Paleobiology

CAMBRIDGE
UNIVERSITY PRESS

Identifying the big questions in paleontology: A community-driven project

Journal:	*Paleobiology*
Manuscript ID	PAB-2024-0042.R2
Manuscript Type:	Review
Date Submitted by the Author:	n/a
Complete List of Authors:	Smith, Jansen; Paleontological Research Institution and its Museum of the Earth, Collections Dowding, Elizabeth; Friedrich-Alexander-Universitat Erlangen-Nurnberg Abdelhady, Ahmed; Minia University Faculty of Science, Abondio, Paolo; IRCCS Istituto Delle Scienze Neurologiche di Bologna Araújo, Ricardo; Universidade de Lisboa, Instituto de Plasmas e Fusão Nuclear & Centro de Recursos Naturais e Ambiente (CERENA), Instituto Superior Técnico Aze, Tracy; University of Plymouth, School of Biological and Marine Sciences Balisi, Mairin; Raymond M. Alf Museum of Paleontology; Natural History Museum of Los Angeles County, La Brea Tar Pits and Museum; University of California Merced, Department of Life and Environmental Sciences Buatois, Luis; University of Saskatchewan, Department of Geological Sciences Carvajal-Chitty, Humberto; Universidad Simón Bolívar, Departamento de Estudios Ambientales Chattopadhyay, Devapriya; IISER Pune, Earth and Climate Science Coiro, Mario; University of Vienna, Department of Palaeontology Dietl, Gregory; Paleontological Research Institution; Cornell University, Department of Earth and Atmospheric Sciences González Arango, Catalina; Universidad de los Andes, Departamento de Ciencias Biológicas Kevrekidis, Charalampos; Museum für Ur- und Ortsgeschichte Kimmig, Julien; Staatliches Museum für Naturkunde Karlsruhe; University

of North Dakota, The Harold Hamm School of Geology and Geological Engineering
Mychajliw, Alexis; Middlebury College, Department of Biology & Program in Environmental Studies; Natural History Museum of Los Angeles County, La Brea Tar Pits and Museum
Pimiento, Catalina; University of Zurich, Department of Paleontology; Swansea University, Department of Biosciences
Regalado Fernández, Omar; Senckenberg Forschungsinstitut und Naturmuseum, Curation
Schroeder, Katlin; Yale University, Institute for Biospheric Studies
Warnock, Rachel; Friedrich-Alexander-Universitat Erlangen-Nurnberg, Department of Geography and Geosciences
Yang, Tzu-Ruei; National Museum of Natural Science; National Chung Hsing University, Department of Life Sciences; National Cheng Kung University, Department of Earth Sciences
Yasuhara, Moriaki; The University of Hong Kong, School of Biological Sciences, Area of Ecology and Biodiversity, Swire Institute of Marine Science, Institute for Climate and Carbon Neutrality, and Musketeers Foundation Institute of Data Science; City University of Hong Kong, State Key Laboratory of Marine Pollution
Akita, Lailah; University of Ghana, Department of Marine and Fisheries Sciences
Allen, Bethany; ETH Zurich, Department of Biosystems Science and Engineering; Swiss Institute of Bioinformatics, Computational Evolution Group
Anderson, Brendan; Paleontological Research Institution and its Museum of the Earth,
Andréoletti, Jérémy; Université PSL, Institut de Biologie, École Normale Supérieure
Archuby, Fernando; Universidad Nacional de la Plata, Centro de Estudios Integrales de la Dinámica Exógena; Consejo Nacional de Investigaciones Científicas y Técnicas
Ballen, Gustavo; Universidade Estadual Paulista Julio de Mesquita Filho, Instituto de Biociências
Bari, Md. Ibrahimul; Indian Institute of Technology Bhubaneswar, Geology; JIS University, Geology
Benton, Michael; University of Bristol, Palaeobiology Research Group, School of Earth Sciences
Bergh, Eugene; North-West University, Unit for Environmental Sciences and Management
Brambilla, Luciano; Universidad Nacional de Rosario, Centro de Estudios Interdisciplinarios
Brombacher, Anieke; Yale University, Department of Earth & Planetary Sciences
Chan, Yong Kit Samuel; National University of Singapore, Department of Biological Sciences
Chiarenza, Alfio Alessandro; University College London, Department of Earth Sciences
Chinzorig, Tsogtbaatar; North Carolina State University at Raleigh, Department of Biological Sciences; Mongolian Academy of Sciences, Division of Paleozoology, The Institute of Paleontology; North Carolina Museum of Natural Sciences
Coates, Kadane; The University of the West Indies, Department of Chemistry
Cordie, David; Edgewood College, Division of Physical, Computational, and Mathematical Sciences
Cortés-Sánchez, Miguel; University of Seville, Department of Prehistory and Archaeology
Cruz-Vega, Eduardo; University of Puerto Rico Mayaguez, Geology
Cybulski, Jonathan; Smithsonian Tropical Research Institute; University of Rhode Island - Narragansett Bay Campus, Graduate School of

Oceanography
De Baets, Kenneth; University of Warsaw, Institute of Evolutionary Biology
De Entrambasaguas, Julia; Universidad de Zaragoza; Instituto Universitario de Investigación de Ciencias Ambientales de Aragón
Dillon, Erin; Smithsonian Tropical Research Institute; University of California Santa Barbara, Department of Ecology, Evolution, and Marine Biology
Du, Andrew; Colorado State University, Anthropology and Geography
Dunhill, Alexander; University of Leeds, School of Earth and Environment
Erlandson, Jon; University of Oregon, Museum of Natural & Cultural History
Forel, Marie-Béatrice; Centre de recherche en Paléontologie Paris, Muséum national d'Histoire naturelle
Foster, William; Universität Hamburg, Institute for Geology
Gates, Terry; North Carolina State University at Raleigh, Biological Sciences; North Carolina Museum of Natural Sciences, Paleontology
Gavryushkina, Alexandra; Canterbury University, School of Mathematics and Statistics
Grace, Molly; University of Oxford, Department of Biology
Grossart, Hans-Peter; Leibniz-Institute of Freshwater Ecology and Inland Fisheries in the Forschungsverbund Berlin eV, Plankton and Microbial Ecology; Potsdam University, Institute of Biochemistry and Biology
Hänsel, Patrick; Friedrich-Alexander-Universitat Erlangen-Nurnberg, GeoZentrum Nordbayern
Harnik, Paul; Colgate University, Department of Geology
Hopkins, Melanie; American Museum of Natural History, Division of Paleontology (Invertebrates)
Hopkins, Samantha; University of Oregon, Earth Sciences
keyi, Hu; Nanjing University, School of Earth Sciences and Engineering
Huang, Huai-Hsuan; Princeton University, Department of Geosciences
Irmis, Randall; University of Utah, Natural History Museum of Utah and Department of Geology & Geophysics
Jaques, Victory; Brno University of Technology Central European Institute of Technology, CTLab; Charles University, Institute of Geology and Palaeontology
Jenkins, Xavier; Idaho State University, Department of Biological Sciences
Jukar, Advait; University of Arizona, Department of Geosciences
Kelley, Patricia; University of North Carolina Wilmington, Earth and Ocean Sciences
Kihn, Romina; Consejo Nacional de Investigaciones Científicas y Técnicas; Universidad Nacional de La Pampa
Klompmaker, Adiël; University of Alabama, Department of Museum Research and Collections & Alabama Museum of Natural History
Kocsis, Ádám; Friedrich-Alexander-Universitat Erlangen-Nurnberg, GeoZentrum Nordbayern
Kriwet, Jürgen; UZAII, Department of Palaeontology; University of Vienna, Palaeontology
Lazarus, David; Retired
Liao, Chun-Chi; National Museum of Natural Science; Chinese Academy of Sciences
Lin, Chien-Hsiang; Academia Sinica, Biodiversity Research Center
Louys, Julien; Griffith University, Australian Research Centre for Human Evolution
Lozano-Fernandez, Jesus; University of Barcelona, Department of Genetics, Microbiology and Statistics & Biodiversity Research Institute (IRBio)
Lozano-Francisco, María; University of Málaga, Ecology and Geology
Lueders-Dumont, Jessica; Boston College, Earth and Environmental Sciences

Malvé, Mariano; IBIOMAR-CONICET
Martindale, Rowan; The University of Texas at Austin, Department of Earth and Planetary Sciences
Mazzini, Ilaria; CNR, Institute of Environmental Geology and Geoengineering (IGAG)
Modenini, Giorgia; University of Bologna, BiGeA Department
Mondal, Subhronil; Indian Institute of Science Education and Research Kolkata, Geology
Mondini, Mariana; Universidad Nacional de Córdoba, Laboratorio de Zooarqueología y Tafonomía de Zonas Áridas (LaZTA), Instituto de Antropología de Córdoba (IDACOR), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); Universidad de Buenos Aires, Facultad de Filosofía y Letras
Monferran, Mateo; Universidad Nacional del Nordeste, Ciencias de la Tierra, Centro de Ecologia Aplicada del Litoral
Mulvey, Laura; Friedrich-Alexander-Universität Erlangen-Nürnberg Naturwissenschaftliche Fakultät, Department of Geography and Geosciences
Nanglu, Karma; Harvard University, Museum of Comparative Zoology and Department of Organismic and Evolutionary Biology
Nguyen, Jacqueline; Australian Museum; Flinders University
Norris, Richard; University of California San Diego Scripps Institution of Oceanography
O'Dea, Aaron; Smithsonian Tropical Research Institute; Sistema Nacional de Investigación (SENACYT)
Ollendorf, Amy; Applied Earthworks Inc, Paleontology Division
Orihuela, Johanset; Florida International University, Department of Earth and Environment
Pandolfi, John; The University of Queensland, School of the Environment
Pereira, Telmo; Universidade Autónoma de Lisboa; Instituto Politécnico de Tomar; Universidade de Coimbra, Centro de Geociências; Universidade de Lisboa, Centro de Arqueologia
Piro, Alejandra; Universidad Nacional de la Plata, División Paleontología Vertebrados, Museo de La Plata, Facultad de Ciencias Naturales y Museo; Consejo Nacional de Investigaciones Científicas y Técnicas
Plotnick, Roy; University of Illinois at Chicago, Earth and Environmental Sciences
Plaza-Torres, Stephanie ; University of Colorado Boulder, Department of Geological Sciences
Porto, Arthur; Florida Museum of Natural History
Prieto-Márquez, Albert ; Universitat Autònoma de Barcelona, Institut Català de Paleontologia Miquel Crusafont (ICP-CERCA)
Punyasena, Surangi; University of Illinois at Urbana-Champaign, Plant Biology
Quental, Tiago; Universidade de São Paulo
Raja, Nussaïbah; Friedrich-Alexander-Universität Erlangen-Nürnberg,
Ranaivosoa, Voajanahary; Université d'Antananarivo, Mention Bassins Sedimentaires Evolution Conservation
Ribas-Deulofeu, Lauriane ; National Taiwan University, Institute of Oceanography
Rivals, Florent; Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA); Universitat Rovira i Virgili, Departament d'Història i Història de l'Art
Roden, Vanessa; Friedrich-Alexander-Universitat Erlangen-Nurnberg, GeoZentrum Nordbayern
Rosso, Antonietta; University of Catania, Department of Biological, Geological and Environmental Sciences
Saleh, Farid; University of Lausanne, Institute of Earth Sciences
Salvador, Rodrigo; UiT The Arctic University of Norway, The Arctic University Museum of Norway
Saupe, Erin; University of Oxford, Department of Earth Sciences

	Schneider, Simon; CASP Sclafani, Judith; University of California Davis, Earth and Planetary Sciences Smith, Martin; University of Durham, Earth Sciences Souron, Antoine; PACEA, Université de Bordeaux Steinbauer, Manuel; University of Bayreuth, Bayreuth Center of Ecology and Environmental Research (BayCEER) & Bayreuth Center of Sport Science (BaySpo) Stewart, Matthew; Griffith University, Australian Research Centre for Human Evolution Tambussi, Claudia; CONICET Cordoba, Centro de Investigaciones en Ciencias de la Tierra (CICTERRA) Thomas, Ellen; Yale University, Earth & Planetary Sciences; Wesleyan University, Earth & Environmental Sciences Tschopp, Emanuel; Universität Hamburg, Department of Animal Biodiversity; American Museum of Natural History, Department of Vertebrate Paleontology; Universidade Nova de Lisboa, GeoBioTec Tütken, Thomas; Johannes Gutenberg Universität Mainz Institut für Geowissenschaften, AG für Angewandte und Analytische Paläontologie Varela, Sara; Universidad de Vigo, Department of Ecology and Animal Biology Vezzosi, Raul; Centro de Investigaciones Científicas y Transferencia de Tecnología a la Producción, Laboratorio de Paleontologíia de Vertebrados; Universidad Autónoma de Entre Ríos, Cátedra de Paleontología, Facultad de Ciencia y Tecnología Villaseñor, Amelia; University of Arkansas, Anthropology Weinkauf, Manuel; Univerzita Karlova, Institute of Geology and Palaeontology Zanno, Lindsay; North Carolina Museum of Natural Sciences; North Carolina State University at Raleigh, Department of Biological Sciences Zhang, Chi; Institute of Vertebrate Paleontology and Paleoanthropology Chinese Academy of Sciences, Zhao, Qi; Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology Kiessling, Wolfgang; Friedrich-Alexander-Universitat Erlangen-Nurnberg, GeoZentrum Nordbayern
Geographic Location:	Global
Taxonomy:	All
Analysis:	Review
Geologic Age:	All
Topic:	paleontology
Abstract:	Paleontology provides insights into the history of the planet, from the origins of life billions of years ago to the biotic changes of the recent. The scope of paleontological research is as vast as it is varied, and the field is constantly evolving. In an effort to identify “Big Questions” in paleontology, experts from around the world came together to build a list of priority questions the field can address in the years ahead. The 89 questions presented herein (grouped in 11 themes) represent contributions from nearly 200 international scientists. These questions touch on common themes including biodiversity drivers and patterns, integrating data types across spatiotemporal scales, applying paleontological data to contemporary biodiversity and climate issues, and effectively utilizing innovative methods and technology for new paleontological insights. In addition to these theoretical questions, discussions touch upon structural concerns within the field, advocating for an increased valuation of specimen-based research, protection of natural

	heritage sites, and the importance of collections infrastructure, along with a stronger emphasis on human diversity, equity, and inclusion. These questions offer a starting point—an initial nucleus of consensus that paleontologists can expand on—for engaging in discussions, securing funding, advocating for museums, and fostering continued growth in shared research directions.

Identifying the big questions in paleontology: A community-driven project

Smith, J.A., Dowding, E.M.†, Abdelhady, A.A.†, Abondio, P.†, Araújo, R.†, Aze, T.†, Balisi, M.†, Buatois, L.A.†, Carvajal-Chitty, H.†, Chattopadhyay, D.†, Coiro, M.†, Dietl, G.P.†, González Arango, C.†, Kevrekidis, C.†, Kimmig, J.†, Mychajliw, A.M.†, Pimiento, C.†, Regalado Fernández, O.R.†, Schroeder. K.M.†, Warnock, R.C.M.†, Yang, T.R.†, Yasuhara, M.†, Akita, L.G., Allen, B.J., Anderson, B.M., Andréoletti, J., Archuby, F.M., Ballen, G.A., Bari, M.I., Benton, M.J., Bergh, E.W., Brambilla, L., Brombacher, A., Chan, Y.K.S., Chiarenza, A.A., Chinzorig, T., Coates, K.M., Cordie, D.R., Cortés-Sánchez, M., Cruz-Vega, E.J., Cybulski, J.D., De Baets, K., De Entrambasaguas, J., Dillon, E.M., Du, A., Dunhill, A.M., Erlandson, J.M., Forel, M.B., Foster, W.J., Gates, T.A., Gavryushkina, A., Grace, M.K., Grossart, H.P., Hänsel, P., Harnik, P.G., Hopkins, M.J., Hopkins, S., Hu, K., Huang, H.H.M., Irmis, R.B., Jaques, V.A.J., Jenkins, X.A., Jukar, A.M., Kelley, P.H., Kihn, R.G., Klompmaker, A.A., Kocsis, Á.T., Kriwet, J., Lazarus, D., Liao, C.C., Lin, C.H., Louys, J., Lozano-Fernandez, J., Lozano-Francisco, M.C., Lueders-Dumont, J.A., Malvè, M.E., Martindale, R.C., Mazzini, I., Modenini, G., Mondal, S., Mondini, M., Monferran, M.D., Mulvey, L.P.A., Nanglu, K., Nguyen, J.M.T., Norris, R., O'Dea, A., Ollendorf, A.L., Orihuela, J., Pandolfi, J.M., Pereira, T., Piro, A., Plotnick, R.E., Plaza-Torres, S.M., Porto, A., Prieto-Márquez, A., Punyasena, S.W., Quental, T.B., Raja, N.B., Ranaivosoa, V., Ribas-Deulofeu, L., Rivals, F., Roden, V.J., Rosso, A., Saleh, F., Salvador, R.B., Saupe, E.E., Schneider, S., Sclafani, J.A., Smith, M.R., Souron, A., Steinbauer, M.J., Stewart, M., Tambussi, C.P., Thomas, E., Tschopp, E., Tütken, T., Varela, S., Vezzosi, R.I., Villaseñor, A., Weinkauf, M.F.G., Zanno, L.E., Zhang, C., Zhao, Q., Kiessling, W.†

† indicates leadership role in a working group

Authors are listed alphabetically in two groups: working group leaders and group members

Corresponding: Jansen Smith (smithja@d.umn.edu)

RRH: BIG QUESTIONS IN PALEONTOLOGY

LRH: JANSEN A SMITH ET AL.

Abstract.—Paleontology provides insights into the history of the planet, from the origins of life billions of years ago to the biotic changes of the recent. The scope of paleontological research is as vast as it is varied, and the field is constantly evolving. In an effort to identify "Big Questions" in paleontology, experts from around the world came together to build a list of priority questions the field can address in the years ahead. The 89 questions presented herein (grouped in 11 themes) represent contributions from nearly 200 international scientists. These questions touch on common themes including biodiversity drivers and patterns, integrating data types across spatiotemporal scales, applying paleontological data to contemporary biodiversity and climate issues, and effectively utilizing innovative methods and technology for new paleontological insights. In addition to these theoretical questions, discussions touch upon structural concerns within the field, advocating for an increased valuation of specimen-based research, protection of natural heritage sites, and the importance of collections infrastructure, along with a stronger emphasis on human diversity, equity, and inclusion. These questions offer a starting point—an initial nucleus of consensus that paleontologists can expand on—for engaging in discussions, securing funding, advocating for museums, and fostering continued growth in shared research directions.

Resumen.—La paleontología permite conocer la historia del planeta, desde los orígenes de la vida hace miles de millones de años hasta los cambios bióticos de épocas recientes. El ámbito de la investigación paleontológica es tan vasto como variado y está en constante evolución. En un esfuerzo por identificar las "grandes preguntas" de la paleontología, expertos de todo el mundo se reunieron para elaborar una lista de cuestiones prioritarias que el campo puede abordar en los próximos años. Las 89 preguntas aquí presentadas (agrupadas en 11 temas) representan las contribuciones de casi 200 científicos internacionales. Estas preguntas se refieren a temas comunes, entre los que se incluyen los motores y patrones de la biodiversidad, la integración de tipos de datos a través de escalas espacio-temporales, la aplicación de datos paleontológicos en cuestiones contemporáneas de biodiversidad y clima, y la utilización eficaz de métodos y tecnologías innovadoras para obtener nuevos conocimientos paleontológicos. Además de estas interrogantes teóricas, los debates abordan inquietudes estructurales dentro del campo, y abogan por una mayor valoración de la investigación basada en especímenes, la protección de los sitios del patrimonio natural y la importancia de la infraestructura de las colecciones; junto con un mayor énfasis en la diversidad humana, la equidad y la inclusión. Estas preguntas representan un punto de partida—un núcleo inicial de consenso que los paleontólogos pueden ampliar—para fomentar debates, obtener financiación, abogar por el apoyo continuo de los museos y estimular el crecimiento continuo en direcciones de investigación compartidas.

Riassunto — La paleontologia offre spunti fondamentali per comprendere la storia del pianeta, dalle origini della vita miliardi di anni fa fino ai cambiamenti biotici più recenti. L'ambito della ricerca paleontologica è tanto vasto quanto diversificato e rappresenta un campo in continua evoluzione. In questo studio, esperti provenienti da tutto il mondo si sono riuniti per redigere un elenco di "Grandi Domande" prioritarie che la paleontologia potrà affrontare nei prossimi anni. Le 89 domande qui presentate, raggruppate in 11 temi, rappresentano il contributo di circa 200 scienziati internazionali. Queste domande riguardano tematiche come i meccanismi e i pattern di biodiversità, l'integrazione di varie tipologie di dati su scale spazio-temporali multiple, l'applicazione delle conoscenze paleontologiche ai problemi attuali di crisi della biodiversità e climatica, e l'uso efficace di metodi e tecnologie innovative per ottenere nuove intuizioni

paleontologiche. Oltre a questi temi teorici, la discussione si focalizza su problematiche strutturali del campo, promuovendo una maggiore valorizzazione della ricerca basata sui campioni, la protezione dei siti di interesse culturale e paleontologico, e l'importanza delle infrastrutture per preservare le collezioni, insieme a una crescente enfasi su un apporto multiculturale, equo e inclusivo. Queste domande costituiscono un punto di partenza — un nucleo di consenso iniziale che i paleontologi possono espandere — per avviare discussioni, ottenere finanziamenti, promuovere i musei e favorire una crescita continua verso direzioni condivise di ricerca.

Author Affiliations:

Jansen A. Smith. Department of Earth and Atmospheric Sciences, University of Minnesota Duluth, Duluth, Minnesota 55812 USA; GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: smithja@d.umn.edu

Elizabeth M. Dowding†. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: dowdingem@gmail.com

Ahmed Awad Abdelhady†. Geology Department, Minia University, Al Minya, Al Minya 61519 Egypt; Email: ahmed.abdelhady@mu.edu.eg

Paolo Abondio†. IRCCS Istituto delle Scienze Neurologiche di Bologna, Bologna, Emilia-Romagna 40139 Italy; Email: paolo.abondio2@unibo.it

Ricardo Araújo†. Instituto de Plasmas e Fusão Nuclear & Centro de Recursos Naturais e Ambiente (CERENA), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, 1049-001 Portugal; Email: ricardo.araujo@tecnico.ulisboa.pt

Tracy Aze†. School of Biological and Marine Sciences, University of Plymouth, Plymouth, Devon PL4 8AA United Kingdom; Email: tracy.aze@plymouth.ac.uk

Mairin Balisi†. Raymond M. Alf Museum of Paleontology, Claremont, California 91711 United States; La Brea Tar Pits and Museum, Natural History Museums of Los Angeles County, Los Angeles, California 90036 United States; Department of Life and Environmental Sciences, University of California-Merced, Merced, California 95343 USA; Email: mbalisi@alfmuseum.org

Luis A. Buatois†. Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E2 Canada; Email: luis.buatois@usask.ca

Humberto Carvajal-Chitty†. Departamento de Estudios Ambientales, Universidad Simón Bolívar, Valle de Sartenejas, Baruta/Miranda 89000 Venezuela; Email: hchitty@usb.ve

Devapriya Chattopadhyay†. Department of Earth and Climate Science, IISER Pune, Pune, MH 411008 India; Email: devapriya@iiserpune.ac.in

Mario Coiro†. Department of Palaeontology, University of Vienna, Vienna, Vienna 1090 Austria; Email: mar.coiro@gmail.com

Gregory P. Dietl†. Paleontological Research Institution, Ithaca, NY 14850 USA; Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853 USA; Email: gpd3@cornell.edu

Catalina González Arango†. Departamento de Ciencias Biológicas, Universidad de los Andes, Bogotá, 111711 Colombia; Email: c.gonzalez2579@uniandes.edu.co

Charalampos Kevrekidis†. Museum für Ur- und Ortsgeschichte, Museumszentrum Quadrat, Bottrop, Nordrhein-Westfalen 46236 Germany; Email: Charalampos.Kevrekidis@bottrop.de

Julien Kimmig†. Paläontologie und Evolutionsforschung, Abteilung Geowissenschaften, Staatliches Museum für Naturkunde Karlsruhe, 76133 Karlsruhe, Germany; Harold Hamm School of Geology and Geological Engineering, University of North Dakota, Grand Forks, ND 58202, United States of America; Email: julien.kimmig@smnk.de

Alexis M. Mychajliw†. Department of Biology & Program in Environmental Studies, Middlebury College, Middlebury, Vermont 05753 USA; La Brea Tar Pits and Museum, Natural History Museums of Los Angeles County, Los Angeles, California 90036 United States; Email: amychajliw@middlebury.edu

Catalina Pimiento†. Department of Paleontology, University of Zurich, Zurich, 8006 Switzerland; Department of Biosciences, Swansea University, Swansea, SA28PP United Kingdom; Email: catalina.pimientohernandez@pim.uzh.ch

Omar Rafael Regalado Fernández†. Curation, Senckenberg Naturmuseum Frankfurt, Frankfurt am Main, Hesse 60395 Germany; Email: omar-rafael.regalado-fernandez@senckenberg.de

Katlin M. Schroeder†. Institute for Biospheric Studies, Yale University, New Haven, Connecticut 06520 United States of America; Email: Kat.schroeder@yale.edu

Rachel C. M. Warnock†. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: rachel.warnock@fau.de

Tzu-Ruei Yang†. Department of Geology, National Museum of Natural Science, Taichung 404023 Taiwan; Department of Life Sciences, National Chung Hsing University, Taichung, 402202 Taiwan; Department of Earth Sciences, National Cheng Kung University, Tainan, 701401 Taiwan; Email: tzurueiyang@nmns.edu.tw

Moriaki Yasuhara†. School of Biological Sciences, Area of Ecology and Biodiversity, Swire Institute of Marine Science, Institute for Climate and Carbon Neutrality, and Musketeers Foundation Institute of Data Science, The University of Hong Kong, Hong Kong SAR, China; State Key Laboratory of Marine Pollution, City University of Hong Kong, Kowloon, Hong Kong SAR, China; Email: moriakiyasuhara@gmail.com or yasuhara@hku.hk

Lailah Gifty Akita. Department of Marine and Fisheries Sciences, University of Ghana, P.O. Box LG 99, Legon-Campus, Greater-Accra, Ghana; Email: lgakita@ug.edu.gh

Bethany J. Allen. Department of Biosystems Science and Engineering, ETH Zurich, Basel, Basel-Stadt 4056 Switzerland; Computational Evolution Group, Swiss Institute of Bioinformatics, Lausanne, Vaud 1015 Switzerland; Email: bethany.allen@bsse.ethz.ch

Brendan M. Anderson. Paleontological Research Institution, Ithaca, New York 14850, USA; Email: BMA53@Cornell.edu

Jérémy Andréoletti. Institut de Biologie, École Normale Supérieure, Université PSL, CNRS, INSERM, Paris, 75005 France; Email: jeremy.andreoletti@gmail.com

Fernando M. Archuby. Centro de Estudios Integrales de la Dinámica Exógena, Universidad Nacional de La Plata, La Plata (1900), Provincia de Buenos Aires, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Ciudad Autónoma de Buenos Aires, CABA C1425FQB Argentina; Email: farchuby@gsuite.fcnym.unlp.edu.ar

Gustavo A. Ballen. Instituto de Biociências, Universidade Estadual Paulista "Júlio de Mesquita Filho", Botucatu, SP 18618-689 Brazil; Email: gustavo.a.ballen@gmail.com

Md. Ibrahimul Bari. Geology, Indian Institute of Technology Bhubaneswar, Bhubaneswar, Odisha 752050 India; Geology, JIS University, Kolkata, West Bengal 700109 India; Email: md.ibrahimul.bari@gmail.com

Michael J. Benton, Palaeobiology Research Group, School of Earth Sciences, University of Bristol, Life Sciences Building, Bristol, BS8 1TQ, U.K.; Email: mike.benton@bristol.ac.uk

Eugene W. Bergh. Unit for Environmental Sciences and Management, North-West University, Potchefstroom, 2531 South Africa; Email: eugene.bergh@nwu.ac.za

Luciano Brambilla. Centro de Estudios Interdisciplinarios, Universidad Nacional de Rosario, Rosario, Santa Fe 2000 Argentina; Email: lbrambilla@fbioyf.unr.edu.ar

Anieke Brombacher. Department of Earth & Planetary Sciences, Yale University, New Haven, Connecticut 06511 USA; Email: anieke.brombacher@yale.edu

Yong Kit Samuel Chan. Department of Biological Sciences, National University of Singapore, Singapore, 117558 Singapore; Email: samuelchanyk@gmail.com

Alfio Alessandro Chiarenza. Department of Earth Sciences, University College London, London, London WC1E 6BS UK; Email: a.chiarenza15@gmail.com

Tsogtbaatar Chinzorig. Department of Biological Sciences, North Carolina State University, Raleigh, North Carolina 27695 USA; Division of Paleozoology, The Institute of Paleontology, Mongolian Academy of Sciences, Ulaanbaatar, 15160 Mongolia; North Carolina Museum of Natural Sciences, Raleigh, North Carolina 27601 USA Email: ctsogtb@ncsu.edu

Kadane M. Coates. Department of Chemistry, The University of the West Indies, Mona, Kingston, JMAAW15 Jamaica; Email: kadanecoates@yahoo.com

David R. Cordie. Division of Physical, Computational, and Mathematical Sciences, Edgewood College, Madison, Wisconsin 53711 USA; Email: dcordie@edgewood.edu

Miguel Cortés-Sánchez. Department of Prehistory and Archaeology. University of Seville, Sevilla, 41004 España; Email: mcortes@us.es

Eduardo J. Cruz-Vega. Geology, The University of Puerto Rico, Mayagüez Campus, Mayagüez , Puerto Rico 00680 USA; Email: eduardo.cruz1@upr.edu

Jonathan D. Cybulski. Smithsonian Tropical Research Institute, Balboa, 0843, Republic of Panamá; Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882 U.S.A.; Email: cybulski.j@gmail.com

Kenneth De Baets. Institute of Evolutionary Biology, University of Warsaw, Faculty of Biology, Warsaw, 02-089 Poland; Email: k.de-baets@uw.edu.pl

Julia De Entrambasaguas. Departamento de Ciencias de la Tierra, Universidad de Zaragoza, Zaragoza, 50009 Spain; Instituto Universitario de Investigación de Ciencias Ambientales de Aragón (IUCA), Zaragoza, 50009 Spain; Email: jdeentrambasaguas@unizar.es

Erin M. Dillon. Smithsonian Tropical Research Institute, Balboa, 0843, Republic of Panamá; Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, Santa Barbara, California 93106 U.S.A.; Email: emdillon23@gmail.com

Andrew Du. Department of Anthropology & Geography, Colorado State University, Fort Collins, Colorado 80523 United States; Email: Andrew.Du2@colostate.edu

Alexander M. Dunhill. School of Earth and Environment, University of Leeds, Leeds, LS2 9JT UK; Email: a.dunhill@leeds.ac.uk

Jon M. Erlandson. Museum of Natural & Cultural History, University of Oregon, Eugene, Oregon 97403-1224 USA; Email: jerland@uoregon.edu

Marie-Béatrice Forel. Muséum national d'Histoire naturelle. Centre de Recherche en Paléontologie - Paris (CR2P). 8 rue Buffon, 75005 Paris, France; Email: marie-beatrice.forel@mnhn.de

William J. Foster. Institute for Geology, Universität Hamburg, Hamburg, 20146 Germany; Email: william.foster@uni-hamburg.de

Terry A. Gates. Biological Sciences, North Carolina State University, Raleigh, North Carolina 27695 United States; Paleontology, North Carolina Museum of Natural Sciences, Raleigh, North Carolina 27611 United States; Email: tagates@ncsu.edu

Alexandra Gavryushkina. School of Mathematics and Statistics, Canterbury University, Christchurch, Canterbury 8041 New Zealand; Email: sasha.gavryushkina@canterbury.ac.nz

Molly K. Grace. Department of Biology, University of Oxford, Oxford, OX1 3SZ United Kingdom; Email: molly.grace@biology.ox.ac.uk

Hans-Peter Grossart. Plankton and Microbial Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), 16775-Stechlin, Germany; Institute of Biochemistry and Biology, Potsdam University, 14469-Potsdam, Germany; Email: hanspeter.grossart@igb-berlin.de

Patrick Hänsel. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: patrick.haensel@fau.de

Paul G. Harnik. Department of Earth and Environmental Geosciences, Colgate University, Hamilton, New York 13346 USA; Email: pharnik@colgate.edu

Melanie J. Hopkins. Division of Paleontology (Invertebrates), American Museum of Natural History, New York, New York 10024 USA; Email: mhopkins@amnh.org

Samantha Hopkins. Department of Earth Sciences and Museum of Natural and Cultural History, University of Oregon, Eugene, Oregon 97403 USA; Email: shopkins@uoregon.edu

Keyi Hu. School of Earth Sciences and Engineering, Nanjing University, Nanjing, Jiangsu 210023 China; Email: Kyhu@nju.edu.cn

Huai-Hsuan M. Huang. Department of Geosciences, Princeton University, Princeton, New Jersey 08545 USA; Email: hh6077@princeton.edu

Randall B. Irmis. Natural History Museum of Utah and Department of Geology & Geophysics, University of Utah, Salt Lake City, Utah 84108-1214 U.S.A.; Email: irmis@umnh.utah.edu

Victory A. J. Jaques. CTLab, Central European Institute of Technology - Brno University of Technology, Brno, Moravia 61200 Czech Republic; Institute of Geology and Palaeontology, Charles University, Prague, Bohemia 128 43 Czech Republic; Email: victory.jaques@gmail.com

Xavier A. Jenkins. Department of Biological Sciences, Idaho State University, Pocatello, Idaho 83201 USA; Email: xavierjenkins@isu.edu

Advait M. Jukar. Department of Geosciences, University of Arizona, Tucson, AZ 85721 USA; Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington DC 20013 USA; Division of Vertebrate Paleontology, Yale Peabody Museum, New Haven, CT 06520 USA; Email: advaitjukar@arizona.edu

Patricia H. Kelley. Earth and Ocean Sciences, University of North Carolina Wilmington, Wilmington, NC 28461-5944 USA; Email: kelleyp@uncw.edu

Romina G. Kihn. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santa Rosa, La Pampa 6300 Argentina; Universidad Nacional de La Pampa (UNLPam), Santa Rosa, La Pampa 6300 Argentina; Email: rgkihn@gmail.com

Adiël A. Klompmaker. Department of Museum Research and Collections & Alabama Museum of Natural History, University of Alabama, Tuscaloosa, Alabama 35487 USA; Email: adielklompmaker@gmail.com

Ádám T. Kocsis. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: adam.kocsis@fau.de

Jürgen Kriwet. Department of Palaeontology, UZAII; Geocentre, University of Vienna, Josef-Holaubek-Platz 2, Vienna, 1090 Austria; Email: juergen.kriwet@univie.ac.at

David Lazarus. Retired. Berlin, Germany; Email: raddaveb@icloud.com

Chun-Chi Liao. National Museum of Natural Science, Taichung, 404605 Taiwan; Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, 100044 China; Email: jacky340@yahoo.com.tw

Chien-Hsiang Lin. Biodiversity Research Center, Academia Sinica, Taipei, 11529 Taiwan; Email: chlin.otolith@gmail.com

Julien Louys. Australian Research Centre for Human Evolution, Griffith University, Brisbane, Queensland 4111 Australia; Email: j.louys@griffith.edu.au

Jesus Lozano-Fernandez. Department of Genetics, Microbiology and Statistics & Biodiversity Research Institute (IRBio), University of Barcelona, Barcelona, 08028 Spain; Email: jesus.lozano@ub.edu

María C. Lozano-Francisco. Ecology and Geology, University of Málaga, Málaga, 29010 Spain; Email: mclozano@uma.es

Jessica A. Lueders-Dumont. Earth and Environmental Sciences, Boston College, Chestnut Hill, Massachusetts 02467 United States; Email: jessica.lueders-dumont@bc.edu

Mariano Ezequiel Malvé. IBIOMAR-CONICET, Blvd. Brown 2915, Puerto Madryn, Chubut U9120 Argentina; Email: marianomalve@gmail.com

Rowan C. Martindale. Department of Earth and Planetary Sciences, The University of Texas at Austin, Austin, Texas 78712 United States; Email: Martindale@jsg.utexas.edu

Ilaria Mazzini. Institute of Environmental Geology and Geoengineering (IGAG), CNR - National Research Council of Italy, Rome, 00185 Italy; Email: ilaria.mazzini@cnr.it

Giorgia Modenini. BiGeA Department, University of Bologna, Bologna, 40126 Italy; Email: giorgia.modenini2@unibo.it

Subhronil Mondal. Department of Earth Sciences, Indian Institute of Science Education and Research (IISER) Kolkata, Mohanpur, West Bengal 741246 INDIA; Email: subhronil.m@gmail.com

Mariana Mondini. Laboratorio de Zooarqueología y Tafonomía de Zonas Áridas (LaZTA), Instituto de Antropología de Córdoba (IDACOR), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) - Universidad Nacional de Córdoba, Córdoba, 5000 Argentina; Facultad de Filosofía y Letras, Universidad de Buenos Aires, Ciudad Autónoma de Buenos Aires, 1406 Argentina; Email: mmondini@conicet.gov.ar

Mateo Daniel Monferran. Ciencias de la Tierra, Centro de Ecologia Aplicada del Litoral - Universidad Nacional del Nordeste, Corrientes, Corrientes 3400 Argentina; Email: monfdm@gmail.com

Laura P.A. Mulvey. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: laura.l.mulvey@fau.de

Karma Nanglu. Museum of Comparative Zoology and Department of Organismic and Evolutionary Biology, Harvard University, 26 Oxford Street, Cambridge, MA 02138, USA; Email: knanglu@fas.harvard.edu

Jacqueline M.T. Nguyen. Australian Museum, Sydney, New South Wales 2010 Australia; Flinders University, Adelaide, South Australia 5042 Australia; Email: jacqueline.nguyen@australian.museum

Richard Norris. Scripps Institution of Oceanography, University of California, La Jolla, California, 92093-0244 USA; Email: rnorris@ucsd.edu

Aaron O'Dea. Smithsonian Tropical Research Institute, Balboa, 0843, Republic of Panamá; Sistema Nacional de Investigación (SENACYT), Panamá, Republic of Panamá; Email: odeaa@si.edu

Amy L. Ollendorf. Paleontology Division, Applied EarthWorks, Inc., Pasadena, California 91107 USA; Email: aollendorf@appliedearthworks.com

Johanset Orihuela. Department of Earth and Environment, Florida International University, Miami, Florida 33199 USA; Email: Paleonycteris@gmail.com

John M. Pandolfi. School of the Environment, The University of Queensland, St Lucia, Queensland 4072 Australia; Email: j.pandolfi@uq.edu.au

Telmo Pereira. Universidade Autónoma de Lisboa, Lisbon, 1169-023; Instituto Politécnico de Tomar, Tomar, 2300-313; CGeo, Centro de Geociências da Universidade de Coimbra, Coimbra, 3030-790; UNIARQ, Centro de Arqueologia da Universidade de Lisboa, Lisboa, 1600-214, Portugal; Email: telmojrpereira@gmail.com

Alejandra Piro. División Paleontología Vertebrados, Museo de La Plata, Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Paseo del Bosque S/N, La Plata, Buenos Aires, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas

(CONICET), Ciudad Autónoma de Buenos Aires, CABA C1425FQB Argentina; Email: apiro@fcnym.unlp.edu.ar

Roy E. Plotnick. Department of Earth and Environmental Sciences, University of Illinois Chicago, Chicago, Illinois 60607 USA; E-mail: plotnick@uic.edu

Stephanie Marie Plaza-Torres. Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado 80309 United States of America; Email: stephanie.plazatorres@gmail.com

Arthur Porto. Florida Museum of Natural History, University of Florida, Gainesville, FL 32605 US; Email: arthur.porto@ufl.edu

Albert Prieto-Márquez. Institut Català de Paleontologia Miquel Crusafont (ICP-CERCA), Universitat Autònoma de Barcelona, c/ Escola Industrial 23, 08201 Sabadell, Barcelona, Spain; Email: albert.prieto@icp.cat

Surangi W. Punyasena. Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA; Email: spunya1@illinois.edu

Tiago B. Quental. Departamento de Ecologia, Universidade de São Paulo, São Paulo, SP 05508-090 Brazil; Email: tbquental@usp.br

Nussaïbah B. Raja. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: nussaibah.raja.schoob@fau.de

Voajanahary Ranaivosoa. Mention Bassins Sedimentaires Evolution Conservation, Université d'Antananarivo, Faculté des Sciences, Antananarivo101, Madagascar; Email: rnvoaj@gmail.com

Lauriane Ribas-Deulofeu. Institute of Oceanography, National Taiwan University, Taipei, Taipei 106 Taiwan; Email: lauriane.ribas@gmail.com

Florent Rivals. Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Tarragona, 43007 Spain; ICREA, Barcelona, 08010 Spain; Departament d'Història i Història de l'Art, Universitat Rovira i Virgili, 43002 Tarragona, Spain; Email: florent.rivals@icrea.cat

Vanessa Julie Roden. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: vanessa.roden@posteo.net

Antonietta Rosso. Department of Biological, Geological and Environmental Sciences, University of Catania, 95129-Catania, Italy; Email: rosso@unict.it

Farid Saleh. Institute of Earth Sciences, University of Lausanne, Lausanne, Vaud 1004 Switzerland; Email: farid.nassim.saleh@gmail.com

Rodrigo B. Salvador. Finnish Museum of Natural History, University of Helsinki, Helsinki, Uusimaa 00100 Finland; The Arctic University Museum of Norway, UiT - The Arctic University of Norway, Tromsø, Troms og Finnmark 9006 Norway; Email: salvador.rodrigo.b@gmail.com

Erin E. Saupe. Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN United Kingdom; Email: eesaupe@gmail.com

Simon Schneider. CASP, Cambridge, CB3 0UD United Kingdom; Email: simon.schneider@casp.org.uk

Judith A. Sclafani. Earth and Planetary Sciences, University of California Davis, Davis, CA 95616 USA; Email: jasclafani@gmail.com

Martin R. Smith. Earth Sciences, University of Durham, Durham, England DH1 3LE UK; Email: martin.smith@durham.ac.uk

Antoine Souron. Univ. Bordeaux, CNRS, Ministère de la Culture, PACEA, UMR 5199, F-33600 Pessac, France; Email: antoine.souron@u-bordeaux.fr

Manuel J. Steinbauer. Bayreuth Center of Ecology and Environmental Research (BayCEER) & Bayreuth Center of Sport Science (BaySpo), University of Bayreuth, Bayreuth, 95448 Germany; Email: Manuel.Steinbauer@uni-bayreuth.de

Mathew Stewart. Australian Research Centre for Human Evolution, Griffith University, Brisbane, Australia, Brisbane, QLD 4111 Australia; Email: mathew.stewart@griffith.edu.au

Claudia P. Tambussi. Centro de Investigaciones en Ciencias de la Tierra (CICTERRA), UNC, CONICET, Avenida Vélez Sársfield 1611, X5016GCA, Córdoba, Argentina, Email: tambussi.claudia@conicet.gov.ar; tambussi@gmail.com

Ellen Thomas. Earth & Planetary Sciences, Yale University, New Haven, CT 06511 USA; Earth & Environmental Sciences, Wesleyan University, Middletown, CT 06459 USA; Email: ellen.thomas@yale.edu

Emanuel Tschopp. Department of Animal Biodiversity, Universität Hamburg, Hamburg, 20146 Germany; Department of Vertebrate Paleontology, American Museum of Natural History, New York City, NY 10024 USA; GeoBioTec, Universidade NOVA de Lisboa, Caparica, 2829-516 Portugal; Email: emanuel.tschopp@uni-hamburg.de

Thomas Tütken. AG für Angewandte und Analytische Paläontologie, Institut für Geowissenschaften, Mainz, 55128 Germany; Email: tuetken@uni-mainz.de

Sara Varela. Department of Ecology and Animal Biology, Universidade de Vigo, Vigo, Galicia 36310 Spain; Email: sara.varela@uvigo.gal

Raul Ignacio Vezzosi. Laboratorio de Paleontologíia de Vertebrados, Centro de Investigaciones Científicas y Transferencia de Tecnología a la Producción (CONICET, Gob. E.R., UADER), España 149, Diamante E3105BWA, Argentina; Cátedra de Paleontología, Facultad de Ciencia y Tecnología, Universidad Autónoma de Entre Ríos, Diamante, Entre Ríos E3105BWA Argentina; Email: vezzosiraul@gmail.com

Amelia Villaseñor. Anthropology, University of Arkansas, Fayetteville, Arkansas 72764 United States; Email: avillase@uark.edu

Manuel F. G. Weinkauf. Institute of Geology and Palaeontology, Univerzita Karlova, Prague, 128 43 Czech Republic; Email: weinkauf.scientific@gmail.com

Lindsay E. Zanno. Paleontology, North Carolina Museum of Natural Sciences, Raleigh, North Carolina 27601 USA; Department of Biological Sciences, North Carolina State University, Raleigh, North Carolina 27695 USA; Email: lindsay.zanno@naturalsciences.org

Chi Zhang. Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, 100044 China; Email: zhangchi@ivpp.ac.cn

Qi Zhao. Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, 100044 China; Email: zhaoqi@ivpp.ac.cn

Wolfgang Kiessling†. GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91054 Germany; Email: wolfgang.kiessling@fau.de

Introduction

Paleontology offers an important scientific contribution by asking questions about life throughout the billions of years of Earth's history. The field itself has expanded from one based principally on collecting and documenting fossils to a hypothesis-driven, evidence-based field of inquiry using increasingly-complex data, analytical approaches, and computational techniques. Paleontologists examine a range of topics about the history of life, including extinction, the evolution of organisms, biodiversity, the impact of climate changes, and the complex dynamics between life and other components of the Earth system. These comprehensive studies of life in the past provide critical context for understanding life on the planet today and the possible responses to ongoing environmental changes.

As in all scientific disciplines, the questions pursued by paleontologists fall on a spectrum, from large overarching questions that are central to the discipline to questions that are more specific and focus on smaller scales, pressing topics, or contribute a component for addressing broader questions. The large overarching questions are likely to be persistent, but we can begin to address these grand themes by asking specific questions at various levels of resolution. For example, while a consensus exists on the principal features of the broad trajectory of life preserved in the fossil record, continued and closer examination of the record is required to resolve the details of evolutionary processes, environmental perturbations, and random effects that led to the modern configuration of life on Earth. As the resolution of studies becomes more specific, questions can range from "to which taxon does this specimen belong?" to questions such as "what is the role of abiotic and biotic interactions in driving biodiversity patterns?" Whereas "smaller" questions like the former are foundational to studying paleontology and merit support on their own, it is questions such as the latter (i.e., a "big question") that are the scope of this paper, as they indicate the current state of the discipline and its aims for future scientific development.

Through the "Big Questions" project detailed herein, we seek to provide a roadmap for how paleontological research might develop in the coming years, as prioritized by members of the paleontological community. A big question (BQ) is defined here as an open-ended question of high scientific importance that can be answered within a reasonable timeframe. Defined in this way, BQs become priority questions that can be used to emphasize the importance of the discipline to the larger research community, as well as to direct scientific effort and research funding (Sutherland et al. 2009; Willis and Bhagwat 2010; Parsons et al. 2014; Seddon et al. 2014). For our purposes, we considered a "reasonable timeframe" to be several years, though some questions may require a longer duration to address (e.g., the duration of a career). The amount of time needed to answer a BQ with precision and accuracy is variable and dependent on many factors, including technological advances and available resources.

The answer to a BQ should represent a substantive leap forward in the community's understanding of an issue or address a knowledge gap. "Scientific importance" requires examination of the perceived value of a BQ within the paleontological community, the broader scientific community, and its transference to society at large. Incorporating a diverse set of individuals engaged in paleontological research increases the confidence with which we can present research directions that can justifiably be defined as scientifically important to the international paleontological community. As such, the BQs project represents a democratic perspective of the paleontological discipline by individuals conducting germane research; we acknowledge that this effort was influenced by the opinions of those who participated, who represent a small percentage of the global paleontological community.

As the discipline of paleontology continues to grow in scope and application, paleontologists have a responsibility to routinely reflect on, criticize, discuss, and refine research directions, the best practices for conducting professional activities, and the cohesion of the discipline across geopolitical boundaries. Here we present the outputs of such an effort, providing an examination of the current state of paleontological research as expressed by the questions pursued in this discipline.

Methods

Project Contributors

The "Big Questions" project is a community initiative, coordinated through the PaleoSynthesis Project, that sought to engage a broad range of scientists working in paleontology and related disciplines (e.g., archaeology, biology, climate science, geology). Members of the Big Questions coordination team (JAS, WK) invited participation from the community through three solicitations requesting the submission of BQs in 2020 and 2021. The first solicitation was distributed in June 2020 using the PaleoNet listserver and to members of societies including the Palaeontological Association, Paleontological Society, and Paläontologische Gesellschaft. To reach a broader audience, the coordination team issued a second call in January 2021, again using PaleoNet but expanding to include social media (Facebook, Twitter - now X) and listservers for the Ecological Society of America (Ecolog-L) and the Conservation Paleobiology Network (CPN-L).

In March 2021, the first virtual, plenary meeting was held for those individuals who indicated they would like to contribute to the project. As an outcome, participants in the meeting recognized that the group was dominated by individuals from the United States and Europe

(Table 1). Consequently, a third solicitation was distributed in late March 2021 using the same approach as the second solicitation, this time with versions in English, French, Italian, Chinese, and Spanish (reflecting widely spoken language proficiencies in the existing group of participants). Participants involved *via* the first two solicitations were encouraged to use their personal networks to invite participants from places and with backgrounds not already represented in the project.

Working Group Assignments

As a part of the first two solicitations, participants were asked to submit questions they felt were outstanding in the field of paleontology (Table 2). The coordination team then created twelve themes that captured as much of the variation as possible from the submitted questions. Individuals who joined the BQ project during the third solicitation were asked to self-select the best category for their questions since the twelve themes had already been established. All assignments (from all solicitations) were checked for consistency and, when a question pertained to multiple themes, it was assigned to each relevant theme (Figure 2). Ten of the groups focused on scientific questions (one of which was dropped due to overlaps with questions in related groups; Table 2) and two groups centered on structural issues relating to how paleontology is practiced, as scientific questions and scientific practice are not distinct domains.

All participating individuals were asked to rank their top five theme preferences (Table 2) and assigned to their highest available preference, while attempting to balance numbers and diverse group composition using inferences regarding aspects to participants' identities (e.g., career stage, country, gender identity). Such inferences are undoubtedly flawed (e.g., institutional affiliation may not reflect a participant's nationality), but were an attempt to form diverse groups using incomplete information. Participants were given the additional option to join one of the groups addressing structural issues (Fundamental Issues, Looking Inward and Outward). All participants were given the option to volunteer as a working group leader, and one to three leaders were selected for each group from those volunteers, with consideration for representation of the diverse backgrounds of individuals participating in the project.

Refinement of Big Questions

Under the direction of working group leaders, the working groups were tasked with refining the set of questions assigned to their theme (Supplemental Material 1) into a condensed set of 8 – 12 preliminary questions. As a guide for this process, all were asked to consider the following discrete criteria (from Sutherland et al. 2009) for what a BQ entails:

1. Addresses an important gap in knowledge
2. More than just a general topic area (e.g., “climate change”)
3. Answerable through a realistic research design
4. Has a spatial and temporal scale that can be addressed by a research team
5. Has a factual answer that does not depend on value judgments
6. Tends not to be situationally dependent (i.e., answerable with “it all depends”)
7. Is not likely to be answerable with “yes” or “no”

Groups accomplished this goal through a combination of strategies, chosen by group leaders, including one or more of: (1) separating questions into sub-themes and condensing on common ideas; (2) formation of subgroups to evaluate subsets of questions; (3) virtual meetings to discuss refinements; and, (4) drafting of questions to combine those that existed or cover omitted topics.

Following refinement of the preliminary questions by each group, all questions were compiled for cross-group comments. Participants were asked to suggest revisions, evaluate the importance of each question, and identify overlaps. The coordination team then compiled and summarized responses according to the importance of questions and overlaps. Group leaders coordinated efforts within and among groups to refine the questions further on the basis of this compiled information (Tables 3 – 13). Finally, each working group drafted text to contextualize their questions, forming the first version of this manuscript.

The Big Questions in Paleontology

The three solicitations for submission of Big Questions resulted in 528 contributed questions. (Supplemental Material 1: Raw Questions). The number of questions assigned to a given theme ranged from 14 to 76 (Table 2). Groups refined these questions (Supplemental Material 1: Preliminary Questions) to a preliminary list including 4 – 16 questions from each group (Table 2).

After feedback from all BQ participants, working groups again refined their questions, producing 5 – 10 final questions from each group (Table 2; Figure 1). The BQs are available in Tables 3 – 13 (in non-ordered lists from each group), clustered in related themes, starting with questions pertaining to topics that might affect any paleontological study (e.g., preservation, scaling, taxonomy). In the eleven sections that follow, explanatory text accompanies the set of questions from each working group, with questions referred to in the text by working group acronyms (see section headers and tables for acronyms) and non-ordered, unranked numbering. Given the strong relationships among different areas of research in paleontology, there are overlaps in the topics of some questions, which can be taken to indicate important, cross-cutting themes within the discipline (Figure 2).

The Adequacy of the Fossil Record (AFR; Table 3)

The fossil record is our primary window into the origin and evolution of life on Earth, providing the only direct line of evidence for these events. Yet, the fossil record is composed primarily of organisms with anatomical, behavioral, and ecological attributes that enhance their preservation potential (AFR1, Table 3; Kidwell and Flessa 1995; Behrensmeyer et al. 2000; Sansom et al. 2010; Klompmaker et al. 2017; Saleh et al. 2020, 2021). Preservational biases are also often exacerbated by other biases introduced throughout the life of specimens (AFR2; e.g., Seilacher et al. 1985; Behrensmeyer et al. 2000; Louys et al. 2017; Krone et al. 2024)—for example, those relating to acquisition and curation, collecting, digitization, geography and geopolitics, publication, specimen preservation, storage, and transport (Flessa et al. 1992; Whitaker and Kimmig 2020; Raja et al. 2022; Johnson et al. 2023). Methods development for evaluating and mitigating these biases continues to be an important area of research (AFR1 – 3; e.g., Dunhill et al. 2014; Stewart et al. 2021; De Baets et al. 2022; Na et al. 2023; Antell et al. 2024; Hohmann et al. 2024). Adding to the challenge presented by these biases, maintenance of existing collections and capacity for new collections are threatened by a lack of funding, curatorial staff, and adequate storage facilities, both physical and digital (AFR3; Allmon et al. 2018; Marshall et al. 2018).

Differences in data collection and reporting methods can compound biases in paleontological studies, as researchers have specific purposes when they acquire data (AFR4) and these idiosyncrasies can limit future uses of the data. To reduce duplication of data, reduce research costs, and increase versatility, it is imperative to document and clearly communicate data acquisition and management practices (e.g., as through the extended specimen concept; Lendemer et al. 2020; Hardisty et al. 2022; Monfils et al. 2022). Establishing best practices in these areas will benefit paleontology as we move towards a Big Data future (i.e., data characterized by great variety, volume, and/or velocity; Balazka and Rodighiero, 2020), and digitization of existing and new specimens is becoming increasingly common (AFR2; Berents et al. 2010; Allmon et al. 2018).

Methodological, imaging, and analytical advances—geochemical approaches in particular (e.g., non-traditional stable isotopes, synchrotron, handheld XRF)—have created new opportunities for evaluating preservational processes (e.g., Gueriau et al. 2016; Teng et al. 2017). For example, advances in organic geochemistry have increased the capacity to extract biomolecules and biomarkers from fossil and sedimentary archives (e.g., Schweitzer et al. 2008; Briggs and Summons 2014; Vinther 2015; Falk and Wolkenstein 2017; Demarchi 2020; Wiemann et al. 2020; McNamara et al. 2021). However, it remains to be seen how deep in time biomolecules can be found and with what accuracy and resolution the methods can be applied through geological time (AFR5). Inorganic geochemistry has also advanced fundamentally in the last decades, as stable isotope (traditional and non-traditional) and clumped isotope systems provide new insights in studies of pCO_2, pH, paleophysiology, mass extinctions and the paleobiology and paleoenvironment of fossil taxa (e.g., Casey and Post 2011; Cook et al. 2015; Kimmig and Holmden 2017; Martin et al. 2017; Chen et al. 2018; Kral et al. 2022; Jung et al., 2024). Geochemical advances, and continuing improvements to technology and equipment, also are expanding the scope of paleontology by enhancing our understanding of diagenesis, morphology, paleoecology, and paleoclimate (AFR6, AFR7; e.g., Smith et al. 2021; Abdelhady et al. 2023; Comans et al. 2024).

The changing global environment also presents new challenges and opportunities for sampling the fossil record (AFR8). For example, as sea level rises and extreme weather events become more common, some existing fossil collecting sites along the coasts may be submerged (e.g., chalk deposits in Europe), while the same processes might lead to the exposure of new sites (e.g., Reimann et al. 2018; Vousdoukas et al. 2022). It is also likely that rising temperatures causing the loss of permafrost and glacial ice will expose previously inaccessible outcrops that offer new opportunities for research, even as the changing climate alters erosional processes that may influence fossil exposure and quality (AFR8; e.g., Clark et al. 2021).

Scaling Ecological and Evolutionary Processes and Patterns (SEP; Table 4)

The scale of an investigation influences the observation and interpretation of ecological and evolutionary processes (SEP1 – 4, Table 4). In paleontology, scale often relates to the temporal and spatial dimensions of taxa, patterns, or processes (SEP2, SEP3). Ecological and evolutionary processes occur at multiple spatiotemporal scales but identifying or demonstrating their significance at all scales is challenging and rare (SEP4; Jablonski 2008; Price and Schmitz 2016; Rapacciuolo and Blois 2019; Louys et al. 2021; Liow et al. 2023). Evaluating the effects of scaling in the fossil record is further complicated by the need to identify and address the incompleteness of the record (SEP3, SEP5; Peters and Heim 2011; Benson et al. 2021; and see *The Adequacy of the Fossil Record*). The data captured in the fossil record are imperfect and biased, providing only a glimpse of longer and shorter processes, patterns, and interactions (SEP3, SEP5 – 7; Faith et al. 2021; Flannery-Sutherland et al. 2022; Dunne et al. 2023).

Paleontological research into the ecological and evolutionary drivers of observed patterns is flourishing, as emergent research areas—for example, conservation paleobiology (Dietl et al. 2015; Dillon et al. 2022), geobiology (Knoll et al. 2012), phylogenetic paleoecology (Lamsdell et al. 2017)—bridge subdisciplines and broach connections between the micro- and macro-evolutionary scales (SEP2, SEP5 – 7; e.g., Machado et al. 2023; Rolland et al. 2023). Paleontologists must grapple with demonstrating links to the biology of modern organisms (i.e., neontology) in studies at various scales in the fossil record (Dietl et al. 2019; Rapacciuolo and Blois 2019). Unifying paleo- and neontological data can reveal more about the natural world than either could do in isolation (e.g., Hlusko et al. 2016, Smith et al. 2023b); however, the efficacy of cross-scale analyses needs continued examination. Macroecology (Brown, 1995; McGill 2019) may provide one option to incorporate a conceptual basis for this work as, for example, studies of the metacommunity concept—a set of local communities that are linked by dispersal of multiple, potentially interacting species (Leibold et al. 2004)—provide a framework for examining scale-based problems. A tenet of this concept is that the study of local patterns and processes is not sufficient to understand the structure and dynamics of a metacommunity (Leibold et al. 2004). Studying metacommunity composition and community assembly over space and time acknowledges the fluidity and connection of communities and seeks common patterns across metacommunities (SEP6; e.g., Muscente et al. 2018, 2022; Eden et al. 2022; Gibert et al. 2022). The relationship between the processes on evolutionary scales, their relative influence, and fluctuations through time continue to be important topics (SEP2, SEP4, SEP8).

Over the course of Earth's history, the biosphere has had a profound impact on the geosphere in ways that we are still working to fully comprehend (SEP9). Studying the interaction from an abiotic perspective highlights the feedback mechanisms and interactions within the

Earth-life system, as traces of life are ubiquitous, from Earth's mantle to the atmosphere (Pawlik et al. 2020; Giuliani et al. 2022).

Phylogenetics, Taxonomy, and Systematics (PTS; Table 5)

The fossil record contains unique information on the diversity of previous life forms, and their relationships to one another, which provides retrospective context for cataloging and understanding life on the planet today. Phylogenetics is often perceived simply as a tool for inferring evolutionary relationships or organizing biodiversity but also can be seen more broadly as a framework for hypothesis testing and reconstructing past events that are not directly observable in the fossil record (Bromham 2016). This can include estimating species divergence times, studying trait evolution, or quantifying diversification dynamics. Although speciation and extinction have a long history of study, these processes are complex and some aspects require further study to improve our understanding (PTS1, PTS2, Table 5). By adopting new methodologies, improving data collection practices, and integrating various types of data centered around current, carefully constructed taxonomies, we can unlock the full potential of hypothesis testing using phylogenetic approaches (PTS3).

Phylogenies are often constructed using molecular data, but there are many benefits to including information from other sources, such as the fossil record (PTS4, PTS5; Parham et al. 2012; Lee and Palci 2015; Mongiardino Koch et al. 2021; Wright et al. 2022). Other data sources, such as developmental biology, may also prove useful in phylogenetic inference (PTS6). The field requires a multi-disciplinary perspective informed by computer and data science, ecology, geology, geochronology, phylogenomics, and statistics (Parham et al. 2012; Liow et al. 2023). Phylogenomics and deep learning can help to discern and organize biodiversity, but their accuracy will always depend on the quality of their input data, which necessitates reliable systematics and taxonomic identifications (e.g., Bortolus 2008). The accuracy of phylogenetic analyses that include fossils relies on information about taxonomies and their associated uncertainties (Bortolus 2008; Parham et al. 2012; Soul and Friedman 2015; Barido-Sottani et al. 2023). Taxonomy and comparative anatomy are invaluable in understanding diversification history and character evolution, establishing homologies, quantifying variability, and generating testable hypotheses using phylogenetics and species delimitation methods (Barido-Sottani et al. 2023). These research fields must be supported in their own right (Agnarsson and Kuntner 2007; Löbl et al. 2023, Smith et al. 2023*c*).

Integrating different data types requires explicit process-based models (PTS7, PTS8), such as the fossilized birth-death model, which models speciation, extinction, and fossilization simultaneously (Stadler 2010; Heath et al. 2014). Combined with models of molecular and morphological evolution, this framework allows for statistical inference of dated phylogenies that include extant and fossil taxa. Most existing models treat speciation and character evolution as independent (Warnock and Wright 2020), but further refinement of this framework can illuminate the tempo and mechanisms of speciation (PTS1). Comprehensive analyses also require approaches that capture uncertainty and biases while concurrently allowing for varied approaches to weighting of molecular and morphological data (PTS9). We can construct explicit Bayesian hierarchical models to incorporate different data types while accounting for uncertainty in a principled and intuitive way (e.g., Höhna et al. 2016; Bouckaert et al. 2019; Ronquist et al. 2021). It is also imperative to assess the trade-off between data availability, computational efficiency, and model complexity. Simulations play an important role in confronting this challenge and parameter identifiability issues associated with phylogenetic models, by helping to explore the performance of available methods, potential limitations of data, and the expectations under null hypotheses (Barido-Sottani et al. 2019; Louca and Pennell 2020; Höhna et al. 2022; Mulvey et al. 2024).

Environmental and geological processes influence the course of evolution (e.g., Arakaki et al. 2011; Hannisdal and Peters 2011; De Baets et al. 2016; Kocsis et al. 2021). Incorporating these processes into phylogenetics will elucidate their interaction with biological events, linking large-scale processes, such as the extent and timing of climatic change, continental breakup, or changes in depositional rates through time with evolutionary phenomena (PTS10).

Biodiversity Dynamics in Space and Time (BST; Table 6)

Quantifying and interpreting biodiversity dynamics over time is a long-standing theme in paleontology (Phillips 1860; Sepkoski et al. 1981; Benson et al. 2021), leading to questions such as whether there are constraints on global biodiversity (BST1, Table 6; Alroy et al. 2008; Harmon and Harrison 2015; Rabosky and Hurlbert 2015; Close et al. 2020). Given the challenge of fully documenting modern biodiversity (Mora et al. 2011), we cannot expect to know absolute biodiversity in the past, but we can estimate relative changes in biodiversity. Genuine trajectories of biodiversity through time can be uncovered only if we can account for spatial differences and temporal changes in preservation potential, as well as other biases particular to the fossil record (e.g., Smiley 2018; Krone et al. 2024; and see *The Adequacy of the Fossil Record*). By dissecting the components of these trajectories, we can identify drivers of originations and extinctions in deep time (BST5; and see *Adaptations, Innovations, Origins*). To fully understand biodiversity, we must first agree on the most effective methods for measuring biodiversity over different time scales (BST6; see *Scaling Ecological and Evolutionary Processes and Patterns*). Such a consensus can help address pressing questions, including whether modern biodiversity is an outlier in geological time (BST7).

Spatial aspects of biodiversity, such as the latitudinal diversity gradient (Humboldt 1808), are as important as temporal patterns. An extensive literature explores causes of the latitudinal diversity gradient, including its dynamics over geological time scales (Jablonski et al. 2006; Allen et al. 2020, 2023; Zacaï et al. 2021; Quintero et al. 2023; Fenton et al. 2023). Evidence points to a close link between the intensity of the latitudinal diversity gradient and paleoclimate (Mannion et al. 2014; Yasuhara et al. 2020; Yasuhara and Deutsch 2022), but exactly how the latitudinal diversity gradient changed over time remains an open question (BST2).

Biodiversity patterns are the result of extinctions, originations, and the intricate interactions between living organisms and their environment. Identifying the specific factors that drive global changes in biodiversity, and disentangling the individual and combined effects of these factors, requires careful research and analysis (BST3; and see *Biodiversity Drivers*). Approaches leveraging new tools—including mechanistic models (e.g., Saupe et al. 2019), machine learning (e.g., Raja et al. 2021), and network analysis (e.g., Muscente et al. 2018, 2022; Woodhouse et al. 2023)—can identify key drivers of global and regional biodiversity, and biodiversity hotspots through time (Cermeño et al. 2022), or at least provide testable hypotheses. We are only beginning to understand and quantify the role of biodiversity as a driver of ecosystem function in the paleontological record (BST4), underscoring the need for consistent units of measure across spatiotemporal scales (BST6; McGuire et al. 2023).

Biodiversity Drivers (BD; Table 7)

In paleontology, documenting patterns of biodiversity is a central theme, but understanding the factors that drive these patterns is a large task (Jablonski 2008, 2017; Ezard et al. 2016; Di Martino et al. 2018). We can, however, begin to address this challenge by decomposing the task into more manageable questions and hypotheses that extend across taxonomic levels. Comparing taxa with differing ecological characteristics (BD1, Table 7) may help disentangle prevailing drivers—including anthropogenic drivers—under shared and disparate environmental conditions or times of perturbation (BD2; Harnik 2011; Klompmaker et al. 2013; Hull et al. 2015; Trubovitz et al. 2023). In order to compare the potential drivers across taxonomic groups, and to do so on different spatial and temporal scales, it is crucial to standardize, harmonize, and clearly communicate study design and methods (Hayek et al. 2019). Doing so will help us establish broader principles that transcend specific taxonomic, spatial, and temporal contexts (BD3).

Abiotic and biotic conditions change through time at varying rates and magnitudes, and their effects on biodiversity and ecosystem dynamics warrant further study (BD4, BD7). It has been suggested that abiotic drivers act over broad spatiotemporal scales (e.g., Court Jester model, Barnosky 2001), whereas biotic drivers are more applicable on local and shorter scales (e.g., Red Queen model; Benton 2009; Vermeij and Roopnarine 2013; Wisz et al. 2013). The relative significance of these sets of drivers remains uncertain (BD6; e.g., Eichenseer et al. 2019; Bush and Payne 2021; Spiridonov and Lovejoy 2022), underscoring the importance of conceptual models for how biodiversity responds to them (Vrba 1985, 1992, 1993, 1995; Mancuso et al. 2022). There is evidence that diversification patterns observed at higher taxonomic levels (e.g., family) are not always replicated at lower levels (e.g., species; Jablonski 2007; Hendricks et al. 2014; Balisi and Van Valkenburgh 2020). Across each of these variables, the effects of scale on which hypothesis is supported (i.e., biotic or abiotic drivers) merit further consideration—in some instances, relationships may be reversed when comparing shorter ecological and longer evolutionary timescales (BD3; e.g., De Baets et al. 2021). Further exploration with differing spatiotemporal scales, taxonomic groups, and ecologies is needed, as it remains a challenge to dissect the complex interplay between ecology, microevolution, and macroevolution on geological timescales (BD8, BD9; e.g., Liow and Taylor 2019; Liow et al. 2023). Examining the reciprocal effects of biological evolution as an actor, as well as in feedbacks and as a primary driver in other Earth systems, is a promising research direction (BD5).

Adaptations, Innovations, Origins (AIO; Table 8)

The evolutionary history of many species (and higher taxa) is demarcated by adaptive novelties and innovations, and repeated migration, dispersal, and colonization events as species have evolved and survived through morphological adaptation, ontogenetic shifts, and novel behaviors (AIO1, Table 8; e.g., Nylin et al. 2018; Stigall 2019). Colonizing regions in new environments and adapting to cope with the challenges induced by new environmental pressures has led to the development and emergence of advantageous novelties over time. These novelties increase the capacity of individuals to survive, thrive, and reproduce (AIO1, AIO2; e.g., Patton et al. 2021; Tihelka et al. 2022; Woehle et al. 2022). Observing modern species and their responses to stimuli provides paleontologists with a means to connect microevolutionary processes and patterns to those observed over evolutionary timescales in the fossil record (AIO6), which are obscured by taphonomic processes (AIO3). Improving data integration across scales, leveraging new methods, and better accounting for biases can help us answer longstanding questions on topics relating to phylogenomic conflict (Parins-Fukuchi et al. 2021), evolutionary patterns (e.g., phyletic gradualism versus punctuated equilibrium, Gould and Eldredge 1972; Hunt 2007; Hunt et al. 2015; Tsuboi et al. 2024), and phylogenetic relationships (Wright et al. 2022).

The interdependence among ecological determinants and biological features requires thorough examination to reveal the inextricable relationship between micro- and macroevolutionary processes, environmental change, and preservation (AIO4 – 6; e.g., Lamsdell et al. 2020; Almécija et al. 2021; see *Adequacy of the Fossil Record*). To develop these research directions (AIO5 – 7), hypotheses on the emergence of major features (e.g., Naranjo-Ortiz and Gabaldón 2019; Murdock 2020), changes in morphology (e.g., Anderson and Ruxton 2020; Hopkins and To 2022), ontogeny (e.g., Chevalier et al. 2021; Friend et al. 2021; Lanzetti et al. 2022), and behavior (e.g., Berbee et al. 2020; Yamamoto and Caterino 2023) require contextualization with spatiotemporal, taphonomic, and preservational constraints (AIO3, 4). Answering these questions can facilitate the examination of overarching patterns in biotic developmental and community responses to perturbation throughout the history of life, and can possibly be projected to the future (AIO6). Studies on the emergence of adaptations, innovative features, ontogenetic strategies, behaviors, and the development of novelties can provide paleontology with crucial insights into the processes of evolution and extinction, as well as the interactions between individuals, species, and communities (AIO5 – 7; Barido-Sottani et al. 2020; Brocklehurst and Benson 2021; Stansfield et al. 2021; Dunhill et al. 2022).

Extinction Dynamics (ED; Table 9)

The understanding that species are ephemeral and will eventually become extinct is now a fundamental principle of paleontology (Cuvier 1813; Darwin 1859; MacLeod 2014; Marshall 2017)—and potentially scales up from species to faunas and paleocommunities (e.g., Muscente et al. 2022). This concept is integral to the study of the history of life on Earth, as it helps to explain changes in biodiversity observed in the fossil record (Jablonski 1991; McKinney 1997). At the same time, extinction is a major theme in modern bioscience relating to impacts of anthropogenic stressors (e.g., climate change, habitat change, pollution; McKinney 1997; Dirzo et al. 2014). As usual for comparisons of the modern and fossil records, attempting to bridge the differences in study characteristics (e.g., evolutionary history of ecosystems; spatiotemporal completeness, extent, and resolution; taxonomic completeness; Foote 2000; Eichenseer et al. 2019; Foster et al. 2023; Pohl et al. 2023; Finnegan et al. 2024) over which extinction can be observed necessitates reflection on which data types are suitable to facilitate cross-scale studies and comparisons (ED1, Table 9; Lotze et al. 2011; Andréoletti and Morlon 2024).

The Big Five mass extinctions originally were defined using the concept of statistical outliers (Raup and Sepkoski 1982) at a high taxonomic level, using a specific rate metric, and based on skeletonized marine organisms. An updated definition of mass extinction is long overdue, as is a dialogue on how pattern and process should be included in the definition (ED2; Marshall 2023). This definition would precipitate the reexamination of whether mass extinctions are associated with consistent vulnerabilities of specific morphological and ecological traits (ED3, ED4; Foster et al. 2023) and whether their phases and recovery patterns are comparable (ED6, ED7; Hull et al. 2015).

Another aspect of extinction dynamics is whether functional diversity is maintained across mass extinction events (ED5), and thus the ecological impact of the event (Bambach et al. 2007; Foster and Twitchett 2014; Aberhan and Kiessling 2015; Dunhill et al. 2018; Muscente et al. 2018; Cribb et al. 2023). Mass extinctions are often attributed to abiotic changes (e.g., changes in temperature, oxygen content, pH), and finding thresholds relating to magnitudes and rates of such changes remains a priority (ED8; Song et al. 2021). Species also are likely to experience secondary extinction cascades due to the loss of critical biotic interactions (e.g., predator-prey relationships) in trophic or other biological interaction networks (Roopnarine 2006; Dunne and Williams 2009). If we are to truly understand the dynamics of extinction events in the fossil record and use them to predict extinction risk in our human-dominated world (Barnosky et al. 2011; Braje and Erlandson 2013; Song et al. 2021; Vahdati et al. 2022), we need to understand the interplay between primary and secondary extinction events via the inclusion of biotic interactions in studies of extinction selectivity (e.g., Sanders et al. 2018; Dunhill et al. 2022; Mulvey et al. 2022).

Climate Change Past and Present (CPP; Table 10)

Paleontologists often reconstruct past climates using fossils or geochemical proxies, and this remains a major theme in the biogeosciences (CPP1, Table 10). For example, examining stable oxygen isotopes in fossils can reveal climate change across temporal scales, from the lifespan of individual organisms (e.g., Nützel et al. 2010; Alberti et al. 2013) to the eon-scale (e.g., Song et al. 2019; Grossman and Joachimski 2022). However, smoothly integrating data across these temporal scales remains challenging (CPP1). Assessing biotic responses to changing climates is becoming a major theme in paleontology, with several pertinent questions (CPP2 – 9; e.g., Rita et al. 2019; Piazza et al. 2020; Nätscher et al. 2023). Nevertheless, it is critical to avoid circular reasoning where climate reconstructions based on fossil proxies subsequently are used to interpret fossils.

A host of variables—including direct and indirect measures of nutrient levels, temperature, pCO_2, precipitation, salinity, pH, oxygen and other isotopes—can be used to examine the influence of climate on biodiversity (Bijma et al. 2013; Saupe et al. 2019; Jane et al. 2021; Jackson and O'Dea 2023; Lin et al. 2023; Yasuhara and Deutsch 2023; Malanoski et al. 2024). Elucidating the relative importance of these variables on biodiversity can guide conservation efforts (CPP2, CPP8), although best practices for bridging the mismatch in temporal scales studied in paleontology and those of interest to policymakers remain elusive (CPP3, and see *Scaling Ecological and Evolutionary Processes and Patterns*; Smith et al. 2018; Pimiento and Antonelli 2022; Groff et al. 2023; Kiessling et al. 2023). Bridging these gaps can benefit from studies leveraging conservatism of physiology (Reddin et al. 2020), simulations (e.g., Hunt 2012; Barido-Sottani et al. 2019; Raja et al. 2021; Smith et al. 2022), and the pursuit of higher resolution paleontological datasets (Smith et al. 2023b). The application of paleontological observations to conservation practice remains primarily aspirational (Groff et al. 2023); however, leveraging the need for temporal context to understand climate change is a promising avenue for integrating paleontological data (Smith et al. 2018; Dietl et al. 2019; Kiessling et al. 2019, 2023).

Climate sensitivity has been defined as the global mean temperature increase when atmospheric CO2 equivalent concentration is doubled (IPCC 2021) and we can use this framework to define "ecosystem sensitivity" (CPP4). For example, how much will ecological structure—a concept challenging to objectively measure (e.g., Parrott, 2010; LaRue et al. 2023)—change on average with a given increase in temperature? A more straightforward assessment of shifts in spatial distribution is also possible, as there is modern (Lenoir et al. 2020) and past (Wing et al. 2005; McElwain 2018) evidence of species ranges tracking climate. Still, the signal is complex (Reddin et al. 2018, 2020), primarily due to sampling constraints and limited temporal resolution, and merits further examination (CPP5). In isolation from, or in combination with range shifts, the degree to which species can adapt their niches over time is crucial to predicting how they will respond to ongoing climate change (CPP6). Fossil data support niche stability at low taxonomic levels (Hopkins et al. 2014; Saupe et al. 2014; Stigall 2014; Antell et al. 2020); however, thermal tolerances have evolved across the domains of life (Storch et al. 2014), suggesting that the rate and relative frequency at which tolerances evolve are key features in niche evolution.

The impacts of climate change on biotic systems are numerous (Pörtner 2021), but cascading effects are less well known (CPP7; e.g., Pecl et al. 2017; Słowiński et al. 2018). For example, differential range shifts of species in response to climate may lead to novel communities, with new biotic interactions and elevated potential for secondary extinctions (ED9; Pecl et al. 2017; Chiarenza et al. 2023). Identifying cascading effects in the fossil record is likely difficult but important to reveal the interplay of abiotic and biotic drivers under climate change (O'Keefe et al. 2023).

Conservation Paleobiology (CPB; Table 11)

Conservation paleobiology, which seeks to apply the methods and theories of paleontology to the conservation and restoration of biodiversity and ecosystem services (Dietl et al. 2015), has emerged as a pathway for paleontologists to engage with conservation issues. A key theme in these questions is the integration of multiple types of data and methods across scales (CPB2, CPB4, CPB6, Table 11) to provide insights about biodiversity change (CPB3 – 5, CPB8). Questions in this section crosscut many of the other sections—especially *Climate Change Past and Present*—as conservation paleobiology is an emergent area of research in paleontology that is informed by the entire discipline.

Many paleontologists are seeking ways to more directly connect their science to practice (CPB1, CPB2, CPB8; Dillon et al. 2022). Though there are several success stories of paleontological data application (e.g., Everglades restoration; Marshall et al. 2014), only 10.8% of published conservation paleobiology studies have had a demonstrable effect on conservation practice (comparable to other areas of conservation science; see Groff et al. 2023). A cultural shift in the norms and practices of the paleontological community is required to produce research results that more closely align with the needs and concerns of practitioners (Dietl et al. 2023). How to get there is a big question (CPB1). At the same time, questions that form the theoretical basis for conservation paleobiology (CPB3 - 7) remain research priorities, offering opportunities for scientific progress while highlighting gaps in our understanding of biodiversity and ecosystem function, and by extension, ecosystem services (Dillon et al. 2022). For example, it remains a significant challenge to untangle the different drivers that push ecosystems beyond their natural limits and to understand the resulting responses over time(CPB5). The extent to which paleoecological records can be utilized to broaden the temporal perspective for detecting critical transitions in ecosystems and signals of changing resilience (CPB7) is also not fully understood. Nor is it known how, and under which circumstances, looking to the past can contribute productively to setting baselines for ecosystem recovery (CPB4) or anticipating a climate-changed future (CPB3). Such knowledge could support conservation management and planning efforts designed to help reduce the loss of biodiversity and ecosystem services (CPB8) in the face of environmental change. Theoretical development in these areas is foundational for paleontology and is essential for the discipline to grow as an applied area of research to provide insights about future changes in the human-dominated world (Dietl and Flessa 2011; Dietl et al.

2015, 2019; Barnosky et al. 2017; Dillon et al. 2022; Pimiento and Antonelli 2022; Groff et al. 2023; Kiessling et al. 2023; Kowalewski et al. 2023; Zuschin 2023).

Fundamental Issues (FI; Table 12)

Every scientific discipline relies on a dedicated community and supportive infrastructure. To protect paleontology's foundational resources, infrastructure updates are needed (FI1, FI3, FI5, Table 12). Best practices for collecting, curating, and archiving paleontological data and heritage are developing, but a consensus remains a work in progress (FI1). Assigning specimens an accurate taxonomy in a sound systematic framework is critical for their utility and inclusion in a shareable resource (e.g., GBIF, iDigBio, the Paleobiology Database, FI3; Marshall et al. 2018). The accuracy and resolution of taxonomic identifications strongly affect biodiversity measurements and interpretation, but this fundamental work is consistently undervalued in the current system for rewarding academics (FI3; Agnarsson and Kuntner 2007; Mabry et al. 2022; Salvador et al. 2022, Smith et al. 2023*c*). As a result, taxonomic expertise is under threat (e.g., Agnarsson and Kuntner 2007; Salvador et al. 2022). Even so, novel methods for taxonomic analysis (e.g., machine learning; Romero et al. 2020; De Baets 2021; Punyasena et al. 2022; Abdelhady et al. 2023; Adaïmé et al. 2024) hold the potential to make taxonomic work more efficient, reproducible, and sustainable. Reliable taxonomic, locality, and stratigraphic information are essential for building physical (e.g., samples) and digital (e.g., metadata, imagery) storage infrastructure that allows comparison and integration among researchers and scientific disciplines (Löbl et al. 2023). These improvements require a community effort that is supported by sustainable long-term funding—particularly in the Global South (e.g., Valenzuela-Toro and Viglino 2021; Raja et al. 2022). This funding can enable expanded accessibility, use, and combination of data, which are critical for facilitating interdisciplinary research (Allmon et al. 2018; Kaufman et al. 2018, Smith et al. 2023*c*). Through interdisciplinary research and study programs, the field can continue to expand (FI3). For example, studies of prehistory demonstrate long-standing human collection and use of fossils from the Middle Pleistocene onward, creating new opportunities to understand human behavior through interactions with fossils (Cortés-Sánchez et al. 2020). Interdisciplinarity will continue to generate new creative approaches with valuable perspectives from other disciplines (e.g., archaeology, biology) while providing new insights on long-pursued questions in paleontology (FI2 – 4).

Paleontology is also economically and societally important (FI4, FI5). Economic contributions include resource exploration, regional tourism (Perini and Calvo 2008; Kibria et al. 2019), and diverse products based on paleontological research (e.g., books, clothing, film and television works, theme parks, toys, video games). Aside from these outputs, paleontology requires greater valorization within the scientific community and broader public (FI4, FI5; Plotnick et al. 2023). Geosites are non-renewable areas important for understanding Earth's history through the observation of biological and geological phenomena. Protecting and conserving important outcrops (e.g., Atkinson et al. 2005; Maran 2014; Mexicana 2020; Neto De Carvalho et al. 2021; Carvalho and Leonardi 2022), and access to them, necessitates transparent discussion among all who interact with and care about the sites (e.g., paleontologists, landowners, traditional custodians of the land, universities, industrial companies, museums, government). Additionally, collection spaces are the physical repositories of our geoheritage (e.g. museums, geological surveys) and require sustained support from governments, academics, and the public. The primary evidence that paleontologists rely on (physical specimens) are under threat due to restructuring in funding models and museum closures, which removes from the public a pathway for engagement with geoheritage. Public engagement provides a valuable means to increase the profile of paleontology. This work, and the people involved in it, require significant investment to draw together science, economy, and culture to care for Earth and life's heritage (FI1, FI4, FI5).

As scientists, we have a responsibility to communicate with the public about our work yet many researchers receive no formal training on how to perform this duty (e.g., Salvador et al. 2021), and these activities are secondary in hiring and promotion decisions (FI2, FI4; e.g., Davies et al. 2021; Raja and Dunne 2022). Without an informed public, policymakers cannot craft legislation that benefits the greatest number of people, and individuals cannot make accurate data-driven decisions. The roles of paleontologists continue to diversify, with a large proportion of graduates working outside of academia in settings with variable skill requirements (FI2; e.g., industry, conservation, education, government; Keane et al. 2021). Paleontologists need skills to make them academically, economically, and socially valuable so they can share information about the long-term changes and variability that life on Earth has experienced with increased proficiency.

Looking Inward and Outward (LIO; Table 13)

Whereas paleontologists are keenly aware of the taphonomic biases constraining our view of past biodiversity, we have not systematically studied the biases linked to the identities and practices shaping how we collect, analyze, and interpret the fossil record. Presently, socio-economic factors disproportionately influence the sampling coverage of both modern ecosystems and past biodiversity (Cisneros et al. 2022; Monarrez et al. 2022; Raja et al. 2022). Many perspectives and data are missing, which contributes to an incomplete understanding of past and present global biodiversity and restricts the development of ecological and evolutionary theory (LIO1, Table 13; Mohammed et al. 2022; Raja et al. 2022). Identifying and addressing these biases and challenges in paleontology (e.g., dominance of the English language; Cisneros et al. 2022; Raja et al. 2022), and incorporating as many diverse perspectives as possible, will lead to a better understanding of all aspects of life on Earth (LIO2, LIO3).

Though many people globally have undertaken the study of past life, including within Indigenous traditions and local communities (Mayor 2007; Benoit et al. 2024), the earliest data points of Western academic paleontology are tied to the expansion of colonial empires (Monarrez et al. 2022; Scarlett 2022). Current research infrastructure is often built on these colonial legacies, including specimens held in museum collections (LIO4; Bradley et al. 2014; Cisneros et al. 2022; Mohammed et al. 2022; Monarrez et al. 2022; Raja et al. 2022). Digitization efforts are making museum collections and exhibits more accessible internationally to those with internet access, but digital representations do not necessarily provide the same research and engagement opportunities as physical specimens and have their own complications (e.g., compliance with sharing policies, digital quality and resolution, large file sizes, internet access and bandwidth; Falkingham 2012; Lewis 2019). Natural history specimens and geosites are often considered to be natural heritage items (including status as UNESCO sites, https://whc.unesco.org/en/list/), and calls for repatriation are growing in number (Bradley et al. 2014; Vogel 2019), making evaluating this issue in paleontology a priority (LIO4; see *Foundational Issues*).

Researchers, institutions, and funding bodies must make proactive decisions to avoid contributing further to colonial legacies by evaluating the power dynamics of international collaborations while contending with the curation of specimens collected in the past (LIO5; e.g., Dunne et al. 2022). These decisions can run counter to incentives for publication on “novelty” and unique specimens, which are often gleaned from fieldwork in key geographic regions (e.g., Myanmar; LIO6; Dunne et al. 2022; Raja et al. 2022).

More broadly, fieldwork is not equally accessible to everyone despite its high value as a component of science education (e.g., Shinbrot et al. 2022). As in all the sciences with fieldwork components, paleontologists must grapple with safety and equity considerations including mechanisms for reporting sexual harassment and assault (Clancy et al. 2014), explicit discussions about the safety of people of marginalized identities in field conditions (Demery and Pipkin 2021; Rudzki et al. 2022), and accessibility and inclusive design of field experiences for people with disabilities (LIO6; Stokes et al. 2019).

The exclusion and attrition of groups of people with particular identities and affinities (i.e., minoritized or marginalized groups) from academia have previously been described as a passive, leaky pipeline; however, this metaphor downplays the challenges posed by racism, colonial legacies, and systemic bias at institutional levels, which are now more accurately described as a “hostile obstacle course” (e.g., Bernard and Cooperdock 2018; Valenzuela-Toro and Viglino 2021; Berhe et al. 2022; Carter et al. 2022). Recognizing that these challenges exist, paleontologists must identify and embrace practices that create a more inclusive and equitable culture (LIO7; Valenzuela-Toro and Viglino 2021; Carter et al. 2022; Cisneros et al. 2022; Raja et al. 2022). Current diversity, equity, and inclusion tasks fall disproportionately on minoritized individuals, yet often are not considered in tenure and promotion assessments (LIO8; Jimenez et al. 2019). Although individual actions are important, support for diversity, equity, and inclusion must come from the highest levels of leadership (e.g., those making funding decisions) to signal their value (Dutt 2021; Chen et al. 2022). In implementing these changes, we can iteratively add to our dataset of changing outcomes in paleontology to evaluate whether such actions are effective (LIO2) and how this affects our understanding of both past and future worlds (LIO1).

Concluding remarks

The present state of paleontological research is complex and constantly changing. Considering the limited number of paleontologists employed professionally in comparison to other scientific fields (e.g., Keane et al. 2021; Plotnick et al. 2024), it is prudent to develop a shared research agenda that the paleontological community can jointly address (Figure 3). The questions presented here are unavoidably influenced by the perspectives of those participating and by the initial set of questions submitted. However, we have attempted to minimize this influence through our strategy for an inclusive approach to question submission, project participation, and authorship. Doing so gives us confidence that these BQs faithfully represent a forward-looking agenda for the discipline of paleontology.

Whether this list of questions is taken as a whole, separated by theme, or piecemeal as individual questions, we encourage all in the paleontological community to use these BQs as a tool to communicate the importance of paleontology and for securing research funding. Indeed, as the questions presented here have emerged from a community-wide effort, they likely are more representative of the state of the field than if the exercise was conducted with a top-down approach by a select few individuals, and this element may add credibility and power to arguments for funding in paleontology, broadly. As in other endeavors to define priority questions (e.g., Sutherland et al. 2009; Seddon et al. 2014), we expect a variety of uses (e.g., development of research projects, spurring discussion on the importance of different BQs) and audiences (e.g., other scientists, funding bodies, students, the general public). We anticipate these BQs will be used by researchers as framing and inspiration for new research directions, and as a tool they can use to justify paleontological research to funding organizations (Figure 3). The BQs reiterate the substantive contributions of museums and physical collection spaces, making clear a need for sustained funding of the repositories of our geoheritage. The BQs highlight the breadth and vitality of paleontology, and the important and substantive role the discipline will continue to play in pushing the frontiers of understanding throughout the life sciences.

Many of the questions included here are directed at pursuing long-standing hypotheses on how life has evolved and responded to environmental change. A large portion also pertains to the application of paleontological data to the biodiversity and environmental crises that permeate the modern world. Questions in each of these areas share common considerations, including the effects of scale on observations and the ever-present challenge of assessing the adequacy of the fossil record to address these questions. Reflecting larger ongoing discussions in science and society, there is also an emphasis on conducting paleontological research more inclusively and equitably as a community. Through efforts like this Big Questions project that bring together groups of people with many backgrounds, expertises, and motivations, we aspire to grow and strengthen the global paleontological community. Our collective understanding of the history, and future, of life on Earth will only be improved by creating a cohesive discipline where all interested individuals can contribute.

Acknowledgments

The Big Questions in Paleontology project was possible because of the participation of many members of the global paleontology community, and we thank all who contributed at any stage of the project. The project was coordinated through the PaleoSynthesis Project hosted at

Friedrich-Alexander Universität Erlangen-Nürnberg, with funding from the Volkswagen Foundation (Az 96 796). We thank the editor (James Crampton) and two anonymous reviewers for their comments on a previous version of this manuscript.

Competing Interests

The authors declare none.

Data Availability Statement

The Supplementary Material containing raw and preliminary questions is available at https://doi.org/10.5281/zenodo.14278551.

Literature Cited

Abdelhady, A. A., B. Seuss, S. Jain, K. H. Abdel-Raheem, A. Elsheikh, M. S. Ahmed, A. M. Elewa, and A. M. Hussain. 2023: New and emerging technologies in paleontology and paleobiology: A horizon scanning review. Journal of African Earth Sciences:105155.

Aberhan, M., and W. Kiessling. 2015: Persistent ecological shifts in marine molluscan assemblages across the end-Cretaceous mass extinction. Proceedings of the National Academy of Sciences USA 112:7207–7212.

Adaïmé, M.-É., S. Kong, and S. W. Punyasena. 2024: Deep learning approaches to the phylogenetic placement of extinct pollen morphotypes. PNAS nexus 3:pgad419.

Agnarsson, I., and M. Kuntner. 2007: Taxonomy in a changing world: seeking solutions for a science in crisis. Systematic Biology 56:531–539.

Alberti, M., F. T. Fürsich, and D. K. Pandey. 2013: Seasonality in low latitudes during the Oxfordian (Late Jurassic) reconstructed via high-resolution stable isotope analysis of the oyster Actinostreon marshi (J. Sowerby, 1814) from the Kachchh Basin, western India. International Journal of Earth Sciences 102:1321–1336.

Allen, B. J., P. B. Wignall, D. J. Hill, E. E. Saupe, and A. M. Dunhill. 2020: The latitudinal diversity gradient of tetrapods across the Permo-Triassic mass extinction and recovery interval. Proceedings of the Royal Society B: Biological Sciences 287:20201125.

Allen, B. J., M. E. Clapham, E. E. Saupe, P. B. Wignall, D. J. Hill, and A. M. Dunhill. 2023: Estimating spatial variation in origination and extinction in deep time: a case study using the Permian–Triassic marine invertebrate fossil record. Paleobiology 49:509–526.

Allmon, W. A., G. P. Dietl, J. R. Hendricks, and R. M. Ross. 2018: Bridging the two fossil records: Paleontology's "big data" future resides in museum collections. Pp.35–44 in Museums at the Forefront of the History and Philosophy of Geology: History Made, History in the Making. Geological Society of America, Boulder, Colorado, USA.

Almécija, S., A. S. Hammond, N. E. Thompson, K. D. Pugh, S. Moyà-Solà, and D. M. Alba. 2021: Fossil apes and human evolution. Science 372:eabb4363.

Alroy, J., M. Aberhan, D.J. Bottjer, M. Foote, F.T. Fürsich, P.J. Harries, A.J. Hendy, S.M. Holland, L.C. Ivany, W. Kiessling, and M.A. Kosnik, 2008: Phanerozoic trends in the global diversity of marine invertebrates. Science 321: 97–100.

Anderson, S. C., and G. D. Ruxton. 2020: The evolution of flight in bats: a novel hypothesis. Mammal Review 50:426–439.

Andréoletti, J., and H. Morlon. 2024: Comparing extinction rates: past, present, and future. Pp.348–365 in S. M. Scheiner, ed. Encyclopedia of Biodiversity (Third Edition). Academic Press, Oxford.

Antell, G. S., W. Kiessling, M. Aberhan, and E. E. Saupe. 2020: Marine biodiversity and geographic distributions are independent on large scales. Current Biology 30:115–121.

Antell, G. T., R. B. J. Benson, and E. E. Saupe. 2024: Spatial standardization of taxon occurrence data—a call to action. Paleobiology:1–17.

Arakaki, M., P.-A. Christin, R. Nyffeler, A. Lendel, U. Eggli, R. M. Ogburn, E. Spriggs, M. J. Moore, and E. J. Edwards. 2011: Contemporaneous and recent radiations of the world's major succulent plant lineages. Proceedings of the National Academy of Sciences 108:8379–8384.

Atkinson, T. P., R. J. Buta, and D. C. Kopaska-Merkel. 2005: Saving the Union Chapel Mine: how a group of determined amateurs teamed up with professionals to save a world-class trackway site in Alabama. Pennsylvanian Footprints in the Black Warrior Basin of Alabama: Alabama Paleontological Society Monograph:191–200.

Balazka, D., and D. Rodighiero. 2020: Big data and the Little Big Bang: an epistemological (R)evolution. Frontiers in Big Data: 3:1–31.

Balisi, M. A., and B. Van Valkenburgh. 2020: Iterative evolution of large-bodied hypercarnivory in canids benefits species but not clades. Communications Biology 3:1–9.

Bambach, R. K., A. M. Bush, and D. H. Erwin. 2007: Autecology and the filling of ecospace: key metazoan radiations. Palaeontology 50:1–22.

Barido-Sottani, J., W. Pett, J. E. O'Reilly, and R. C. Warnock. 2019: FossilSim: an R package for simulating fossil occurrence data under mechanistic models of preservation and recovery. Methods in Ecology and Evolution 10:835–840.

Barido-Sottani, J., A. Pohle, K. De Baets, D. Murdock, and R. C. Warnock. 2023: Putting the F into FBD analysis: tree constraints or morphological data? Palaeontology 66:e12679.

Barido-Sottani, J., N. M. Van Tiel, M. J. Hopkins, D. F. Wright, T. Stadler, and R. C. Warnock. 2020: Ignoring fossil age uncertainty leads to inaccurate topology and divergence time estimates in time calibrated tree inference. Frontiers in Ecology and Evolution 8:fevo.2020.00183.

Barnosky, A. D. 2001: Distinguishing the effects of the Red queen and Court Jester on Miocene mammal evolution in the northern Rocky Mountains. Journal of Vertebrate Paleontology 21:172–185.

Barnosky, A. D., N. Matzke, S. Tomiya, G. O. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. McGuire, E. L. Lindsey, and K. C. Maguire. 2011: Has the Earth's sixth mass extinction already arrived? Nature 471:51.

Barnosky, A. D., E. A. Hadly, P. Gonzalez, J. Head, P. D. Polly, A. M. Lawing, J. T. Eronen, D. D. Ackerly, K. Alex, E. Biber, J. Blois, J. Brashares, G. Ceballos, E. Davis, G. P. Dietl, R. Dirzo, H. Doremus, M. Fortelius, H. W. Greene, J. Hellmann, T. Hickler, S. T. Jackson, M. Kemp, P. L. Koch, C. Kremen, E. L. Lindsey, C. Looy, C. R. Marshall, C. Mendenhall, A. Mulch, A. M. Mychajliw, C. Nowak, U. Ramakrishnan, J. Schnitzler, K. D. Shrestha, K. Solari, L. Stegner, M. A. Stegner, N. C. Stenseth, M. H. Wake, and Z. Zhang. 2017: Merging paleobiology with conservation biology to guide the future of terrestrial ecosystems. Science 355:eaah4787.

Behrensmeyer, A. K., S. M. Kidwell, and R. A. Gastaldo. 2000: Taphonomy and paleobiology. Paleobiology 26:103–147.

Benoit, J., C. R. Penn-Clarke, R. Rust, D. P. Groenewald, P. Vickers-Rich, and C. W. Helm. 2024: Indigenous knowledge of palaeontology in Africa. Geological Society, London, Special Publications 543:SP543-2022–2236.

Benson, R. B., R. Butler, R. A. Close, E. Saupe, and D. L. Rabosky. 2021: Biodiversity across space and time in the fossil record. Current Biology 31:R1225–R1236.

Benton, M. J. 2009: The Red Queen and the Court Jester: species diversity and the role of biotic and abiotic factors through time. Science 323:728–732.

Berbee, M. L., C. Strullu-Derrien, P.-M. Delaux, P. K. Strother, P. Kenrick, M.-A. Selosse, and J. W. Taylor. 2020: Genomic and fossil windows into the secret lives of the most ancient fungi. Nature Reviews Microbiology 18:717–730.

Berents, P., M. Hamer, and V. Chavan. 2010: Towards demand driven publishing: approaches to the prioritization of digitization of natural history collections data. Biodiversity Informatics 7:113–119.

Berhe, A. A., R. T. Barnes, M. G. Hastings, A. Mattheis, B. Schneider, B. M. Williams, and E. Marín-Spiotta. 2022: Scientists from historically excluded groups face a hostile obstacle course. Nature Geoscience 15:2–4.

Bernard, R. E., and E. H. G. Cooperdock. 2018: No progress on diversity in 40 years. Nature Geoscience 11:292–295.

Bijma, J., H.-O. Pörtner, C. Yesson, and A. D. Rogers. 2013: Climate change and the oceans–What does the future hold? Marine Pollution Bulletin 74:495–505.

Bortolus, A. 2008: Error cascades in the biological sciences: the unwanted consequences of using bad taxonomy in ecology. AMBIO: A Journal of the Human Environment 37:114–118.

Bouckaert, R., T. G. Vaughan, J. Barido-Sottani, S. Duchêne, M. Fourment, A. Gavryushkina, J. Heled, G. Jones, D. Kühnert, N. D. Maio, M. Matschiner, F. K. Mendes, N. F. Müller, H. A. Ogilvie, L. du Plessis, A. Popinga, A. Rambaut, D. Rasmussen, I. Siveroni, M. A. Suchard, C.-H. Wu, D. Xie, C. Zhang, T. Stadler, and A. J. Drummond. 2019: BEAST 2.5: An advanced software platform for Bayesian evolutionary analysis. PLOS Computational Biology 15:e1006650.

Bradley, J., P. Adgemis, and L. Haralampou. 2014: “Why can’t they put their names?”: colonial photography, repatriation and social memory. History and Anthropology 25:47–71.

Braje, T. J., and J. M. Erlandson. 2013: Human acceleration of animal and plant extinctions: A Late Pleistocene, Holocene, and Anthropocene continuum. Anthropocene 4:14–23.

Briggs, D. E., and R. E. Summons. 2014: Ancient biomolecules: their origins, fossilization, and role in revealing the history of life. BioEssays 36:482–490.

Brocklehurst, N., and R. J. Benson. 2021: Multiple paths to morphological diversification during the origin of amniotes. Nature Ecology & Evolution 5:1243–1249.

Bromham, L. 2016: Testing hypotheses in macroevolution. Studies in History and Philosophy of Science Part A 55:47–59.

Brown, J.H. 1995: Macroecology. University of Chicago Press, Chicago.

Bush, A. M., and J. L. Payne. 2021: Biotic and Abiotic controls on the Phanerozoic history of marine animal biodiversity. Annual Review of Ecology, Evolution, and Systematics 52:269–289.

Carter, A. M., E. H. Johnson, and E. R. Schroeter. 2022: Long-term retention of diverse paleontologists requires increasing accessibility. Frontiers in Ecology and Evolution 10.

Carvalho, I. de S., and G. Leonardi. 2022: The invisibles of science and the paleontological heritage: the Brazilian study case. Geoheritage 14:107.

Casey, M. M., and D. M. Post. 2011: The problem of isotopic baseline: Reconstructing the diet and trophic position of fossil animals. Earth-Science Reviews 106:131–148.

Cermeño, P., C. García-Comas, A. Pohl, S. Williams, M. J. Benton, C. Chaudhary, G. Le Gland, R. D. Müller, A. Ridgwell, and S. M. Vallina. 2022: Post-extinction recovery of the Phanerozoic oceans and biodiversity hotspots. Nature 607:507–511.

Chen, C. Y., S. S. Kahanamoku, A. Tripati, R. A. Alegado, V. R. Morris, K. Andrade, and J. Hosbey. 2022: Systemic racial disparities in funding rates at the National Science Foundation. eLife 11:e83071.

Chen, J., I. P. Montañez, Y. Qi, S. Shen, and X. Wang. 2018: Strontium and carbon isotopic evidence for decoupling of pCO2 from continental weathering at the apex of the late Paleozoic glaciation. Geology 46:395–398.

Chevalier, T., T. Colard, A. Colombo, L. Golovanova, V. Doronichev, and J.-J. Hublin. 2021: Early ontogeny of humeral trabecular bone in Neandertals and recent modern humans. Journal of Human Evolution 154:102968.

Chiarenza, A. A., A. M. Waterson, D. N. Schmidt, P. J. Valdes, C. Yesson, P. A. Holroyd, M. E. Collinson, A. Farnsworth, D. B. Nicholson, S. Varela, and P. M. Barrett. 2023: 100 million years of turtle paleoniche dynamics enable the prediction of latitudinal range shifts in a warming world. Current Biology 33:109-121.e3.

Cisneros, J. C., N. B. Raja, A. M. Ghilardi, E. M. Dunne, F. L. Pinheiro, O. R. Regalado Fernández, M. A. F. Sales, R. A. Rodríguez-de la Rosa, A. Y. Miranda-Martínez, S. González-Mora, R. A. M. Bantim, F. J. de Lima, and J. D. Pardo. 2022: Digging deeper into colonial palaeontological practices in modern day Mexico and Brazil. Royal Society Open Science 9:210898.

Clancy, K. B., R. G. Nelson, J. N. Rutherford, and K. Hinde. 2014: Survey of academic field experiences (SAFE): Trainees report harassment and assault. PloS one 9:e102172.

Clark, J., J. Bayarsaikhan, A. V. Miller, S. Vanderwarf, I. Hart, G. Caspari, and W. T. T. Taylor. 2021: Mongolia's frozen heritage: a summary of the archaeology of the cultural cryosphere. Journal of Glacial Archaeology 5:103–120.

Close, R. A., R. B. Benson, E. E. Saupe, M. E. Clapham, and R. J. Butler. 2020: The spatial structure of Phanerozoic marine animal diversity. Science 368:420–424.

Comans, C. M., S. M. Smart, E. R. Kast, Y. Lu, T. Lüdecke, J. N. Leichliter, D. M. Sigman, T. Ikejiri, and A. Martínez-García. 2024: Enameloid-bound δ15N reveals large trophic separation among Late Cretaceous sharks in the northern Gulf of Mexico. Geobiology 22:e12585.

Cook, P. K., M.-A. Languille, E. Dufour, C. Mocuta, O. Tombret, F. Fortuna, and L. Bertrand. 2015: Biogenic and diagenetic indicators in archaeological and modern otoliths: Potential and limits of high definition synchrotron micro-XRF elemental mapping. Chemical Geology 414:1–15.

Cortés-Sánchez, M., M. D. Simón-Vallejo, J.-C. Corral, M. del C. Lozano-Francisco, J. L. Vera-Peláez, F. J. Jiménez-Espejo, A. García-Alix, C. de las Heras, R. M. Sánchez, M. D. Bretones García, I. Barandiarán-Maestu, and A. Morales-Muñiz. 2020: Fossils in Iberian prehistory: A review of the palaeozoological evidence. Quaternary Science Reviews 250:106676.

Cribb, A. T., K. K. Formoso, C. H. Woolley, J. Beech, S. Brophy, P. Byrne, V. C. Cassady, A. L. Godbold, E. Larina, and P. Maxeiner. 2023: Contrasting terrestrial and marine ecospace dynamics after the end-Triassic mass extinction event. Proceedings of the Royal Society B 290:20232232.

Cuvier, G. 1813: Essay on the Theory of the Earth. Routledge, p.

Darwin, C. 1859: On the Origin of Species by Means of Natural Selection, Or, the Preservation of Favoured Races in the Struggle for Life. Appleton and Company, New York, p.

Davies, S. W., H. M. Putnam, T. Ainsworth, J. K. Baum, C. B. Bove, S. C. Crosby, I. M. Côté, A. Duplouy, R. W. Fulweiler, A. J. Griffin, T. C. Hanley, T. Hill, A. Humanes, S. Mangubhai, A. Metaxas, L. M. Parker, H. E. Rivera, N. J. Silbiger, N. S. Smith, A. K. Spalding, N. Traylor-Knowles, B. L. Weigel, R. M. Wright, and A. E. Bates. 2021: Promoting inclusive metrics of success and impact to dismantle a discriminatory reward system in science. PLOS Biology 19:e3001282.

De Baets, K. 2021: Performance of machine-learning approaches in identifying ammonoid species based on conch properties. Peer Community in Paleontology 1:100010.

De Baets, K., A. Antonelli, and P. C. Donoghue. 2016: Tectonic blocks and molecular clocks. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20160098.

De Baets, K., J. W. Huntley, D. Scarponi, A. A. Klompmaker, and A. Skawina. 2021: Phanerozoic parasitism and marine metazoan diversity: dilution versus amplification. Philosophical Transactions of the Royal Society B 376:20200366.

De Baets, K., E. Jarochowska, S. Z. Buchwald, C. Klug, and D. Korn. 2022: Lithology controls ammonoid size distributions. Palaios 37:744–754.

Demarchi, B. 2020: Amino acids and proteins in fossil biominerals: an introduction for archaeologists and palaeontologists. John Wiley & Sons, p.

Demery, A.-J. C., and M. A. Pipkin. 2021: Safe fieldwork strategies for at-risk individuals, their supervisors and institutions. Nature Ecology & Evolution 5:5–9.

Di Martino E., J.B.C. Jackson, P.D. Taylor, and K.G. Johnson. 2018: Differences in extinction rates drove modern biogeographic patterns of tropical marine biodiversity. Science Advances, 4: eaaq1508

Dietl, G. P., and K. W. Flessa. 2011: Conservation paleobiology: Putting the dead to work. Trends in Ecology & Evolution 26:30–37.

Dietl, G. P., J. A. Smith, and S. R. Durham. 2019: Discounting the past: the undervaluing of paleontological data in conservation science. Frontiers in Ecology and Evolution 7:108.

Dietl, G. P., S. R. Durham, C. Clark, and R. Prado. 2023: Better together: Building an engaged conservation paleobiology science for the future. Ecological Solutions and Evidence 4:e12246.

Dietl, G. P., S. M. Kidwell, M. Brenner, D. A. Burney, K. W. Flessa, S. T. Jackson, and P. L. Koch. 2015: Conservation paleobiology: Leveraging knowledge of the past to inform conservation and restoration. Annual Review of Earth and Planetary Sciences 43:79–103.

Dillon, E. M., J. Q. Pier, J. A. Smith, N. B. Raja, D. Dimitrijević, E. L. Austin, J. D. Cybulski, J. De Entrambasaguas, S. R. Durham, and C. Grether. 2022: What is conservation paleobiology? Tracking 20 years of research and development. Frontiers in Ecology and Evolution:1117.

Dirzo, R., H. S. Young, M. Galetti, G. Ceballos, N. J. Isaac, and B. Collen. 2014: Defaunation in the Anthropocene. Science 345:401–406.

Dunhill, A. M., B. Hannisdal, and M. J. Benton. 2014: Disentangling rock record bias and common-cause from redundancy in the British fossil record. Nature Communications 5:4818.

Dunhill, A. M., W. J. Foster, J. Sciberras, and R. J. Twitchett. 2018: Impact of the Late Triassic mass extinction on functional diversity and composition of marine ecosystems. Palaeontology 61:133–148.

Dunhill, A. M., K. Zarzyczny, J. O. Shaw, J. W. Atkinson, C. T. Little, and A. P. Beckerman. 2024: Extinction cascades, community collapse, and recovery across a Mesozoic hyperthermal event. Nature Communications 15: 8599.

Dunne, E. M., N. B. Raja, P. P. Stewens, Zin-Maung-Maung-Thein, and K. Zaw. 2022: Ethics, law, and politics in palaeontological research: The case of Myanmar amber. Communications Biology 5:1–10.

Dunne, E. M., S. E. Thompson, R. J. Butler, J. Rosindell, and R. A. Close. 2023: Mechanistic neutral models show that sampling biases drive the apparent explosion of early tetrapod diversity. Nature Ecology & Evolution:1–10.

Dunne, J. A., and R. J. Williams. 2009: Cascading extinctions and community collapse in model food webs. Philosophical Transactions of the Royal Society B: Biological Sciences 364:1711–1723.

Dutt, K. 2021: Addressing racism through ownership. Nature Geoscience 14:58–58.

Eden, R., A. Manica, and E. G. Mitchell. 2022: Metacommunity analyses show an increase in ecological specialisation throughout the Ediacaran period. PLOS Biology 20:e3001289.

Eichenseer, K., U. Balthasar, C. W. Smart, J. Stander, K. A. Haaga, and W. Kiessling. 2019: Jurassic shift from abiotic to biotic control on marine ecological success. Nature Geoscience 12:638–642.

Ezard, T. H. G., T. B. Quental, and M. J. Benton. 2016: The challenges to inferring the regulators of biodiversity in deep time. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150216.

Faith, J. T., A. Du, A. K. Behrensmeyer, B. Davies, D. B. Patterson, J. Rowan, and B. Wood. 2021: Rethinking the ecological drivers of hominin evolution. Trends in Ecology & Evolution 36:797–807.

Falk, H., and K. Wolkenstein. 2017: Natural product molecular fossils. Progress in the Chemistry of Organic Natural Products:1–126.

Falkingham, P. 2012: Acquisition of high resolution three-dimensional models using free, open-source, photogrammetric software. Palaeontologia Electronica 15:1T:15p.

Fenton, I. S., T. Aze, A. Farnsworth, P. Valdes, and E.E. Saupe. 2023: Origination of the modern-style diversity gradient 15 million years ago. Nature, 614: 708-712.

Finnegan, S., P. G. Harnik, R. Lockwood, H. K. Lotze, L. McClenachan, and S. S. Kahanamoku. 2024: Using the Fossil Record to Understand Extinction Risk and Inform Marine Conservation in a Changing World. Annual Review of Marine Science 16:307–333.

Flannery-Sutherland, J. T., D. Silvestro, and M. J. Benton. 2022: Global diversity dynamics in the fossil record are regionally heterogeneous. Nature Communications 13:2751.

Flessa, K., M. Kowalewski, and S. E. Walker. 1992: Post-collection taphonomy: shell destruction and the Chevrolet. Palaios 7:553–554.

Foote, M. 2000: Origination and extinction components of taxonomic diversity: Paleozoic and post-Paleozoic dynamics. Paleobiology 26:578–605.

Foster, W. J., and R. J. Twitchett. 2014: Functional diversity of marine ecosystems after the Late Permian mass extinction event. Nature Geoscience 7:233–238.

Foster, W. J., B. J. Allen, N. H. Kitzmann, J. Münchmeyer, T. Rettelbach, J. D. Witts, R. J. Whittle, E. Larina, M. E. Clapham, and A. M. Dunhill. 2023: How predictable are mass extinction events? Royal Society Open Science 10:221507.

Friend, D. S., B. M. Anderson, and W. D. Allmon. 2021: Geographic contingency, not species sorting, dominates macroevolutionary dynamics in an extinct clade of neogastropods (Volutospina; Volutidae). Paleobiology 47:236–250.

Gibert, C., A. Zacaï, F. Fluteau, G. Ramstein, O. Chavasseau, G. Thiery, A. Souron, W. Banks, F. Guy, D. Barboni, P. Sepulchre, C. Blondel, G. Merceron, and O. Otero. 2022: A coherent biogeographical framework for Old World Neogene and Pleistocene mammals. Palaeontology 65:e12594.

Giuliani, A., R. N. Drysdale, J. D. Woodhead, N. J. Planavsky, D. Phillips, J. Hergt, W. L. Griffin, S. Oesch, H. Dalton, and G. R. Davies. 2022: Perturbation of the deep-Earth carbon cycle in response to the Cambrian Explosion. Science Advances 8:eabj1325.

Gould, S. J., and N. Eldredge. 1972: Punctuated equilibria: an alternative to phyletic gradualism. Models in paleobiology 1972:82–115.

Groff, D. V., C. M. MacKenzie, J. Q. Pier, A. B. Shaffer, and G. P. Dietl. 2023: Knowing but not doing: Quantifying the research-implementation gap in conservation paleobiology. Frontiers in Ecology and Evolution 11:1058992.

Grossman, E. L., and M. M. Joachimski. 2022: Ocean temperatures through the Phanerozoic reassessed. Scientific Reports 12:1–13.

Gu, Z., L. Gu, R. Eils, M. Schlesner, and B. Brors. 2014: Circlize implements and enhances circular visualization in R. Bioinformatics 30:2811–2812.

Gueriau, P., S. Bernard, and L. Bertrand. 2016: Advanced synchrotron characterization of paleontological specimens. Elements 12:45–50.

Hannisdal, B., and S. E. Peters. 2011: Phanerozoic Earth system evolution and marine biodiversity. Science 334:1121–1124.

Hardisty, A. R., E. R. Ellwood, G. Nelson, B. Zimkus, J. Buschbom, W. Addink, R. K. Rabeler, J. Bates, A. Bentley, J. A. B. Fortes, S. Hansen, J. A. Macklin, A. R. Mast, J. T. Miller, A. K. Monfils, D. L. Paul, E. Wallis, and M. Webster. 2022: Digital Extended Specimens: Enabling an Extensible Network of Biodiversity Data Records as Integrated Digital Objects on the Internet. BioScience 72:978–987.

Harmon, L. J., and S. Harrison. 2015: Species diversity is dynamic and unbounded at local and continental scales. The American Naturalist 185:584–593.

Harnik, P. G. 2011: Direct and indirect effects of biological factors on extinction risk in fossil bivalves. Proceedings of the National Academy of Sciences 108:13594–13599.

Hayek, L.-A. C., M. A. Buzas, and E. Thomas. 2019: Identifying disruptions to the ecological balance of nature: a foraminiferal example across the initiation of the Paleocene–Eocene thermal maximum. Paleobiology 45:98–113.

Heath, T. A., J. P. Huelsenbeck, and T. Stadler. 2014: The fossilized birth–death process for coherent calibration of divergence-time estimates. Proceedings of the National Academy of Sciences 111:E2957–E2966.

Hendricks, J. R., E. E. Saupe, C. E. Myers, E. J. Hermsen, and W. D. Allmon. 2014: The generification of the fossil record. Paleobiology 40:511–528.

Hlusko, L. J., C. A. Schmitt, T. A. Monson, M. F. Brasil, and M. C. Mahaney. 2016: The integration of quantitative genetics, paleontology, and neontology reveals genetic underpinnings of primate dental evolution. Proceedings of the National Academy of Sciences 113:9262–9267.

Hohmann, N., J.R. Koelewijn, P Burgess, and E. Jarochowska. 2024: Identification of the mode of evolution in incomplete carbonate successions. BMC Ecology and Evolution, 24: 113.

Höhna, S., B. T. Kopperud, and A. F. Magee. 2022: CRABS: Congruent rate analyses in birth–death scenarios. Methods in Ecology and Evolution 13:2709–2718.

Höhna, S., M. J. Landis, T. A. Heath, B. Boussau, N. Lartillot, B. R. Moore, J. P. Huelsenbeck, and F. Ronquist. 2016: RevBayes: Bayesian phylogenetic inference using graphical models and an interactive model-specification language. Systematic Biology 65:726–736.

Hopkins, M. J., and R. To. 2022: Long-term clade-wide shifts in trilobite segment number and allocation during the Palaeozoic. Proceedings of the Royal Society B: Biological Sciences 289:20221765.

Hopkins, M. J., C. Simpson, and W. Kiessling. 2014: Differential niche dynamics among major marine invertebrate clades. Ecology letters 17:314–323.

Hull, P. M., S. A. F. Darroch, and D. H. Erwin. 2015: Rarity in mass extinctions and the future of ecosystems. Nature 528:345–351.

Humboldt, A. v. 1808: Ansichten der Natur. Tübingen, Cotta, p.

Hunt, G. 2007: The relative importance of directional change, random walks, and stasis in the evolution of fossil lineages. Proceedings of the National Academy of Sciences 104:18404–18408.

———. 2012: Measuring rates of phenotypic evolution and the inseparability of tempo and mode. Paleobiology 38:351–373.

Hunt, G., M. J. Hopkins, and S. Lidgard. 2015: Simple versus complex models of trait evolution and stasis as a response to environmental change. Proceedings of the National Academy of Sciences 112:4885–4890.

IPCC. 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pp.2391 in V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, eds. Cambridge University Press, Cambridge, UK and New York, USA.

Jablonski, D. 1991: Extinctions: a paleontological perspective. Science 253:754–757.

———. 2007: Scale and hierarchy in macroevolution. Palaeontology 50:87–109.

———. 2008: Biotic interactions and macroevolution: extensions and mismatches across scales and levels. Evolution: International Journal of Organic Evolution 62:715–739.

———. 2017: Approaches to macroevolution: 2. Sorting of variation, some overarching issues, and general conclusions. Evolutionary Biology 44:451–475.

Jablonski D, K. Roy, J.W. Valentine. 2006: Out of the tropics: evolutionary dynamics of the latitudinal diversity gradient. Science 314:102-106.

Jackson, J. B. C., and A. O'Dea. 2023: Evolution and environment of Caribbean coastal ecosystems. Proceedings of the National Academy of Sciences 120:e2307520120.

Jane, S. F., G. J. A. Hansen, B. M. Kraemer, P. R. Leavitt, J. L. Mincer, R. L. North, R. M. Pilla, J. T. Stetler, C. E. Williamson, R. I. Woolway, L. Arvola, S. Chandra, C. L. DeGasperi, L. Diemer, J. Dunalska, O. Erina, G. Flaim, H.-P. Grossart, K. D. Hambright, C. Hein, J. Hejzlar, L. L. Janus, J.-P. Jenny, J. R. Jones, L. B. Knoll, B. Leoni, E. Mackay, S.-I. S. Matsuzaki, C. McBride, D. C. Müller-Navarra, A. M. Paterson, D. Pierson, M. Rogora, J. A. Rusak, S. Sadro, E. Saulnier-Talbot, M. Schmid, R. Sommaruga, W. Thiery, P. Verburg, K. C. Weathers, G. A. Weyhenmeyer, K. Yokota, and K. C. Rose. 2021: Widespread deoxygenation of temperate lakes. Nature 594:66–70.

Jimenez, M. F., T. M. Laverty, S. P. Bombaci, K. Wilkins, D. E. Bennett, and L. Pejchar. 2019: Underrepresented faculty play a disproportionate role in advancing diversity and inclusion. Nature Ecology & Evolution 3:1030–1033.

Johnson, K. R., I. F. P. Owens, and THE GLOBAL COLLECTION GROUP. 2023: A global approach for natural history museum collections. Science 379:1192–1194.

Jung, J., S.F., Zoppe, T. Söte, S. Moretti, N.N. Duprey, A.D. Foreman, T. Wald, H. Vonhof, G.H. Haug, D.M. Sigman, and A. Mulch. 2024: Coral photosymbiosis on Mid-Devonian reefs. Nature, 1-7.

Kaufman, D. S., N. Abram, M. Evans, P. Francus, H. Goosse, H. Linderholm, M.-F. Loutre, B. Martrat, H. McGregor, R. Neukom, S. St. George, C. Turney, and L. von Gunten. 2018: Technical note: Open-paleo-data implementation pilot – the PAGES 2k special issue. Climate of the Past 14:593–600.

Keane, C., L. Gonzales, and D. Robinson. 2021: Status of Recent Geoscience Graduates. American Geosciences Institute, Alexandria, VA USA, 73 p.

Kibria, A., S. B. Akhundjanov, and R. Oladi. 2019: Fossil fuel share in the energy mix and economic growth. International Review of Economics & Finance 59:253–264.

Kidwell, S. M., and K. W. Flessa. 1995: The quality of the fossil record: populations, species, and communities. Annual Review of Ecology and Systematics:269–299.

Kiessling, W., J. A. Smith, and N. B. Raja. 2023: Improving the relevance of paleontology to climate change policy. Proceedings of the National Academy of Sciences 120:e2201926119.

Kiessling, W., N. B. Raja, V. J. Roden, S. T. Turvey, and E. E. Saupe. 2019: Addressing priority questions of conservation science with palaeontological data. Philosophical Transactions of the Royal Society B: Biological Sciences 374:20190222.

Kimmig, S. R., and C. Holmden. 2017: Multi-proxy geochemical evidence for primary aragonite precipitation in a tropical-shelf 'calcite sea' during the Hirnantian glaciation. Geochimica et Cosmochimica Acta 206:254–272.

Klompmaker, A. A., C. E. Schweitzer, R. M. Feldmann, and M. Kowalewski. 2013: The influence of reefs on the rise of Mesozoic marine crustaceans. Geology 41:1179–1182.

Klompmaker, A.A., R.W. Portell, and M.G. Frick. 2017: Comparative experimental taphonomy of eight marine arthropods indicates distinct differences in preservation potential. Palaeontology 60:773–794.

Knoll, A. H., D. E. Canfield, and K. O. Konhauser. 2012: Fundamentals of geobiology. John Wiley & Sons, p.

Kocsis, Á. T., C. J. Reddin, C. R. Scotese, P. J. Valdes, and W. Kiessling. 2021: Increase in marine provinciality over the last 250 million years governed more by climate change than plate tectonics. Proceedings of the Royal Society B 288:20211342.

Kowalewski, M., R. Nawrot, D. Scarponi, A. Tomašových, and M. Zuschin. 2023: Marine conservation palaeobiology: What does the late Quaternary fossil record tell us about modern-day extinctions and biodiversity threats? Cambridge Prisms: Extinction 1:e24.

Kral, A. G., M. Lagos, P. Guagliardo, T. Tütken, and T. Geisler. 2022: Rapid alteration of cortical bone in fresh-and seawater solutions visualized and quantified from the millimeter down to the atomic scale. Chemical Geology 609:121060.

Krone, I. W., K. M. Magoulick, and R. M. Yohler. 2024: All the Earth will not remember: how geographic gaps structure the record of diversity and extinction. Paleobiology 50:214–225.

Lamsdell, J. C., V. E. McCoy, O. A. Perron-Feller, and M. J. Hopkins. 2020: Air breathing in an exceptionally preserved 340-million-year-old sea scorpion. Current Biology 30:4316–4321.

Lamsdell, J. C., C. R. Congreve, M. J. Hopkins, A. Z. Krug, and M. E. Patzkowsky. 2017: Phylogenetic paleoecology: tree-thinking and ecology in deep time. Trends in Ecology & Evolution 32:452–463.

Lanzetti, A., R. Portela-Miguez, V. Fernandez, and A. Goswami. 2022: Testing heterochrony: Connecting skull shape ontogeny and evolution of feeding adaptations in baleen whales. Evolution & Development 25:257–273.

LaRue, E.A., R.T. Fahey, B.C., Alveshere, J.W. Atkins, P. Bhatt, B. Buma, A. Chen, S. Cousins, J.M. Elliott, A.J. Elmore, and C.R. Hakkenberg, 2023: A theoretical framework for the ecological role of three-dimensional structural diversity. Frontiers in Ecology and the Environment 21: 4–13.

Lee, M. S., and A. Palci. 2015: Morphological phylogenetics in the genomic age. Current Biology 25:R922–R929.

Leibold, M. A., M. Holyoak, N. Mouquet, P. Amarasekare, J. M. Chase, M. F. Hoopes, R. D. Holt, J. B. Shurin, R. Law, D. Tilman, M. Loreau, and A. Gonzalez. 2004: The metacommunity concept: A framework for multi-scale community ecology. Ecology Letters 7:601–613.

Lendemer, J., B. Thiers, A. K. Monfils, J. Zaspel, E. R. Ellwood, A. Bentley, K. LeVan, J. Bates, D. Jennings, D. Contreras, L. Lagomarsino, P. Mabee, L. S. Ford, R. Guralnick, R. E. Gropp, M. Revelez, N. Cobb, K. Seltmann, and M. C. Aime. 2020: The Extended Specimen Network: A Strategy to Enhance US Biodiversity Collections, Promote Research and Education. BioScience 70:23–30.

Lenoir, J., R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, and G. Grenouillet. 2020: Species better track climate warming in the oceans than on land. Nature Ecology & Evolution 4:1044–1059.

Lewis, D. 2019: The fight for control over virtual fossils. Nature 567:20–23.

Lin, C.-H., C.-L. Wei, S. L. Ho, and L. Lo. 2023: Ocean temperature drove changes in the mesopelagic fish community at the edge of the Pacific Warm Pool over the past 460,000 years. Science Advances 9:eadf0656.

Liow, L. H., and P. D. Taylor. 2019: Cope's Rule in a modular organism: Directional evolution without an overarching macroevolutionary trend. Evolution 73:1863–1872.

Liow, L. H., J. Uyeda, and G. Hunt. 2023: Cross-disciplinary information for understanding macroevolution. Trends in Ecology & Evolution 38:250–260.

Löbl, I., B. Klausnitzer, M. Hartmann, and F.-T. Krell. 2023: The silent extinction of species and taxonomists—An appeal to science policymakers and legislators. Diversity 15:1053.

Lotze, H. K., J. M. Erlandson, M. J. Hardt, R. D. Norris, K. Roy, T. D. Smith, and C. R. Whitcraft. 2011: How do we know about the past. Pp.137–161 in J. B. C. Jackson, K. E. Alexander, and E. Sala, eds. Shifting Baselines: The Past and the Future of Ocean Fisheries. Island Press, Washington, DC.

Louca, S., and M. W. Pennell. 2020: Extant timetrees are consistent with a myriad of diversification histories. Nature 580:502–505.

Louys, J., G. J. Price, and K. J. Travouillon. 2021: Space-time equivalence in the fossil record, with a case study from Pleistocene Australia. Quaternary Science Reviews 253:106764.

Louys, J., S. Kealy, S. O’Connor, G. Price, S. Hawkins, K. P. Aplin, Y. Rizal, J. Zaim, M. Mahirta, and D. Tanudirjo. 2017: Differential preservation of vertebrates in Southeast Asian caves. .

Mabry, M. E., F. Zapata, D. L. Paul, P. M. O’Connor, P. S. Soltis, D. C. Blackburn, and N. B. Simmons. 2022: Monographs as a nexus for building extended specimen networks using persistent identifiers. Bulletin of the Society of Systematic Biologists 1.

Machado, F. A., C. S. Mongle, G. Slater, A. Penna, A. Wisniewski, A. Soffin, V. Dutra, and J. C. Uyeda. 2023: Rules of teeth development align microevolution with macroevolution in extant and extinct primates. Nature Ecology & Evolution:1–11.

MacLeod, N. 2014: The geological extinction record: History, data, biases, and testing. Geological Society of America Special Papers 505:1–28.

Malanoski, C.M., A. Farnsworth, D.J. Lunt, P.J. Valdes, and E.E. Saupe. 2024: Climate change is an important predictor of extinction risk on macroevolutionary timescales. Science, 383: 1130–1134.

Mancuso, A. C., R. B. Irmis, T. E. Pedernera, L. C. Gaetano, C. A. Benavente, and B. T. Breeden III. 2022: Paleoenvironmental and biotic changes in the Late Triassic of Argentina: testing hypotheses of abiotic forcing at the basin scale. Frontiers in Earth Science 10.

Mannion, P. D., P. Upchurch, R. B. Benson, and A. Goswami. 2014: The latitudinal biodiversity gradient through deep time. Trends in ecology & evolution 29:42–50.

Maran, S. A. 2014: Conservation of paleontological heritage in Serbia: from philosophy to practice. Bulletin of the Natural History Museum:7–28.

Marshall, C. R. 2017: Five palaeobiological laws needed to understand the evolution of the living biota. Nature ecology & evolution 1:0165.

———. 2023: Forty years later: The status of the “Big Five” mass extinctions. Cambridge Prisms: Extinction 1:e5.

Marshall, C. R., S. Finnegan, E. C. Clites, P. A. Holroyd, N. Bonuso, C. Cortez, E. Davis, G. P. Dietl, P. S. Druckenmiller, and R. C. Eng. 2018: Quantifying the dark data in museum fossil collections as palaeontology undergoes a second digital revolution. Biology letters 14:20180431.

Marshall, F. E., G. L. Wingard, and P. A. Pitts. 2014: Estimates of natural salinity and hydrology in a subtropical estuarine ecosystem: implications for greater everglades restoration. Estuaries and Coasts 37:1449–1466.

Martin, J. E., T. Tacail, and V. Balter. 2017: Non-traditional isotope perspectives in vertebrate palaeobiology. Palaeontology 60:485–502.

Mayor, A. 2007: Place names describing fossils in oral traditions. Geological Society, London, Special Publications 273:245–261.

McElwain, J. C. 2018: Paleobotany and global change: Important lessons for species to biomes from vegetation responses to past global change. Annual Review of Plant Biology 69:761–787.

McGill, B. J. 2019: The what, how and why of doing macroecology. Global Ecology and Biogeography 28:6–17.

McGuire, J. L., A. M. Lawing, S. Díaz, and N. Chr. Stenseth. 2023: The past as a lens for biodiversity conservation on a dynamically changing planet. Proceedings of the National Academy of Sciences 120:e2201950120.

McKinney, M. L. 1997: Extinction vulnerability and selectivity: combining ecological and paleontological views. Annual review of ecology and systematics 28:495–516.

McNamara, M. E., V. Rossi, T. S. Slater, C. S. Rogers, A.-L. Ducrest, S. Dubey, and A. Roulin. 2021: Decoding the evolution of melanin in vertebrates. Trends in ecology & evolution 36:430–443.

Mexicana, P. 2020: How is the paleontological heritage of Mexico and other Latin American countries protected? Paleontología Mexicana 9:83–90.

Mohammed, R. S., G. Turner, K. Fowler, M. Pateman, M. A. Nieves-Colón, L. Fanovich, S. B. Cooke, L. M. Dávalos, S. M. Fitzpatrick, and C. M. Giovas. 2022: Colonial legacies influence biodiversity lessons: How past trade routes and power dynamics shape present-day scientific research and professional opportunities for Caribbean scientists. The American Naturalist 200:140–155.

Monarrez, P. M., J. B. Zimmt, A. M. Clement, W. Gearty, J. J. Jacisin, K. M. Jenkins, K. M. Kusnerik, A. W. Poust, S. V. Robson, J. A. Sclafani, K. T. Stilson, S. D. Tennakoon, and C. M. Thompson. 2022: Our past creates our present: a brief overview of racism and colonialism in Western paleontology. Paleobiology 48:173–185.

Monfils, A. K., E. R. Krimmel, D. L. Linton, T. D. Marsico, A. B. Morris, and B. R. Ruhfel. 2022: Collections Education: The Extended Specimen and Data Acumen. BioScience 72:177–188.

Mongiardino Koch, N., R. J. Garwood, and L. A. Parry. 2021: Fossils improve phylogenetic analyses of morphological characters. Proceedings of the Royal Society B 288:20210044.

Mora, C., D. P. Tittensor, S. Adl, A. G. Simpson, and B. Worm. 2011: How many species are there on Earth and in the ocean? PLoS biology 9:e1001127.

Mulvey, L. P., R. C. Warnock, and K. De Baets. 2022: Where traditional extinction estimates fall flat: using novel cophylogenetic methods to estimate extinction risk in platyhelminths. Proceedings of the Royal Society B 289:20220432.

Mulvey, L. P., May, M. R., Brown, J. M., Höhna, S., Wright, A. M., and R.C. Warnock. 2024: Assessing the adequacy of morphological models using posterior predictive simulations. Systematic Biology, syae055.

Murdock, D. J. 2020: The ‘biomineralization toolkit’ and the origin of animal skeletons. Biological Reviews 95:1372–1392.

Muscente, A. D., R. C. Martindale, A. Prabhu, X. Ma, P. Fox, R. M. Hazen, and A. H. Knoll. 2022: Appearance and disappearance rates of Phanerozoic marine animal paleocommunities. Geology 50:341–345.

Muscente, A. D., A. Prabhu, H. Zhong, A. Eleish, M. B. Meyer, P. Fox, R. M. Hazen, and A. H. Knoll. 2018: Quantifying ecological impacts of mass extinctions with network analysis of fossil communities. Proceedings of the National Academy of Sciences 115:5217–5222.

Na, L., Q. Li, C. Krause, M. Zhu, and W. Kiessling. 2023: Revisiting the Phanerozoic rock–diversity relationship. Geological Magazine:1–10.

Naranjo-Ortiz, M. A., and T. Gabaldón. 2019: Fungal evolution: major ecological adaptations and evolutionary transitions. Biological Reviews 94:1443–1476.

Nätscher, P. S., J. Gliwa, K. De Baets, A. Ghaderi, and D. Korn. 2023: Exceptions to the temperature–size rule: no Lilliput Effect in end-Permian ostracods (Crustacea) from Aras Valley (northwest Iran). Palaeontology 66:e12667.

Neto De Carvalho, C., A. N. Baucon, A. N. Bayet-Goll, and J. N. Belo. 2021: The Penha Garcia Ichnological Park at Naturtejo UNESCO Global Geopark (Portugal): a geotourism destination in the footprint of the Great Ordovician Biodiversification Event. Geoconservation Research 4:70–79.

Neuwirth, E. 2022: RColorBrewer: ColorBrewer Palettes. .

Nützel, A., M. Joachimski, and M. L. Correa. 2010: Seasonal climatic fluctuations in the Late Triassic tropics—High-resolution oxygen isotope records from aragonitic bivalve shells (Cassian Formation, Northern Italy). Palaeogeography, Palaeoclimatology, Palaeoecology 285:194–204.

Nylin, S., S. Agosta, S. Bensch, W. A. Boeger, M. P. Braga, D. R. Brooks, M. L. Forister, P. A. Hambäck, E. P. Hoberg, and T. Nyman. 2018: Embracing colonizations: a new paradigm for species association dynamics. Trends in Ecology & Evolution 33:4–14.

O'Keefe, F. R., R. E. Dunn, E. M. Weitzel, M. R. Waters, L. N. Martinez, W. J. Binder, J. R. Southon, J. E. Cohen, J. A. Meachen, L. R. G. DeSantis, M. E. Kirby, E. Ghezzo, J. B. Coltrain, B. T. Fuller, A. B. Farrell, G. T. Takeuchi, G. MacDonald, E. B. Davis, and E. L. Lindsey. 2023: Pre–Younger Dryas megafaunal extirpation at Rancho La Brea linked to fire-driven state shift. Science 381:eabo3594.

Parham, J. F., P. C. J. Donoghue, C. J. Bell, T. D. Calway, J. J. Head, P. A. Holroyd, J. G. Inoue, R. B. Irmis, W. G. Joyce, D. T. Ksepka, J. S. L. Patané, N. D. Smith, J. E. Tarver, M. van Tuinen, Z. Yang, K. D. Angielczyk, J. M. Greenwood, C. A. Hipsley, L. Jacobs, P. J. Makovicky, J. Müller, K. T. Smith, J. M. Theodor, R. C. M. Warnock, and M. J. Benton. 2012: Best practices for justifying fossil calibrations. Systematic Biology 61:346–359.

Parins-Fukuchi, C., G. W. Stull, and S. A. Smith. 2021: Phylogenomic conflict coincides with rapid morphological innovation. Proceedings of the National Academy of Sciences 118:e2023058118.

Parsons, E. C. M., B. Favaro, A. A. Aguirre, A. L. Bauer, L. K. Blight, J. A. Cigliano, M. A. Coleman, I. M. Cote, M. Draheim, and S. Fletcher. 2014: Seventy-one important questions for the conservation of marine biodiversity. Conservation Biology 28:1206–1214.

Parrott, L. 2010: Measuring ecological complexity. Ecological Indicators 10: 1069-1076.

Patton, A. H., L. J. Harmon, M. del Rosario Castañeda, H. K. Frank, C. M. Donihue, A. Herrel, and J. B. Losos. 2021: When adaptive radiations collide: Different evolutionary trajectories between and within island and mainland lizard clades. Proceedings of the National Academy of Sciences 118:e2024451118.

Pawlik, Lukasz, B. Buma, P. Šamonil, J. Kvaček, A. Galązka, P. Kohout, and I. Malik. 2020: Impact of trees and forests on the Devonian landscape and weathering processes with implications to the global Earth's system properties-A critical review. Earth-Science Reviews 205:103200.

Pecl, G. T., M. B. Araújo, J. D. Bell, J. Blanchard, T. C. Bonebrake, I.-C. Chen, T. D. Clark, R. K. Colwell, F. Danielsen, and B. Evengård. 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355:eaai9214.

Perini, M. M., and J. O. Calvo. 2008: Paleontological tourism: an alternative income to vertebrate paleontology. Arquivos do Museu Nacional 66:285–289.

Peters, S. E., and N. A. Heim. 2011: Macrostratigraphy and macroevolution in marine environments: testing the common-cause hypothesis. Geological Society, London, Special Publications 358:95–104.

Phillips, J. 1860: Life on the Earth: its origin and succession. Macmillan and Company, p.

Piazza, V., C. V. Ullmann, and M. Aberhan. 2020: Temperature-related body size change of marine benthic macroinvertebrates across the Early Toarcian Anoxic Event. Scientific reports 10:4675.

Pimiento, C., and A. Antonelli. 2022: Integrating deep-time palaeontology in conservation prioritisation. Frontiers in Ecology and Evolution 10:959364.

Plotnick, R. E., B. M. Anderson, S. J. Carlson, A. M. Jukar, J. Kimmig, and E. Petsios. 2023: Paleontology is far more than new fossil discoveries. Scientific American.

Plotnick et al. 2024: Employment in Paleontology: Status and Trends in the United States. Paleobiology: in press

Pohl, A., R. G. Stockey, X. Dai, R. Yohler, G. Le Hir, D. Hülse, A. Brayard, S. Finnegan, and A. Ridgwell. 2023: Why the Early Paleozoic was intrinsically prone to marine extinction. Science Advances 9:eadg7679.

Pörtner, H.-O. 2021: Climate impacts on organisms, ecosystems and human societies: integrating OCLTT into a wider context. Journal of Experimental Biology 224:jeb238360.

Price, S. A., and L. Schmitz. 2016: A promising future for integrative biodiversity research: an increased role of scale-dependency and functional biology. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150228.

Punyasena, S. W., D. S. Haselhorst, S. Kong, C. C. Fowlkes, and J. E. Moreno. 2022: Automated identification of diverse Neotropical pollen samples using convolutional neural networks. Methods in Ecology and Evolution 13:2049–2064.

Quintero, I., M. J. Landis, W. Jetz, and H. Morlon. 2023: The build-up of the present-day tropical diversity of tetrapods. Proceedings of the National Academy of Sciences USA 120:e2220672120.

R Core Team. 2023: R: A Language and Environment for Statistical Computing. .

Rabosky, D. L., and A. H. Hurlbert. 2015: Species richness at continental scales is dominated by ecological limits. The American Naturalist 185:572–583.

Raja, N. B., and E. M. Dunne. 2022: Publication pressure threatens the integrity of palaeontological research. The Geological Curator 11:407–418.

Raja, N. B., A. Lauchstedt, J. M. Pandolfi, S. W. Kim, A. F. Budd, and W. Kiessling. 2021: Morphological traits of reef corals predict extinction risk but not conservation status. Global Ecology and Biogeography 30:1597–1608.

Raja, N. B., E. M. Dunne, A. Matiwane, T. M. Khan, P. S. Nätscher, A. M. Ghilardi, and D. Chattopadhyay. 2022: Colonial history and global economics distort our understanding of deep-time biodiversity. Nature Ecology & Evolution 6:145–154.

Rapacciuolo, G., and J. L. Blois. 2019: Understanding ecological change across large spatial, temporal and taxonomic scales: integrating data and methods in light of theory. Ecography 42:1247–1266.

Reddin, C. J., Á. T. Kocsis, and W. Kiessling. 2018: Marine invertebrate migrations trace climate change over 450 million years. Global Ecology and Biogeography 27:704–713.

Reddin, C. J., P. S. Nätscher, Á. T. Kocsis, H.-O. Pörtner, and W. Kiessling. 2020: Marine clade sensitivities to climate change conform across timescales. Nature Climate Change 10:249–253.

Reed, L., and S. Bourne. 2013: Old cave, new stories: the interpretative evolution of Blanche Cave, Naracoorte, South Australia. Journal of the Australasian Cave and Karst Management Association 90:11–28.

Reimann, L., A. T. Vafeidis, S. Brown, J. Hinkel, and R. S. J. Tol. 2018: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. Nature Communications 9:4161.

Rita, P., P. Nätscher, L. V. Duarte, R. Weis, and K. De Baets. 2019: Mechanisms and drivers of belemnite body-size dynamics across the Pliensbachian–Toarcian crisis. Royal Society open science 6:190494.

Rolland, J., L. F. Henao-Diaz, M. Doebeli, R. Germain, L. J. Harmon, L. L. Knowles, L. H. Liow, J. E. Mank, A. Machac, and S. P. Otto. 2023: Conceptual and empirical bridges between micro-and macroevolution. Nature Ecology & Evolution 7:1181–1193.

Romero, I. C., S. Kong, C. C. Fowlkes, C. Jaramillo, M. A. Urban, F. Oboh-Ikuenobe, C. D'Apolito, and S. W. Punyasena. 2020: Improving the taxonomy of fossil pollen using convolutional neural networks and superresolution microscopy. Proceedings of the National Academy of Sciences 117:28496–28505.

Ronquist, F., J. Kudlicka, V. Senderov, J. Borgström, N. Lartillot, D. Lundén, L. Murray, T. B. Schön, and D. Broman. 2021: Universal probabilistic programming offers a powerful approach to statistical phylogenetics. Communications Biology 4:1–10.

Roopnarine, P. D. 2006: Extinction cascades and catastrophe in ancient food webs. Paleobiology 32:1–19.

Rudzki, E. N., S. E. Kuebbing, D. R. Clark, B. Gharaibeh, M. J. Janecka, R. Kramp, K. D. Kohl, T. Mastalski, M. E. Ohmer, and M. M. Turcotte. 2022: A guide for developing a field research safety manual that explicitly considers risks for marginalized identities in the sciences. Methods in Ecology and Evolution 13:2318–2330.

Saleh, F., J. B. Antcliffe, B. Lefebvre, B. Pittet, L. Laibl, F. P. Peris, L. Lustri, P. Gueriau, and A. C. Daley. 2020: Taphonomic bias in exceptionally preserved biotas. Earth and Planetary Science Letters 529:115873.

Saleh, F., O. G. Bath-Enright, A. C. Daley, B. Lefebvre, B. Pittet, A. Vite, X. Ma, M. G. Mángano, L. A. Buatois, and J. B. Antcliffe. 2021: A novel tool to untangle the ecology and fossil preservation knot in exceptionally preserved biotas. Earth and Planetary Science Letters 569:117061.

Salvador, R. B., D. C. Cavallari, D. Rands, and B. M. Tomotani. 2022: Publication practice in taxonomy: global inequalities and potential bias against negative results. PLOS ONE 17:e0269246.

Salvador, R. B., B. M. Tomotani, K. L. O'Donnell, D. C. Cavallari, J. V. Tomotani, R. A. Salmon, and J. Kasper. 2021: Invertebrates in science communication: confronting scientists' practices and the public's expectations. Frontiers in Environmental Science 9.

Sanders, D., E. Thébault, R. Kehoe, and F. J. Frank van Veen. 2018: Trophic redundancy reduces vulnerability to extinction cascades. Proceedings of the National Academy of Sciences 115:2419–2424.

Sansom, R. S., S. E. Gabbott, and M. A. Purnell. 2010: Decay of vertebrate characters in hagfish and lamprey (Cyclostomata) and the implications for the vertebrate fossil record. Proceedings of the Royal Society B: Biological Sciences 278:1150–1157.

Saupe, E. E., J. R. Hendricks, A. T. Peterson, and B. S. Lieberman. 2014: Climate change and marine molluscs of the western North Atlantic: future prospects and perils. Journal of Biogeography 41:1352–1366.

Saupe, E. E., C. E. Myers, A. Townsend Peterson, J. Soberón, J. Singarayer, P. Valdes, and H. Qiao. 2019: Spatio-temporal climate change contributes to latitudinal diversity gradients. Nature ecology & evolution 3:1419–1429.

Scarlett, J. P. 2022: The harmful legacy of colonialism in natural hazard risk. Nature Communications 13:6945.

Schweitzer, M. H., R. Avci, T. Collier, and M. B. Goodwin. 2008: Microscopic, chemical and molecular methods for examining fossil preservation. Comptes Rendus Palevol 7:159–184.

Seddon, A. W. R., A. W. Mackay, A. G. Baker, H. J. B. Birks, E. Breman, C. E. Buck, E. C. Ellis, C. A. Froyd, J. L. Gill, L. Gillson, E. A. Johnson, V. J. Jones, S. Juggins, M. Macias-Fauria, K. Mills, J. L. Morris, D. Nogués-Bravo, S. W. Punyasena, T. P. Roland,

A. J. Tanentzap, K. J. Willis, M. Aberhan, E. N. van Asperen, W. E. N. Austin, R. W. Battarbee, S. Bhagwat, C. L. Belanger, K. D. Bennett, H. H. Birks, C. Bronk Ramsey, S. J. Brooks, M. de Bruyn, P. G. Butler, F. M. Chambers, S. J. Clarke, A. L. Davies, J. A. Dearing, T. H. G. Ezard, A. Feurdean, R. J. Flower, P. Gell, S. Hausmann, E. J. Hogan, M. J. Hopkins, E. S. Jeffers, A. A. Korhola, R. Marchant, T. Kiefer, M. Lamentowicz, I. Larocque-Tobler, L. López-Merino, L. H. Liow, S. McGowan, J. H. Miller, E. Montoya, O. Morton, S. Nogué, C. Onoufriou, L. P. Boush, F. Rodriguez-Sanchez, N. L. Rose, C. D. Sayer, H. E. Shaw, R. Payne, G. Simpson, K. Sohar, N. J. Whitehouse, J. W. Williams, and A. Witkowski. 2014: Looking forward through the past: Identification of 50 priority research questions in palaeoecology. Journal of Ecology 102:256–267.

Seilacher, A., W.E. Reif, F. Westphal, R. Riding, E. N. K. Clarkson, H. B. Whittington, H. B. Whittington, and S. C. Morris. 1985: Sedimentological, ecological and temporal patterns of fossil Lagerstätten. Philosophical Transactions of the Royal Society of London. B, Biological Sciences 311:5–23.

Sepkoski, J. J., R. K. Bambach, D. M. Raup, and J. W. Valentine. 1981: Phanerozoic marine diversity and the fossil record. Nature 293:435–437.

Shinbrot, X. A., K. Treibergs, L. M. A. Hernández, D. Esparza, K. Ghezzi-Kopel, M. Goebel, O. J. Graham, A. B. Heim, J. A. Smith, and M. K. Smith. 2022: The Impact of Field Courses on Undergraduate Knowledge, Affect, Behavior, and Skills: A Scoping Review. BioScience 72:1007–1017.

Słowiński, M., P. Skubała, I. Zawiska, A. Kruk, M. Obremska, K. Milecka, and F. Ott. 2018: Cascading effects between climate, vegetation, and macroinvertebrate fauna in 14,000-

year palaeoecological investigations of a shallow lake in eastern Poland. Ecological Indicators 85:329–341.

Smiley, T. M. 2018: Detecting diversification rates in relation to preservation and tectonic history from simulated fossil records. Paleobiology 44:1–24.

Smith, H. E., J. J. Bevitt, J. Zaim, Y. Rizal, Aswan, M. R. Puspaningrum, A. Trihascaryo, G. J. Price, G. E. Webb, and J. Louys. 2021: High-resolution high-throughput thermal neutron tomographic imaging of fossiliferous cave breccias from Sumatra. Scientific Reports 11:19953.

Smith, J. A., S. R. Durham, and G. P. Dietl. 2018: Conceptions of long-term data among marine conservation biologists and what conservation paleobiologists need to know. Pp.23–54 in C. L. Tyler and C. L. Schneider, eds. Marine Conservation Paleobiology. Springer International Publishing, Cham.

Smith, J. A., M. J. Pruden, J. C. Handley, S. R. Durham, and G. P. Dietl. 2023a: Assessing the utility of death assemblages as reference conditions in a common benthic index (M-AMBI) with simulations. Geological Society, London, Special Publications 529:131–151.

Smith, J. A., M. C. Rillo, Á. T. Kocsis, M. Dornelas, D. Fastovich, H.-H. M. Huang, L. Jonkers, W. Kiessling, Q. Li, and L. H. Liow. 2023b: BioDeepTime: A database of biodiversity time series for modern and fossil assemblages. Global Ecology and Biogeography 32:1680–1689.

Smith, J. A., N. B. Raja, T. Clements, D. Dimitrijević, E. M. Dowding, E. M. Dunne, B. M. Gee, P. L. Godoy, E. M. Lombardi, L. P. A. Mulvey, P. S. Nätscher, C. J. Reddin, B. Shirley, R. C. M. Warnock, and Á. T. Kocsis. 2023c: Increasing the equitability of data citation in paleontology: capacity building for the big data future. Paleobiology:1–12.

Song, H., P. B. Wignall, H. Song, X. Dai, and D. Chu. 2019: Seawater temperature and dissolved oxygen over the past 500 million years. Journal of Earth Science 30:236–243.

Song, H., D. B. Kemp, L. Tian, D. Chu, H. Song, and X. Dai. 2021: Thresholds of temperature change for mass extinctions. Nature communications 12:4694.

Soul, L. C., and M. Friedman. 2015: Taxonomy and phylogeny can yield comparable results in comparative paleontological analyses. Systematic Biology 64:608–620.

Spiridonov, A., and S. Lovejoy. 2022: Life rather than climate influences diversity at scales greater than 40 million years. Nature 607:307–312.

Stadler, T. 2010: Sampling-through-time in birth–death trees. Journal of Theoretical Biology 267:396–404.

Stansfield, E., P. Mitteroecker, S. Y. Vasilyev, S. Vasilyev, and L. N. Butaric. 2021: Respiratory adaptation to climate in modern humans and Upper Palaeolithic individuals from Sungir and Mladeč. Scientific Reports 11:7997.

Stewart, M., W. C. Carleton, and H. S. Groucutt. 2021: Climate change, not human population growth, correlates with Late Quaternary megafauna declines in North America. Nature Communications 12:965.

Stigall, A. L. 2014: When and how do species achieve niche stability over long time scales? Ecography 37:1123–1132.

———. 2019: The invasion hierarchy: ecological and evolutionary consequences of invasions in the fossil record. Annual Review of Ecology, Evolution, and Systematics 50:355–380.

Stokes, A., A. D. Feig, C. L. Atchison, and B. Gilley. 2019: Making geoscience fieldwork inclusive and accessible for students with disabilities. Geosphere 15:1809–1825.

Storch, D., L. Menzel, S. Frickenhaus, and H.-O. Pörtner. 2014: Climate sensitivity across marine domains of life: limits to evolutionary adaptation shape species interactions. Global change biology 20:3059–3067.

Sutherland, W. J., W. M. Adams, R. B. Aronson, R. Aveling, T. M. Blackburn, S. Broad, G. Ceballos, I. M. Côté, R. M. Cowling, and G. A. B. Da Fonseca. 2009: One hundred questions of importance to the conservation of global biological diversity. Conservation biology 23:557–567.

Teng, F.-Z., N. Dauphas, and J. M. Watkins. 2017: Non-traditional stable isotopes: retrospective and prospective. Reviews in mineralogy and geochemistry 82:1–26.

Tihelka, E., R. J. Howard, C. Cai, and J. Lozano-Fernandez. 2022: Was there a Cambrian explosion on land? The case of arthropod terrestrialization. Biology 11:1516.

Trubovitz, S., J. Renaudie, D. Lazarus, and P. J. Noble. 2023: Abundance does not predict extinction risk in the fossil record of marine plankton. Communications Biology 6:1–10.

Tsuboi, M., J. Sztepanacz, S. De Lisle, K.L. Voje, M. Grabowski, M.J. Hopkins, A. Porto, M. Balk, M. Pontarp, D. Rossoni, et al. 2024: The paradox of predictability provides a bridge between micro-and macroevolution. Journal of Evolutionary Biology, voae103.

Vahdati, A. R., J. D. Weissmann, A. Timmermann, M. P. de León, and C. P. Zollikofer. 2022: Exploring Late Pleistocene hominin dispersals, coexistence and extinction with agent-based multi-factor models. Quaternary Science Reviews 279:107391.

Valenzuela-Toro, A. M., and M. Viglino. 2021: Latin American challenges. Nature 598:374–375.

Vermeij, G. J., and P. D. Roopnarine. 2013: Reining in the Red Queen: the dynamics of adaptation and extinction reexamined. Paleobiology 39:560–575.

Vinther, J. 2015: A guide to the field of palaeo colour: Melanin and other pigments can fossilise: Reconstructing colour patterns from ancient organisms can give new insights to ecology and behaviour. BioEssays 37:643–656.

Vogel, G. 2019: Natural history museums face their own past. Science 363:1371–1372.

Vousdoukas, M. I., J. Clarke, R. Ranasinghe, L. Reimann, N. Khalaf, T. M. Duong, B. Ouweneel, S. Sabour, C. E. Iles, C. H. Trisos, L. Feyen, L. Mentaschi, and N. P. Simpson. 2022: African heritage sites threatened as sea-level rise accelerates. Nature Climate Change 12:256–262.

Vrba, E. S. 1985: Environment and evolution: alternative causes of the temporal distribution of evolutionary events. South African Journal of Science 81:229–236.

———. 1992: Mammals as a key to evolutionary theory. Journal of mammalogy 73:1–28.

———. 1993: Turnover-pulses, the Red Queen, and related topics. American Journal of Science 293:418.

———. 1995: On the connections between paleoclimate and evolution. Paleoclimate and evolution, with emphasis on human origins.

Warnock, R. C., and A. M. Wright. 2020: Understanding the tripartite approach to Bayesian divergence time estimation. Cambridge University Press, p.

Westerhold, T., N. Marwan, A. J. Drury, D. Liebrand, C. Agnini, E. Anagnostou, J. S. K. Barnet, S. M. Bohaty, D. D. Vleeschouwer, F. Florindo, T. Frederichs, D. A. Hodell, A. E. Holbourn, D. Kroon, V. Lauretano, K. Littler, L. J. Lourens, M. Lyle, H. Pälike, U. Röhl, J. Tian, R. H. Wilkens, P. A. Wilson, and J. C. Zachos. 2020: An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science.

Whitaker, A. F., and J. Kimmig. 2020: Anthropologically introduced biases in natural history collections, with a case study on the invertebrate paleontology collections from the middle Cambrian Spence Shale Lagerstätte. Palaeontologia Electronica 23:a58.

Wiemann, J., J. M. Crawford, and D. E. Briggs. 2020: Phylogenetic and physiological signals in metazoan fossil biomolecules. Science Advances 6:eaba6883.

Willis, K. J., and S. A. Bhagwat. 2010: Questions of importance to the conservation of biological diversity: answers from the past. Climate of the Past 6:759–769.

Wing, S. L., G. J. Harrington, F. A. Smith, J. I. Bloch, D. M. Boyer, and K. H. Freeman. 2005: Transient floral change and rapid global warming at the Paleocene-Eocene boundary. Science 310:993–996.

Wisz, M. S., J. Pottier, W. D. Kissling, L. Pellissier, J. Lenoir, C. F. Damgaard, C. F. Dormann, M. C. Forchhammer, J.-A. Grytnes, A. Guisan, R. K. Heikkinen, T. T. Høye, I. Kühn, M. Luoto, L. Maiorano, M.-C. Nilsson, S. Normand, E. Öckinger, N. M. Schmidt, M. Termansen, A. Timmermann, D. A. Wardle, P. Aastrup, and J.-C. Svenning. 2013: The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. Biological Reviews 88:15–30.

Woehle, C., A.-S. Roy, N. Glock, J. Michels, T. Wein, J. Weissenbach, D. Romero, C. Hiebenthal, S. N. Gorb, J. Schönfeld, and T. Dagan. 2022: Denitrification in foraminifera has an ancient origin and is complemented by associated bacteria. Proceedings of the National Academy of Sciences 119:e2200198119.

Woodhouse, A., A. Swain, W. F. Fagan, A. J. Fraass, and C. M. Lowery. 2023: Late Cenozoic cooling restructured global marine plankton communities. Nature 614:713–718.

Wright, A. M., D. W. Bapst, J. Barido-Sottani, and R. C. M. Warnock. 2022: Integrating fossil observations Into phylogenetics using the fossilized birth–death model. Annual Review of Ecology, Evolution, and Systematics 53:251–273.

Yamamoto, S., and M. S. Caterino. 2023: A remarkable new fossil species of Amplectister with peculiar hindleg modifications (Coleoptera: Histeridae): further evidence for myrmecophily in Cretaceous clown beetles. Palaeoworld 32:481–489.

Yasuhara, M., C.-L. Wei, M. Kucera, M. J. Costello, D. P. Tittensor, W. Kiessling, T. C. Bonebrake, C. R. Tabor, R. Feng, A. Baselga, K. Kretschmer, B. Kusumoto, and Y. Kubota. 2020: Past and future decline of tropical pelagic biodiversity. Proceedings of the National Academy of Sciences 117:12891–12896.

Yasuhara, M., and C. A. Deutsch. 2022: Paleobiology provides glimpses of future ocean: Fossil records from tropical oceans predict biodiversity loss in a warmer world. Science 375: 25–26.

Yasuhara, M., and C. A. Deutsch. 2023: Tropical biodiversity linked to polar climate. Nature 614: 626–628.

Zacaï, A., C. Monnet, A. Pohl, G. Beaugrand, G. Mullins, D. M. Kroeck, and T. Servais. 2021: Truncated bimodal latitudinal diversity gradient in early Paleozoic phytoplankton. Science Advances 7:eabd6709.

Zuschin, M. 2023: Challenges of Conservation Paleobiology: From baselines to novel communities to the necessity for granting rights to nature. Palaios 38:259–263.

Figures:

Figure 1. The question pathway in the Big Questions project. Questions were submitted by the global community in one of three solicitations. Submitted questions were assigned to working groups (n=12) composed of self-identified topic-experts who chose to participate in the project. Working groups were guided by one to three leaders (larger icons) and refined their assigned questions to a preliminary list. These preliminary questions were assessed by the entire Big Questions team to improve question quality and reduce redundancies in questions from different groups. Using the whole-team feedback, working groups (reduced to eleven due to overlaps, Table 2) produced a refined set of final big questions. Created with BioRender.com

Figure 2. Assignments of originally submitted questions to different working groups. Each question was assigned to at least one group and many were also assigned to a second group with topic overlap. Width of the outer circle represents the number of questions assigned to each working group (counts also provided in parentheses). Bands connecting different working groups represent the questions assigned to each of the groups, with thicker bands indicating a larger number of questions shared between groups. Created in R Statistical Software (v4.3.1; R Core Team 2023) using the circlize package (Gu et al. 2014) and the Paired palette from RColorBrewer (Neuwirth 2022).

Figure 3. The Big Questions project can be used as a tool to guide research in paleontology and to advocate for the importance of funding paleontological research.

Tables:

Table 1. Countries and administrative regions represented in the Big Questions project by affiliations of the authorship team, with respect to when individuals joined the project. Note: as countries and administrative regions represented are derived from the institutional affiliations of the authors, this is likely an underestimate of the number of countries and administrative regions represented by individuals in this project.

Table 2. Working group themes and numbers of questions related to these groups at three stages of the project. The number of individuals assigned to each group is also provided, with the number of group leaders in parentheses.

Table 3. Big questions for the working group on *The Adequacy of the Fossil Record*.

Table 4. Big questions for the working group on *Scaling Ecological and Evolutionary Processes and Patterns*.

Table 5. Big questions for the working group on *Phylogenetics, Taxonomy, and Systematics*.

Table 6. Big questions for the working group on *Biodiversity Dynamics in Space and Time*.

Table 7. Big questions for the working group on *Biodiversity Drivers*.

Table 8. Big questions for the working groups on *Adaptations, Innovations, Origins*.

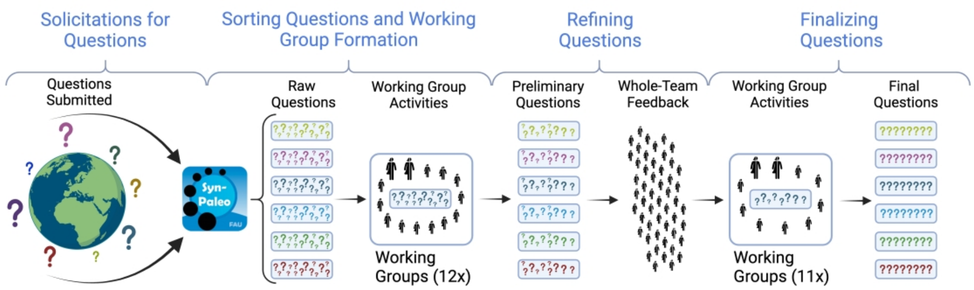
Table 9. Big questions for the working groups on *Extinction Dynamics*.

Table 10. Big questions for the working groups on *Climate Change Past and Present*.

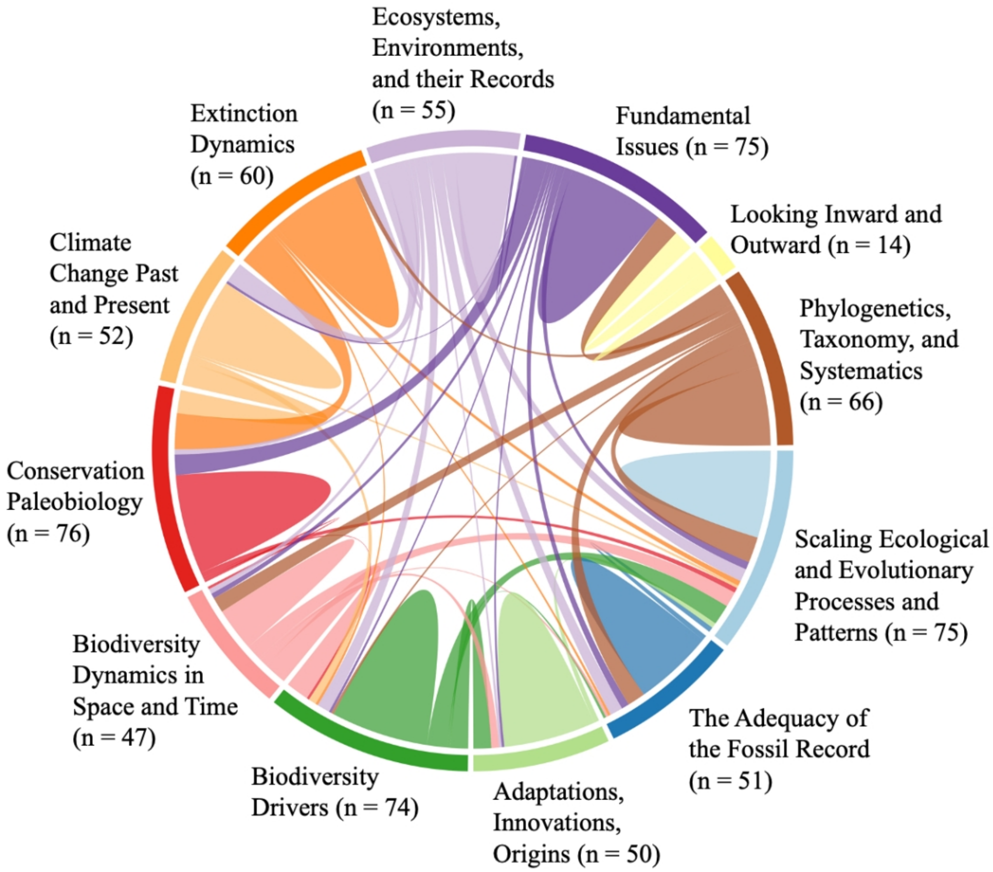
Table 11. Big questions for the working groups on *Conservation Paleobiology*.

Table 12. Big questions for the working groups on *Fundamental Issues*.

Table 13. Big questions for the working groups on *Looking Inward and Outward*.



381x177mm (300 x 300 DPI)



381x381mm (80 x 80 DPI)

Unable to Convert Image

The dimensions of this image (in pixels) are too large to be converted. For this image to convert, the total number of pixels (height x width) must be less than 40,000,000 (40 megapixels).

Table 1. Countries and administrative regions represented in the Big Questions project by affiliations of the authorship team, with respect to when individuals joined the project. Note: as countries and administrative regions represented are derived from the institutional affiliations of the authors, this is likely an underestimate of the number of countries and administrative regions represented by individuals in this project.

	First Solicitation	Second Solicitation	Third Solicitation	Authorship Team
Country/ Administrative Region (AR)	**Number of Affiliations (% of solicitation total)**	**Number of Affiliations (% of solicitation total)**	**Number of Affiliations (% of solicitation total)**	**Number of Affiliations (% of authorship total)**
Argentina	3 (5.8%)		10 (13.9%)	10 (6.1%)
Australia	1 (1.9%)	2 (5.1%)	2 (2.8%)	5 (3.1%)
Austria		2 (5.1%)		2 (1.2%)
Brazil			2 (2.8%)	2 (1.2%)
Canada			1 (1.4%)	1 (0.6%)
China			4 (5.6%)	4 (2.5%)
Colombia		1 (2.6%)		1 (0.6%)
Czech Republic	2 (3.8%)	1 (2.6%)		3 (2.0%)
Egypt		1 (2.6%)		1 (0.6%)
France			2 (2.8%)	2 (1.2%)
Germany	14 (26.9%)	4 (10.3%)	1 (1.4%)	18 (11.0%)
Ghana	1 (1.9%)			1 (0.6%)
Hong Kong SAR, China	1 (1.9%)			1 (0.6%)
India			4 (5.6%)	4 (2.5%)
Italy	1 (1.9%)	2 (5.1%)	1 (1.4%)	4 (2.5%)
Jamaica		1 (2.6%)		1 (0.6%)
Madagascar			2 (2.8%)	2 (1.2%)
Mongolia			1 (1.4%)	1 (0.6%)
New Zealand			1 (1.4%)	1 (0.6%)
Norway		1 (2.6%)		1 (0.6%)
Panama	2 (3.8%)	1 (2.6%)	2 (2.8%)	5 (3.1%)
Poland	1 (1.9%)			1 (0.6%)

Portugal	1 (1.9%)		2 (2.8%)	3 (2.0%)
Singapore			1 (1.4%)	1 (0.6%)
South Africa			1 (1.4%)	1 (0.6%)
Spain	5 (9.6%)	2 (5.1%)	3 (4.2%)	10 (6.1%)
Switzerland			4 (5.6%)	4 (2.5%)
Taiwan		1 (2.6%)	2 (2.8%)	6 (3.7%)
UK	2 (3.8%)	3 (7.7%)	1 (1.4%)	9 (5.5%)
USA	18 (34.6%)	16 (41.0%)	19 (26.4%)	47 (28.8%)
Venezuela		1 (2.6%)		1 (0.6%)
Affiliations Added	**52**	**39**	**72**	**163**
Countries/AR Added	**13**	**7**	**11**	**31**

Table 2. Working group themes and numbers of questions related to these groups at three stages of the project. The number of individuals assigned to each group is also provided, with the number of group leaders in parentheses.

Working group themes	**Number of assigned participants (group leaders)**	**Initial questions assigned to group**	**Preliminary questions**	**Final questions**
Adaptations, Innovations, Origins (AIO)	17 (2)	50	4	7
Biodiversity Drivers (BD)	17 (2)	74	9	9
Biodiversity Dynamics in Space and Time (BST)	17 (2)	47	8	7
Climate Change Past and Present (CPP)	16 (2)	52	10	9
Conservation Paleobiology (CPB)	17 (2)	76	6	8
Ecosystems, Environments, and their Records	16 (2)	55	16	0**
Extinction Dynamics (ED)	17 (2)	60	11	9
Phylogenetics, Taxonomy, and Systematics (PST)	17 (3)	66	11	10
Scaling Ecological and Evolutionary Processes and Patterns (SEP)	16 (1)	75	11	9
The Adequacy of the Fossil Record (AFR)	16 (2)	51	11	8

Fundamental Issues (FI)	22 (2)	75	9	5
Looking Inward and Outward (LIO)	24 (1)	14	11	8
Total Questions:		695*	117	89

* Total is greater than the number of submitted questions (n = 528) because, when a question was relevant to more than one group, it was assigned to each of those groups for consideration.

** The theme "Ecosystems, Environments, and Their Records" was included originally but, after the whole-team feedback phase (Figure 1), considerable overlaps with questions from other groups were apparent and all questions from this theme were ultimately dispersed elsewhere or subsumed by questions in other groups.

Table 3. Big questions for the working group on *The Adequacy of the Fossil Record*.

Unique ID	**Big Question**
AFR1	How can we best quantify preservation and collecting biases?
AFR2	How do we develop methods to identify, minimize, and correct data entry biases?
AFR3	How do we account for data loss in historical collections and publications?
AFR4	How do we standardize taxonomic, stratigraphic, and ecological reporting during data acquisition?
AFR5	How can we improve the collection of biomolecules from fossils, and what are the limits for biomolecule analysis?
AFR6	How can we correlate marine and terrestrial strata more precisely?
AFR7	In what ways can we use isotopic systems and geochemical methods to help identify preservation biases?
AFR8	Which opportunities and threats for fossil discovery will arise as a result of the changing climate?

Table 4. Big questions for the working group on *Scaling Ecological and Evolutionary Processes and Patterns*.

Unique ID	Big Question
SEP1	Which evolutionary and ecological processes (local to global) can be best evaluated using the fossil record?
SEP2	In the fossil record, how do we interpret and measure ecological and evolutionary trends at different taxonomic, spatial, and temporal scales to infer directionality or causality?
SEP3	How do we address the spatial, temporal, and taxonomic incompleteness of the fossil record to be able to interpret ecological and evolutionary processes and patterns at different scales?
SEP4	How can we identify and counteract spatial and temporal transmutations (a change in the relationship between variables caused by crossing data scales, leading to interpretive error) within ecological and evolutionary models?
SEP5	Given incompleteness of the fossil record and spatiotemporal averaging, how do we estimate rates of change in taxonomic composition, community structure, ecosystem function, niches, traits, life modes, turnover etc., using the fossil record?
SEP6	What drives metacommunity composition and community assembly over time and space?
SEP7	How do external environmental drivers (e.g., plate tectonics, global temperature, sea level) influence the structure of biological systems at different spatiotemporal scales?
SEP8	What are the signatures of emergent processes at macroevolutionary timescales (e.g., species sorting, species selection, clade competition)?
SEP9	How do biological systems impact the abiotic systems and the feedback between them at different scales?

Table 5. Big questions for the working group on *Phylogenetics, Taxonomy, and Systematics*.

Unique ID	**Big Question**
PTS1	What causes the mechanism of speciation or character evolution to change over time?
PTS2	Which abiotic and biotic factors determine species longevity (stratigraphic duration)?
PTS3	Which aspects of the macroevolutionary process are identifiable in the molecular or fossil records using phylogenetic methods, and under which circumstances?
PTS4	How can traditional taxonomy be used to inform the process of selecting the best operational taxonomic unit for a particular phylogenetic analysis (e.g. diversification, disparification, phylogeny)?
PTS5	How can taxonomic practice help to harmonize boundaries between taxa in fossil and extant groups?
PTS6	How can we collect and integrate developmental data observable in the fossil record (e.g., timing of organogenesis, gene expression) into phylogenetic approaches?
PTS7	How much phylogenetic information can be gained from combining different types of data (e.g. morphology, stratigraphy, biogeography, environmental)?
PTS8	How can we improve the performance of phylogenetic inference through the development of better methods?
PTS9	How do we improve the representation of uncertainty and bias from the fossil and geological records in phylogenetic inference?
PTS10	What can we learn about environmental and geological processes using phylogenetic methods?

Table 6. Big questions for the working group on *Biodiversity Dynamics in Space and Time*.

Unique ID	Big Question
BST1	What is the global diversity trend through time and how is diversity constrained, if at all?
BST2	How have large-scale spatial diversity patterns (e.g., latitudinal diversity gradient, distribution of diversity hotspots) changed across deep time?
BST3	What are important drivers of global trends in taxonomic diversity or ecological disparity, and has their relative importance changed through time?
BST4	What is the relationship between deep-time biodiversity (e.g., taxonomic richness, ecomorphological disparity) and ecosystem function (the combination of all biological interactions and physical processes occurring in an ecosystem)?
BST5	What are the drivers of origination in space and time?
BST6	What is a common basis (e.g., taxonomic units, morphological traits) that can be used consistently to bridge modern and fossil biodiversity research?
BST7	In what ways is the "Anthropocene" creating a unique signature in biodiversity over geologic time (both direct and indirect effects; e.g., changes in climate and in connectivity)?

Table 7. Big questions for the working group on *Biodiversity Drivers*.

Unique ID	**Big Question**
BD1	How does the ecological niche of species influence their response to perturbation?
BD2	How does the prevailing climate state experienced by species and communities influence their response to perturbation?
BD3	How do methodological choices influence the outcome of studies investigating the relative importance of abiotic and biotic drivers in driving biodiversity dynamics?
BD4	How do the rate and magnitude of environmental change impact diversification?
BD5	How did biologic evolution affect the evolution of other Earth systems (e.g., litho-, atmo-, and hydrosphere)?
BD6	How has the relative importance of biotic and abiotic drivers of biodiversity and extinction changed through time?
BD7	What is the relative role of biotic and abiotic drivers in increasing ecosystem complexity?
BD8	To what extent do population-based characteristics determine resilience to extinction through geological time?
BD9	How do changes in community structure observed at the population level relate to evolutionary changes in ecosystems through time?

Table 8. Big questions for the working groups on *Adaptations, Innovations, Origins*.

Unique ID	Big Question
AIO1	What were the geological and biological drivers of the origin of life, and major groups of organisms such as eukaryotes, plants, animals, and fungi?
AIO2	How were major life transitions (e.g., origins of biomineralization, early Paleozoic diversifications, terrestrialization, evolution of planktonic lifestyle) in Earth's history associated with major changes in the geological and/or biological environment?
AIO3	How is our understanding of the origination of novelties and innovations affected by fossil preservation, the global quality of the fossil record, and stratigraphic completeness?
AIO4	What are best practices for integrating different analytical tools and techniques to improve our interpretation of the ecological context and timing of the origin of adaptations and features?
AIO5	How have changes in ontogeny (i.e., life history traits such as larval/juvenile ecology, growth, and developmental patterns including heterochronies) influenced macroevolution or themselves been influenced by environmental change?
AIO6	Which common patterns of morphological or behavioral responses to environmental change on evolutionary timescales can be identified and how do these compare with modern systems on ecological timescales?
AIO7	Which observable differences in the origin and fixation of features at different scales of biological hierarchy can be identified and what generated these patterns?

Table 9. Big questions for the working groups on *Extinction Dynamics*.

Unique ID	**Big Question**
ED1	Which data types can be used to most effectively compare past extinctions to the current biodiversity crisis?
ED2	With our changing understanding of extinctions, how should the definition of "mass extinction" be updated to reflect a unified concept?
ED3	Which, if any, biotic traits associated with survival through a mass extinction (e.g. body size, trophic mode, species associations) are universal across taxa and/or time?
ED4	Which, if any, ecological impacts of extinction are generalizable across time?
ED5	To what extent are ecological functions maintained following the extinction of species?
ED6	To what extent are the phases of events (e.g., collapse, recovery) during extinctions consistent across different biotic crises?
ED7	Which, if any, patterns in the process and timing of recovery following extinction events are universal across clades?
ED8	At what threshold can climate or other abiotic change cause an extinction?
ED9	What is the role of cascading biological effects in extinction dynamics?

Table 10. Big questions for the working groups on *Climate Change Past and Present*.

Unique ID	**Big Question**
CPP1	How can fossils best be used to reconstruct climate change over different time scales?
CPP2	Which climate factors are the proximate drivers of extinction?
CPP3	How can we best use the fossil record to predict climate change impacts on the modern biota?
CPP4	What is the "ecosystem sensitivity" of ecosystem structure in response to climate change?
CPP5	How have the spatial distributions of organisms shifted in response to climate change?
CPP6	How have organisms' tolerances changed in response to climate change?
CPP7	Which cascading effects of climate change can be identified from the fossil record?
CPP8	What adaptation and management options for conservation biology can be derived from past biosphere responses to climate change?
CPP9	How has climate change affected the evolution of life?

Table 11. Big questions for the working groups on *Conservation Paleobiology*.

Unique ID	**Big Question**
CPB1	What translational science strategies could be adopted to ensure that conservation paleobiology research remains relevant and aligned with the priorities of environmental resource managers and conservation practitioners?
CPB2	How do we integrate multiple types of paleontological data (e.g., molecular, environmental, ecological) with planning and decision support tools for guiding ecosystem management?
CPB3	How can our understanding of past episodes of environmental change be used to develop scenarios of biological responses to modern and future environmental stressors?
CPB4	How can we use paleontological data to define meaningful ecological baselines that are relevant to conservation across spatial and temporal scales?
CPB5	How can the fossil record inform our ability to diagnose and mitigate the effects of multiple interacting human and non-human drivers of environmental change on biodiversity and ecosystem functioning?
CPB6	How can we compare rates of biodiversity change (e.g., extinction, adaptation, geographic range shifts) across ecological, historical, and paleontological timescales?
CPB7	How can recent sedimentary records expand the temporal scope over which ecological resilience can be evaluated?
CPB8	In what ways can paleoenvironmental reconstructions improve the accuracy and scope of ecosystem services risk assessments?

Table 12. Big questions for the working groups on *Fundamental Issues*.

Unique ID	Big Question
FI1	How can we efficiently collect, store, and combine different paleontological data types in an openly accessible and inclusive way?
FI2	What are best practices for training paleontologists to have a broad set of skills (e.g., data analyses, research skills, soft skills) that is transferable to an increasingly wider range of job requirements inside and outside of academia?
FI3	How can we best motivate taxonomic and systematic work and facilitate cross-talk and collaboration with other paleontological disciplines?
FI4	How can paleontologists communicate findings and foster critical thinking skills so that the public can understand the utility of paleontological information and differentiate valid scientific ideas from other ideas?
FI5	What are the best practices for the protection and valorization of geosites and unique fossil heritage?

Table 13. Big questions for the working groups on *Looking Inward and Outward*.

Unique ID	Big Question
LIO1	How is our understanding of past ecological and evolutionary processes shaped by biases in publication by location, authorship, language use, and funding availability?
LIO2	Which processes drive turnover in diversity trends (e.g., gender identities, different geographic regions) of academic paleontologists over time, and how could increased diversity lead to increasingly diverse products and outcomes?
LIO3	Which socioeconomic and identity factors—and their intersections—underlie variability in publication rate, professional advancement, and grant awards among the global paleontology community, both historically and in the present day?
LIO4	To what extent are paleontological specimen collecting and repository practices built on a legacy of colonial economic structures and how can we avoid recapitulating these interactions today across individual and institutional collaborations?
LIO5	How should qualities of fossil origin (e.g., country, sovereignty, collection process, local collaborative involvement, political conflict) be considered when designing research and navigating potential trade-offs in ethics and scientific value?
LIO6	Which settings (e.g., economic, cultural, physical) govern the biogeography of where paleontological field work occurs and who (e.g., gender/ethnic identity) carries out—and benefits from—that work?
LIO7	Which institutional and mentorship attributes, such as accountability mechanisms, facilitate equitable collaboration among paleontologists, avoid bias, and promote the retention of students from backgrounds and identities currently underrepresented in paleontology?
LIO8	How do we integrate and sustain a commitment to diversity, equity, and inclusion initiatives into the foundations of hiring, promotion, and funding schemes in paleontology?