Received: 23 June 2021 | Accepted: 31 July 2021
DOI: 10.1111/conl.12834

Conservation Letters
A journal of the Society for Conservation Biology
Open Access
WILEY

VIEWPOINT

A conservation roadmap for the subterranean biome

J. Judson Wynne[1] | Francis G. Howarth[2] | Stefano Mammola[3,4] | Rodrigo Lopes Ferreira[5] | Pedro Cardoso[3] | Tiziana Di Lorenzo[6] | Diana M. P. Galassi[7] | Rodrigo A. Medellin[8] | Bruce W. Miller[9] | David Sánchez-Fernández[10] | Maria Elina Bichuette[11] | Jayant Biswas[12] | Cory W. BlackEagle[13] | Chaichat Boonyanusith[14] | Isabel R. Amorim[15] | Paulo Alexandre Vieira Borges[15] | Penelope J. Boston[16] | Reynold N. Cal[17] | Naowarat Cheeptham[18] | Louis Deharveng[19] | David Eme[20] | Arnaud Faille[21] | Danté Fenolio[22] | Cene Fišer[23] | Žiga Fišer[23] | Samuel M. ʻOhukaniʻōhiʻa Gon III[24] | Forough Goudarzi[25] | Christian Griebler[26] | Stuart Halse[27] | Hannelore Hoch[28] | Enock Kale[29] | Aron D. Katz[30] | Ľubomír Kováč[31] | Thomas M. Lilley[3] | Shirish Manchi[32] | Raoul Manenti[33] | Alejandro Martínez[4] | Melissa B. Meierhofer[3] | Ana Z. Miller[34] | Oana Teodora Moldovan[35] | Matthew L. Niemiller[36] | Stewart B. Peck[37] | Thais Giovannini Pellegrini[5] | Tanja Pipan[38] | Charity M. Phillips-Lander[39] | Celso Poot[40] | Paul A. Racey[41] | Alberto Sendra[42,43] | William A. Shear[44] | Marconi Souza Silva[5] | Stefano Taiti[45] | Mingyi Tian[46] | Michael P. Venarsky[47] | Sebastián Yancovic Pakarati[48,49,50] | Maja Zagmajster[23] | Yahui Zhao[51]

[1] Department of Biological Sciences, Center for Adaptable Western Landscapes, Northern Arizona University, Flagstaff, Arizona

[2] Hawaii Biological Survey, Bishop Museum, Honolulu, Hawaii

[3] Finnish Museum of Natural History Luomus, University of Helsinki, Helsinki, Finland

[4] DarkMEG—Molecular Ecology Group, Water Research Institute, National Research Council of Italy, Verbania Pallanza, Italy

[5] Centro de Estudos em Biologia Subterrânea, Setor de Biodiversidade Subterrânea, Departamento de Ecologia e Conservação, Universidade Federal de Lavras, Minas Gerais, Brazil

[6] Research Institute on Terrestrial Ecosystem of the Italian National Research Council, Florence, Italy

[7] Department of Life, Health & Environmental Sciences, University of L'Aquila, L'Aquila, Italy

[8] Instituto de Ecologia, Universidad Nacional Autónoma de México, México

[9] Wildlife Conservation Society, Bronx Zoo, Bronx, NY (Ret.) and Bat Sound Services, Canadian Lakes, Michigan

[10] Departamento de Ecología e Hidrología, Universidad de Murcia, Murcia, Spain

[11] Laboratório de Estudos Subterrâneos, Departamento de Ecologia e Biologia Evolutiva, Universidade Federal de São Carlos, São Carlos, São Paulo, Brazil

[12] National Cave Research and Protection Organization, Raipur, Chhattisgarh, India

[13] Department of Geosciences, Eastern Kentucky University, Richmond, Kentucky

[14] School of Biology, Nakhon Ratchasima Rajabhat University, Nakhon Ratchasima, Thailand

[15] Centre for Ecology, Evolution and Environmental Changes/Azorean Biodiversity Group and Universidade dos Açores, Faculty of Agrarian and Environmental Sciences, Azores, Portugal

[16] NASA Ames Research Center, Moffett Field, California

[17] Runaway Creek Nature Reserve, Belmopan, Belize

[18] Department of Biological Sciences, Faculty of Science, Thompson Rivers University, Kamloops, British Columbia, Canada

[19] Museum National d'Histoire Naturelle, Paris, France

[20] IFREMER Centre Atlantique, Unité Ecologie et Modèles pour l'Halieutique, Nantes, France

[21] Stuttgart State Museum of Natural History, Stuttgart, Germany

[22] Center for Conservation and Research, San Antonio Zoo, San Antonio, Texas

[23] SubBio Lab, Department of Biology, Biotechnical Faculty, University of Ljubljana, Slovenia

[24] The Nature Conservancy, Honolulu, Hawaii

[25] Department of Environment, Isfahan University of Technology, Isfahan, Iran

[26] Department of Functional and Evolutionary Ecology, Division of Limnology, University of Vienna, Vienna, Austria

[27] Bennelongia Environmental Consultants, Perth, Australia

[28] Department Center for Integrative Biodiversity Discovery, Museum für Naturkunde, Leibniz Institute for Research on Evolution and Biodiversity, Berlin, Germany

[29] Ecomate Management Ltd., Boroko, NCD, Papua New Guinea

[30] Engineer Research and Development Center, U.S. Army Corps of Engineers, Champaign, Illinois

[31] Department of Zoology, Institute of Biology and Ecology, P.J. Šafárik University, Košice, Slovakia

[32] Conservation Ecology Division, Salim Ali Centre for Ornithology and Natural History, Coimbatore, India

[33] Department of Environmental Science and Policy, Università degli Studi di Milano, Milan, Italy

[34] Laboratório HERCULES, University of Évora, Évora, Portugal and Instituto de Recursos Naturales y Agrobiología de Sevilla, Consejo Superior de Investigaciones Científicas, Seville, Spain

[35] Emil Racovita Institute of Speleology, Cluj-Napoca Department, Cluj-Napoca, Romania

[36] Department of Biological Sciences, The University of Alabama in Huntsville, Huntsville, Alabama

[37] Canadian Museum of Nature, Ottawa, Ontario, Canada

[38] ZRC SAZU Karst Research Institute, Ljubljana, Slovenia and UNESCO Chair on Karst Education, University of Nova Gorica, Vipava, Slovenia

[39] Space Science and Engineering Division, Southwest Research Institute, San Antonio, Texas

[40] The Belize Zoo and Tropical Education Center, Belmopan, Belize and School of Natural Resources and Environment, University of Florida, Gainesville, Florida

[41] Centre for Ecology and Conservation, University of Exeter, UK

[42] Colecciones Entomológicas Torres-Sala, Servei de Patrimoni Històric, Ajuntament de València, València, Spain

[43] Departament de Didàctica de les Ciències Experimentals i Socials, Facultat de Magisteri, Universitat de València, València, Spain

[44] Department of Biology, Hampden-Sydney College, Hampden Sydney, Virginia

[45] Istituto di Ricerca sugli Ecosistemi Terrestri CNR-IRET, Museo di Storia Naturale, Sezione di Zoologia, Firenze, Italy

[46] Department of Entomology, College of Plant Protection, South China Agricultural University, Guangzhou, China

[47] Department of Biodiversity Conservation and Attractions, Government of Western Australia, Washington, Kensington, Australia

[48] Laboratorio de Socioecosistemas, Departamento de Ecología, Universidad Autónoma de Madrid, Madrid, Spain

[49] Consejo Asesor de Monumentos Nacionales de Chile - Rapa Nui, Chile

[50] Manu Project, Rapa Nui, Chile

[51] Key Laboratory of Zoological Systematics and Evolution, Institute of Zoology, Chinese Academy of Sciences, Beijing, China

Correspondence

J. Judson Wynne, Department of Biological Sciences, Center for Adaptable Western Landscapes, Northern Arizona University, Flagstaff, AZ 86011.

Email: jut.wynne@nau.edu

Abstract

The 15th UN Convention on Biological Diversity (CBD) (COP15) will be held in Kunming, China in October 2021. Historically, CBDs and other multilateral treaties have either alluded to or entirely overlooked the subterranean biome. A multilateral effort to robustly examine, monitor, and incorporate the subterranean biome into future conservation targets will enable the CBD to further improve the ecological effectiveness of protected areas by including groundwater resources, subterranean ecosystem services, and the profoundly endemic subsurface biodiversity. To this end, we proffer a conservation roadmap that embodies five conceptual areas: (1) science gaps and data management needs; (2) anthropogenic stressors; (3) socioeconomic analysis and conflict resolution; (4) environmental education; and (5) national policies and multilateral agreements.

KEYWORDS
biodiversity, caves, convention on biological diversity, hypogean, indicator species

The 15th UN Convention on Biological Diversity (CBD) (COP15) (UNEP, 2021) will be held in Kunming, China in October 2021. Historically, CBDs and other multilateral treaties have either alluded to or entirely overlooked the subterranean biome (Sánchez-Fernández et al., 2021). Importantly, while the post-2020 global biodiversity framework (IUCN, 2020) briefly mentioned subterranean ecosystems, the need for an effective protected area network to safeguard biodiversity, freshwater, and ecosystem services had been strenuously and broadly emphasized. Globally, only ~7% of the modeled extent of the subterranean biome overlaps with protected areas (Sánchez-Fernández et al., 2021).

As the upcoming CBD meeting will be held in the South China Karst, a region supporting the highest diversity of subterranean-adapted fishes, beetles, and millipedes globally (and likely to emerge as a subterranean biodiversity hotspot), we provide this roadmap for conserving the world's subterranean resources. Through a multilateral effort to robustly examine, monitor, and incorporate the subterranean biome into future conservation targets, the CBD will further improve the ecological effectiveness of protected areas by including groundwater resources, subterranean ecosystem services, and the profoundly endemic subsurface biodiversity (Elshall et al., 2020; Mammola et al., 2019, 2020). To this end, this roadmap embodies five conceptual areas: (1) science gaps and data management needs; (2) anthropogenic stressors; (3) socioeconomic analysis and conflict resolution; (4) environmental education; and (5) national policies and multilateral agreements.

Perhaps even more than surface ecosystems, the terrestrial subterranean biome is riddled by extensive knowledge gaps (Box 1, Figure 1). For example, for most known subterranean-obligate species, we have little more than observational data from a few human-accessible localities (Mammola et al., 2019, 2020); this makes assessing species for protective management extremely challenging. While the importance of ecosystem services associated with groundwater quality and cave-roosting bats is relatively well-documented (Elshall et al., 2020; Griebler et al., 2014; Mammola et al., 2019), a substantial effort will be required to quantify the scope, importance, and habitat requirements of subterranean bioindicator and ecosystem service species (Elshall et al., 2020).

Natural history information on the subterranean biome lags equally behind. Data deficiencies to be addressed should include developing a network of voucher specimen collections available both in brick-and-mortar locations and as digital archives. Additionally, the creation or adoption of an array of digital archives, tantamount to the World Karst Spring hydrograph database (Olarinoye et al., 2020), will provide conservationists and resource managers with the data to identify research needs and foster international and interdisciplinary collaborations. Such archives must house information on the geospatial extent of subterranean habitats, reference barcode/genetic and functional trait data on subterranean species, and synergistically contribute to or augment existing archives (Frick et al., 2020) (e.g., GBIF, iDigBio, and BoldSystems).

Although researchers have qualitatively summarized most of the likely anthropogenic stressors threatening subterranean biodiversity and ecosystem function (Box 2) (Elshall et al., 2020; Griebler et al., 2014; Leclère et al., 2020; Mammola et al., 2020), their potential impacts have not been quantified (Mammola et al., 2020). Strategically focused, global studies to examine key impacts (in particular, surface habitat loss) (Hedrick et al., 2020) should be conducted across a range of subterranean habitats, a panoply of associated indicators, and ecosystem service and short-range endemic species. Through such a coordinated effort, researchers and policymakers can amass the information required to develop mitigation strategies to optimize decision-making.

Solutions (Box 3) will require scientists and legislators to work closely with local communities and municipalities to both ameliorate future land-use disputes and to find sustainable and economically viable pathways

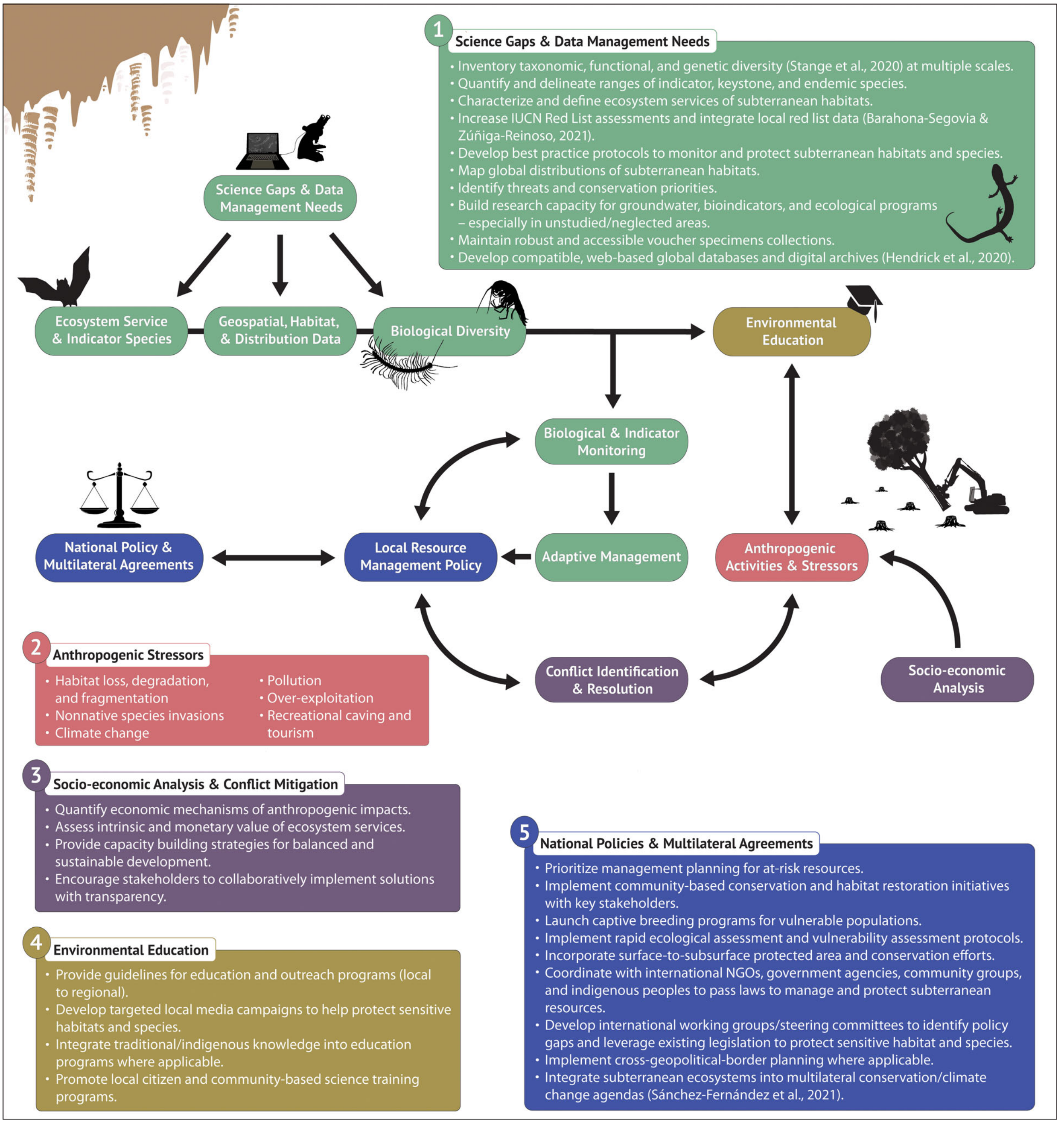

FIGURE 1 Conservation roadmap flows from addressing data gaps and data management needs (green ovals with callout box) to policy development and implementation (blue). Data acquisition and management moves in two directions: (1) toward a feedback loop of monitoring, adaptive management, and local resource policy development – with monitoring and management iteratively improved as scientific data dictates; and (2) to providing information necessary to create educational outreach programs (yellow), which are further sculpted by human activities (red). Socio-economic analyses (purple) aim to both characterize and lessen anthropogenic impacts and stressors. This information then feeds into local resource management formulation; national policy and multilateral agreements are both shaped and influenced by local decision-making

forward. Importantly, 50% of humans rely on groundwater for consumption, while 43% use it for agricultural purposes (Elshall et al., 2020). As we increasingly convert natural ecosystems to agriculture, pastureland, and human habitation, surface biodiversity, and ecosystem function (Gibson et al., 2011), as well as aquifers and other groundwater habitats will become increasingly threatened and degraded. To maximize effectiveness and reduce conservation conflicts, improved dialog between social and natural scientists must occur so that social, political, and scientific contexts are well articulated, and stakeholders can negotiate with complete transparency (Gibson et al., 2011).

Successful environmental and conservation education programs (Box 4) should be crafted to: (i) address local problems/topics; (ii) establish partnerships and programs with local researchers and resource managers; (iii) emphasize action focused projects (e.g., ecological restoration, cave cleanups, and monitoring bioindicators and bat/bird roosts); and (iv) create targeted projects that quantify and report program outcomes (Redpath et al., 2013). Educational efforts must be established in partnership with local schools and universities, scientific organizations, indigenous and community groups, businesses, nongovernmental organizations, and government agencies.

Conservation policies (Box 5) to protect significant subterranean habitats are lacking at most regional and national levels (Mammola et al., 2020). However, policies have been implemented to better manage local and regional groundwater resources (Elshall et al., 2020). Barring the European Union's Habitat Directive (which marginally considers subterranean habitats; EU, 2021), no multilateral agreements have been adopted to specifically include the subterranean biome (Sánchez-Fernández et al., 2021). Solidly integrating surface with subsurface conservation targets through equitable stakeholder participation represents a foundational next step toward optimally securing the groundwater supply (Elshall et al., 2020), safeguarding ecosystem services (Frick et al., 2020; Mammola et al., 2020), and protecting subterranean diversity.

While numerous lacunae exist concerning subterranean resources, sound directives can be enacted promptly with adaptive management. This roadmap represents a viable framework for near-term and longer duration conservation actions to protect the world's subterranean ecosystems. Formulating targets to further reduce threats to the subterranean biome is essential to this year's CBD meeting in Kunming. We must act now.

AUTHOR CONTRIBUTIONS

J. Judson Wynne and Stefano Mammola conceived the project. Francis Howarth developed the initial roadmap. All other authors contributed to roadmap development and finalization.

ETHICS STATEMENT

No data collection or scientific inquiries requiring ethics considerations were undertaken. Thus, this work complies with appropriate ethical standards.

DATA ACCESSIBILITY STATEMENT

We did not collect any primary data to develop this manuscript. All references that aided in refining our positions are provided.

CONFLICT OF INTEREST

We declare no conflict of interest with this work.

ORCID

J. Judson Wynne https://orcid.org/0000-0003-0408-0629
Stefano Mammola https://orcid.org/0000-0002-4471-9055
Diana M. P. Galassi https://orcid.org/0000-0002-6448-2710
David Sánchez-Fernández https://orcid.org/0000-0003-1766-0761
Maria Elina Bichuette https://orcid.org/0000-0002-9515-4832
Jayant Biswas https://orcid.org/0000-0001-6422-6111
Cory W. BlackEagle https://orcid.org/0000-0002-3968-6850
Chaichat Boonyanusith https://orcid.org/0000-0003-1487-2160
Isabel R. Amorim https://orcid.org/0000-0001-6847-3320
David Eme https://orcid.org/0000-0001-8790-0412
Samuel M. ʻOhukaniʻōhiʻa Gon III https://orcid.org/0000-0003-0397-3089
Ľubomír Kováč https://orcid.org/0000-0001-8194-2128
Thais Giovannini Pellegrini https://orcid.org/0000-0001-6725-9429
Stefano Taiti https://orcid.org/0000-0002-4909-6037

REFERENCES

Ardoin, N. M., Bowers, A. W., & Gaillard, E. (2020). Environmental education outcomes for conservation: A systematic review. *Biological Conservation*, *241*, 108224. https://doi.org/10.1016/j.biocon.2019.108224.

Barahona-Segovia, R. M., & Zúñiga-Reinoso, A. (2021). An overview of Neotropical arthropod conservation efforts using risk assessment lists. *Journal of Insect Conservation*, *25*, 361–376. https://link.springer.com/article/10.1007/s10841-021-00306-x.

Elshall, A. S., Arik, A. D., El-Kadi, A. I., Pierce, S., Ye, M., Burnett, K. M., Wada, C. A., Bremer, L. L., & Chun, G. (2020). Groundwater sustainability: A review of the interactions between science and policy. *Environmental Research Letters*, *15*, 093004.

[EU] European Union. (2021). The Habitats Directive https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

Frick, W. F., Kingston, T., & Flanders, J. (2020). A review of the major threats and challenges to global bat conservation. *Annals of the New York Academy of Sciences*, *1469*, 5–25.

Gibson, L., Lee, T. M., Koh, L. P., Brook, B. W., Gardner, T. A., Barlow, J., Peres, C. A., Bradshaw, C. J., Laurance, W. F., Lovejoy, T. E., & Sodhi, N. S. (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, *478*, 378–381.

Griebler, C., Malard, F., & Lefébure, T. (2014). Current developments in groundwater ecology—From biodiversity to ecosystem function and services. *Current Opinion of Biotechnology*, *27*, 159–167. https://doi.org/10.1016/j.copbio.2014.01.018.

Hedrick, B. P., Heberling, J. M., Meineke, E. K., Turner, K. G., Grassa, C. J., Park, D. S., Kennedy, J., Clarke, J. A., Cook, J. A., Blackburn, D. C., Edwards, S. V., & Edwards, S. V. (2020). Digitization and the future of natural history collections. *Bioscience*, *70*, 243–251. https://doi.org/10.1093/biosci/biz163.

[IUCN] International Union for the Conservation of Nature. (2020). Interim position on updated zero draft Post-2020 Global Biodiversity Framework, Version 9.12.20. https://www.iucn.org/sites/dev/files/content/documents/iucn_interim_position_p2020_updated_zero_draft_09.12.20.pdf

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J. P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., …Freeman, R. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, *585*, 551–556.

Mammola, S., Cardoso, P., Culver, D. C., Deharveng, L., Ferreira, R. L., Fišer, C., Galassi, D. M., Griebler, C., Halse, S., Humphreys, W. F., Isaia, M., Malard, F., Martinez, A., Moldovan, O. T., Niemiller, M. L., Pavlek, M., Reboleira, A. S. P. S., Souza-Silva, M., Teeling, E. C., … Zagmajster, M. (2019). Scientists' warning on the conservation of subterranean ecosystems. *Bioscience*, *69*, 641–650. https://academic.oup.com/bioscience/article/69/8/641/5519083?login=true.

Mammola, S., Amorim, I. R., Bichuette, M. E., Borges, P. A., Cheeptham, N., Cooper, S. J., Culver, D. C., Deharveng, L., Eme, D., Ferreira, R. L., Fišer, C., Fišer, Ž, Fong, D. W., Griebler, C., Jeffery, W. R., Jugovic, J., Kowalko, J. E., Lilley, T. M., Malard, F., & Cardoso, P. (2020). Fundamental research questions in subterranean biology. *Biological Reviews*, *95*, 1855–1872.

Olarinoye, T., Gleeson, T., Marx, V., Seeger, S., Adinehvand, R., Allocca, V., Andreo, B., Apaéstegui, J., Apolit, C., Arfib, B., Auler, A., Bailly-Comte, V., Barberá, J. A., Batiot-Guilhe, C., Bechtel, T., Binet, S., Bittner, D., Blatnik, M., Bolger, T., & Auler, A. (2020). Global karst springs hydrograph dataset for research and management of the world's fastest-flowing groundwater. *Scientific Data*, *7*, 1–9. https://www.nature.com/articles/s41597-019-0346-5?sf230264220=1.

Redpath, S. M., Young, J., Evely, A., Adams, W. M., Sutherland, W. J., Whitehouse, A., Amar, A., Lambert, R. A., Linnell, J. D., Watt, A., & Gutierrez, R. J. (2013). Understanding and managing conservation conflicts. *Trends in Ecology & Evolution*, *28*, 100–109.

Sánchez-Fernández, D., Galassi, D. M. P., Wynne, J. J., Cardoso, P., & Mammola, S. (2021). Don't forget subterranean ecosystems in climate change agendas. *Nature Climate Change*, *11*, 458–459. https://www.nature.com/articles/s41558-021-01057-y.

Stange, M., Barrett, R. D., & Hendry, A. P. (2020). The importance of genomic variation for biodiversity, ecosystems and people. *Nature Reviews Genetics*, *22*, 89–105. https://www.nature.com/articles/s41576-020-00288-7.

[UNEP] United Nations Environment Project. (2021). 15th Convention on Biological Diversity, COP15. https://www.cbd.int/meetings/COP-15

How to cite this article: Wynne JJ, Howarth FG, Mammola S, et al. A conservation roadmap for the subterranean biome. *Conservation Letters*. 2021;*14:*e12834. https://doi.org/10.1111/conl.12834