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1 Worldwide Soundscapes: a synthesis of 2 passive acoustic monitoring across realms 3

4 Authors & affiliations

5 Kevin FA Darras^{1,2,3C}, Rodney Rountree^{4,5}, Steven Van Wilgenburg⁶, Anna F Cord^{3,7}, Frederik
6 Pitz³, Youfang Chen², Lijun Dong⁹, Amandine Gasc¹⁰, Tzu-Hao Lin¹¹, Patrick Mauritz Diaz¹²,
7 Shih-Hung Wu¹³, Marcus Salton¹⁴, Sarah Marley¹⁵, Laura Schillé¹⁶, Paul Jacobus
8 Wensveen¹⁷, Camille Desjonquères^{18,19}, Orlando Acevedo-Charry^{20,21}, Matyáš Adam²²,
9 Jacopo Aguzzi²³, Michel André²⁴, Alexandre Antonelli^{25,26,27}, Leandro Aparecido Do
10 Nascimento²⁸, Giulliana Appel²⁹, Christos Astaras³⁰, Andrey Atemasov^{31,32}, Luc Barbaro³³,
11 Fritjof Basan³⁴, Carly Batist^{35,36}, Adriá López Baucells³⁷, Julio Ernesto Baumgarten³⁸, Just T
12 Bayle Sempere³⁹, Kristen Bellisario⁴⁰, Asaf Ben David⁴¹, Oded Berger-Tal⁴², Matthew G
13 Betts⁴³, Iqbal Bhalla⁴⁴, Thiago Bicudo³⁵, Marta Bolgan⁴⁵, Sara Bombaci⁴⁶, Martin
14 Boullhesen⁴⁷, Tom Bradfer-Lawrence^{48,49}, Robert A Briers⁵⁰, Michal Budka⁵¹, Katie
15 Burchard⁵², Alice Calvente⁵³, Maite Cerezo-Araujo⁵⁴, Gunnar Cerwén⁵⁵, Maria Chistopolova⁵⁶,
16 Christopher W Clark⁵⁷, Benjamin Cretois⁵⁸, Chapin Czarnecki⁵⁹, Luis P da Silva^{60,61}, Wigna da
17 Silva⁶², Laurence H De Clippele⁶³, David de la Haye⁶⁴, Ana Silvia de Oliveira Tissiani⁶⁵, Devin
18 de Zwaan^{66,67}, Ricardo Díaz-Delgado⁶⁸, Pedro Diniz⁶⁹, Dorgival Diógenes Oliveira-Júnior^{70,71},
19 Thiago Dorigo⁷², Saskia Dröge⁷³, Marina Duarte^{74,75}, Adam Duarte⁷⁶, Kerry Dunleavy⁷⁷,
20 Robert Dziak⁷⁸, Simon Elise^{79,80}, Hiroto Enari⁸, Haruka S Enari⁸, Florence Erbs²⁴, Nina
21 Ferrari⁴³, Luane Ferreira⁶², Abram B Fleishman⁷⁷, Bárbara Freitas^{81,82,83}, Nick Friedman⁸⁴,
22 Jérémy SP Froidevaux^{48,85}, Svetlana Gogoleva⁸⁶, Maria Isabel Gonçalves³⁸, Carolina
23 Gonzaga⁷⁴, José Miguel González Correa³⁹, Eben Goodale⁸⁷, Benjamin Gottesman⁵⁷, Ingo
24 Grass⁸⁸, Jack Greenhalgh⁸⁹, Jocelyn Gregoire⁹⁰, Jonas Hagge⁹¹, William Halliday⁹², Antonia
25 Hammer⁹³, Tara Hanf-Dressler⁹⁴, Samara Haver⁹⁵, Daniel Hending⁹⁶, Jose Hernandez-
26 Blanco⁵⁶, Thomas Hiller⁸⁸, Joe Chun-Chia Huang⁹⁷, Katie Lois Hutchinson⁹⁸, Janet Jackson⁹⁹,
27 Alain Jacot¹⁰⁰, Olaf Jahn^{101,102}, Jasper Kanes^{^^}, Ellen Kenchington¹⁰³, Sebastian Kepfer-
28 Rojas¹⁰⁴, Justin Kitzes⁵⁹, Tharaka Kusuminda¹⁰⁵, Yael Lehnardt⁴², Paula Leitman⁷², José
29 Leon¹⁰⁶, Cicero Simão Lima-Santos^{70,71}, Kyle John Lloyd^{107,108,109}, Audrey Looby^{110,111}, David
30 López-Bosch³⁷, Tatiana Maeda¹¹², Christos Mammides¹¹³, Gabriel Marcacci¹⁰⁰, Matthias
31 Markolf^{114,115}, Marinez Isaac Marques⁶⁵, Charles W Martin¹¹⁰, Dominic A Martin^{116,117}, Kathy
32 Martin^{66,118}, Matthew McKown⁷⁷, Logan JT McLeod¹¹⁹, Oliver Metcalf¹²⁰, Christoph Meyer¹²¹,
33 Grzegorz Mikusinski¹²², Larissa Sayuri Moreira Sugai⁵⁷, Dave Morris⁹⁹, Sandra Müller¹²³,
34 Kelsie A Murchy¹²⁴, Maria Mas Navarro³⁷, Rym Nouioua¹²⁵, Julian D Olden¹²⁶, Steffen
35 Oppel^{49,100}, Anna N Osiecka¹²⁷, Miles Parsons⁹², Filipa Isabel Pereira Samarra¹⁷, Cristian
36 Pérez-Granados¹²⁸, Liliana Piatti¹²⁹, Mauro Pichorim^{70,71}, Thiago Pinheiro⁶², Jean-Nicolas
37 Pradervand¹⁰⁰, Craig Radford¹³⁰, Emiliano Ramalho³⁵, Laura K Reynolds¹³¹, Klaus Riede¹⁰¹,
38 Talen Rimmer¹²⁴, Ricardo Rocha⁹⁶, Luciana Rocha⁶², Samuel RP-J Ross¹³², Carolyn
39 Rosten¹³³, Carlos Salustio-Gomes^{70,71}, Philip Samartzis¹³⁴, José Santos⁶², Kevin
40 Scharffenberg¹³⁵, Renée P Schoeman¹³⁶, Karl-Ludwig Schuchmann⁶⁵, Esther Sebastián-
41 González¹²⁸, Fannie Shabangu^{137,138}, Taylor Shaw¹²³, Xiaoli Shen¹³⁹, David Singer⁹¹, Jenni
42 Stanley¹⁴⁰, Karolin Thomisch¹⁴¹, Laura Torrent³⁷, Juan Traba^{142,143}, Junior A Tremblay¹⁴⁴,
43 Sunny Tseng¹⁴⁵, Mao-Ning Tuanmu¹⁴⁶, Marisol Valverde¹⁴⁷, Ben Vernasco^{76,148}, Raiane Vital
44 da Paz^{70,71}, Matthew Ward¹⁴⁹, Matthew Weldy^{43,150}, Julia Wiel⁵⁸, Jacob Willie¹⁵¹, Heather
45 Wood¹⁵², Songhai Li^{9C}, Renata Sousa-Lima^{62C}, Thomas Cherico Wanger^{2C}

46
47 C: corresponding authors

48
49 1: EFNO, ECODIV, INRAE, Domaine des Barres, Nogent-sur-Vernisson, Centre-Val de
50 Loire, 45290, France

- 51 2: Sustainable Agricultural Systems & Engineering Lab, School of Engineering, Westlake
52 University, No. 600 Dunyu Road, Sandun Town, Xihu District, Hangzhou, Zhejiang
53 province, , China
- 54 3: Chair of Computational Landscape Ecology, Faculty of Environmental Sciences, Dresden
55 University of Technology, Helmholtzstr. 10, Dresden, 01069, Germany
- 56 4: Biology Department, University of Victoria, Cunningham Building, Room 202, PO Box
57 1700 STN CSC, Victoria, BC, V8W 2Y2, Canada
- 58 5: The Fish Listener, , , 23 Joshua Lane, Waguoit, MA, 2536, U.S.A.
- 59 6: Terrestrial Unit, Prairie Region, Canadian Wildlife Service, Environment & Climate
60 Change Canada, Prairie & Northern Wildlife Research Centre, 115 Perimeter Road,
61 Saskatoon, Saskatchewan, S7N 0X4, Canada
- 62 7: Agro-ecological Modeling Group, Faculty of Agriculture, University of Bonn, Niebuhrstr.
63 1a, Bonn, 53113, Germany
- 64 8: Wildlife Ecology & Management, Faculty of Agriculture, Yamagata University, 1-23
65 Wakabamachi, Tsuruoka, Yamagata, 9978555, Japan
- 66 9: Marine Mammal and Marine Bioacoustics Laboratory, Department of Deep Sea Science,
67 Institute of Deep-sea Science and Engineering Chinese Academy of Sciences, 28 Luhuitou
68 Road, Sanya, Hainan, 572000, China
- 69 10: Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale, , Aix
70 Marseille Univ, Avignon Univ, CNRS, IRD, Campus Aix Technopôle de l'environnement
71 Arbois Méditerranée Avenue Louis Philibert Bât Villemin, Aix-en-Provence, 13545, France
- 72 11: Marine Ecoacoustics and Informatics Lab, Biodiversity Research Center, Academia
73 Sinica, 128 Academia Road, Section 2, Nankang, Taipei , , 11529, Taiwan
- 74 12: Climate Change and Biodiversity, , Hanns R. Neumann Stiftung Indonesia, , Muaradua,
75 OKU Selatan, South Sumatera, 32212, Indonesia
- 76 13: Biodiversity Indicator Lab, Division of Habitats and Ecosystems, Endemic Species
77 Research Institute, 1 Minsheng East Road, Jiji Town, Nantou County, Taiwan, 552005,
78 Taiwan
- 79 14: Australian Antarctic Division, Science Branch, Department of Climate Change, Energy,
80 Environment and Water, Channel Highway, Kingston, Tasmania, 7050, Australia
- 81 15: Scotland's Rural College, Craibstone Estate, Aberdeen, AB21 9YA, United Kingdom
- 82 16: BIOGECO, INRAE, University of Bordeaux, 69 route d'Arcachon, Cestas, 33610, France
- 83 17: Westman Islands Research Centre, , University of Iceland, Ægisdgata 2, Vestmannaeyjar,
84 900, Iceland
- 85 18: Institut de Systématique, Évolution, Biodiversité, , Muséum National d'Histoire naturelle,
86 Rue Buffon, Paris, 75005, France
- 87 19: Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, LECA, , , Grenoble,
88 38000, France
- 89 20: Colección de Sonidos Ambientales Mauricio Álvarez-Rebolledo - Colecciones
90 Biológicas, Subdirección de Investigaciones, Instituto de Investigación de Recursos
91 Biológicos Alexander von Humboldt, Claustro de San Agustín, Villa de Leyva, Boyacá, ,
92 Colombia
- 93 21: Quantitative Ecology Lab & Ordway Lab of Ecosystem Conservation, School of Natural
94 Resources and Environment, Department of Wildlife Ecology and Conservation, & Florida
95 Museum of Natural History, University of Florida, 715 Newell Dr, Building 866 & 1659
96 Museum Rd, Dickinson Hall 315, Gainesville, Florida, 32611, U.S.A.
- 97 22: Department of Environmental Security, Faculty of Logistics and Crisis Management,
98 Tomas Bata University, Studentské nám. 1532, Uherské Hradiště, , 68601, Czech Republic
- 99 23: Marine Science Institute, ICM, CSIC, ICM, CSIC, Paseig Barceloneta, Barcelona, , Spain
- 100 24: Laboratory of Applied Bioacoustics, , Polytechnic University of Catalonia,
101 BarcelonaTech, Rambla Exposicion, 24, Vilanova I la Geltrú, Barcelona, 8800, Spain
- 102 25: Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AE, United Kingdom, , Kew,
103 Richmond, Surrey, TW9 3AE, United Kingdom
- 104 26: Gothenburg Global Biodiversity Centre, Department of Biological and Environmental
105 Sciences, University of Gothenburg, Box 461, Göteborg, SE 40530, Sweden

- 106 27: Department of Plant, , University of Oxford, South Parks Road, Oxford, OX1 3RB, United
107 Kingdom
- 108 28: Bioacoustics Group, Science Department, Biometrio.earth, Dr. Schönemann Str. 38,
109 Saarbrücken, 66123, Germany
- 110 29: Biodiversidade e Serviços Ecossistêmicos, Instituto Tecnológico Vale, Boaventura da
111 Silva, 955, Belém, PA, 66055-090, Brazil
- 112 30: Wildlife Lab, Forest Research Institute, Hellenic Agricultural Organization - DIMITRA
113 (ELGO-DIMITRA), Vasilika, Thessaloniki, TK 57006, Greece
- 114 31: Department of Zoology and Animal Ecology, School of Biology, V.N.Karazin Kharkiv
115 National University, 4 Svobody Square, Kharkiv, 61022, Ukraine
- 116 32: Research Department, National Park 'Homilshanski Lisy', 27 Monastyrska Street,
117 Koropove village, Kharkiv region, 63437, Ukraine
- 118 33: DYNAFOR, University of Toulouse, INRAE, Chemin de Borde-Rouge, Castanet-Tolosan,
119 F-31326, France
- 120 34: Federal Maritime and Hydrographic Agency (BSH), , , Bernhard-Nocht Straße 78,
121 Hamburg, 20359, Germany
- 122 35: Rainforest Connection, Science department, , 440 Cobia Drive, Suite 1902, , TX, 77494,
123 U.S.A.
- 124 36: Arbimon, , , , , U.S.A.
- 125 37: BiBio Research Group, , Natural Sciences Museum of Granollers, Av. Francesc Macià
126 51, Granollers, Catalonia, 08402, Spain
- 127 38: Applied Ecology & Conservation Lab, Biological Sciences, Universidade Estadual de
128 Santa Cruz, Rodovia Jorge Amado km 16, Salobrinho, Ilhéus, Bahia, 45662900, Brazil
- 129 39: Marine Biological Acoustic, Marine Sciences and Applied Biology , University of Alicante,
130 C/ San Vicente del Raspeig s/n, San Vicente del Raspeig, Alicante, 3690, Spain
- 131 40: HIFI Lab, John Martinson Honors College, Purdue University West Lafayette Indiana,
132 1101 Third Street, West Lafayette, Indiana , 47906, U.S.A.
- 133 41: Tamar Dayan's Lab, School of zoology, Steinhardt Museum of Natural History, Tel-Aviv
134 university, Klausner 12, Tel-Aviv, Tel-Aviv, 6997801, Israel
- 135 42: The Conservation Behavior Research Group, Mitrani Department of Desert Ecology,
136 Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev,
137 Midreshet Ben-Gurion, , 8499000, Israel
- 138 43: Forest Landscape Ecology Lab, Department of Forest Ecosystems and Society, Oregon
139 State University, , , , U.S.A.
- 140 44: School of Geography and the Environment, Oxford University, South Parks Rd, Oxford,
141 OX1 3QY, United Kingdom
- 142 45: Ocean Science Consulting Limited, , , Spott Road, Dunbar, EH42 1RR , United Kingdom
- 143 46: Equity in Ecological Research Lab, Department of Fish, Wildlife, and Conservation
144 Biology, Colorado State University, 1474 Campus Delivery, Fort Collins, Colorado, 80521,
145 U.S.A.
- 146 47: Instituto de Ecorregiones Andinas (INECOA-UNJu-CONICET), Facultad de Ingeniería,
147 Universidad Nacional de Jujuy, Gorriti 237, San Salvador de Jujuy, Jujuy, 4600, Argentina
- 148 48: Biological and Environmental Sciences, University of Stirling, Stirling, Stirlingshire, FK9
149 4LA, Scotland
- 150 49: Centre for Conservation Science, RSPB, 2 Lochside View, Edinburgh Park, Edinburgh, ,
151 EH12 9DH, United Kingdom
- 152 50: Centre for Conservation and Restoration Science, School of Applied Sciences,
153 Edinburgh Napier University, Sighthill Campus, Edinburgh, EH11 4BN, United Kingdom
- 154 51: Department of Behavioural Ecology, Faculty of Biology, Adam Mickiewicz University,
155 Uniwersytetu Poznańskiego 6, Poznań, 61614, Poland
- 156 52: Northeast Fisheries Science Center, Narragansett Laboratory, , 28 Tarzwell Drive,
157 Narragansett, RI, 2882, U.S.A.
- 158 53: Laboratório de Botânica Sistemática, Departamento de Botânica, Ecologia e Zoologia,
159 Universidade Federal do Rio Grande do Norte, Av. Sen. Salgado Filho 3000, Natal, Rio
160 Grande do Norte, 59078-900, Brazil

- 161 54: South Iceland Research Centre, , University of Iceland, Lindarbraut 4, Laugarvatn, 840,
162 Iceland
- 163 55: Sensola SLU Multisensory Outdoor Laboratory, Department of Landscape Architecture,
164 Planning and Management, Swedish University of Agricultural Sciences, SLU, Sundsvägen
165 4-6, Alnarp, 23053, Sweden
- 166 56: , , , ,
- 167 57: K. Lisa Yang Center for Conservation Bioacoustics , Cornell Lab of Ornithology , Cornell
168 University , 159 Sapsucker Woods Rd , New York , 14850, U.S.A.
- 169 58: Miljødata, Norwegian Institute for Nature Research, Høgskoleringen 9, Trøndelag,
170 Trondheim, 7034, Norway
- 171 59: Department of Biological Sciences, University of Pittsburgh, Clapp Hall, Fifth and Ruskin
172 Avenues, Pittsburgh, PA, 15237, U.S.A.
- 173 60: CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO
174 Laboratório Associado, Campus de Vairão, Universidade do Porto-InBIO, Universidade do
175 Porto, Campus de Vairão, Rua Padre Armando Quintas, Porto, 4485-661 Vairão, Portugal
- 176 61: BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, University of
177 Porto, Campus de Vairão, Rua Padre Armando Quintas, Porto, 4485-661 Vairão, Portugal
- 178 62: EcoAcoustic Research Hub (EAR Hub), Biosciences Center, Universidade Federal do
179 Rio Grande do Norte, Av. Sen. Salgado Filho 3000, Natal, Rio Grande do Norte, 59078-900,
180 Brazil
- 181 63: School of Biodiversity, One Health & Veterinary Medicine, University of Glasgow,
182 Graham Kerr Building, Hillhead street 82, Scotland, United Kingdom, G12 8QQ, United
183 Kingdom
- 184 64: School of Arts and Cultures, Newcastle University, , Newcastle upon Tyne, NE1 7RU,
185 United Kingdom
- 186 65: INAU Pantanal Biodata Center, National Institute of Science and Technology in
187 Wetlands (INAU), Computational Bioacoustics Research Unit (CO.BRA), Federal University
188 of Mato Grosso (UFMT), Cuiabá, 2367 Fernando Correa da Costa Ave, Mato Grosso,
189 78060-900, Brazil
- 190 66: Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall,
191 Vancouver, British Columbia, V6T 1Z4, Canada
- 192 67: Department of Biology, Mount Allison University, 63B York Street, Sackville, New
193 Brunswick, E4L 1E7, Canada
- 194 68: Estación Biológica de Doñana-CSIC, , CSIC, c/ Americo Vespucio 26, Sevilla, 41092,
195 Spain
- 196 69: Laboratório de Comportamento Animal, Departamento de Zoologia, Universidade de
197 Brasília, Instituto de Ciências Biológicas, Distrito Federal, 70910-900, Brazil
- 198 70: Laboratório de Ornitologia, Departamento de Botânica e Zoologia, Universidade Federal
199 do Rio Grande do Norte, Av. Sen. Salgado Filho 3000, Natal, RN, 59078-900, Brazil
- 200 71: Programa de Pós-Graduação em Ecologia, Centro de Biociências, Universidade Federal
201 do Rio Grande do Norte, Av. Sen. Salgado Filho 3000, Natal, RN, 59078-900, Brazil
- 202 72: Lifeplan Rio de Janeiro / Araçá project, , , Estrada Hans Garlipp, s/n, Macaé de Cima,
203 Fazenda Bacchus, Nova Friburgo, 28605-270, Brazil
- 204 73: Forest, Nature and Landscape, KU Leuven, Celestijnenlaan 200e, Leuven, 3001,
205 Belgium
- 206 74: ECOA - Laboratory of Bioacoustics, Post graduate Program in Vertebrate Biology /
207 Museum of Natural Sciences, Pontifical Catholic University of Minas Gerais, , Minas
208 Gerais, , Brazil
- 209 75: Environmental Studies Center (CEA), , Sao Paulo State University - UNESP, Av. 24a,
210 1515, Bela Vista, Rio Claro, Sao Paulo, 13506-900, Brazil
- 211 76: Pacific Northwest Research Station, U.S.D.A. Forest Service, 3625 93rd Ave. SW,
212 Olympia, Washington, 98512, U.S.A.
- 213 77: Conservation Metrics, Inc., 145 McAllister Way, Santa Cruz, CA, 95060, U.S.A.
- 214 78: Acoustics Program, Pacific Marine Environmental Laboratory, National Oceanic and
215 Atmospheric Administration, 2030 SE Marine Science Drive, Newport, OR, 97365, U.S.A.

- 216 79: Reef Pulse S.A.S., NA, NA, Allée Maureau, Sainte-Clotilde, Reunion Island, 97490,
217 France
- 218 80: UMR 9220 ENTROPIE, Faculté des sciences et technologies, University of Reunion
219 Island, Avenue René Cassin, Sainte-Clotilde, Reunion Island, 97490, France
- 220 81: National Museum of Natural Sciences, Spanish National Research Council, Calle José
221 Gutiérrez Abascal 2, Madrid, 28006, Spain
- 222 82: Centre de Recherche sur la Biodiversité et l'Environnement (UMR 5300 CNRS-IRD-
223 TINPT-UPS), Université Paul Sabatier, 118 route de Narbonne, Toulouse, 31062 Toulouse
224 Cedex 9, France
- 225 83: Facultad de Ciencias, Universidad Autónoma de Madrid, C. Darwin 2, Madrid, 28049,
226 Spain
- 227 84: Centre for Taxonomy and Morphology, Leibniz Institute for the Analysis of Biodiversity
228 Change, Museum of Nature Hamburg, Martin-Luther-King-Platz 3, Hamburg, 20146,
229 Germany
- 230 85: Centre d'Ecologie et des Sciences de la Conservation (CESCO, UMR 7204), Museum
231 National d'Histoire Naturelle, Place de la Croix, Concarneau, Finistère, 29900, France
- 232 86: Laboratory of tropical ecology, , A.N. Severtsov Institute of Ecology and Evolution of
233 Russian Academy of Sciences, Leninsky Prospect, 33, Moscow, 119071, Russia
- 234 87: Department of Health and Environmental Science, , Xi'an Jiaotong-Liverpool University,
235 No. 8 Chongwen Road, Suzhou Industrial Park, Suzhou, Jiangsu, 215123, China
- 236 88: Ecology of Tropical Agricultural Systems, Institute of Agricultural Sciences in the Tropics,
237 University of Hohenheim, Garbenstrasse 13, Stuttgart, 70599, Germany
- 238 89: School of Biological Sciences , Life Sciences Building, University of Bristol, 24 Tyndall
239 Ave, Bristol, BS8 1TQ, United Kingdom
- 240 90: Migratory Bird Unit, Northern Region, Canadian Wildlife Service, Environment and
241 Climate Change Canada, 5019 - 52nd Street, Yellowknife, Northwest Territories, X1A 2P7,
242 Canada
- 243 91: Species and Habitat Conservation, Forest Nature Conservation, Northwest German
244 Forest Research Institute, Prof.-Oelkers-Str. 6, Hann. Münden, Lower Saxony, 34346,
245 Germany
- 246 92: Wildlife Conservation Society Canada, 169 Titanium Way, Whitehorse, Yukon, Y1A 0E9,
247 Canada
- 248 93: Applied Zoology and Nature Conservation, Zoological Institute and Museum, University
249 of Greifswald, Loitzer Strasse 26, Greifswald, 17489, Germany
- 250 94: Bat Lab, Department of Evolutionary Ecology, Leibniz Institute for Zoo and Wildlife
251 Research, Alfred-Kowalke-Straße 17, Berlin, 10315, Germany
- 252 95: Cooperative Institute for Marine Ecosystem and Resources Studies, , National Oceanic
253 and Atmospheric Administration Pacific Marine Environmental Laboratory and Oregon State
254 University, 2030 SE Marine Science Drive, Newport, OR, 97365, USA
- 255 96: Department of Biology, University of Oxford, , Oxford, OX1 3SZ, United Kingdom
- 256 97: Bat Squad Lab, Department of Life Science, National Taiwan Normal University, No. 88,
257 Section 4, Tingzhou Rd, Wenshan District, Taipei City, 116, Taiwan
- 258 98: Nature based Solutions Initiative, Department of Biology , University of Oxford, 11A
259 Mansfield Road, Oxford, OX13SZ, England
- 260 99: Centre for Northern Forest Ecosystem Research, Ministry of Northern Development,
261 Mines, Natural Resources and Forestry, Ontario Government, 103 – 421 James Street
262 South, Thunder Bay, Ontario, P7E 2V6, Canada
- 263 100: Swiss Ornithological Institute, Seerose 1, Sempach, 6204, Switzerland
- 264 101: Zoological Research Museum Alexander Koenig, , Leibniz Institute for the Analysis of
265 Biodiversity Change , Adenauerallee 160, Bonn, 53113, Germany
- 266 102: Museum für Naturkunde, , Leibniz-Institut für Evolutions- und Biodiversitätsforschung,
267 Invalidenstraße 43, Berlin, 10115, Germany
- 268 103: , , , ,
- 269 104: Ecology and Nature Management, Geosciences and Natural Resource Management,
270 University of Copenhagen, Rolighedsvej 23, Frederiksberg, 1958, Denmark

- 271 105: Department of Agricultural Biology, Faculty of Agriculture, University of Ruhuna,
272 Mapalana, Kamburupitiya, x, , Sri Lanka
- 273 106: Fundación de Conservación Jocotoco, Fundación de Conservación Jocotoco,
274 Fundación de Conservación Jocotoco, Valladolid N24-414 y Luis Cordero, Quito, 170525,
275 Ecuador
- 276 107: Landscape Conservation Programme, Conservation Division, BirdLife South Africa, ,
277 Gauteng, , South Africa
- 278 108: Afromontane Research Unit, Department of Zoology and Entomology, University of the
279 Free State, , Phuthaditjhaba, , South Africa
- 280 109: Centre for Statistics in Ecology, the Environment and Conservation, Department of
281 Statistical Sciences, University of Cape Town, , Cape Town, , South Africa
- 282 110: Nature Coast Biological Station, Institute of Food and Agricultural Sciences, University
283 of Florida, 552 1st Street, Cedar Key, Florida, 32625, U.S.A.
- 284 111: Fisheries and Aquatic Sciences, Institute of Food and Agricultural Sciences, University
285 of Florida, 136 Newins-Ziegler Hall, Florida, 32611, U.S.A.
- 286 112: Sound Forest Lab, The Nelson Institute of Environmental Studies and The Department
287 of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1650 Linden Drive,
288 Wisconsin, 53706, U.S.A.
- 289 113: Nature Conservation Unit, , Frederick University, 7, Yianni Frederickou Street, Nicosia,
290 1036, Cyprus
- 291 114: Madagascar Programme, , Chances for Nature, Brauweg 9a, Göttingen, 37073,
292 Germany
- 293 115: Cologne Zoo, Riehler Straße 173, Köln, Lower Saxony, 50735, Germany
- 294 116: Biodiversity, Macroecology and Biogeography, Faculty of Forest Sciences and Forest
295 Ecology, University of Goettingen, Büsgenweg 1, Göttingen, Niedersachsen, 37077,
296 Germany
- 297 117: Plant Ecology, Institute of Plant Sciences, University of Bern, Altenbergrain 21, Bern,
298 Bern, 3013, Switzerland
- 299 118: Pacific Wildlife Research Center, Environment and Climate Change Canada, 5421
300 Robertson Road, Delta, British Columbia, V4K 3Y3, Canada
- 301 119: Migratory Bird Unit, Northern Region, Canadian Wildlife Service, Environment and
302 Climate Change Canada, 91780 Alaska Highway, Whitehorse, Yukon Territory, Y1A 5B7,
303 Canada
- 304 120: Lancaster Environment Centre, Lancaster University, Library Ave, Bailrigg, Lancaster,
305 LA1 4YQ, United Kingdom
- 306 121: Environmental Research and Innovation Centre, School of Science, Engineering and
307 Environment, University of Salford, Peel Building, Salford, M5 4WT, United Kingdom
- 308 122: School for Forest Management, Swedish University of Agricultural Sciences SLU, Box
309 43, Skinnskatteberg, SE-739 21, Sweden
- 310 123: Chair of Geobotany, Chair of Geobotany, University of Freiburg, Schaenzlestr. 1,
311 Freiburg im Breisgau, 79104, Germany
- 312 124: Fisheries Ecology and Conservation Lab, Department of Biology , University of Victoria,
313 3800 Finnerty Rd., Victoria, British Columbia, V8P 5C2, Canada
- 314 125: Department of Botany and Biodiversity Research, Faculty of Life Sciences, University of
315 Vienna, Rennweg 14, Vienna, 1030, Austria
- 316 126: School of Aquatic and Fishery Sciences, University of Washington, 1122 NE Boat
317 Street, Seattle, Washington, 98105, U.S.A.
- 318 127: Polar Ecology Group, Department of Vertebrate Ecology and Zoology, University of
319 Gdańsk, Poland, Wita Stwosza 59, Gdańsk, , 80-308, Poland
- 320 128: Department of Ecology, University of Alicante, Cra. San Vicente del raspeig sn,
321 Alicante, 3690, Spain
- 322 129: Laboratório de Ecologia, Instituto de Biociências, Universidade Federal de Mato Grosso
323 do Sul, , , , , Brazil
- 324 130: Institute of Marine Science, , University of Auckland, Private Bag 92019. Auckland Mail
325 Centre, Auckland, 1142, New Zealand

- 326 131: Department of Soil, Water, and Ecosystem Sciences, Institute of Food and Agricultural
327 Sciences, University of Florida, 2181 McCarty Hall A, Florida, 32611, U.S.A.
328 132: Integrative Community Ecology Unit, , Okinawa Institute of Science and Technology
329 Graduate University, 1919-1 Tancha, Onna-son, Kunigami-gun, Okinawa, 904-0495, Japan
330 133: Salmonid fishes, Norwegian Institute for Nature Research, Høgskoleringen 9,
331 Trøndelag, Trondheim, 7034, Norway
332 134: Cold Climate Research Lab, School of Art, RMIT University, 124 La Trobe Street,
333 Melbourne, Victoria, 3000, Australia
334 135: Fisheries and Oceans Canada, Freshwater Institute, 501 University Crescent,
335 Winnipeg, Manitoba, R3T 2N6, Canada
336 136: Centre for Marine Science and Technology, , Curtin University, , Perth, 6102, Western
337 Australia
338 137: Fisheries Management Branch, Department of Forestry, Fisheries and the
339 Environment, , Foreshore, Cape Town, 8000, South Africa
340 138: Mammal Research Institute Whale Unit, Department of Zoology and Entomology,
341 University of Pretoria, Hatfield, Pretoria, 28, South Africa
342 139: State Key Laboratory of Vegetation and Environmental Change, Institute of Botany,
343 Chinese Academy of Sciences, , Beijing, 100093, China
344 140: Coastal Marine Field Station, School of Science, University of Waikato, 58 Cross Road,
345 Sulphur Point, Tauranga, 3110, New Zealand
346 141: Ocean Acoustics Group, , Alfred Wegener Institute Helmholtz Centre for Polar and
347 Marine Research, Klussmannstr. 3d, Bremerhaven, 27570, Germany
348 142: Department of Ecology, Universidad Autónoma de Madrid, Darwin 2, Madrid, 28049,
349 Spain
350 143: Centro de Investigación en Biodiversidad y Cambio Global, Universidad Autónoma de
351 Madrid, Darwin 2, Madrid, 28049, Spain
352 144: Wildlife Research Division, Environment and Climate Change Canada, 801-1550,
353 avenue d'Estimauville, Québec (Québec) , G1J 0C3, Canada
354 145: Natural Resources & Environmental Studies, University of Northern British Columbia,
355 3333 University Way, British Columbia, V2N 4Z9, Canada
356 146: Asian Soundscape Monitoring Network, Biodiversity Research Center, Academia
357 Sinica, 128 Academia Road, Section 2, Nankang, Taipei , , 11529, Taiwan
358 147: Department of Ecology and Evolutionary Biology & K. Lisa Yang Center for
359 Conservation Bioacoustics, , Cornell University, Corson Mudd, 215 Tower Road, Ithaca,
360 New York, 14853, U.S.A.
361 148: Department of Biology, Whitman College, 345 Boyer Ave, Walla Walla, Washington,
362 99362, U.S.A.
363 149: Talarak Foundation, Inc., Negros Forest Park, Bacolod City, Negros Occidental, 6100,
364 Philippines
365 150: Department of Forest Ecosystems and Society, Oregon State University, 3180 SW
366 Jefferson Way, Corvallis, Oregon, 97331, U.S.A.
367 151: Centre for Research and Conservation, Royal Zoological Society of Antwerp, , , , , ,
368 Belgium
369 152: Department of Physical Geography, Stockholm University, SE-106 91 Stockholm,
370 Stockholm, 10691, Sweden
371
372 ^c: corresponding authors
373

374 Abstract

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

378 across realms. We present metadata from 358 datasets recorded since 1991 in and above
379 land and water constituting the first global synthesis of sampling coverage across spatial,
380 temporal, and ecological scales. We compiled summary statistics (sampling locations,
381 deployment schedules, focal taxa, and recording parameters) and used eleven case studies
382 to assess trends in biological, anthropogenic, and geophysical sounds. Terrestrial sampling
383 is spatially denser (42 sites/M·km²) than aquatic sampling (0.2 and 1.3 sites/M·km² in
384 oceans and freshwater) with only one subterranean dataset. Although diel and lunar cycles
385 are well-covered in all realms, only marine datasets (65%) comprehensively sample all
386 seasons. Across realms, biological sounds show contrasting diel activity, while declining with
387 distance from the equator and anthropogenic activity. PAM can thus inform phenology,
388 macroecology, and conservation studies, but representation can be improved by widening
389 terrestrial taxonomic breadth, expanding coverage in the high seas, and increasing spatio-
390 temporal replication in freshwater habitats. Overall, PAM shows considerable promise to
391 support global biodiversity monitoring efforts.

392

393 Main text

394 Introduction

395 Sounds permeate all realms on Earth — terrestrial, freshwater, marine, and subterranean¹.
396 Passive Acoustic Monitoring (PAM) captures soundscapes that document soniferous life
397 ("biophony"), human activities ("anthropophony"), and some geophysical events
398 ("geophony")²⁻⁶. In ecoacoustics and soundscape ecology^{7,8}, PAM can measure levels and
399 impacts of global change (e.g., climate change, urbanization, deep-sea mining)⁹⁻¹¹, monitor
400 ecosystem health, recovery, and restoration¹²⁻¹⁴, assess human-environment interactions
401 (public health, cultural ecosystem services)^{15,16} and guide conservation (protected area
402 management, landscape planning)^{17,18}.

403 Despite the wide-ranging and increasing soundscape sampling effort, the data distribution
404 remains undescribed. Currently soundscape-recording communities are only networked
405 within realms and their methodologies differ. Previous reviews focused on single realms and
406 were either systematic¹⁹⁻²² or qualitative^{3,23}. Marine scientist networks using PAM exist²⁴, but
407 the freshwater community is nascent, and the terrestrial community grows faster than it can
408 unite. Acoustic calibration and sound propagation modeling are advanced in aquatic
409 studies²⁵ but seldom considered in terrestrial ones (except ^{26,27}). Artificial intelligence can
410 identify increasing numbers of species on land²⁸ whereas aquatic sounds still challenge
411 identification^{29,30}. Overall, there is much to gain from sharing data, experience, and methods
412 among PAM users.

413 Cross-realm PAM studies can yield new theoretical answers³¹ and applied solutions:
414 soundscapes track terrestrial and marine resilience to natural disasters³²; sound and silence
415 durations in multiple realms follow universal distributions³³. Transnational sampling could
416 form the basis for comprehensive soniferous biodiversity monitoring, just like community-
417 initiated telemetry databases³⁴, collaborative camera trap surveys³⁵, individual animal
418 observation networks³⁶, and invasive species control syntheses³⁷ advanced entire research
419 fields. A global PAM network could establish historical biodiversity baselines, support
420 systematic long-term and large-scale monitoring, and connect with the public through citizen
421 science. Such information is critical to inform global biodiversity policies such as the
422 Kunming-Montreal Global Biodiversity Framework.

423 We present the "Worldwide Soundscapes" project, the first global PAM meta-database and
424 network. We use it to quantify the known state of PAM efforts, highlight apparent sampling
425 gaps and biases, illustrate the potential of cross-realm PAM syntheses for research, and
426 federate PAM users. The project currently holds 307 contributors who collated metadata
427 about 358 passively-recorded, replicated soundscape datasets. Metadata describe the exact
428 spatio-temporal coverage, sampled ecosystems (IUCN Global Ecosystem Typology: GET),
429 transmission medium (air, water, or soil), focal taxa (IUCN Red list), recording settings, and
430 data and publication availability. We inferred coverage within administrative (Global
431 Administrative Database: GADM; International Hydrographic Organisation: IHO) and
432 protected areas (World Database on Protected Areas: WDPA) from geographic locations.
433 We selected recordings referenced in the meta-database to quantify soundscape
434 components (biophony, anthropophony, geophony) across eleven ecosystems from all
435 realms. We showcase their relevance to macroecology, conservation biology, and phenology
436 research and identify opportunities to advance the global PAM network. The publicly-

437 accessible meta-database^{38,39} continues to grow to enhance accessibility of data and
438 remains open for metadata contributions, facilitating future syntheses.

439 **Results**

440 **Summary dataset statistics**

441 To date, 358 validated soundscape meta-datasets (hereafter "datasets") have been
442 registered in our database from across the globe, dating back to 1991 (Fig. 1D). A dataset
443 gathers a team's metadata on a study or project. Metadata were validated by checking that
444 all fields were filled in and formatted correctly, and then cross-checked by their respective
445 contributors using site maps and recording timelines³⁹ on ecoSound-web⁴⁰. Based on the
446 GET definition of four 'core' realms, our database includes 259, 80, 18, and 1 validated
447 datasets from the terrestrial, marine, freshwater, and subterranean realms, respectively. The
448 transmission medium was air for terrestrial and subterranean datasets and mostly water for
449 aquatic datasets, as three datasets with aerial above-water recordings were included in the
450 freshwater and marine realms. The majority of datasets (84%) include both spatial and
451 temporal replicates (Fig. 1C). Few datasets have openly-accessible recordings (10-15%, Fig.
452 S1). Presently, few terrestrial and freshwater datasets (27% and 22% respectively) are
453 associated with DOI-referenced publications in contrast to marine datasets (44%) (Fig. S1).

454 **Spatial sampling coverage and density**

455 The database contains 11 093 sampling sites, including 147 polar, 8 455 temperate, and 2
456 491 tropical sites (Fig 1C). On land, 10 387 sites are located within 79 (out of 263) GADM
457 level 0 areas (Fig. 2B), primarily in the Northern Hemisphere (Table S1). Most terrestrial
458 sites occur in Canada (28%), followed by the United States (18%), but a significant
459 proportion is widely distributed (23% do not belong to the top 10 GADM areas). Few
460 terrestrial sites (8%) are located in WDPA category Ia, Ib, or II areas. Our database currently
461 lacks data from vast areas in Russia, Greenland, the Antarctic, interior Australia, North
462 Africa, and Central Asia. Site elevations range from sea level up to 3 420 m (Fig. 2A), but
463 mountains above 4 000 m in the Northern Hemisphere, above 2 000 m in the Southern
464 Hemisphere, as well as the Transantarctic Mountains are currently not represented in the
465 data. At sea, 469 sites are located within 32 (out of 101) IHO sea areas. Most marine sites
466 occur in the North Pacific Ocean (22%), followed by Southeast Alaskan and British
467 Columbian coastal waters (17%), but a significant proportion is widespread (17% do not
468 belong to the top 10 IHO areas). Many sites are situated in WDPA high-protection category
469 Ia and II areas (14%). Our database currently lacks datasets from Arctic waters off Eurasia,
470 the Southeast Pacific, and Southeast Asian coastal areas. Sampling sites span ocean
471 depths from sea water surface to depths of 10 090 m, but tropical bathypelagic and Southern
472 benthic areas are poorly represented (Table S2). Few GADM areas (11) are represented in
473 the freshwater datasets. Spain holds most freshwater sites (56%). Few freshwater sites (2%)
474 are in WDPA category II or Ib areas. Freshwater bodies are sampled at elevations from sea
475 level up to 950 m. Mountain freshwater bodies and those in Africa, Asia, and Oceania are
476 currently not represented in our database. The database contains seven subterranean sites
477 situated in Brazil between 277 and 810 m.

478 **Temporal sampling extent, coverage, and density**

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

481 (spring, summer, autumn, winter - only for temperate sites) (Fig. 3A). Dawn and dusk diel
482 windows are shorter than day and night diel windows for most locations and less intensively
483 sampled. The lunar phase cycle is evenly covered across realms and comprehensively
484 covered within datasets (Fig. S2). In the terrestrial realm, daytime coverage surpasses
485 nighttime coverage (611 vs. 398 years), while 75% of datasets sampled all diel time
486 windows. Terrestrial datasets mostly sampled spring (415 years, 32%) and summer (564
487 years, 44%) while 24% sampled all seasons. Temporal coverage per site is highest in Japan
488 (272 days) and Taiwan (250 days). In the marine realm, temporal coverage among diel time
489 windows is even and 88% of marine datasets sampled all diel time windows. Marine
490 datasets have high and similar coverage for winter and spring (117 and 122 years, combined
491 59% of seasonal coverage) and 65% cover the full seasonal cycle. In the freshwater realm,
492 temporal coverage among diel time windows is even and 76% of freshwater datasets
493 sampled all diel time windows. Similarly, 24% sampled all seasons. The subterranean
494 tropical sites primarily covered the nighttime, across all seasons.

495 **Sampling in ecosystems**

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

514 **Target taxa and frequency ranges**

515 Most marine datasets do not target specific taxa (70%) and use wide frequency ranges from
516 0.01 to 30 kHz (mean bounds of frequency ranges across datasets, Fig. 4B). Marine
517 datasets that focus on single taxa comprise cetaceans (8%, 0.006 - 7 kHz) and fish (8%,
518 0.003 - 29 kHz). Similarly, most freshwater datasets are taxonomically unspecific (66%) and
519 cover frequencies from 1 to 22 kHz. Some datasets (20%) focus on ray-finned fish, covering
520 frequencies from 0.001 to 23 kHz. In contrast, terrestrial datasets mostly target single taxa
521 and have narrow frequency ranges. Bird-focused datasets are most common (44%),
522 spanning frequencies from 0.06 to 21 kHz, while bat-focused datasets are next (12%) and
523 range from 5 to 139 kHz. Taxonomically unspecific datasets account for 24% of datasets,
524 covering a broad range from 0.1 to 24 kHz. Generally, datasets targeting multiple taxa use
525 wider frequency ranges than those targeting single taxa.

526 **Soundscape case studies**

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

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

549 **Discussion**

550 The "Worldwide Soundscapes" project has — to our knowledge — assembled the first global
551 meta-database of PAM datasets across realms. We analysed its current content to quantify
552 sampling extent, coverage, and density across spatiotemporal and ecological scales. We
553 annotated soundscapes from eleven ecosystems to investigate macroecological,
554 conservation biology, and phenological trends. The database remains open for
555 contributions³⁹ and can be openly accessed to source datasets and initiate collaborative
556 studies³⁸. Next, we discuss the state and potential of PAM globally (Table 1).

557 Our results likely represent global PAM trends, even though spatial gaps reflect the
558 background of the project contributors. Our database still misses some national programs
559 (e.g., Australian Acoustic Observatory⁴³), but otherwise our terrestrial coverage is similar to a
560 recent systematic review²¹. The gaps in North Africa and Northeastern Europe correspond
561 with the paucity of bioacoustic datasets for these regions⁴⁴. Our database comprises 469
562 marine sampling locations while 991 were found in a recent systematic review²⁰, but most
563 overlap (Fig S2). Marine tropical waters that are under-represented in our database reflect
564 gaps found in the International Quiet Ocean Experiment network coverage⁴⁵. Our marine and
565 terrestrial database coverage is thus broadly comparable with published data. However, as
566 the database originates from an active network of researchers, it represents the current
567 availability of mostly as-yet unpublished data (Fig. S1). To our knowledge, no other spatially-
568 explicit review of freshwater sampling exists for comparison, and no other work quantified
569 temporal coverage.

570 Geographic coverage strikingly differs between realms: marine coverage is sparse but
571 widespread; terrestrial coverage is comparatively intensive in the Americas and Western
572 Europe; freshwater coverage is scattered. This partly reflects funding priorities for where
573 conservation and active management priorities lie, for instance in biodiversity hotspots and
574 densely-populated areas. Technical limits in extreme environments also drive geographic
575 patterns: high latitudes and elevations entail extremely cold temperatures that present
576 challenges for operation and maintenance, some of which can be solved with robust power
577 setups (solar panels, freeze-resistant batteries). Marine deployments are generally even
578 more constrained due to costly and demanding underwater work, but some deployments
579 reach the poles as water temperatures are buffered below the freezing point. Affordable
580 underwater recorders⁴⁶ may help to intensify sampling of marine coastal areas and close
581 gaps in freshwater coverage. By contrast, terrestrial monitoring is generally straightforward.
582 Northern temperate areas outside of Northeastern Europe are comparatively better covered,
583 and the tropics outside of Africa better represented. It appears that gaps in North Africa,
584 Central Asia, and Northeastern Europe arise from differential research means and priorities
585 between countries. Taken together, these gaps help to correct spatial biases⁴⁷ and to identify
586 high-priority, unique research areas that should be included in global assessments.

587 Currently, only marine studies achieve relatively even coverage of temporal cycles. Indeed,
588 offshore deployments — especially in the deep sea — are expensive and limited duration
589 deployments are not cost-effective⁴⁸. Marine soundscapes fluctuate stochastically⁴⁹, but the
590 ocean buffers water temperatures so that animals retain a basal activity level year-round.
591 Although lunar phases affect marine life^{50–52}, we did not consider lunar tides, which affect
592 some ecosystems. In the terrestrial and freshwater realms, most deployments cover the
593 entire diel cycle but monitoring on land focuses either on diurnal birds or on nocturnal bats,
594 as found in the literature²¹. In contrast, although seasons drive activity cycles on land too^{53,54},
595 spring- and summertime monitoring is disproportionately common and we lack a thorough
596 understanding of seasonal dynamics. Terrestrial deployments in particular may be short for
597 logistic reasons: in the cold, batteries struggle and access is harder; recorders are at risk of
598 theft; and limited numbers may cycle between sites⁵⁵. Lunar phases — probably evenly
599 sampled by chance — also influence land animals⁵⁶ but should be explicitly considered.
600 Overall, we encourage longer-duration setups with regularly-spread sampling inside
601 temporal cycles to alleviate the higher expenses, energy consumption, storage, and traded-
602 off spatial coverage⁵⁷. Global changes impact soundscapes in largely unpredictable ways
603 through changing species distributions and phenology, necessitating higher and unbiased
604 coverage across multiple time scales — including inter-annual ones — to successfully
605 monitor ongoing changes⁵⁸.

606 Re-use of soundscape datasets is restricted by their taxonomic focus. Admittedly,
607 taxonomically untargeted, long, and regular deployments in oceans, coupled to large
608 detection ranges, concurrently sample many taxa⁵⁹. However, many soundscape recordings
609 sample particular frequencies, often in the human-audible range⁶⁰, although biophony ranges
610 from infrasound⁶¹ to ultrasound⁶². For instance, studies of toothed whales or bats often use
611 triggers and high-pass filters to record purely ultrasonic recordings only when signals are
612 detected, resulting in spectrally-restricted and temporally-biased soundscape recordings.
613 Less-studied taxa such as anurans and insects could effectively be co-sampled by adjusting
614 ongoing deployments, so we encourage terrestrial researchers to maximise frequency
615 ranges to enhance interdisciplinary collaboration. These collaborations can help to mutualise

616 resources for mitigating potentially prohibitive power, storage, transportation, and post-
617 processing costs⁶³. Emerging embedded-AI audio detectors may offer an alternative⁶⁴, but
618 soundscape recordings will remain essential for broader application.

619 In every realm, ecosystems await acoustic discovery. Except for one dataset from aerobic
620 caves, we lack data from all subterranean realms (anthropogenic voids, ground streams, sea
621 caves), while endolithic systems may be the only irrelevant ecosystem for biophony. Access
622 is usually challenging or restricted for non-specialists, but subterranean biodiversity shows
623 high spatial turnover⁶⁵. Freshwater datasets were less rare, but several ones with
624 unreplicated sampling could not be included. Temporary, dynamic water bodies (seasonal,
625 episodic, and ephemeral ecosystems) are not yet well-studied⁶⁶ although they are accessible
626 from land. Notably, sounds can pass the boundary between recording media and be
627 captured in so-called holo-soundscapes in freshwater and shallow coastal areas^{5,67,68}.
628 Advances are imminent as the freshwater acoustic research community is growing
629 rapidly^{69,70}. In the oceans, sound propagates far and multiple biomes can be sampled at once
630 (e.g., recorders on the seafloor sample pelagic waters) so that most ecosystems are
631 covered. Still, coverage gaps may exist in rhodolith/Maërl beds, upwelling zones, and
632 deepwater coastal inlets. On land, sampling is biased towards biodiverse forests, and our
633 database coverage suggests that the most challenging terrestrial ecosystems, such as arid
634 zones (sclerophyll hot deserts and semi-deserts, semi-desert steppes), rocky habitats
635 (young rocky pavements, lava flows and screes) but also some vegetated temperate
636 ecosystems (cool temperate heathlands, temperate pyric humid forests, temperate
637 subhumid grasslands) are poorly sampled. Within the IUCN GET framework, soil
638 soundscapes also belong to the terrestrial realm and to date no eligible datasets are in our
639 database, despite recent studies^{71,72}.

640 Our database highlights well-known global sampling biases⁷³ which could be resolved with
641 collaboration to remove cultural and socioeconomic barriers⁷⁴. Technological progress for
642 more affordable equipment renders PAM more accessible in lower-income countries.
643 However, high- and deep-sea work remains considerably more expensive, and tropical
644 developing countries in particular often lack funding for marine programmes requiring large
645 vessels, underwater vehicles, or cabled stations on the seafloor⁴⁸. Our network currently
646 consists of active, English-speaking members from 50 countries. Collaborative projects,
647 shared sea missions, and equipment loans should promote the establishment of soundscape
648 research communities⁷⁵. Increased international collaboration⁷⁵ with scientists and local
649 stakeholders supporting citizen-science⁷⁶ in heavily underrepresented regions would improve
650 not only data coverage, but also representation and dialogue within the field.

651 Collaborative soundscape research relies on interoperable data. We harmonised metadata
652 with a bottom-up approach leading to our global inventory, but comprehensive standards for
653 PAM do not currently exist, even though initiatives for the marine realm are ongoing^{77,78}. Few
654 affordable solutions exist for sharing large audio data volumes⁴⁰, underlining the need for
655 distributed soundscape recording repositories⁷⁹. Marine oil and gas industry projects
656 routinely upload data as part of their efforts to mitigate noise impacts on marine animals⁸⁰,
657 but these recordings often focus on frequencies relevant to seismic prospecting and access
658 may be restricted^{81,82}. Furthermore, recording equipment requires calibration, sound
659 detection spaces need to be measured²⁶, and data privacy must be ensured on land⁸³. In
660 parallel, species sound libraries^{44,84-86} grow and continue to provide invaluable acoustic and
661 taxonomic references. International organisations such as GBIF will be key to roll-out

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

665 A unified approach of ecology with PAM is now possible. More comprehensive coverage is
666 needed to decisively answer research, conservation, and management questions that PAM
667 can address, so we encourage prospective contributors to archive their metadata and join
668 our inclusive project. We show that a large portion of the PAM community is willing to
669 collaborate across realms and form a global network. We advocate for a bolder PAM effort to
670 inform the agenda of soundscape ecology⁸⁷, reaching out to places where no sound has
671 been recorded before as well as to urban settings⁸⁸. The research community may open new
672 avenues to study environmental effects on acoustic activity⁵⁸, social species interactions⁸⁹,
673 human-wildlife relationships⁴¹, function and phylogeny⁹⁰, soundscape effects on human
674 health⁹¹, acoustic adaptation and niche hypotheses^{92,93}, macroecological patterns across
675 ecosystems¹, and initiate an integrated approach to noise impacts on wildlife.

676 PAM is now an established method that can be applied over large spatial and temporal
677 scales. Consistent, large-scale monitoring of the Earth's soundscapes is essential to
678 establish baselines for historical trends⁹⁴ and quantify rapid changes in biodiversity and
679 natural systems. International funding schemes should integrate PAM into biodiversity
680 monitoring platforms such as GBIF⁹⁵ and GEO BON^{96,97}. Soundscapes are just starting to be
681 used in legislation as an ecosystem feature to be preserved⁹⁸. Occupancy maps for
682 soniferous wildlife obtained from PAM would underpin the evaluation of progress towards
683 threat reduction and ecosystem service provision of the Kunming-Montreal Global
684 Biodiversity Framework⁹⁹. By building collaborations around the knowledge frontiers
685 identified here, we can aim to comprehensively describe and understand the acoustic make-
686 up of the planet.

687

688 **Methods**

689 **Ethics & Inclusion statement**

690 The present study has involved people who carried out PAM-based studies as primary
691 contributors. They could be corresponding authors for published studies, referred contacts
692 for unpublished studies, or principal investigators, and were asked to identify further primary
693 and secondary contributors of their study. Primary contributors could become co-authors,
694 and secondary contributors are acknowledged here. Some primary contributors were invited
695 as co-leads to be responsible for particular realms or biomes and are listed in the first-tier
696 authors list. Primary contributors who additionally provided soundscape recordings are also
697 listed in the first-tier authors list. All primary contributors were asked to identify further
698 contacts to reach a comprehensive coverage for the database. Given the nature of the study
699 (using passive acoustic monitoring methods), the research did not suffer from restrictions or
700 prohibitions in the setting of the researchers. Necessary permits from landowners or
701 environmental protection agencies, precautions to limit biological contaminations (e.g.,
702 biofilm on marine recorders) or for animal welfare, and local ethics committee reviews were
703 the responsibility of the respective primary contributors. None of the PAM activities resulted
704 in personal risk to participants; neither did they involve health, safety, security or other risk to
705 researchers. Local and regional research relevant to our study were taken into account in
706 citations throughout the main text.

707 **Database construction**

708 The database construction started in August 2021 within the frame of the Worldwide
709 Soundscapes project³⁸ using collaborative, peer-driven metadata collation. It represents the
710 current state of knowledge about publicly accessible meta-datasets for PAM within our
711 network. We started contacting contributors that we personally know, and co-lead authors
712 helped to contact potential contributors in the respective ecosystem types of their expertise
713 (i.e. terrestrial, urban, freshwater, and marine). We conducted focal publication searches to
714 actively plug coverage gaps by inviting the respective corresponding authors. We posted the
715 call for contributors on specialised ecoacoustics platforms and social media, and will keep
716 the project open for any contributor owning suitable soundscape recordings beyond the
717 present publication. We communicated mostly in English but also in Spanish, French,
718 Portuguese, German, Russian, and Chinese to gather metadata. We ended up including
719 metadata from larger groups such as the Silent Cities project, Ocean Networks Canada, the
720 Australian Acoustic Observatory, and Parks Canada.

721 Primary contributors provided the metadata that formed the basis for the database. Their
722 willingness to be informed through a mailing list, responsibility for their metadata, approval
723 for sharing the meta-data publicly, and willingness to participate in this study as co-authors
724 were explicitly stated in an online form-based collaboration agreement. Primary contributors
725 who became co-authors all fulfilled either data curation (e.g., as providers of structured
726 metadata) or project administration (e.g., as principal investigators designing the
727 corresponding study) roles and additionally a manuscript revision role. Primary contributors
728 cross-validated their metadata using maps and graphical timelines visualising their input. As
729 a result, apart from basic coherence checks conducted by the co-leads and research
730 assistants, the responsibility of the database content is borne by their contributors. The

731 database information page is integrated in our online collaborative ecoacoustics platform
732 ecoSound-web¹⁰⁰ that also hosts the soundscape recordings of the case study
733 (https://ecosound-web.de/ecosound_web/collection/show/49).

734 Our network consists of people reachable through email contact. Out of 588 contacted
735 contributors potentially involved in PAM, 298 (49%) provided some metadata. More datasets
736 exist but 24% of those contacted have not yet responded. This may be due to limitations in
737 sharing research data or, newcomers to PAM, or out-dated contact details. Older
738 soundscape datasets may be stored on analog media that are inaccessible over the internet,
739 but these are more often attended recordings⁵³ — thus not fulfilling our inclusion criteria (see
740 below). The missing share of datasets could be estimated with a systematic literature
741 search, but we posit that our dataset search was exhaustive, and we were able to fill gaps
742 more effectively due to focused calls for missing datasets in our large group of contributors.

743 Potential soundscape recording datasets were required to meet four criteria: 1) stationary —
744 mobile recorders would have complex, constantly changing spatial assignments, thus we
745 excluded recordings from cars, transect walks, or towed deployments; 2) passive —
746 obtained from automated, unattended recorders, without human presence near the acoustic
747 sensor; 3) ambient — with no particular recording direction or temporal selection, as
748 obtained from omnidirectional microphones and with non-triggered recordings; 4) from
749 spatially or temporally replicated study designs (Fig. 1). Datasets with spatial and temporal
750 replication are necessary to disentangle spatial and temporal effects from other soundscape
751 determinants. We considered datasets to have spatial replicates when several sites were
752 sampled simultaneously, and temporally replicated when one site was sampled over multiple
753 days at the same time of day. We chose sampling sites and days as the most elemental
754 units for defining replication in our unified analysis. However, we acknowledge that replicates
755 are defined differently in each study: for instance, sampling sites may only be spatial
756 replicates if they belong to the same category (i.e. habitat, management type). Temporal
757 replicates could also be defined at the scale of other solar and lunar cycles (e.g., multiple full
758 moons). Taken together, our requirements homogenise the dataset to enable statistical
759 analyses across datasets and future collaborative syntheses.

760 **Time and space**

761 Soundscapes are fundamentally determined by their time and location. Wildlife and human
762 activities are broadly determined by solar and lunar cycles^{32,54,56,101}, and geographical
763 positions on the planet relative to the poles or equator, or the land and water surface. For all
764 datasets, we determined their spatial coverage in terms of number of sites, and sampling
765 density as the number of sites within the realms' areal extent (as determined by IUCN GET
766 maps). Although spatial extent could be defined as the area bounded by the sites of a
767 dataset, challenges with calculating extents on the world sphere (especially for datasets with
768 very large extents spanning the globe), and unknown sampling areas covered in each site
769 led us to ignore spatial extents. Until sound detection spaces can be accurately measured,
770 our measure of spatial sampling density using points per area is thus provisional. Indeed,
771 acoustic sampling areas or volumes are extremely rarely measured in terrestrial sites and
772 seldom measured but sometimes simulated in marine environments¹⁰². They vary with sound
773 source intensity, frequency, directivity; recording medium temperature, currents, pressure,
774 humidity (for air); habitat structure such as topography and vegetation structure; ambient
775 sound level. Generally, detection ranges are greater in underwater environments due to the

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

780 We quantified the latitudinal and topographical coverage across realms by collecting latitude,
781 longitude and topography (above and below the sea level) data for each site. Contributors
782 could provide self-measured topography values for sites on land and gaps were filled in
783 using General Bathymetric Chart of the Oceans surface elevation data. For underwater sites,
784 depth values (below sea level for marine sites, below the surface for freshwater) were
785 provided by the contributors. We assigned sampling sites to administrative areas (GADM
786 divisions for freshwater and land, IHO for sea areas) and extracted their WDPA category.
787 Sites' climates were geographically classified into tropical (between -23.5° and 23.5°
788 latitude), polar (below -66.5° or above 66.5° latitude), and temperate (between polar and
789 tropical regions).

790 Contributors were asked to specify the timing of their deployments using start and end dates
791 and times, operation modes (continuous, scheduled, periodical). For scheduled operation
792 schedules (daily start and end times or durations) were required, and duty cycles were
793 required for periodical operation. Duty cycles could additionally be indicated for scheduled
794 deployments. Deployments were assigned to single sampling sites. Subsequently added
795 sites and sampling repetitions were considered as additional deployments within datasets. A
796 temporal framework was used to quantify sampling coverage in three solar and lunar cycles.
797 Temporal information was inferred from the timing of sound recordings relative to time
798 events that structure life and meteorological events on Earth (Fig. 3). Seasonal cycles were
799 inferred only for temperate sites, by splitting the year cycle into four meteorological seasons
800 (winter: December-February, spring: March-May, summer: June-August, fall: September-
801 November). The daily cycle was split into four windows delimiting dawn (from astronomical
802 dawn start at -18° solar altitude until 18° solar altitude), day, dusk (from 18° solar altitude to
803 astronomical dusk end at -18° solar altitude), and night. The lunar illumination cycle was split
804 into two time windows centred on the full and new moon phases. It follows that the extrema
805 and ecotones in the temporal cycles define the relevant sampling time windows, noting that
806 in temperate zones, the equinoxes roughly correspond to thermal ecotones. Seasonal cycles
807 in tropical and polar regions arising from precipitation patterns were not considered in this
808 analysis.

809 **Ecological characterisation**

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

819 **Acoustic frequency ranges**

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

829 **Soundscape case studies**

830 To illustrate how the database can be used for macroecology, conservation biology, and
831 phenology analyses, we selected 121 recordings across a variety of topographical,
832 latitudinal, and anthropisation conditions — all fundamental gradients of assembly filters in
833 both terrestrial and marine realms¹ — belonging to 10 functional groups. We aimed to select
834 datasets containing four spatial replicates within the same functional group, with 10-minute
835 recordings spanning all four diel time windows from the same date during the biologically
836 active season, but the available data did not always allow this (Table S2). We extracted
837 recordings starting at sunrise, solar noon, sunset, and solar midnight. Recordings covered
838 the audible frequency range with sampling frequencies of at least 44.1 kHz in single or dual
839 channel configuration. We acknowledge that this targeted, non-systematic selection is not
840 statistically representative of global patterns but rather illustrative of the database potential.

841 Each recording's spectrogram (i.e., visualisation of sound intensity along time and frequency
842 axes) was annotated with the three fundamental soundscape components: biophony,
843 anthropophony, and geophony. Soundscape recordings were uploaded to ecoSound-web
844 (https://ecosound-web.de/ecosound_web/collection/show/49)⁴⁰ for annotation: KD listened to
845 them and visually inspected the spectrograms (Fast Fourier Transform window size of 1 024)
846 at a visual density of 1 116 pixels per 10 minutes to create annotations. Annotations were
847 rectangular tags on the spectrogram, encompassing only the annotated sound, with defined
848 coordinates in the time and frequency dimensions. Annotations of different soundscape
849 components could overlap if they were simultaneously visible or audible. Annotations of the
850 same soundscape component were adjacent and non-overlapping to avoid double-counting.
851 Soundscape components occurring above 22.05 kHz were excluded from the analysis as we
852 focused on audible frequencies only, which were the frequencies targeted by most
853 recordings. Sounds caused by microphone or recorder self-noise were excluded. All
854 annotations were reviewed by the recording creators using the peer-review mode on
855 ecoSound-web, and only accepted ones were used in the analysis. The annotations were
856 exported and acoustic space occupancy for each soundscape component in each recording
857 was calculated as the proportion of the spectro-temporal space⁶⁰ (i.e., duration multiplied by
858 frequency range, divided by total area of spectrogram; range: 0-1).

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

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

864

865

Display items

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

Aims	Opportunities
Increasing spatial and ecosystemic coverage	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Calibrate equipment and consider detection ranges - Build accessible and sustainable data repositories - Design and adopt standards - Integrate PAM into biodiversity and remote sensing databases

867

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

877

878 **Figure 2: Spatial distribution of sampling sites.** A) Latitudinal and topographic distribution
879 of sampling sites across core realms. Due to their higher representation and to avoid
880 overlapping site clusters, terrestrial sites are shown with transparency. The minimum
881 (deepest seafloor) and maximum (highest elevation of land or sea level) topographical limits
882 (dark grey lines) are shown against latitude, based on General Bathymetric Chart of the
883 Oceans data¹⁰⁵. Minimum topography above the sea level and maximum topography under
884 the sea level were set to zero as the sea level represents the minimum and maximum in
885 these cases. B) Number of sampling sites within different administrative regions (GADM

886 level 0 and IHO sea areas), split by core realm, across WDPa categories (Ia: strict nature
887 reserve; Ib: wilderness area, II: national park). The areas that do not belong to the top 10 in
888 terms of datasets have been aggregated under “others”. One subterranean site in Brazil is
889 not shown. Sites from transitional realms were assigned to their parent core realm.

890

891 **Figure 3: Temporal sampling distribution.** A) Temporal sampling coverage across solar
892 and lunar cycles for the three core realms. Cycles consist of solar (daily and seasonal) and
893 lunar time cycles (lunar phase), subdivided in time windows. Seasons were only analysed in
894 temperate regions. Sampling coverage is represented with sampling days in number labels.
895 B) Mean number of sampling days per site within different administrative regions (GADM
896 level 0, IHO areas, WDPa categories), split by core realm. WDPa categories (Ia: strict
897 nature reserve; Ib: wilderness area, II: national park) are shown separately. One
898 subterranean site in Brazil is not shown. Numbers to the right of bars indicate the number of
899 sites the means were calculated from. Sites from transitional realms were assigned to their
900 parent core realm.

901

902 **Figure 4: Sampling distribution across ecological scales.** A) Spatial extent of realms,
903 based on major areas according to IUCN GET (coloured disk area proportional to area);
904 spatial sampling density (in sites per Mkm²) and coverage (in number of sites); temporal
905 extent (mean range between first and last recording day), coverage (days sampled per site
906 and density (proportion of days sampled per extent). B) Frequency ranges of datasets
907 across realms (using Nyquist frequency i.e., actual recorded frequencies) for the main
908 studied taxa. The dots at the ends of colored lines represent means of the lowest and
909 highest recorded frequencies, and the range between the minimum and maximum of these
910 values are indicated with black error bars. The limits of human hearing are indicated with
911 dashed lines. Number of datasets indicated above lines - datasets can be counted several
912 times if they contain deployments targeting different taxa.

913

914 **Figure 5: Soundscape components analysis.** A) Mean acoustic space occupancy of
915 soundscape components (biophony, geophony, anthropophony) as calculated from
916 annotations for the selected ecosystems, measured in proportion of spectro-temporal space
917 used, across eleven ecosystems over 150 recordings covering the time windows of the diel
918 cycle. Annotated recordings are accessible at
919 https://ecosound-web.de/ecosound_web/collection/show/49. Sample spectrograms are
920 shown in the background. B) Soundscape component occupancy data illustrate three
921 research questions linked to macroecology (i.e., biophony with distance from equator
922 relationship), conservation biology trade-offs (i.e., biophony with anthropophony
923 relationship); and phenological trends (i.e., mean biophony along diel time windows for each
924 realm). Gray ribbons indicate 95% credible intervals and numbers indicate probabilities of
925 positive or negative relationships.

926

927 [Data availability](#)

928 ● [Database metadata](#) at Zenodo (version 2.0.0)

929 ● [Demonstration collection](#)

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1010 Author contributions

1011 Kevin FA Darras, Rodney Rountree did the conceptualisation. Kevin FA Darras, Steven Van
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1095 [Competing interests](#)

1096 The authors declare to have no competing interests. All authors have seen and approved the
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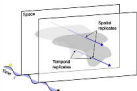
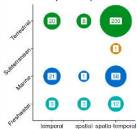
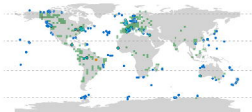
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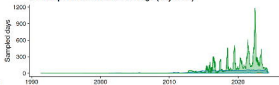
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A - Framework**B - Replication (dataset level)****C - Spatial extent and coverage of sampling sites**

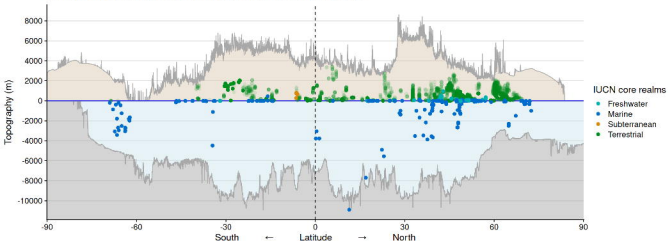
Terrestrial sites

200 400 600

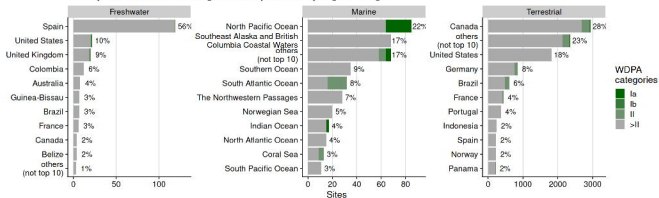
D - Temporal extent and coverage (day level)

Core realm: Freshwater Marine Subterranean Terrestrial

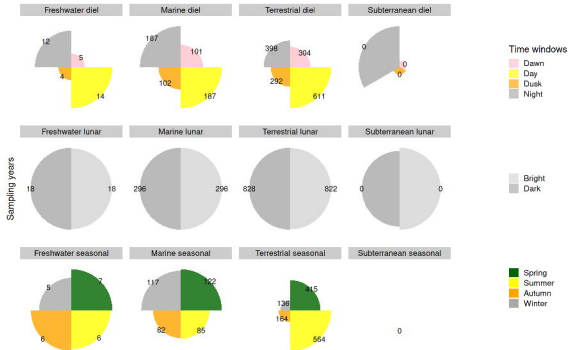
A - Topographical and latitudinal distribution of sampling sites



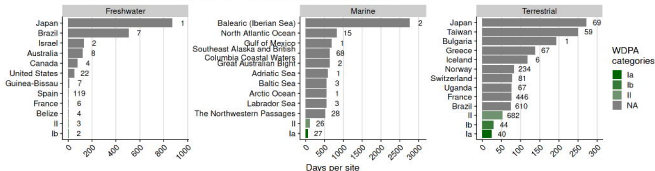
B - Top 10 administrative regions for spatial sampling coverage



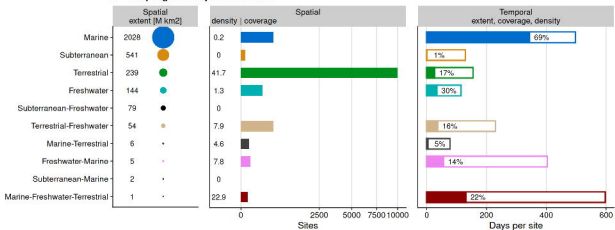
A - Sampling coverage within time cycles



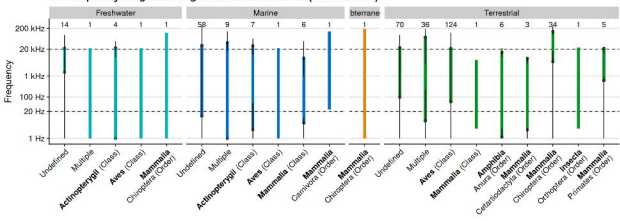
B - Top 10 administrative regions for temporal sampling coverage



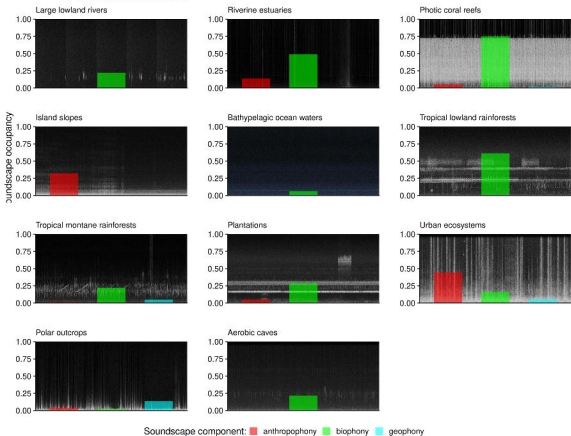
A - Sampling intensity across realms



B - Frequency range and target taxa in core realms (dataset level)



A - Case study soundscapes



B - Illustrative analyses

