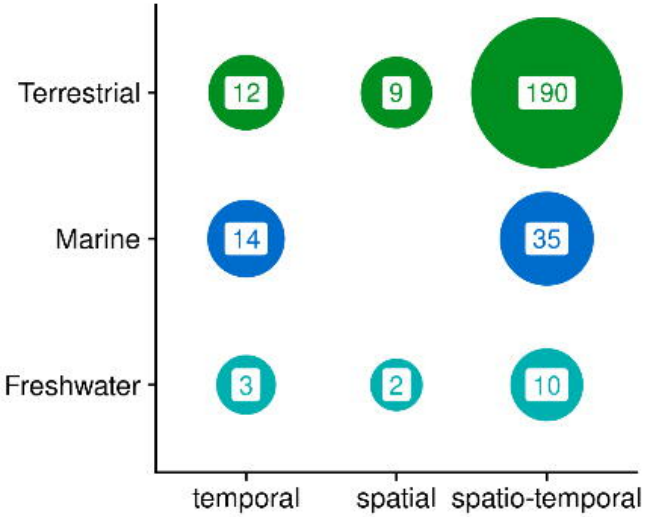
Framework



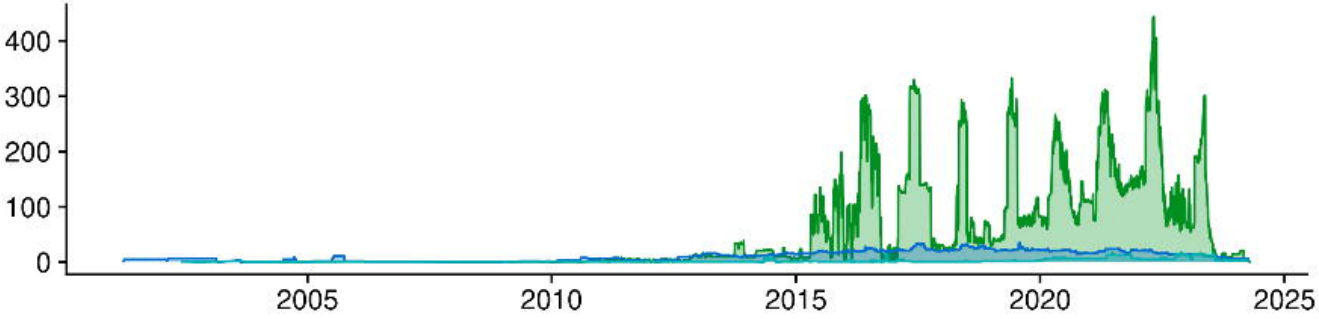
Spatial extent and coverage (sites)



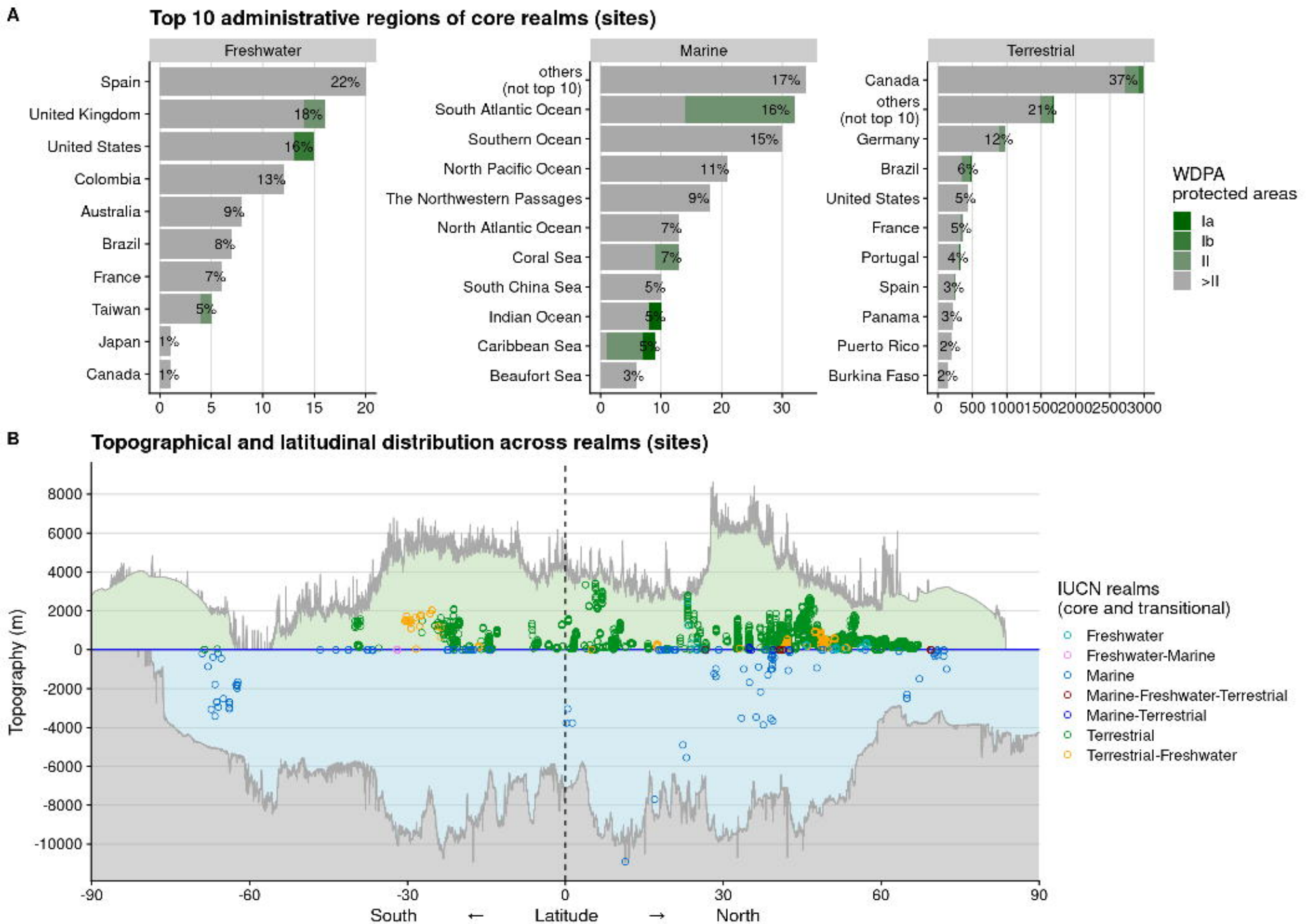
Replication of datasets

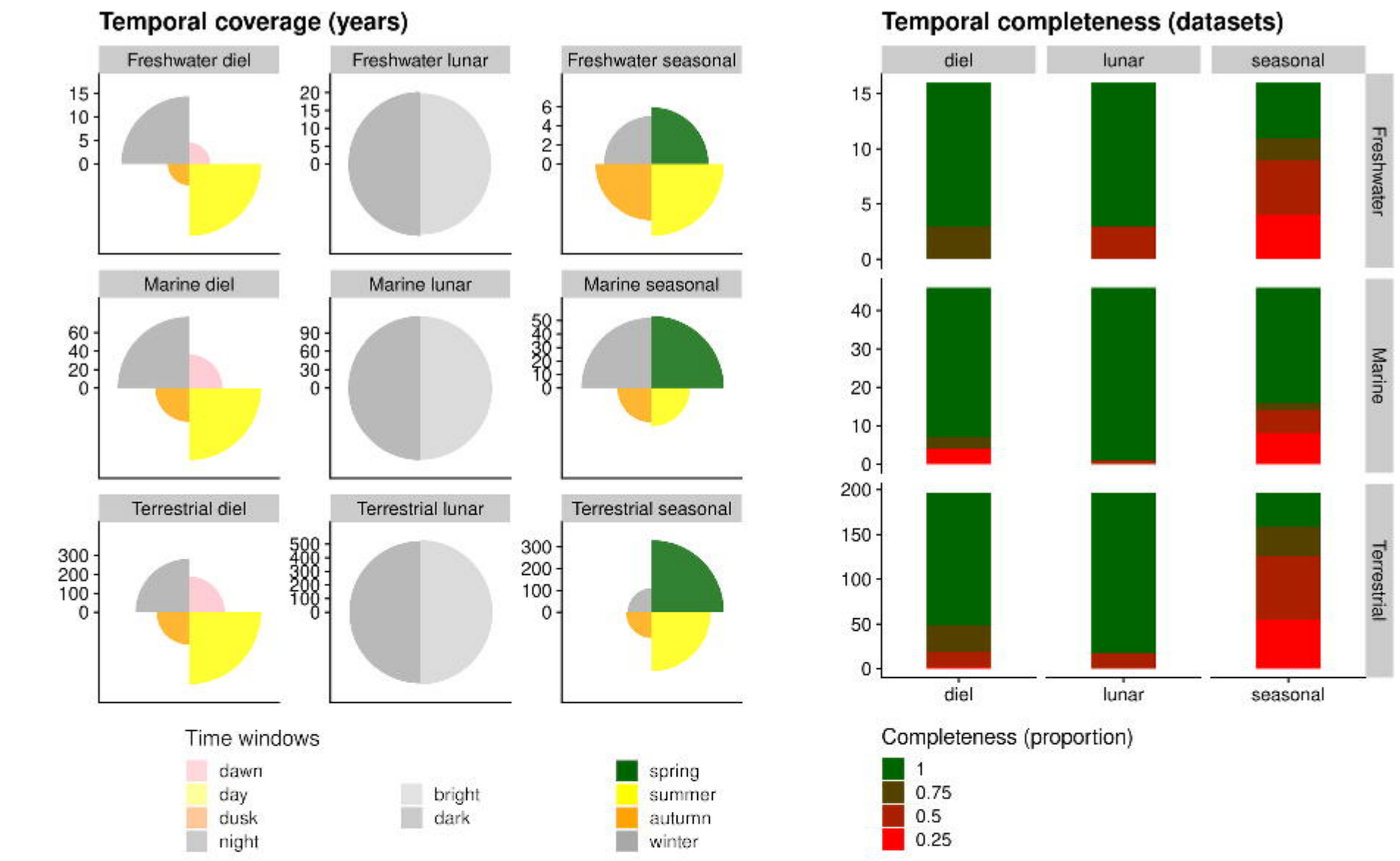


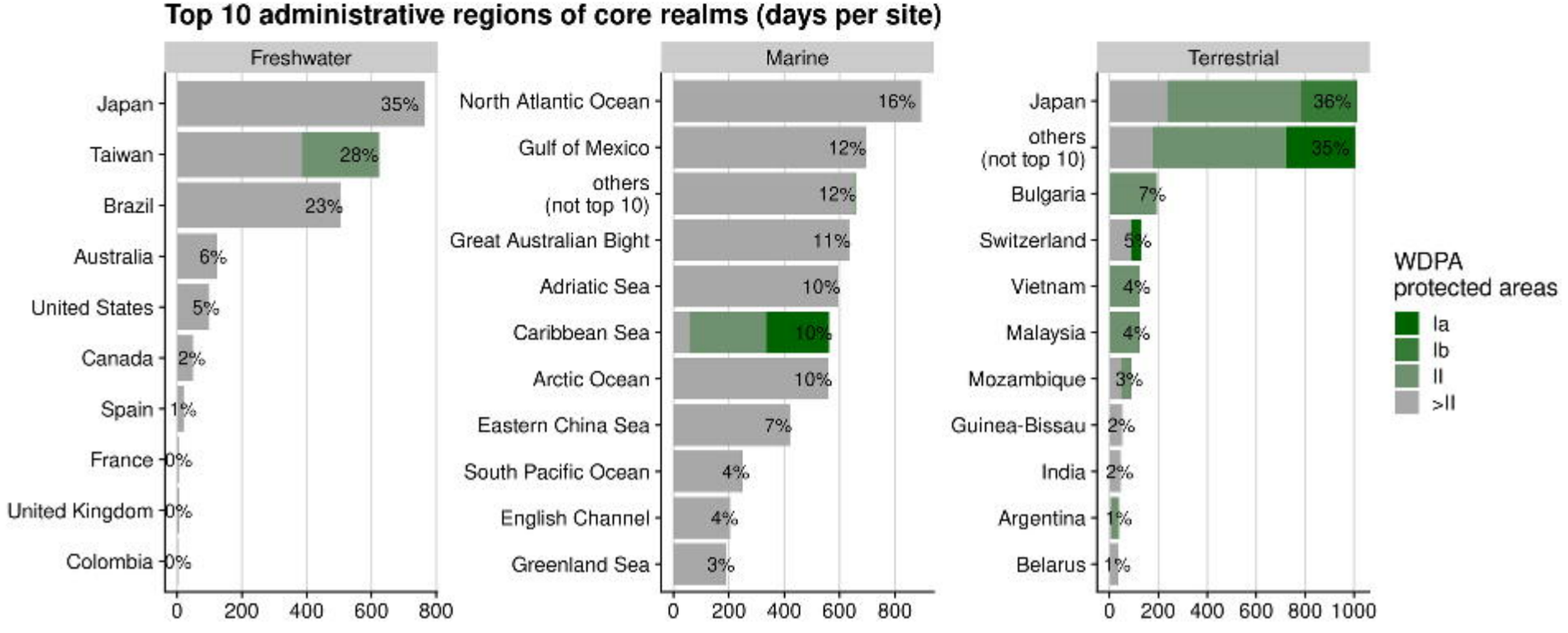
Temporal extent and coverage (days)

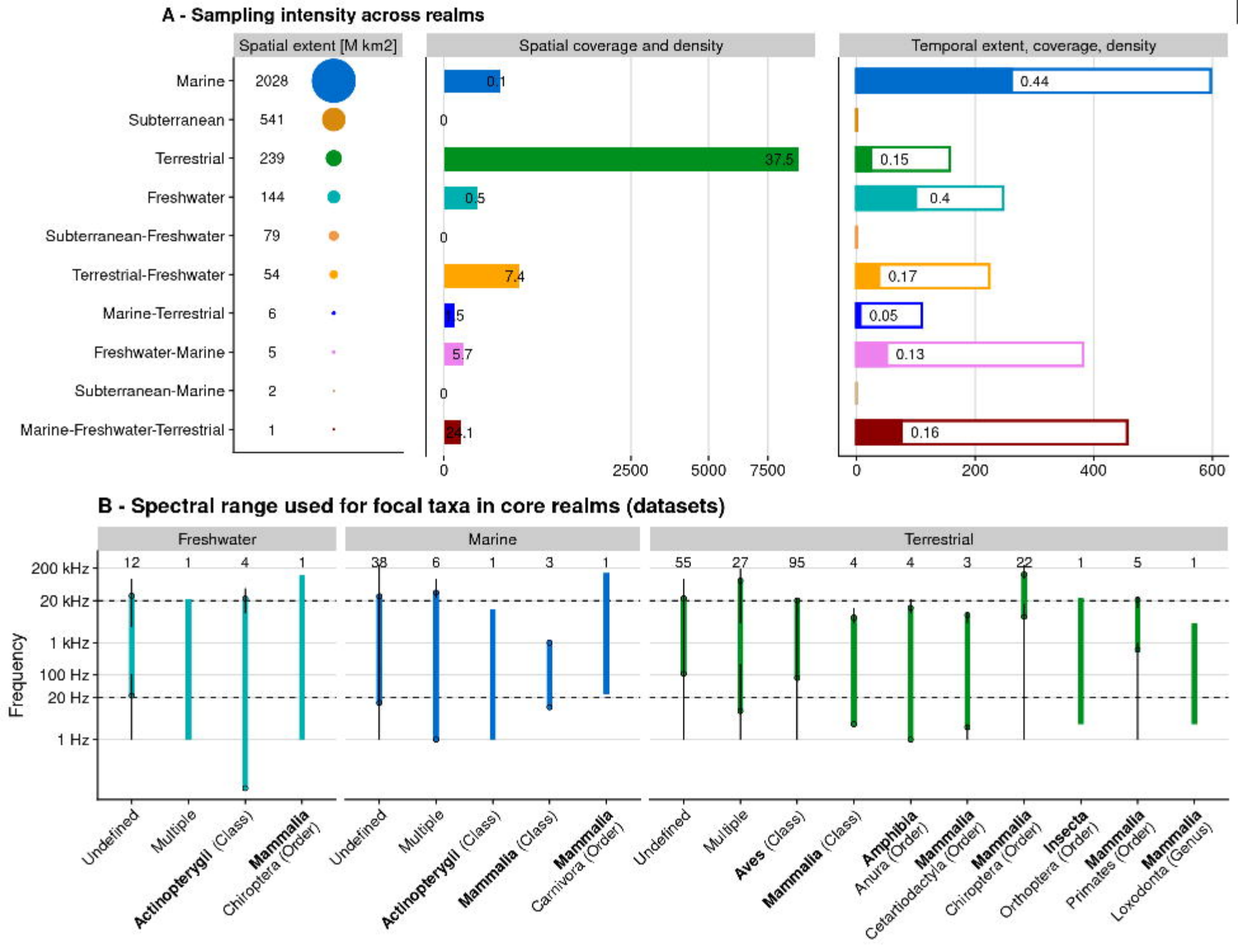


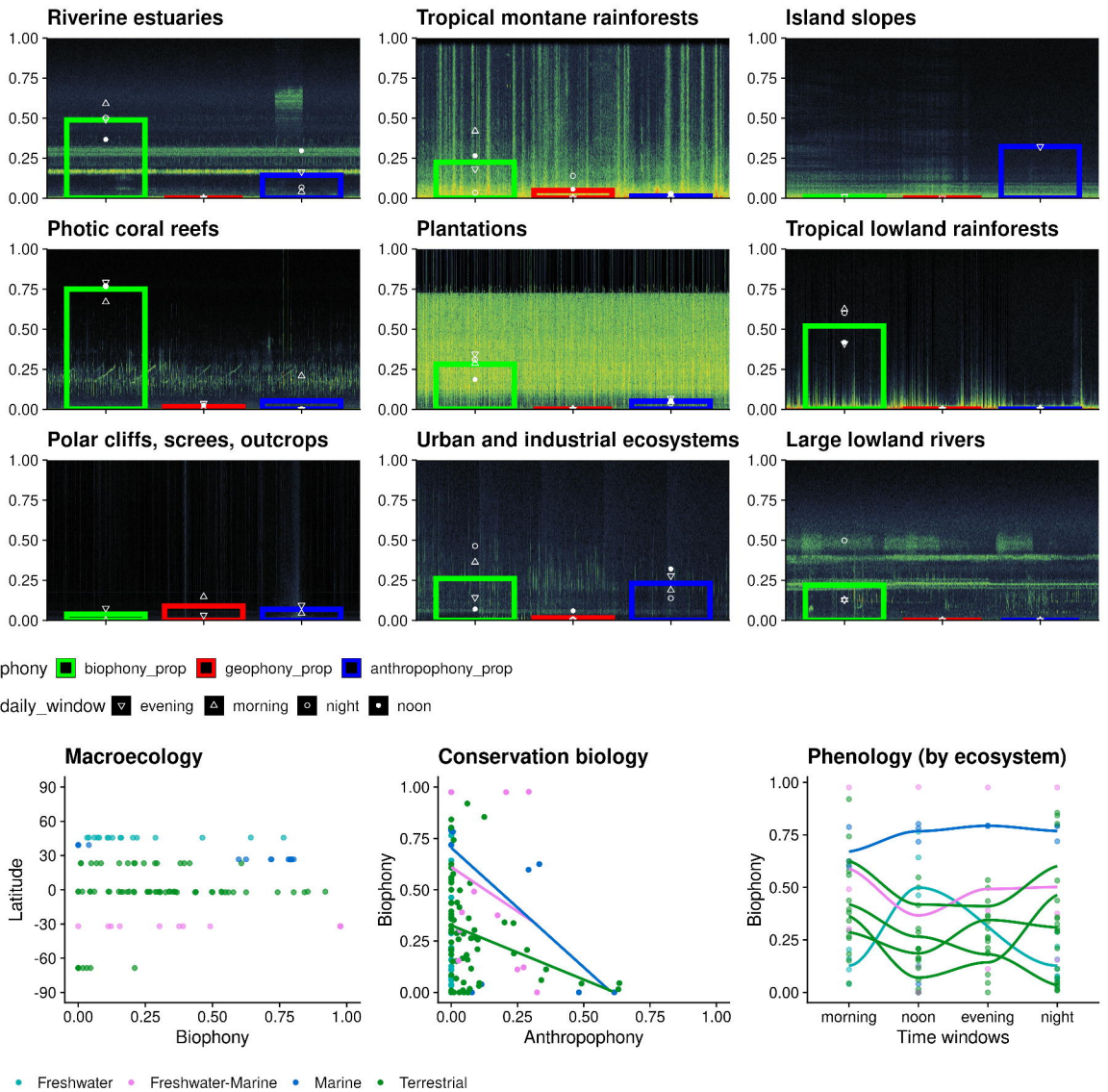
Core realm Freshwater Marine Terrestrial


A
Top 10 administrative regions of core realms (sites)
Freshwater
Spain 22%
United Kingdom 18%
United States 16%
Colombia 13%
Australia 9%
Brazil 8%
France 7%
Taiwan 5%
Japan 1%
Canada 1%
0 5 10 15 20
Marine
others (not top 10) 17%
South Atlantic Ocean 16%
Southern Ocean 15%
North Pacific Ocean 11%
The Northwestern Passages 9%
North Atlantic Ocean 7%
Coral Sea 7%
South China Sea 5%
Indian Ocean 5%
Caribbean Sea 5%
Beaufort Sea 3%
0 10 20 30
Terrestrial
Canada 37%
others (not top 10) 21%
Germany 12%
Brazil 6%
United States 5%
France 5%
Portugal 4%
Spain 3%
Panama 3%
Puerto Rico 2%
Burkina Faso 2%
0 500 1000 1500 2000 2500 3000
WDPA protected areas
Ia
Ib
II
>II
B
Topographical and latitudinal distribution across realms (sites)
Topography (m)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
-90 -60 -30 0 30 60 90
South ← Latitude → North
IUCN realms (core and transitional)
Freshwater
Freshwater-Marine
Marine
Marine-Freshwater-Terrestrial
Marine-Terrestrial
Terrestrial
Terrestrial-Freshwater


Temporal coverage (years)
Freshwater diel
Freshwater lunar
Freshwater seasonal
Marine diel
Marine lunar
Marine seasonal
Terrestrial diel
Terrestrial lunar
Terrestrial seasonal
Temporal completeness (datasets)
diel
lunar
seasonal
Freshwater
Marine
Terrestrial
Time windows
dawn
day
dusk
night
bright
dark
spring
summer
autumn
winter
Completeness (proportion)
1
0.75
0.5
0.25


Top 10 administrative regions of core realms (days per site)
Freshwater
Japan 35%
Taiwan 28%
Brazil 23%
Australia 6%
United States 5%
Canada 2%
Spain 1%
France 0%
United Kingdom 0%
Colombia 0%
Marine
North Atlantic Ocean 16%
Gulf of Mexico 12%
others (not top 10) 12%
Great Australian Bight 11%
Adriatic Sea 10%
Caribbean Sea 10%
Arctic Ocean 10%
Eastern China Sea 7%
South Pacific Ocean 4%
English Channel 4%
Greenland Sea 3%
Terrestrial
Japan 36%
others (not top 10) 35%
Bulgaria 7%
Switzerland 5%
Vietnam 4%
Malaysia 4%
Mozambique 3%
Guinea-Bissau 2%
India 2%
Argentina 1%
Belarus 1%
WDPA protected areas
Ia
Ib
II
>II


A - Sampling intensity across realms
Spatial extent [M km2]
Spatial coverage and density
Temporal extent, coverage, density
Marine
Subterranean
Terrestrial
Freshwater
Subterranean-Freshwater
Terrestrial-Freshwater
Marine-Terrestrial
Freshwater-Marine
Subterranean-Marine
Marine-Freshwater-Terrestrial
2028
541
239
144
79
54
6
5
2
1
0.1
0
37.5
0.5
0
7.4
1.5
5.7
0
24.1
0.44
0.15
0.4
0.17
0.05
0.13
0.16
0
2500
5000
7500
0
200
400
600
B - Spectral range used for focal taxa in core realms (datasets)
Freshwater
Marine
Terrestrial
Frequency
200 kHz
20 kHz
1 kHz
100 Hz
20 Hz
1 Hz
12
1
4
1
38
6
1
3
1
55
27
95
4
4
3
22
1
5
1
Undefined
Multiple
Actinopterygii (Class)
Mammalia Chiroptera (Order)
Undefined
Multiple
Actinopterygii (Class)
Mammalia (Class)
Mammalia Carnivora (Order)
Undefined
Multiple
Aves (Class)
Mammalia (Class)
Amphibia Anura (Order)
Mammalia Cetartiodactyla (Order)
Mammalia Chiroptera (Order)
Insecta Orthoptera (Order)
Mammalia Primates (Order)
Mammalia Loxodonta (Genus)


Riverine estuaries
Tropical montane rainforests
Island slopes
Photic coral reefs
Plantations
Tropical lowland rainforests
Polar cliffs, screes, outcrops
Urban and industrial ecosystems
Large lowland rivers
1.00
0.75
0.50
0.25
0.00
phony
biophony_prop
geophony_prop
anthropophony_prop
daily_window
evening
morning
night
noon
Macroecology
Latitude
Biophony
Conservation biology
Biophony
Anthropophony
Phenology (by ecosystem)
Biophony
morning
noon
evening
night
Time windows
Freshwater
Freshwater-Marine
Marine
Terrestrial