Worldwide Soundscapes: a synthesis of passive acoustic monitoring across realms

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Abstract

The urgency for remote, reliable, and scalable biodiversity monitoring amidst mounting human pressures on climate and ecosystems has sparked worldwide interest in Passive Acoustic Monitoring (PAM), but there has been no comprehensive overview of its coverage

across realms. We present metadata from 358 datasets recorded since 1991 in and above land and water constituting the first global synthesis of sampling coverage across spatial, temporal, and ecological scales. We compiled summary statistics (sampling locations, deployment schedules, focal taxa, and recording parameters) and used eleven case studies to assess trends in biological, anthropogenic, and geophysical sounds. Terrestrial sampling is spatially denser (42 sites/M·km^2) than aquatic sampling (0.2 and 1.3 sites/M·km^2 in oceans and freshwater) with only one subterranean dataset. Although diel and lunar cycles are well-covered in all realms, only marine datasets (65%) comprehensively sample all seasons. Across realms, biological sounds show contrasting diel activity, while declining with distance from the equator and anthropogenic activity. PAM can thus inform phenology, macroecology, and conservation studies, but representation can be improved by widening terrestrial taxonomic breadth, expanding coverage in the high seas, and increasing spatio-temporal replication in freshwater habitats. Overall, PAM shows considerable promise to support global biodiversity monitoring efforts.

Main text

Introduction

Sounds permeate all realms on Earth — terrestrial, freshwater, marine, and subterranean[1]. Passive Acoustic Monitoring (PAM) captures soundscapes that document soniferous life ("biophony"), human activities ("anthropophony"), and some geophysical events ("geophony")[2–6]. In ecoacoustics and soundscape ecology[7,8], PAM can measure levels and impacts of global change (e.g., climate change, urbanization, deep-sea mining)[9–11], monitor ecosystem health, recovery, and restoration[12–14], assess human-environment interactions (public health, cultural ecosystem services)[15,16] and guide conservation (protected area management, landscape planning)[17,18].

Despite the wide-ranging and increasing soundscape sampling effort, the data distribution remains undescribed. Currently soundscape-recording communities are only networked within realms and their methodologies differ. Previous reviews focused on single realms and were either systematic[19–22] or qualitative[3,23]. Marine scientist networks using PAM exist[24], but the freshwater community is nascent, and the terrestrial community grows faster than it can unite. Acoustic calibration and sound propagation modeling are advanced in aquatic studies[25] but seldom considered in terrestrial ones (except [26,27]). Artificial intelligence can identify increasing numbers of species on land[28] whereas aquatic sounds still challenge identification[29,30]. Overall, there is much to gain from sharing data, experience, and methods among PAM users.

Cross-realm PAM studies can yield new theoretical answers[31] and applied solutions: soundscapes track terrestrial and marine resilience to natural disasters[32]; sound and silence durations in multiple realms follow universal distributions[33]. Transnational sampling could form the basis for comprehensive soniferous biodiversity monitoring, just like community-initiated telemetry databases[34], collaborative camera trap surveys[35], individual animal observation networks[36], and invasive species control syntheses[37] advanced entire research fields. A global PAM network could 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.

We present the “Worldwide Soundscapes” project, the first global PAM meta-database and network. 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 holds 307 contributors who collated metadata about 358 passively-recorded, replicated soundscape datasets. Metadata describe the exact spatio-temporal coverage, sampled ecosystems (IUCN Global Ecosystem Typology: GET), transmission medium (air, water, or soil), focal taxa (IUCN Red list), recording settings, and 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, geophony) across eleven ecosystems from all realms. We showcase their relevance to macroecology, conservation biology, and phenology research and identify opportunities to advance the global PAM network. The publicly-

accessible meta-database[38,39] continues to grow to enhance accessibility of data and remains open for metadata contributions, facilitating future syntheses.

Results

Summary dataset statistics

To date, 358 validated soundscape meta-datasets (hereafter "datasets") have been registered in our database from across the globe, dating back to 1991 (Fig. 1D). A dataset gathers a team's metadata on a study or project. Metadata were validated by checking that all fields were filled in and formatted correctly, and then cross-checked by their respective contributors using site maps and recording timelines[39] on ecoSound-web[40]. Based on the GET definition of four 'core' realms, our database includes 259, 80, 18, and 1 validated datasets from the terrestrial, marine, freshwater, and subterranean realms, respectively. The transmission medium was air for terrestrial and subterranean datasets and mostly water for aquatic datasets, as three datasets with aerial above-water recordings were included in the freshwater and marine realms. The majority of datasets (84%) include both spatial and temporal replicates (Fig. 1C). Few datasets have openly-accessible recordings (10-15%, Fig. S1). Presently, few terrestrial and freshwater datasets (27% and 22% respectively) are associated with DOI-referenced publications in contrast to marine datasets (44%) (Fig. S1).

Spatial sampling coverage and density

The database contains 11 093 sampling sites, including 147 polar, 8 455 temperate, and 2 491 tropical sites (Fig 1C). On land, 10 387 sites are located within 79 (out of 263) GADM level 0 areas (Fig. 2B), primarily in the Northern Hemisphere (Table S1). Most terrestrial sites occur in Canada (28%), followed by the United States (18%), but a significant proportion is widely distributed (23% do not belong to the top 10 GADM areas). Few terrestrial sites (8%) are located in WDPA category Ia, Ib, or II areas. Our database currently lacks data from vast areas in Russia, Greenland, the Antarctic, interior Australia, North Africa, and Central Asia. Site elevations range from sea level up to 3 420 m (Fig. 2A), but mountains above 4 000 m in the Northern Hemisphere, above 2 000 m in the Southern Hemisphere, as well as the Transantarctic Mountains are currently not represented in the data. At sea, 469 sites are located within 32 (out of 101) IHO sea areas. Most marine sites occur in the North Pacific Ocean (22%), followed by Southeast Alaskan and British Columbian coastal waters (17%), but a significant proportion is widespread (17% do not belong to the top 10 IHO areas). Many sites are situated in WDPA high-protection category Ia and II areas (14%). Our database currently lacks datasets from Arctic waters off Eurasia, the Southeast Pacific, 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 freshwater datasets. Spain holds most freshwater sites (56%). Few freshwater sites (2%) are in WDPA category II or Ib areas. Freshwater bodies are sampled at elevations from sea level up to 950 m. Mountain freshwater bodies and those in Africa, Asia, and Oceania are currently not represented in our database. The database contains seven subterranean sites situated in Brazil between 277 and 810 m.

Temporal sampling extent, coverage, and density

We compare sampling coverage (in sampled years summed over sites) across time windows of the diel cycle (dawn, dusk, day, night), lunar phases (bright and dark), and the seasons

(spring, summer, autumn, winter - only for temperate sites) (Fig. 3A). Dawn and dusk diel windows are shorter than day and night diel windows for most locations and less intensively sampled. The lunar phase cycle is evenly covered across realms and comprehensively covered within datasets (Fig. S2). In the terrestrial realm, daytime coverage surpasses nighttime coverage (611 vs. 398 years), while 75% of datasets sampled all diel time windows. Terrestrial datasets mostly sampled spring (415 years, 32%) and summer (564 years, 44%) while 24% sampled all seasons. Temporal coverage per site is highest in Japan (272 days) and Taiwan (250 days). In the marine realm, temporal coverage among diel time windows is even and 88% of marine datasets sampled all diel time windows. Marine datasets have high and similar coverage for winter and spring (117 and 122 years, combined 59% of seasonal coverage) and 65% cover the full seasonal cycle. In the freshwater realm, temporal coverage among diel time windows is even and 76% of freshwater datasets sampled all diel time windows. Similarly, 24% sampled all seasons. The subterranean tropical sites primarily covered the nighttime, across all seasons.

Sampling in ecosystems

Our database includes 76 of the 110 GET functional groups and all biomes except anthropogenic shorelines and most subterranean biomes (Table S2). Sampling intensity differed across ecosystem levels - realms, biomes, and functional groups, with transitional realms representing the interface between core realms (Fig. 4A). The terrestrial realm has the third-largest extent and the highest spatial sampling density among realms (42 sites per Mkm^2), but temporal coverage is comparatively low (17% sampled out of mean extent per site: 155 days). The most commonly sampled biome is temperate-boreal forests and woodlands (59% of sites). The marine realm is the most extensive and spatial sampling density is the lowest (0.2 sites per Mkm^2), but temporal sampling extent and coverage are the highest among all realms (69% out of 497 days sampled). The most commonly sampled biomes are the marine shelf and pelagic ocean waters (43% and 42% of sites respectively). The freshwater realm has low spatial sampling densities (1.3 sites per Mkm^2) and high temporal sampling densities (30% out of 115 days sampled). Rivers and streams are most commonly sampled (47% of sites). The terrestrial-freshwater realm, representing 81% of the area of non-subterranean realms, has the third-highest spatial sampling density (7.9 sites per Mkm^2) and similar temporal sampling density to the terrestrial realm (16% days sampled out of 230). The subterranean realm, though second-largest, includes seven tropical sites in aerobic caves from one dataset.

Target taxa and frequency ranges

Most marine datasets do not target specific taxa (70%) and use wide frequency ranges from 0.01 to 30 kHz (mean bounds of frequency ranges across datasets, Fig. 4B). Marine datasets that focus on single taxa comprise cetaceans (8%, 0.006 - 7 kHz) and fish (8%, 0.003 - 29 kHz). Similarly, most freshwater datasets are taxonomically unspecific (66%) and cover frequencies from 1 to 22 kHz. Some datasets (20%) focus on ray-finned fish, covering frequencies from 0.001 to 23 kHz. In contrast, terrestrial datasets mostly target single taxa and have narrow frequency ranges. Bird-focused datasets are most common (44%), spanning frequencies from 0.06 to 21 kHz, while bat-focused datasets are next (12%) and range from 5 to 139 kHz. Taxonomically unspecific datasets account for 24% of datasets, covering a broad range from 0.1 to 24 kHz. Generally, datasets targeting multiple taxa use wider frequency ranges than those targeting single taxa.

Soundscape case studies

We analysed 150 recordings from eleven different ecosystems representing the diversity of soundscapes on Earth, spanning latitudes from 69 degrees South to 67 degrees North (Table S3, Fig. 5A). Biophony dominated with an average soundscape occupation of 30% across all ecosystems, notably: photic coral reefs (Okinawa, Japan) with snapping shrimps and grunting fish choruses (75% soundscape occupancy)[41]; tropical lowland rainforests (Jambi, Indonesia) with buzzing insects and echoing bird and primate songs (61%). Only marine island slopes (off Sanriku, Japan) and polar outcrops (Antarctic) contained no or very little (2%) biophony, respectively. Geophony was absent in most soundscape samples, with the exception of high wind noise in polar outcrops (14%) and some wind in montane tropical forests (5%). Anthropophony occupied on average 9% of the soundscapes. Cities (Jambi, Indonesia; Montreal, Canada) exhibited the highest anthropophony (45%) with prevalent engine noise and human voices, while deep-sea mining and vessel communication caused high anthropophony in marine island slopes (32%)[42]. Silence occupancy was highest in polar outcrops (82%) and large lowland rivers (78%).

The selected soundscapes reveal greater biological activity closer to the equator, a negative relationship between biophony and anthropophony, and variable phenology of soniferous organisms over the diel cycle (Fig. 5). All Bayesian beta regression models for biophony occupancy converged. We detected a negative correlation of biophony occupancy with increasing distance from the equator ($P_{negative}$=1) and with anthropophony occupancy ($P_{negative}$=1). The phenology model predicted biophony occupancy values for each diel time window and realm (Fig. 5B), revealing similar phenology for the terrestrial and marine realm, and opposed freshwater and freshwater-marine realm phenology.

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 annotated soundscapes from eleven ecosystems to investigate macroecological, conservation biology, and phenological trends. The database remains open for contributions[39] and can be openly accessed to source datasets and initiate collaborative studies[38]. Next, we discuss the state and potential of PAM globally (Table 1).

Our results likely represent global PAM trends, even though spatial gaps reflect the background of the project contributors. Our database still misses some national programs (e.g., Australian Acoustic Observatory[43]), but otherwise our terrestrial coverage is similar to a recent systematic review[21]. The gaps in North Africa and Northeastern Europe correspond with the paucity of bioacoustic datasets for these regions[44]. Our database comprises 469 marine sampling locations while 991 were found in a recent systematic review[20], but most overlap (Fig S2). Marine tropical waters that are under-represented in our database reflect gaps found in the International Quiet Ocean Experiment network coverage[45]. Our marine and terrestrial database coverage is thus broadly comparable with published data. However, as the database originates from an active network of researchers, it represents the current availability of mostly as-yet unpublished data (Fig. S1). To our knowledge, no other spatially-explicit review of freshwater sampling exists for comparison, and no other work quantified temporal coverage.

Geographic coverage strikingly differs between realms: marine coverage is sparse but widespread; terrestrial coverage is comparatively intensive in the Americas and Western Europe; freshwater coverage is scattered. This partly reflects funding priorities for where conservation and active management priorities lie, for instance in biodiversity hotspots and densely-populated areas. Technical limits in extreme environments also drive geographic patterns: high latitudes and elevations entail extremely cold 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 poles as water temperatures are buffered below the freezing point. Affordable underwater recorders[46] may help to intensify sampling of marine coastal areas and close gaps in freshwater coverage. By contrast, terrestrial monitoring is generally straightforward. Northern temperate areas outside of Northeastern Europe are comparatively better covered, and the tropics outside of Africa better represented. It appears that gaps in North Africa, Central Asia, and Northeastern Europe arise from differential research means and priorities between countries. Taken together, these gaps help to correct spatial biases[47] and to 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[48]. Marine soundscapes fluctuate stochastically[49], but the ocean buffers water temperatures so that animals retain a basal activity level year-round. Alhough lunar phases affect marine life[50–52], we did not consider lunar tides, which affect some ecosystems. In the terrestrial and freshwater realms, most deployments cover the entire diel cycle but monitoring on land focuses either on diurnal birds or on nocturnal bats, as found in the literature[21]. In contrast, although seasons drive activity cycles on land too[53,54], spring- and summertime monitoring is disproportionately common and we lack a thorough understanding of seasonal dynamics. Terrestrial deployments in particular may be short for logistic reasons: in the cold, batteries struggle and access is harder; recorders are at risk of theft; and limited numbers may cycle between sites[55]. Lunar phases — probably evenly sampled by chance — also influence land animals[56] but should be explicitly considered. Overall, we encourage longer-duration setups with regularly-spread sampling inside temporal cycles to alleviate the higher expenses, energy consumption, storage, and traded-off spatial coverage[57]. 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[58].

Re-use of soundscape datasets is restricted by their taxonomic focus. Admittedly, taxonomically untargeted, long, and regular deployments in oceans, coupled to large detection ranges, concurrently sample many taxa[59]. However, many soundscape recordings sample particular frequencies, often in the human-audible range[60], although biophony ranges from infrasound[61] to ultrasound[62]. For instance, studies of toothed whales or bats often use triggers and high-pass filters to record 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 deployments, so we encourage terrestrial researchers to maximise frequency ranges to enhance interdisciplinary collaboration. These collaborations can help to mutualise

resources for mitigating potentially prohibitive power, storage, transportation, and post-processing costs[63]. Emerging embedded-AI audio detectors may offer an alternative[64], but soundscape recordings will remain essential for broader application.

In every realm, ecosystems await acoustic discovery. Except for one dataset from aerobic caves, we lack data from all subterranean realms (anthropogenic voids, ground streams, sea caves), while endolithic systems may be the only irrelevant ecosystem for biophony. Access is usually challenging or restricted for non-specialists, but subterranean biodiversity shows high spatial turnover[65]. Freshwater datasets were less rare, but several ones with unreplicated sampling could not be included. Temporary, dynamic water bodies (seasonal, episodic, and ephemeral ecosystems) are not yet well-studied[66] although they are accessible from land. Notably, sounds can pass the boundary between recording media and be captured in so-called holo-soundscapes in freshwater and shallow coastal areas[5,67,68]. Advances are imminent as the freshwater acoustic research community is growing rapidly[69,70]. In the oceans, sound propagates far and multiple biomes can be sampled at once (e.g., recorders on the seafloor sample pelagic waters) so that most ecosystems are covered. Still, coverage gaps may exist in rhodolith/Maërl beds, upwelling zones, and deepwater coastal inlets. On land, sampling is biased towards biodiverse forests, and our database coverage suggests that the most challenging terrestrial ecosystems, such as arid zones (sclerophyll hot deserts and semi-deserts, semi-desert steppes), rocky habitats (young rocky pavements, lava flows and screes) but also some vegetated temperate ecosystems (cool temperate heathlands, temperate pyric humid forests, temperate subhumid grasslands) are poorly sampled. Within the IUCN GET framework, soil soundscapes also belong to the terrestrial realm and to date no eligible datasets are in our database, despite recent studies[71,72].

Our database highlights well-known global sampling biases[73] which could be resolved with collaboration to remove cultural and socioeconomic barriers[74]. Technological progress for more affordable equipment renders PAM more accessible in lower-income countries. 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[48]. Our network currently consists of active, English-speaking members from 50 countries. Collaborative projects, shared sea missions, and equipment loans should promote the establishment of soundscape research communities[75]. Increased international collaboration with scientists and local stakeholders supporting citizen-science[76] 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, but comprehensive standards for PAM do not currently exist, even though initiatives for the marine realm are ongoing[77,78]. Few affordable solutions exist for sharing large audio data volumes[40], underlining the need for distributed soundscape recording repositories[79]. Marine oil and gas industry projects routinely upload data as part of their efforts to mitigate noise impacts on marine animals[80], but these recordings often focus on frequencies relevant to seismic prospecting and access may be restricted[81,82]. Furthermore, recording equipment requires calibration, sound detection spaces need to be measured[26], and data privacy must be ensured on land[83]. In parallel, species sound libraries[44,84–86] grow and continue to provide invaluable acoustic and taxonomic references. International organisations such as GBIF will be key to roll-out

standards (e.g., Darwin Core) in a top-down manner. For the moment, we encourage early planning of data archival. In the future, the Worldwide Soundscapes will interoperate with other databases to close remaining coverage gaps.

A unified approach of ecology 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 archive their metadata and join our inclusive project. We show that a large portion of the PAM community is willing to collaborate across realms and form a global network. We advocate for a bolder PAM effort to inform the agenda of soundscape ecology[87], reaching out to places where no sound has been recorded before as well as to urban settings[88]. The research community may open new avenues to study environmental effects on acoustic activity[58], social species interactions[89], human-wildlife relationships[41], function and phylogeny[90], soundscape effects on human health[91], acoustic adaptation and niche hypotheses[92,93], macroecological patterns across ecosystems[1], and initiate an integrated approach to noise impacts on wildlife.

PAM is now an established method that can be applied over large spatial and temporal scales. Consistent, large-scale monitoring of the Earth's soundscapes is essential to establish baselines for historical trends[94] and quantify rapid changes in biodiversity and natural systems. International funding schemes should integrate PAM into biodiversity monitoring platforms such as GBIF[95] and GEO BON[96,97]. Soundscapes are just starting to be used in legislation as an ecosystem feature to be preserved[98]. Occupancy maps for soniferous wildlife obtained from PAM would underpin the evaluation of progress towards threat reduction and ecosystem service provision of the Kunming-Montreal Global Biodiversity Framework[99]. By building collaborations around the knowledge 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 people who carried out PAM-based studies as primary contributors. 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 be responsible for particular realms or biomes and are listed in the first-tier authors list. Primary contributors who additionally provided soundscape recordings 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. Given 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 (e.g., biofilm on marine recorders) or for animal welfare, and local ethics committee reviews were the responsibility of the respective primary contributors. None of the PAM activities resulted in personal risk to participants; neither did they involve health, safety, security or other risk to researchers. Local and regional research relevant to our study were taken into account in citations throughout the main text.

Database construction

The database construction started in August 2021 within the frame of the Worldwide Soundscapes project[38] using collaborative, peer-driven metadata collation. It represents the current state of knowledge about publicly accessible meta-datasets for PAM within our network. We started contacting contributors that we personally know, and co-lead authors helped to contact potential contributors in the respective ecosystem types of their expertise (i.e. terrestrial, urban, freshwater, and marine). We conducted focal publication searches to actively plug coverage gaps by inviting the respective corresponding authors. We posted the call for contributors on specialised ecoacoustics platforms and social media, and will 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, Russian, and Chinese to gather metadata. We ended up including metadata from larger groups such as the Silent Cities project, Ocean Networks Canada, the Australian Acoustic Observatory, and Parks Canada.

Primary contributors provided the metadata that formed the basis for the database. 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 corrresponding study) roles and additionally a manuscript revision role. Primary contributors cross-validated their metadata using maps and graphical timelines visualising their input. 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 contributors. The

database information page is integrated in our online collaborative ecoacoustics platform ecoSound-web[100] that also hosts the soundscape recordings of the case study (https://ecosound-web.de/ecosound_web/collection/show/49).

Our network consists of people reachable through email contact. Out of 588 contacted contributors potentially involved in PAM, 298 (49%) provided some metadata. More datasets exist but 24% of those contacted have not yet responded. This may be due to limitations in sharing research data or, newcomers to PAM, or out-dated contact details. Older soundscape datasets may be stored on analog media that are inaccessible over the internet, but these are more often attended recordings[53] — 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, and we were able to fill gaps more effectively due to focused calls for missing datasets in our large group of contributors.

Potential soundscape recording datasets were required to meet four criteria: 1) stationary — mobile recorders would have complex, constantly changing spatial assignments, thus 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 or temporal selection, as obtained from omnidirectional microphones and with non-triggered recordings; 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 datasets to have spatial replicates when several sites were sampled simultaneously, and temporally replicated when one site was sampled over multiple days at the same time of day. 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: for instance, sampling sites may 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 (e.g., multiple full moons). Taken together, our requirements homogenise 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 activities are broadly determined by solar and lunar cycles[32,54,56,101], and geographical positions on the planet relative to the poles or equator, or the land and water surface. For all datasets, we determined their spatial coverage in terms of number of sites, and sampling density as the number of sites within the realms' areal extent (as determined by IUCN GET maps). Although spatial extent could be defined as the area bounded by the sites of a dataset, challenges with calculating extents on the world sphere (especially for datasets with very large extents spanning the globe), and unknown sampling areas covered in each site led us to ignore spatial extents. Until sound detection spaces can be accurately measured, our measure of spatial sampling density using points per area is thus provisional. Indeed, acoustic sampling areas or volumes are extremely rarely measured in terrestrial sites and seldom measured but sometimes simulated in marine environments[102]. They vary with sound source intensity, frequency, directivity; recording medium temperature, currents, pressure, humidity (for air); habitat structure such as topography and vegetation structure; ambient sound level. Generally, detection ranges are greater in underwater environments due to the

higher density of the recording medium. For all datasets, we also determined their temporal extent (i.e., the time range from the start of the first to the end of the last recording), coverage (i.e., time sampled per site), and density (i.e., proportion of recorded time inside the temporal extent).

We quantified the latitudinal and topographical coverage across realms by collecting latitude, longitude and topography (above and below the sea level) data for each site. Contributors could provide self-measured topography values for sites on land and gaps were filled in using General Bathymetric Chart of the Oceans surface elevation data. For underwater sites, depth values (below sea level for marine sites, below the surface for freshwater) were provided by the contributors. 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 6`.5° latitude), and temperate (between polar and tropical regions).

Contributors were asked to specify the timing of their deployments using start and end dates and times, operation modes (continuous, scheduled, periodical). For scheduled operation schedules (daily start and end times or durations) were required, and duty cycles were required for periodical operation. Duty cycles could additionally be indicated for scheduled deployments. Deployments were assigned to single sampling sites. Subsequently added sites and sampling repetitions were considered as additional deployments within datasets. A temporal framework was used to quantify sampling coverage in three solar and lunar cycles. Temporal information was inferred from the timing of sound recordings relative to time events that structure life and meteorological events on Earth (Fig. 3). Seasonal cycles were inferred only for temperate sites, by splitting the year cycle into four meteorological seasons (winter: December-February, spring: March-May, summer: June-August, fall: September-November). 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 centred on 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. Seasonal cycles in tropical and polar regions arising from precipitation patterns were not considered in this analysis.

Ecological characterisation

We assigned individual sampling locations to ecosystem types following the IUCN GET (https://global-ecosystems.org). Correspondiongly, sites were assigned hierarchically to realms (core or transitional ones), biomes, and functional groups. We calculated the major and minor occurrence areas of all functional groups based on ecosystem maps[1,103,104]. We used these data to quantify spatio-temporal extent, coverage, and sampling density within realms and biomes, and to identify sampling gaps. To identify which taxa acoustic deployments were designed for, deployments were linked to IUCN taxa (class, order, family, or genus) when applicable — some datasets were collected without taxonomic focus. We use these data to depict the acoustic frequency ranges depending on the target taxon.

Acoustic frequency ranges

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

Soundscape case studies

To illustrate how the database can be used for macroecology, conservation biology, and phenology analyses, we selected 121 recordings across a variety of topographical, latitudinal, and anthropisation conditions — all fundamental gradients of assembly filters in both terrestrial and marine realms[1] — belonging to 10 functional groups. We aimed to select datasets containing four spatial replicates within the same functional group, with 10-minute recordings spanning all four diel time windows from the same date during the biologically active season, but the available data did not always allow this (Table S2). We extracted recordings starting at sunrise, solar noon, sunset, and solar midnight. Recordings covered the audible frequency range with sampling frequencies of at least 44.1 kHz in single or dual channel configuration. We acknowledge that this targeted, non-systematic selection is not statistically representative of global patterns but rather illustrative of the database potential.

Each recording's spectrogram (i.e., visualisation of sound intensity along time and frequency axes) was annotated with the three fundamental soundscape components: biophony, anthropophony, and geophony. Soundscape recordings were uploaded to ecoSound-web (https://ecosound-web.de/ecosound_web/collection/show/49)[40] for annotation: KD listened to them and visually inspected the spectrograms (Fast Fourier Transform window size of 1 024) at a visual density of 1 116 pixels per 10 minutes to create annotations. Annotations were rectangular tags on the spectrogram, encompassing only the annotated sound, with defined coordinates in the time and frequency dimensions. Annotations of different soundscape components could overlap if they were simultaneously visible or audible. Annotations of the same soundscape component were adjacent and non-overlapping to avoid double-counting. Soundscape components occurring above 22.05 kHz were excluded from the analysis as we focused on audible frequencies only, which were the frequencies targeted by most recordings. Sounds caused by microphone or recorder self-noise were excluded. All annotations were reviewed by the recording creators using the peer-review mode on ecoSound-web, and only accepted ones were used in the analysis. The annotations were exported and acoustic space occupancy for each soundscape component in each recording was calculated as the proportion of the spectro-temporal space[60] (i.e., duration multiplied by frequency range, divided by total area of spectrogram; range: 0-1).

All Bayesian beta regression models (4 chains of 1000 sampling iterations with 1000 warmup iterations) for biophony occupancy converged as determined by trace plots and R hat values equaling 1. The models using latitude and anthropophony as predictors included

the functional group as a random intercept. The phenology model used diel time windows and realms, as well as their interactions, as predictors.

Display items

Table 1: An agenda towards comprehensive coverage and a global PAM network

Aims	**Opportunities**
Increasing spatial and ecosystemic coverage	- Affordable underwater recorders - Autonomous setups for extreme environments on land - Deploy in subterranean realm - Deploy in dynamic freshwater bodies - Deploy at high latitude and elevation on land
Increasing temporal and taxonomic coverage	- Longer deployments with duty cycles - Cover all seasons in freshwater 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 more languages
Interoperability	- Calibrate equipment and consider detection ranges - Build accessible and sustainable data repositories - Design and adopt standards - Integrate PAM into biodiversity and remote sensing databases

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 degree 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 Fig S3. For panels C and D, Sites from transitional realms were assigned to their parent core realm.*

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[105]. Minimum topography above the sea level and maximum topography under the 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". One subterranean site in Brazil is not shown. Sites from transitional realms were assigned to their parent core realm.

***Figure 3: Temporal sampling distribution**. A) Temporal sampling coverage across solar and lunar cycles for the three core realms. Cycles consist of solar (daily and seasonal) and lunar time cycles (lunar phase), subdivided in time windows. Seasons were only analysed in temperate regions. Sampling coverage is represented with sampling days in number labels. B) Mean number of sampling days per site within different administrative regions (GADM level 0, IHO areas, WDPA categories), split by core realm. WDPA categories (Ia: strict nature reserve; Ib: wilderness area, II: national park) are shown separately. One subterranean site in Brazil is 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.*

***Figure 4: Sampling distribution across ecological scales**. A) Spatial extent of realms, based on major 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 colored lines represent means of the lowest and highest recorded frequencies, and the range 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.*

***Figure 5: Soundscape components analysis.** A) Mean acoustic space occupancy of soundscape components (biophony, geophony, anthropophony) as calculated from annotations for the selected ecosystems, measured in proportion of spectro-temporal space used, across eleven ecosystems over 150 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 macroecology (i.e., biophony with distance from equator relationship), conservation biology trade-offs (i.e., biophony with anthropophony relationship); and phenological trends (i.e., mean biophony along diel time windows for each realm). Gray ribbons indicate 95% credible intervals and numbers indicate probabilities of positive or negative relationships.*

Data availability

- Database metadata at Zenodo (version 2.0.0)
- Demonstration collection

Acknowledgements

We are thankful to our colleagues who supported our work: Carolina Gonzaga, Ellen Kenchington, Jinshan Xu, Abigail Seybert, Abram B. Fleishman, Adriana C. Acero-Murcia, Adrien Charbonneau, Adrià López-Baucells, Aklavik, Alain Paquette, Albert García, Alexander C. Lees, Alexandra Buitrago-Cardona, Alfonso Zúñiga, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Allan G Oliveira, Alpheous, Ambroise N. Zongo, Ana Rainho, Ana Širović, Anamaria Dal Molin, Andros T Gianuca, Annalea Beard, Anne Sourdril, Anthony Tan, Anushka Rege, Aran Mooney, Arne Wenzel, Astrid Brekke Skrindo, Australian Institute of Marine Science, Base de Estudos do Pantanal - UFMS, Bastien Castagneyrol, Bea Maas, Bibiana Gómez-Valencia, Bob Dziak, Bobbi J. Estabrook, Borja Milá, Brian Miller, Bridget Maher, Brittnie Spriel, C. Lisa Mahon, Carolina Ocampo-Ariza, Carolline Z Fieker, Catherine Potvin, Catrin Westphal, Charlotte Roemer, Chistophe Thébaud, Chong Chen, Christina Ieronymidou, Christine Cassin, Christine Erbe, Christopher Clark, Cicero Simao, Claire Attridge, Claudia A. Medina-Uribe, Clément Lemarchand, Colin Bates, Colin KC Wen, Conner Partaker, Cowichan Tribes Lulumexun department - Fisheries and Marine projects staff, Craig A Radford, Curtin University, Cécile Albert, Dadang Dwi Putra, Daisy Dent, Dan Warren, Daniel Mihai Toma, Danny Swainson , Dawit Yemane, Deanna Clement, Dedi Rahman, Dennis Higgs, Dennis Kühnel, Dexter Hodder, Diego Alejandro Gómez-Montes, Diego Balbuena, Diego Gil, Diego Pavón Jórdan, Diogo Provete, Dorgival Diogenes, Dustin Whalen, Edho Walesa Prabowo, Eduardo Rodríguez Martinez, Elizabeth Clingham, Eliziane Oliveira, Ellen Mc Arthur, Elma Kay, Eloy Revilla, Emanuel Stefan Baltag, Emilia Sokolowska, Emilio Tan, En-Hao Liu, Enoc Martinez, Eric Parmentier, Eric Rakotomalala, Erich Fischer, Erika Berenguer, Estância Mimosa Ecoturismo, Evan Economo, Fabio De Leo Cabrera, Faisal Ali Awanrali Khan, Fang-Yee Lin, Fannie W. Shabangu, Filipe F de Deus, Flávio Rodrigues, Francis Juanes, Frederic Sinniger, Frode Fossøy, Gabriel Leite, Gabriel leite, George Best, Gerard Bota, Germany, Giselle Mahung, 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, Ian Avery Bick, Ilias Karmiris, Irfan Fitriawan, Isabelle Côté, Italo A A Rondon, Jacques Keumo Kuenbou, Jakob Tougaard, Jamie Ratliff, Jamieson Atkinson, Janice Ser Huay Lee, Jason Gedamke, Jean Pierre Castro Namuche, Jean-Yves Royer, Jeff Robinson, Jennifer Clark, Jens-Georg Fischer, Jessica Deichmann, Jessica Qualley, Jinshan Xu, Joaquin del Rio, Johan Diepstraten, Johanna Järnegren, John Ewen, John Hildebrand, John Ryan, Jos Barlow, Jose Leon, Jose Manuel Ochoa-Quintero, José Luis Mena, José Nilson Santos, José Wagner, Juan Diego Tovar, Juliana Carolina Herran García, Julie Perrot, Julio Baumgarten, Junior Tremblay, Just T. Bayle Sempere, Justine Magbanua, Jérémy Anso, Jérémy Froidevaux, Jérémy Froideveaux, Jérôme Sueur, Karen H. Beard, Katie Huong, Katie Innes, Kelsie Murchie, Ken Otter, Ken P. Findlay, Kenneth Dudley, Kevin Darras,

Kevin G. Borja-Acosta, Kieran Cox, Kinga Buda, Kris Harmon, Laela Sayigh, Laure Desutter-Grandcolas, Laurel Symes, Lauren Kuehne, Laurence H. De Clippele, Leeann Henry, Leila Hatch, Lenka Brousset, Leonardo Trevelin, Liana Chesini Rossi, Linilson Padovese, Lisa Loseto, Louise Emmerson, Luca Iacobucci, Lucia Di Iorio, Luciana Nacimento , Luis P. da Silva, Mao-Ning Tuanmuu, Marc Lammers, Marcia Maia, Marconi Campos, Marconi Campos Cerqueira, Marcos Vaira, Marcus Rowcliffe, Marlize Muller, Martim Melo, María Jesús García Bianco, Matias Carandell, Matthew J. Weldy, Matthew K Pine, Matthew Slater, Mauricio Akmentins, Max Ritts, Michael Scherer-Lorenzen, Mike van der Schaar, Milton Cezar Ribeiro, Mina Anders, Muhammad Justi Makmun Jusrin, Nadia Pieretti, Niaina Nirina Mahefa Andriamavosoloarisoa, Nicholas Brown, Nicholas Friedman, Nick Gardner, Nicolas Farrugia, Nicolas Pajusco, Nikos Fakotakis, Noam Leader, Nuno Faria, Ocean Acoustics Group, Ocean Networks Canada Society, Olaf Boebel, Omar Hiram Martinez Castillo, Pedro B. Lopes, Peter Ellis, Peter Taylor, Pooja Choksi, Pousada Xaraés, Pshemek Zdroik, Rainforest Connection (RFCx), Refúgio Ecológico Caiman, Refúgio da Ilha Ecolodge, Rex K. Andrew, Richard Kinsey, Rob Rempel, Robert John Young, Robert McCauley, Robert Spaan, Robert Young, Rouvah Andriafanomezantsoa, Saki Harii, Samuel Challéat, Samuel Haché, Sandra Mueller, Sara Gonçalves, Sarab Sethi, Sarah Rowley, Sarika Khanwilkar, Sean Martin, Shannon MacPhee, Shinsuke Kawagucci, Sierra Hunicutt, Sierra Jarriel, Sigal Balshine, Silent cities consortium, Simon Childerhouse, Sina Weier, Sofie Van Parijs, Stan Dosso, Stanislas Wroza, Stephanie Plön, Stephen Insley, Stuart Marsden, Sérgio Moreira, Tatiana Atemasova, Tetsuya Miwa, The Hunters and Trappers Committees of Inuvik, The Inuvialuit-Canada Fisheries Joint Management Committee, Thiago M Ventura, Thomas Sattler, Todor Ganchev, Tomas Altamirano, Tomasz Stanislaw Osiejuk, Tomaz Melo, Tomonari Akamatsu, Tristan Louth-Robins, Tómas Grétar Gunnarsson, Valentin Chevalier, Valerie Linden, Valéria Tavares, Vijay Ramesh, Vu Dinh Thong, Vy Tram Nguyen, Wen-Ling Tsai, Will Duguid, Yenifer Herrera-Varón, You-Fang Chen, Yuhang Song, Zehava Sigal, Zuania Colón-Piñeiro, Zuzana Burivalova, and Tuktoyaktuk.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. 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 U.S. Government determination or policy. 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. BIOMON is funded by the European Union's Horizon Europe programme under grant agreement 101090273. Larissa Sayuri M. Sugai and Liiana Piatti acknowledge grant Fundect T.O.:95/2023; SIAFEM: 33112. This paper is NOAA-PMEL contribution number 5948. Songhai Li acknowledges the National Natural Science Foundation of China (Grant numbers 42225604). Anna Franziska Cord was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2070 – 390732324. This research was also funded by a Westlake University Startup Fund (Thomas C Wanger).

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Wensveen, Camille Desjonquères, Orlando Acevedo-Charry, Matyáš Adam, Michel André, Alexandre Antonelli, Leandro Aparecido Do Nascimento, Giulliana Appel, Christos Astaras, Andrey Atemasov, Luc Barbaro, Fritjof Basan, Carly Batist, Adriá López Baucells, Julio Ernesto Baumgarten, Just T Bayle Sempere, Kristen Bellisario, Asaf Ben David, Oded Berger-Tal, Matthew G Betts, Iqbal Bhalla, Thiago Bicudo, Marta Bolgan, Sara Bombaci, Martin Boullhesen, Tom Bradfer-Lawrence, Robert A Briers, Michal Budka, Katie Burchard, Alice Calvente, Maite Cerezo-Araujo, Gunnar Cerwén, Maria Chistopolova, Christopher W Clark, Benjamin Cretois, Chapin Czarnecki, Luis P da Silva, Wigna da Silva, Laurence H De Clippele, David de la Haye, Ana Silvia de Oliveira Tissiani, Devin de Zwaan, Ricardo Díaz-Delgado, Pedro Diniz, Dorgival Diógenes Oliveira-Júnior, Thiago Dorigo, Saskia Dröge, Marina Duarte, Adam Duarte, Kerry Dunleavy, Robert Dziak, Simon Elise, Hiroto Enari, Haruka S Enari, Florence Erbs, Nina Ferrari, Luane Ferreira, Abram B Fleishman, Bárbara Freitas, Nick Friedman, Jérémy SP Froidevaux, Svetlana Gogoleva, Maria Isabel Gonçalves, Carolina Gonzaga, José Miguel González Correa, Eben Goodale, Benjamin Gottesman, Ingo Grass, Jack Greenhalgh, Jocelyn Gregoire, Jonas Hagge, William Halliday, Antonia Hammer, Tara Hanf-Dressler, Samara Haver, Daniel Hending, Jose Hernandez-Blanco, Thomas Hiller, Joe Chun-Chia Huang, Katie Lois Hutchinson, Janet Jackson, Alain Jacot, Olaf Jahn, Jasper Kanes, Ellen Kenchington, Sebastian Kepfer-Rojas, Tharaka Kusuminda, Yael Lehnardt, Paula Leitman, José Leon, Cicero Simão Lima-Santos, Kyle John Lloyd, Audrey Looby, David López-Bosch, Tatiana Maeda, Christos Mammides, Gabriel Marcacci, Matthias Markolf, Marinez Isaac Marques, Charles W Martin, Dominic A Martin, Kathy Martin, Logan JT McLeod, Oliver Metcalf, Christoph Meyer, Grzegorz Mikusinski, Larissa Sayuri Moreira Sugai, Dave Morris, Sandra Müller, Kelsie A Murchy, Maria Mas Navarro, Rym Nouioua, Julian D Olden, Steffen Oppel, Anna N Osiecka, Miles Parsons, Filipa Isabel Pereira Samarra, Cristian Pérez-Granados, Liliana Piatti, Mauro Pichorim, Thiago Pinheiro, Jean-Nicolas Pradervand, Craig Radford, Emiliano Ramalho, Laura K Reynolds, Klaus Riede, Talen Rimmer, Ricardo Rocha, Luciana Rocha, Samuel RP-J Ross, Carlos Salustio-Gomes, Philip Samartzis, José Santos, Kevin Scharffenberg, Renée P Schoeman, Karl-Ludwig Schuchmann, Esther Sebastián-González, Fannie Shabangu, Taylor Shaw, Xiaoli Shen, David Singer, Jenni Stanley, Karolin Thomisch, Laura Torrent, Juan Traba, Junior A Tremblay, Sunny Tseng, Mao-Ning Tuanmu, Marisol Valverde, Ben Vernasco, Raiane Vital da Paz, Matthew Ward, Matthew Weldy, Julia Wiel, Jacob Willie, Heather Wood, Renata Sousa-Lima contributed to data curation. Kevin FA Darras did the formal analysis. Kevin FA Darras, Anna F Cord, Anna F Cord, Thomas Cherico Wanger acquired funding. Kevin FA Darras, Rodney Rountree, Steven Van Wilgenburg, Frederik Pitz, Youfang Chen, Lijun Dong, Amandine Gasc, Songhai Li conducted the investigation. Kevin FA Darras designed the methodology. Kevin FA Darras, Rodney Rountree, Steven Van Wilgenburg, Lijun Dong, Amandine Gasc, Jacopo Aguzzi, Robert Dziak, Jose Hernandez-Blanco, Ellen Kenchington, Justin Kitzes, Matthew McKown, Carolyn Rosten, Songhai Li, Renata Sousa-Lima administered the project or sub-projects (i.e., collections). Kevin FA Darras provided resources. Kevin FA Darras provided software. Kevin FA Darras, Anna F Cord, Anna F Cord, Songhai Li, Renata Sousa-Lima, Thomas Cherico Wanger conducted supervision. Kevin FA Darras, Frederik Pitz, Youfang Chen, Tzu-Hao Lin, Patrick Mauritz Diaz, Shih-Hung Wu, Marcus Salton, Laura Schillé carried out validation. Kevin FA Darras designed visualisations. Kevin FA Darras, Anna F Cord, Tom Bradfer-Lawrence, Miles Parsons, Samuel RP-J Ross, Anna F Cord wrote the original draft and Kevin FA Darras, Rodney Rountree, Steven Van Wilgenburg, Anna F Cord, Amandine Gasc, Tzu-Hao Lin, Patrick Mauritz Diaz, Shih-Hung Wu, Sarah Marley, Laura Schillé, Paul Jacobus Wensveen, Camille

Desjonquères, Orlando Acevedo-Charry, Matyáš Adam, Jacopo Aguzzi, Michel André, Alexandre Antonelli, Leandro Aparecido Do Nascimento, Giulliana Appel, Christos Astaras, Andrey Atemasov, Luc Barbaro, Fritjof Basan, Carly Batist, Adriá López Baucells, Julio Ernesto Baumgarten, Just T Bayle Sempere, Kristen Bellisario, Asaf Ben David, Oded Berger-Tal, Matthew G Betts, Iqbal Bhalla, Thiago Bicudo, Marta Bolgan, Sara Bombaci, Martin Boullhesen, Tom Bradfer-Lawrence, Robert A Briers, Michal Budka, Katie Burchard, Alice Calvente, Maite Cerezo-Araujo, Gunnar Cerwén, Maria Chistopolova, Christopher W Clark, Benjamin Cretois, Chapin Czarnecki, Luis P da Silva, Wigna da Silva, Laurence H De Clippele, David de la Haye, Ana Silvia de Oliveira Tissiani, Devin de Zwaan, Ricardo Díaz-Delgado, Pedro Diniz, Dorgival Diógenes Oliveira-Júnior, Thiago Dorigo, Saskia Dröge, Marina Duarte, Adam Duarte, Kerry Dunleavy, Robert Dziak, Simon Elise, Hiroto Enari, Haruka S Enari, Florence Erbs, Nina Ferrari, Luane Ferreira, Abram B Fleishman, Bárbara Freitas, Nick Friedman, Jérémy SP Froidevaux, Svetlana Gogoleva, Maria Isabel Gonçalves, Carolina Gonzaga, José Miguel González Correa, Eben Goodale, Benjamin Gottesman, Ingo Grass, Jack Greenhalgh, Jocelyn Gregoire, Jonas Hagge, William Halliday, Antonia Hammer, Tara Hanf-Dressler, Samara Haver, Daniel Hending, Jose Hernandez-Blanco, Thomas Hiller, Joe Chun-Chia Huang, Katie Lois Hutchinson, Janet Jackson, Alain Jacot, Olaf Jahn, Jasper Kanes, Ellen Kenchington, Sebastian Kepfer-Rojas, Justin Kitzes, Tharaka Kusuminda, Yael Lehnardt, Paula Leitman, José Leon, Cicero Simão Lima-Santos, Kyle John Lloyd, Audrey Looby, David López-Bosch, Tatiana Maeda, Christos Mammides, Gabriel Marcacci, Matthias Markolf, Marinez Isaac Marques, Charles W Martin, Dominic A Martin, Kathy Martin, Matthew McKown, Logan JT McLeod, Oliver Metcalf, Christoph Meyer, Grzegorz Mikusinski, Larissa Sayuri Moreira Sugai, Dave Morris, Sandra Müller, Kelsie A Murchy, Maria Mas Navarro, Rym Nouioua, Julian D Olden, Steffen Oppel, Anna N Osiecka, Miles Parsons, Filipa Isabel Pereira Samarra, Cristian Pérez-Granados, Liliana Piatti, Mauro Pichorim, Thiago Pinheiro, Jean-Nicolas Pradervand, Craig Radford, Emiliano Ramalho, Laura K Reynolds, Klaus Riede, Talen Rimmer, Ricardo Rocha, Luciana Rocha, Samuel RP-J Ross, Carolyn Rosten, Carlos Salustio-Gomes, Philip Samartzis, José Santos, Kevin Scharffenberg, Renée P Schoeman, Karl-Ludwig Schuchmann, Esther Sebastián-González, Fannie Shabangu, Taylor Shaw, Xiaoli Shen, David Singer, Jenni Stanley, Karolin Thomisch, Laura Torrent, Juan Traba, Junior A Tremblay, Sunny Tseng, Mao-Ning Tuanmu, Marisol Valverde, Ben Vernasco, Raiane Vital da Paz, Matthew Ward, Matthew Weldy, Julia Wiel, Jacob Willie, Heather Wood, Anna F Cord, Renata Sousa-Lima edited it.

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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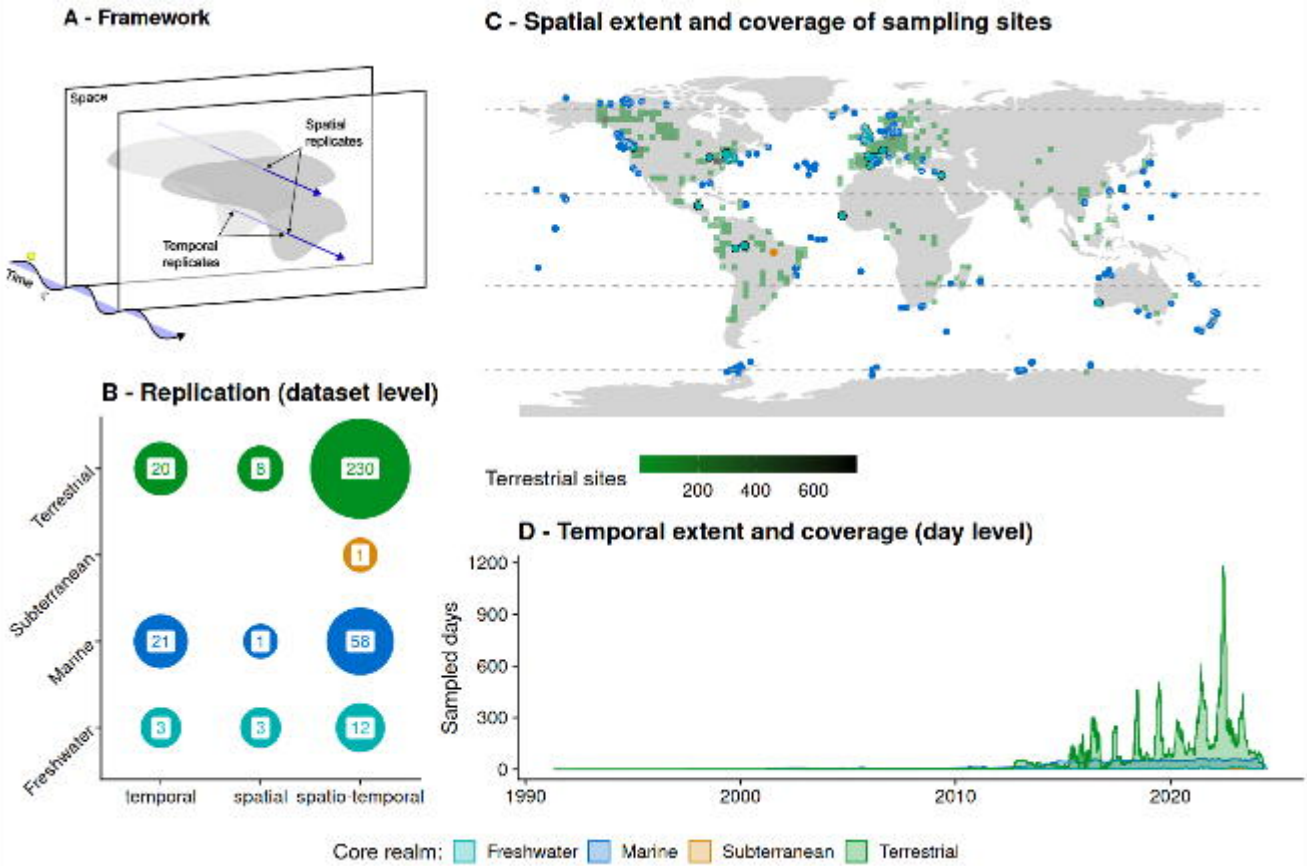
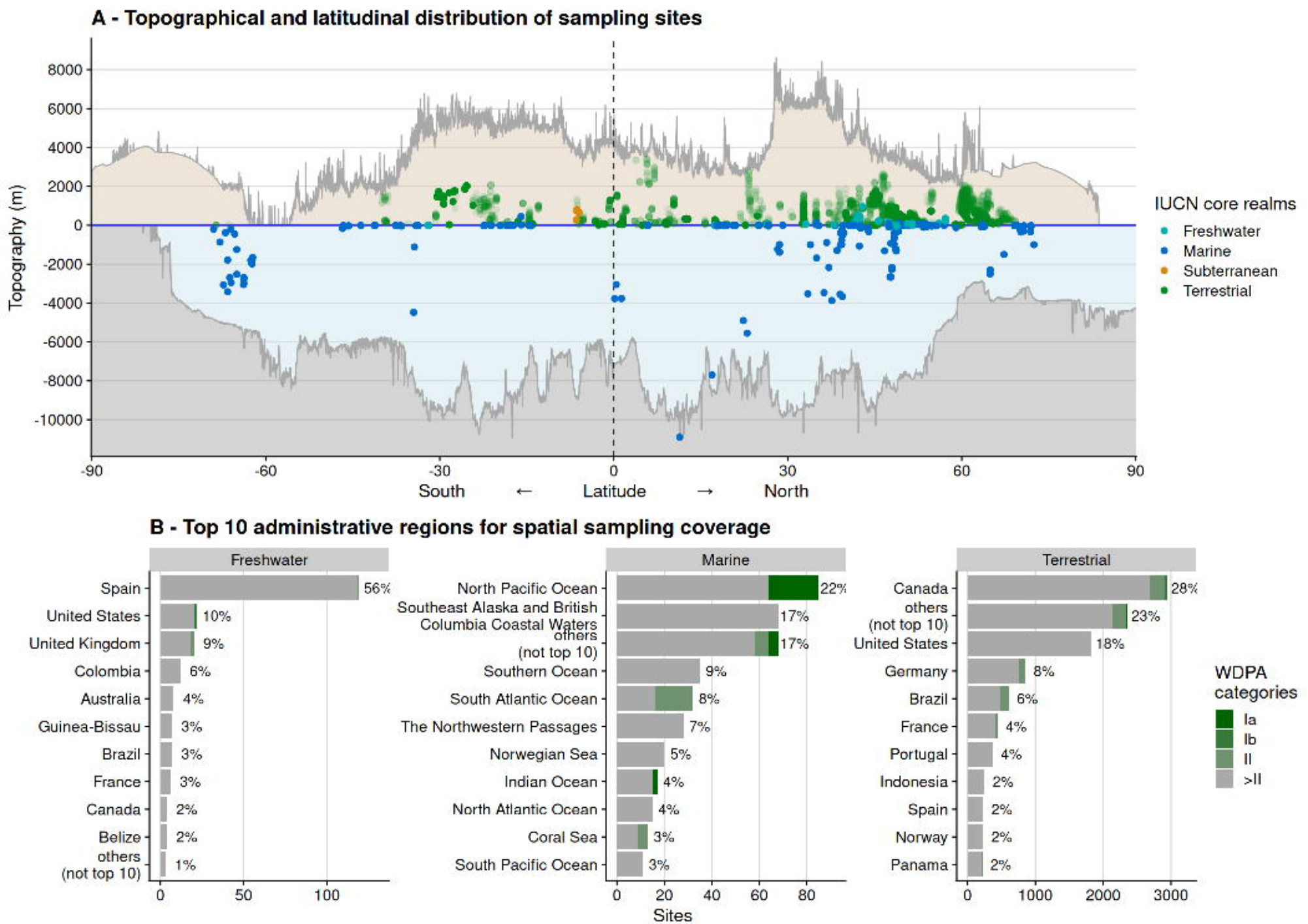
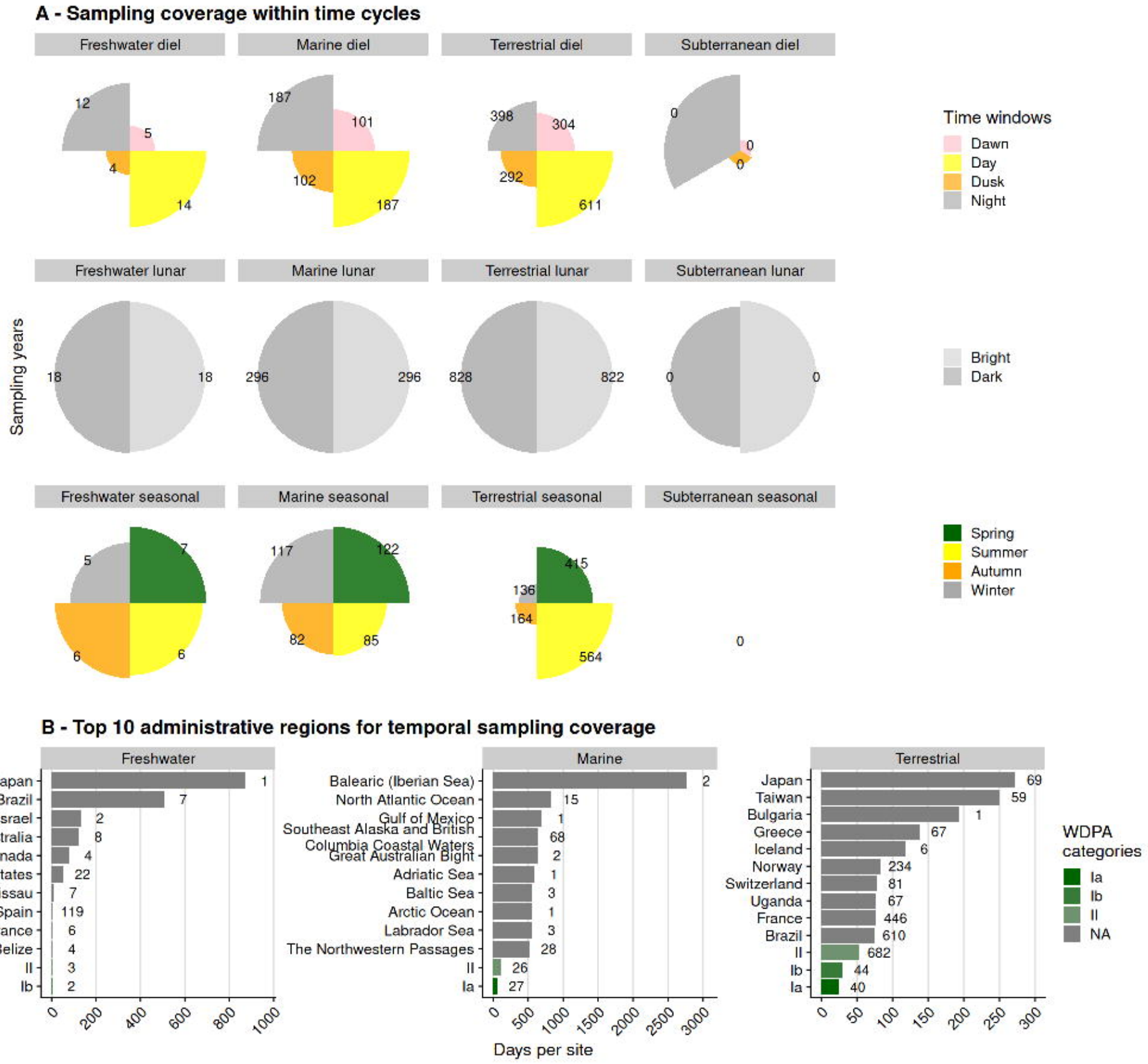
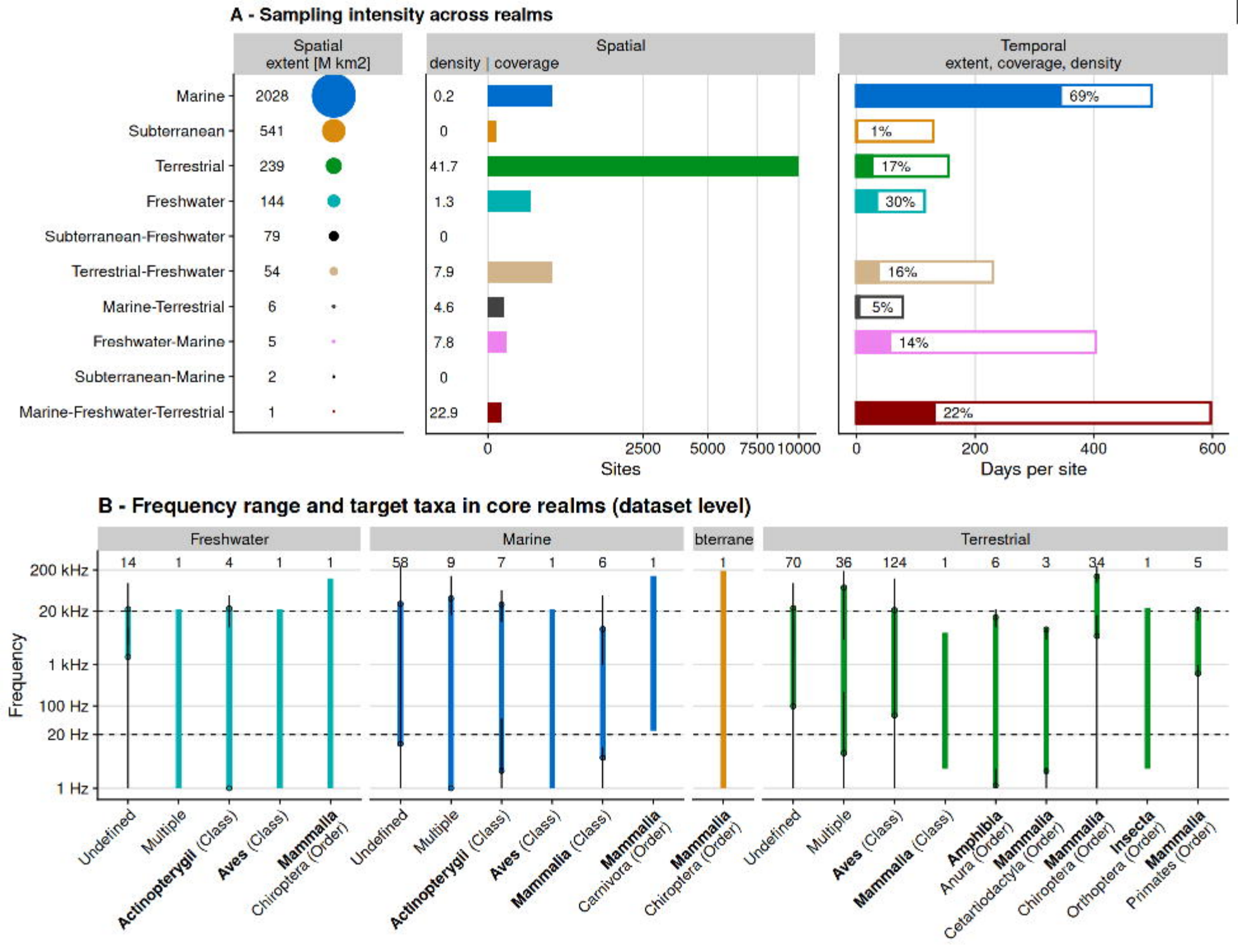
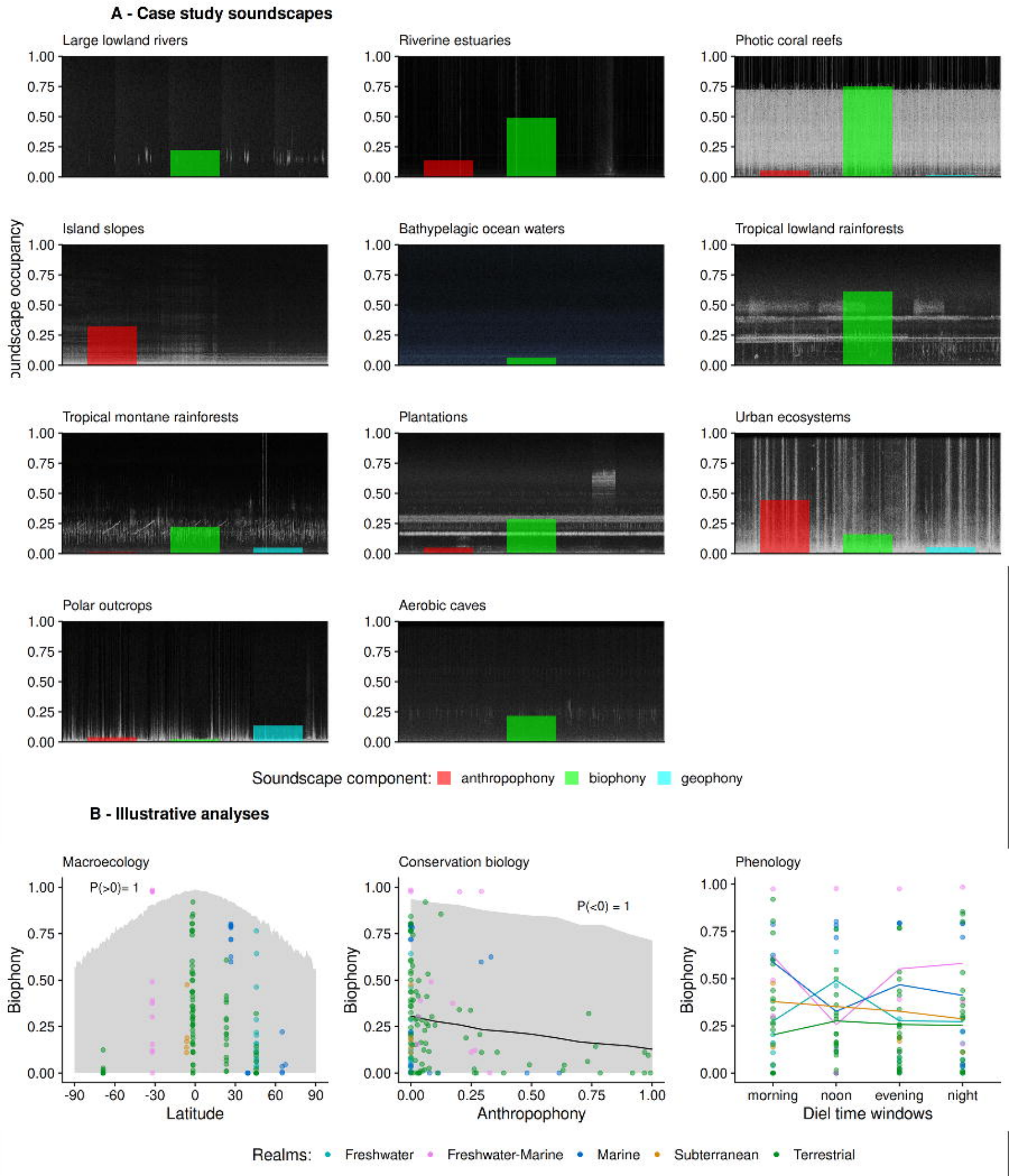

A - Framework
Space
Spatial replicates
Temporal replicates
Time
B - Replication (dataset level)
Terrestrial
Subterranean
Marine
Freshwater
20
8
230
1
21
1
58
3
3
12
temporal
spatial
spatio-temporal
C - Spatial extent and coverage of sampling sites
Terrestrial sites
200
400
600
D - Temporal extent and coverage (day level)
Sampled days
1200
900
600
300
0
1990
2000
2010
2020
Core realm:
Freshwater
Marine
Subterranean
Terrestrial


A - Topographical and latitudinal distribution of sampling sites
Topography (m)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
-90
-60
-30
0
30
60
90
South ← Latitude → North
IUCN core realms
Freshwater
Marine
Subterranean
Terrestrial
B - Top 10 administrative regions for spatial sampling coverage
Freshwater
Spain 56%
United States 10%
United Kingdom 9%
Colombia 6%
Australia 4%
Guinea-Bissau 3%
Brazil 3%
France 3%
Canada 2%
Belize 2%
others (not top 10) 1%
0
50
100
Marine
North Pacific Ocean 22%
Southeast Alaska and British Columbia Coastal Waters 17%
others (not top 10) 17%
Southern Ocean 9%
South Atlantic Ocean 8%
The Northwestern Passages 7%
Norwegian Sea 5%
Indian Ocean 4%
North Atlantic Ocean 4%
Coral Sea 3%
South Pacific Ocean 3%
0
20
40
60
80
Sites
Terrestrial
Canada 28%
others (not top 10) 23%
United States 18%
Germany 8%
Brazil 6%
France 4%
Portugal 4%
Indonesia 2%
Spain 2%
Norway 2%
Panama 2%
0
1000
2000
3000
WDPA categories
Ia
Ib
II
>II


A - Sampling coverage within time cycles
Freshwater diel
Marine diel
Terrestrial diel
Subterranean diel
12
5
4
14
187
101
102
187
398
304
292
611
0
0
0
Time windows
Dawn
Day
Dusk
Night
Freshwater lunar
Marine lunar
Terrestrial lunar
Subterranean lunar
Sampling years
18
18
296
296
828
822
0
0
Bright
Dark
Freshwater seasonal
Marine seasonal
Terrestrial seasonal
Subterranean seasonal
5
7
6
6
117
122
82
85
415
136
164
564
0
Spring
Summer
Autumn
Winter
B - Top 10 administrative regions for temporal sampling coverage
Freshwater
Japan 1
Brazil 7
Israel 2
Australia 8
Canada 4
United States 22
Guinea-Bissau 7
Spain 119
France 6
Belize 4
II 3
Ib 2
0 200 400 600 800 1000
Marine
Balearic (Iberian Sea) 2
North Atlantic Ocean 15
Gulf of Mexico 1
Southeast Alaska and British Columbia Coastal Waters 68
Great Australian Bight 2
Adriatic Sea 1
Baltic Sea 3
Arctic Ocean 1
Labrador Sea 3
The Northwestern Passages 28
II 26
Ia 27
0 500 1000 1500 2000 2500 3000
Days per site
Terrestrial
Japan 69
Taiwan 59
Bulgaria 1
Greece 67
Iceland 6
Norway 234
Switzerland 81
Uganda 67
France 446
Brazil 610
II 682
Ib 44
Ia 40
0 50 100 150 200 250 300
WDPA categories
Ia
Ib
II
NA


A - Sampling intensity across realms
Spatial extent [M km2]
Spatial density | coverage
Temporal extent, coverage, density
Marine 2028 0.2 69%
Subterranean 541 0 1%
Terrestrial 239 41.7 17%
Freshwater 144 1.3 30%
Subterranean-Freshwater 79 0
Terrestrial-Freshwater 54 7.9 16%
Marine-Terrestrial 6 4.6 5%
Freshwater-Marine 5 7.8 14%
Subterranean-Marine 2 0
Marine-Freshwater-Terrestrial 1 22.9 22%
0 2500 5000 7500 10000
Sites
0 200 400 600
Days per site
B - Frequency range and target taxa in core realms (dataset level)
Freshwater
Marine
bterrane
Terrestrial
14 1 4 1 1
58 9 7 1 6 1
1
70 36 124 1 6 3 34 1 5
Frequency
200 kHz
20 kHz
1 kHz
100 Hz
20 Hz
1 Hz
Undefined
Multiple
Actinopterygii (Class)
Aves (Class)
Mammalia Chiroptera (Order)
Mammalia Carnivora (Order)
Mammalia (Class)
Amphibia Anura (Order)
Mammalia Cetartiodactyla (Order)
Insecta Orthoptera (Order)
Mammalia Primates (Order)


A - Case study soundscapes
Large lowland rivers
Riverine estuaries
Photic coral reefs
Island slopes
Bathypelagic ocean waters
Tropical lowland rainforests
Tropical montane rainforests
Plantations
Urban ecosystems
Polar outcrops
Aerobic caves
Soundscape occupancy
1.00
0.75
0.50
0.25
0.00
Soundscape component: anthropophony biophony geophony
B - Illustrative analyses
Macroecology
P(>0)= 1
Biophony
Latitude
-90 -60 -30 0 30 60 90
Conservation biology
P(<0) = 1
Anthropophony
0.00 0.25 0.50 0.75 1.00
Phenology
morning noon evening night
Diel time windows
Realms: Freshwater Freshwater-Marine Marine Subterranean Terrestrial