Biogeosciences Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

Dipankar Dwivedi^{1,1}, A L D Santos^{2,2}, M A Barnard^{3,3}, T M Crimmins^{4,4}, A Malhotra^{5,5}, K A Rod^{6,6}, K S Aho^{7,7}, S M Bell^{8,8}, B Bomfim^{9,9}, F Q Brearley^{10,10}, H Cadillo-Quiroz^{11,11}, J Chen^{12,12}, C M Gough^{13,13}, E B Graham^{6,6}, C R Hakkenberg^{14,14}, L Haygood^{15,15}, G Koren^{16,16}, E Lilleskov^{17,17}, L K Meredith^{18,18}, S Naeher^{19,19}, Z L Nickerson^{20,20}, O Pourret^{21,21}, H.-S Song^{22,22}, M Stahl^{23,23}, N Taş^{24,24}, R Vargas^{25,25}, and S Weintraub-Leff^{20,20}

¹Earth and Environmental Sciences Area

²Federal University of Paraná

 $^{^3{\}rm University}$ of North Carolina at Chapel Hill

⁴USA National Phenology Network

⁵Stanford University

⁶Pacific Northwest National Laboratory

⁷Battelle

⁸Universitat Autònoma de Barcelona (UAB)

⁹Lawrence Berkeley National Labo-ratory

¹⁰Manchester Metropolitan University

¹¹Arizona State University

¹²Michigan State University

 $^{^{13}{}m Virginia}$ Commonwealth University

 $^{^{14}16} School$ of Informatics, Computing & Cyber Systems, Northern Arizona University, Flagstaff, AZ USA

 $^{^{15}\}mathrm{Department}$ of Geosciences, The University of Tulsa, 800 South Tucker Drive, Tulsa, OK 74104

 $^{^{16}\}mathrm{Copernicus}$ Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands

¹⁷US Forest Service

¹⁸School of Natural Resources and the Environment, University of Arizona, 1064 East Lowell Street, Tucson, AZ 85721, USA

 $^{^{19}\}mathrm{GNS}$ Science, 1 Fairway Drive, PO Box 30368, Lower Hutt 5040, New Zealand

²⁰Battelle, National Ecological Observatory Network, 1685 38th St 100, Boulder, CO 80301

²¹UniLaSalle, AGHYLE, 19 rue Pierre Waguet, 60026 Beauvais cedex, France

²²Department of Biological Systems Engineering, Department of Food Science and Technology, University of Nebraska-Lincoln, Lincoln, NE 68583

²³Department of Geology, Union College, Schenectady, NY 12308

²⁴Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, One Cyclotron Road 70A-2250, Berkeley, CA 94720, USA

 $^{^{25}\}mathrm{Department}$ of Plant and Soil Sciences, University of Delaware, Newark, DE 19716, USA

November 30, 2022

Abstract

This article is composed of three independent commentaries about the state of ICON principles (Goldman et al. 2021) in the AGU Biogeosciences section and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: Global collaboration, technology transfer and application (Section 2), Community engagement, citizen science, education, and stakeholder involvement (Section 3), and Field, experimental, remote sensing, and real-time data research and application (Section 4). We discuss needs and strategies for implementing ICON and outline short- and long-term goals. The inclusion of global data and international community engagement are key to tackle grand challenges in biogeosciences. Although recent technological advances and growing open-access information across the world have enabled global collaborations to some extent, several barriers ranging from technical to organizational to cultural have remained in advancing interoperability and tangible scientific progress in biogeosciences. Overcoming these hurdles is necessary to address pressing large-scale research questions and applications in the biogeosciences, where ICON principles are essential. Here, we list several opportunities for ICON, including coordinated experimentation and field observations across global sites, that are ripe for implementation in biogeosciences as a means to scientific advancements and social progress.

Hosted file

essoar.10508474.2.docx available at https://authorea.com/users/462789/articles/608449-biogeosciences-perspectives-on-integrated-coordinated-open-networked-icon-science

Biogeosciences Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

D. Dwivedi¹, A.L.D. Santos², M.A. Barnard³, T.M. Crimmins⁴, A. Malhotra⁵, K.A. Rod⁶, K.S. Aho⁷, S.M. Bell⁸, B. Bomfim⁹, F.Q. Brearley¹⁰, H. Cadillo-Quiroz¹¹, J. Chen¹², C.M. Gough¹³, E.B. Graham^{6,14}, C.R. Hakkenberg¹⁵, L. Haygood^{16,17}, G. Koren¹⁸, E. Lilleskov¹⁹, L.K. Meredith²⁰, S. Naeher²¹, Z.L. Nickerson⁷, O. Pourret²², H.-S. Song²³, M. Stahl²⁴, N. Taş¹, R. Vargas²⁵, and S. Weintraub-Leff⁷

¹Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, One Cyclotron Road 70A-2250, Berkeley, CA 94720, USA,

²Department of Environmental Engineering, Federal University of Paraná, Polytechnic Center Campus, Curitiba, PR 82590-300, Brazil,

³Institute of Marine Sciences, University of North Carolina at Chapel Hill, 3431 Arendell Street, Morehead City, NC 28557, USA,

⁴USA National Phenology Network, School of Natural Resources and the Environment, University of Arizona, 1311 E. 4th St., Ste. 325, Tucson, AZ 85721,

⁵Department of Earth System Science, Stanford University, Stanford, CA 94305, USA,

⁶Earth and Biological Sciences Directorate, Pacific Northwest National Laboratory, Richland, WA 99354,

⁷Battelle, National Ecological Observatory Network, 1685 38th St #100, Boulder, CO 80301,

⁸Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Bellaterra, Spain,

⁹Climate and Ecosystems Sciences Division, Lawrence Berkeley National Laboratory, Calvin Rd., Berkeley, CA, 94705 USA,

¹⁰Department of Natural Sciences, Manchester Metropolitan University, Chester Street, Manchester, M1 5GD, UK,

¹¹School of Life Sciences, Arizona State University, Tempe AZ 85287, USA,

 $^{12}\mbox{Department}$ of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48823

 $^{13}\mbox{Department}$ of Biology, Virginia Commonwealth University, 1000 W. Cary St., Richmond, VA 23284,

 $^{14}{\rm School}$ of Biological Sciences, Washington State University, Richland, WA, 99354,

 $^{15}{\rm School}$ of Informatics, Computing & Cyber Systems, Northern Arizona University, Flagstaff, AZ USA,

²⁰School of Natural Resources and the Environment, University of Arizona, 1064 East Lowell Street, Tucson, AZ 85721, USA,

²¹GNS Science, 1 Fairway Drive, PO Box 30368, Lower Hutt 5040, New Zealand,

Corresponding authors: Dipankar Dwivedi (ddwivedi@lbl.gov)

Key Points:

- Biogeosciences needs ICON principles to address multi-scale global problems and reduce geographical bias in scientific progress.
- Much potential exists for emphasizing people-centric capacity building, involving community members, stakeholders, and citizen scientists within an ICON framework.
- Globally coordinated experimental and field data provide challenges and opportunities for scientific advancement in biogeosciences.

Abstract

This article is composed of three independent commentaries about the state of ICON principles (Goldman et al. 2021) in the AGU Biogeosciences section and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: Global collaboration, technology transfer and application (Section 2), Community engagement, citizen science, education, and stakeholder involvement (Section 3), and Field, experimental, remote sensing, and real-time data research and application (Section 4). We discuss needs and strategies for implementing ICON and outline short- and long-term goals. The inclusion of global data and international community engagement are key to tackle grand challenges in biogeosciences. Although recent technological advances and growing open-access information across the world have

 $^{^{16}\}mathrm{Department}$ of Geosciences, The University of Tulsa, 800 South Tucker Drive, Tulsa, OK 74104,

 $^{^{17}\}mathrm{Boone}$ Pickens School of Geology, Oklahoma State University, 105 Noble Research Center, Stillwater, OK 74075,

¹⁸Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands,

¹⁹US Forest Service,

²²UniLaSalle, AGHYLE, 19 rue Pierre Waguet, 60026 Beauvais cedex, France,

²³Department of Biological Systems Engineering, Department of Food Science and Technology, University of Nebraska-Lincoln, Lincoln, NE 68583

 $^{^{24}\}mbox{Department}$ of Geology, Union College, Schenectady, NY 12308,

 $^{^{25}\}mathrm{Department}$ of Plant and Soil Sciences, University of Delaware, Newark, DE 19716, USA

enabled global collaborations to some extent, several barriers ranging from technical to organizational to cultural have remained in advancing interoperability and tangible scientific progress in biogeosciences. Overcoming these hurdles is necessary to address pressing large-scale research questions and applications in the biogeosciences, where ICON principles are essential. Here, we list several opportunities for ICON, including coordinated experimentation and field observations across global sites, that are ripe for implementation in biogeosciences as a means to scientific advancements and social progress.

Plain Language Summary

Biogeosciences is an interdisciplinary field that requires multi-scale global data and concerted international community efforts to tackle grand challenges. However, several technical, institutional, and cultural hurdles have remained as major roadblocks toward scientific progress, hindering seamless global data acquisition and international community engagement. To bring a paradigm shift in biogeosciences, there is a need to implement integrated, coordinated, open, and networked efforts, collectively known as the ICON principles. In this article, we present three related commentaries about the state of ICON, discuss needs to reduce geographical bias in data for enhancing scientific progress, and identify action items. Action items are primarily people-centric and include but are not limited to: longer-term funding priorities to institutionalize capacity and reduce entry costs, engagement of local stakeholders across the globe, incentivization of collaborations, and development of training and workshops for capacity building.

1 Introduction

Integrated, Coordinated, Open, Networked (ICON) science aims to enhance synthesis, increase resource efficiency, and create transferable knowledge (Goldman et al. 2021). Biogeosciences is an inherently interdisciplinary field that needs ICON to address grand environmental challenges, including anthropogenic climate change and its effects on abiotic and biotic systems. Tackling multi-scale global problems requires reducing geographical bias in data collection and scientific progress. Integrating biology, chemistry, and Earth sciences, the biogeosciences address human impacts on the biophysical and chemical properties of terrestrial and aquatic systems around the globe. However, a variety of hurdles prevent ICON implementation in biogeosciences. As part of a collection of commentaries spanning ICON in the geosciences (Goldman et al. 2021), this article evaluates the state of ICON in biogeosciences and focuses on three aspects surrounding global collaborations, stakeholder engagement, and data research and application in biogeosciences.

2 Global collaboration, technology transfer and application

2.1 The need for ICON in Biogeosciences

Many pressing biogeoscience grand environmental challenges, including climate change and nutrient deposition, are global in scope and transcend political boundaries (Figure 1). These challenges are linked to local-to-global ecosystem processes (e.g., carbon or nitrogen cycling) that require distributed observations across spatial scales. Too often, measurements and networks are defined within political boundaries and concentrated in high-income countries, leading to geographical biases (e.g., Stell et al., 2021). Appropriately addressing these grand challenges requires research to be conducted across countries in a coordinated way. However, participation costs can be prohibitive, especially for developing countries. Given this barrier and the heterogeneity of methods available in biogeosciences, it is critical to develop strong instrumentation and protocol coordination for characterizing biogeochemical pools and fluxes, data archiving, and researcher training (e.g., Hubbard et al., 2020; Varadharajan et al., 2019). Overall, tackling biogeosciences grand challenges requires concerted actions that are integrated, coordinated, open, and networked. Below, we briefly describe several hurdles toward implementing the ICON principles and discuss the path forward for pioneering global biogeosciences.

2.2 Major challenges

Biogeosciences' grand challenges are global and require international collaborations to address them. Integrated and coordinated efforts are needed for success, but organizational and cultural challenges for global collaborations present barriers to interoperability (Vargas et al., 2017). Organizational barriers relate to challenges regarding institutional responsibility and authority as well as the inequality of resources (Mirti et al., 2018). Cultural barriers relate to how scientists perceive the world and their relationships/collaborations. Differences in cultural norms, institutions, education, socioeconomic status, modes of communication, language, infrastructure, and technology complicate collaboration between scholars from different regions, institutes, or sub-disciplines. Recent decades have witnessed an enthusiasm to collaborate in education and research. as most scholars recognize the importance of joint efforts in seeking solutions for global environmental issues. Therefore, open and networked efforts are also needed to address biogeosciences' grand challenges. However, cultural barriers can hinder networking, and institutions may prioritize perceived national over international interests. Even within national borders, there are barriers to open data sharing, such as the desire to avoid competition between smaller and larger research groups due to the availability of disparate resources. International cultural and resource differences further intensify barriers to open and networked efforts because scholars from developing countries may not receive equal recognition for the outcomes of their data (e.g., inclusion on publications,

patents) (Armenteras, 2021). This recognition is critical for addressing local issues, maintaining rigorous research and education programs for their groups, and career and institutional advancement.

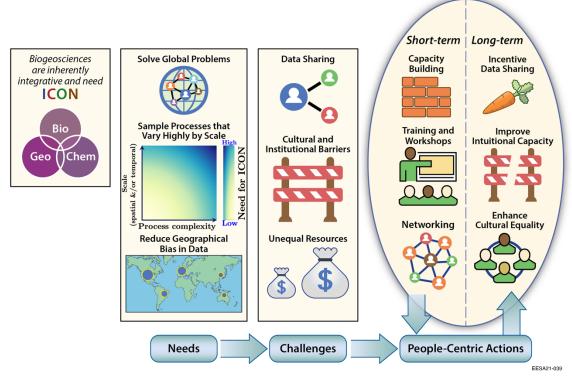


Figure 1: Biogeosciences, an inherently interdisciplinary field, needs ICON (integrated, coordinated, open and networked) to address urgent and multi-scale global problems, where process-complexity and need for ICON increase with scale, and to reduce geographical bias in data and scientific progress. Various challenges hinder ICON in biogeosciences, but perhaps the most critical ones revolve around cultural and institutional barriers that prevent data sharing and cross-border collaborations. Our recommended short- and long-term solutions focus on people-centric actions to breaking these barriers. LMIC: low-to-middle income countries.

2.3 Looking Forward: An Urgent Call for People-centric Actions

To address barriers to ICON in biogeoscience, we call for people-centric actions. In the short-term, investment in capacity- and infrastructure-building, workshops, and training can help overcome barriers to global collaboration. These efforts will favor the development of researchers with a sense of "belonging" to global networks and will facilitate reducing technological barriers (e.g., infrastructure) and global cooperation. Scientific societies, institutions of higher learning, and other research entities can promote these coordinated efforts by

organizing in-person and virtual events. For longer-term actions, we propose top-down incentives that reward ICON activities such as data sharing (e.g., publishing open datasets) and efforts towards integration and coordination of networked efforts (e.g., activities that support or develop networks such as LTER, FLUXNET, ForestPlots). These efforts should carry as much weight as scientific publications for hiring and promotions. Furthermore, longer-term funding priorities are needed for institutionalizing capacity and reducing entry costs, especially for researchers from low-to-middle income countries. Overall, biogeosciences deal with cross-scale and cross-continental problems and need ICON principles.

3 Community engagement, citizen science, education, and stakeholder involvement

3.1 Current state of ICON

The rapid growth in citizen and community science projects in recent years has dramatically increased engagement among non-scientists in the scientific endeavor (Roy et al. 2012, Besançon et al. 2021) and has the potential to yield consistently collected (coordinated) data that are openly accessible (open) through stakeholder engagement (networked). For example, the U.S.-based phenology-focused citizen science program Nature's Notebook utilizes the same published and scientifically-vetted observation protocols as the National Ecological Observation Network (NEON; Denny et al., 2014; Elmendorf et al., 2016), and provides ready access to data contributed by both citizen and professional (NEON) scientists (coordinated, open). Similarly, many research projects taking place at International Long-term Ecological Network sites engage students in integrated and coordinated research (Gosz et al. 2010). However, examples of coordinated, open, networked science engaging communities, stakeholders, and citizen scientists remain rare.

Funding for science and scientific publishing are two areas where changed practices are leading to increased engagement among communities, stakeholders, and citizen scientists. In Australia, New Zealand, and several European countries, publicly funded research projects are required to involve local stakeholders and indigenous communities. Federally-funded research proposals in New Zealand must demonstrate direct involvement and/or benefit to Māori and address indigenous knowledge and innovation, societal and health concerns, and environmental sustainability (Vision Mātauranga; MBIE, 2007). In the U.S.A., expectations for outreach are variable: Department of Energy calls require outreach plans, and the National Science Foundation encourages but does not require outreach and education through grant-funded "broader impacts". A growing number of journals are innovating by ensuring the entire peer-review process is transparent, accessible, and available for an open viewing and/or comment by not only scientists but also stakeholders and policymakers.

3.2 Challenges

A key challenge to engaging stakeholders, community members, and non-professional scientists in ICON science is the limited awareness of or access to **coordinated** established and often technical research protocols, **open data efforts**, and communication channels used by professional scientists. Monitoring protocols are not always readily available for would-be non-professional data collectors or users. Similarly, data repositories and communication channels used by professional scientists remain relatively unknown or inaccessible to stakeholders, community members, and non-professional scientists, challenging efforts to engage these communities while adhering to ICON principles. Such limited ICON-centered interaction between scientists and non-scientists stifles the transfer, application, and translation of global change research that could shape policy and inform decision-making (Enquist et al. 2017).

Another important barrier to greater engagement among scientists and researchers with stakeholders and community members is the persistent and intensifying academic standard that productivity and impact be judged primarily via peer-reviewed articles (Davies et al. 2021, Perkmann et al. 2021). This results in many research findings and data remaining "untranslated" for a non-technical audience, rendering potentially valuable results inaccessible to policymakers, stakeholders, and the general public. Further, scientific journals and databases are frequently inaccessible to the public, presenting additional barriers to open, coordinated science engaging and used by stakeholders, community members, or citizen scientists.

3.3 Opportunities

The intentional engagement of local stakeholders, community members, and educators during the development of a research project has the potential to increase **integrated**, **coordinated**, and **open science**. During project inception and development, researchers could build in ways to involve stakeholders and the public, ranging from defining the scope and priorities of research questions and applications with community expertise to engaging the public in citizen science data collection (**networked**). The requirement that publicly-funded research projects in New Zealand directly involve the native Māori people in project design, execution, and communication of findings has shown that such practices ensure measurable outcomes to research and society (MBIE, 2007).

Increasing research team diversity by involving community members, stakeholders, and other non-professional scientists can amplify data collection by orders of magnitude beyond what researchers alone can achieve and can increase the extent to which science is integrated, open, coordinated, and networked. For example, the "Indigenous Symposium on Water Research Education, and Engagement," held in Montana in 2018 (Chief et al. 2019) brought 36 indigenous scientists, community activists and elders together to discuss topics ranging from groundwater contamination to climate change that is impacting Confederated Salish and Kootenai Tribes. Representation among different genders,

backgrounds, nationalities, and career stages expands perspectives in a project (Sandbrook et al., 2019). Local non-scientists can be great assets to projects, bringing valuable contextual information (Roman et al. 2021).

The AGU's Thriving Earth Exchange offers one opportunity for scientists to connect with communities seeking science support to resolve challenges that require the expertise of scientists, such as issues associated with municipal water quality and community forest health. Existing citizen science projects such as those listed at scistarter.org can provide ready-made infrastructure for engaging members of the public in data collection. Alternatively, researchers may create their own citizen science project leveraging existing infrastructure like that housed at citsci.org and anecdata.org. Including social scientists on project-teams can maximize societal benefits and use of project outputs by non-scientist audiences (Enquist et al. 2017).

Media coverage of biogeoscience research can result in a broader appreciation of research findings and the return on invested funds by the public. Science translation and communication can extend beyond the traditional news media and can be led by researchers themselves, using traditional outlets such as newspaper, radio, television broadcast as well as social media (e.g., Twitter, Reddit, Facebook), blog posts, podcasts, and even comics (Pourret et al. 2020). Funding agencies and publishers could encourage or even require such science translation. This could take the form of non-technical abstracts and reports published alongside research papers. Communication in multiple languages is crucial for the effective dissemination of scientific ideas (Márquez and Porras, 2020).

Finally, annual and tenure reviews should incentivize researcher participation by acknowledging, funding, and rewarding the effort that community and stakeholder engagement and science communication efforts necessitate.

4 Field, Experimental, Remote Sensing, and Real-Time Data for Biogeosciences

4.1 Current state of ICON

Biogeoscience research is often limited by observational and analytical constraints, and by the integration of concepts and applications across sub-disciplines (e.g., land-ocean fluxes in Kothawala et al., 2021). Recently, a proliferation of data networks and observatories have employed principles of ICON science to mitigate these challenges across scientific research: from data collection to publication.

Well-established field sampling networks and observatories, like NEON, ICOS, FLUXNET, and LTERs, generate coordinated data products across disparate study sites and consolidate them (e.g., https://lter.github.io/som-website/; Wieder et al. 2021). ICON principles are likewise evident in the findable, accessible, interoperable, and reusable (FAIR) data policies required by many

journals, which require the provision of direct measurements from independent and less intensively-sampled campaigns to public repositories (e.g., Environmental Data Initiative), thereby allowing for post-hoc cross-scale syntheses. These have increased the number of open-access direct measurements across field, experimental, remote sensing, and real-time data that have facilitated parameter-specific database creation and "bottom-up" scaling efforts.

The growing availability of field-deployable sensors enables real-time data collection of biogeochemical processes and drivers that capture rare phenomena and short-term processes that are critical to ecological monitoring, experimental studies, and predictive models. Openly real-time data are increasingly available in networks like Next Generation Water Observing System (NGWOS), and ecosystem-scale experiments such as SPRUCE (Krassovski et al. 2018) and Biosphere 2 Landscape Evolution Observatory (Volkmann et al. 2018). Additionally, there are coordinated projects to collect field and sensor data at a network of field sites (e.g., Drought-Net, NutNet; Chabbi & Loescher 2017) or under the same research infrastructure (e.g., AnaEE; Clobert et al. 2018).

Satellite remote-sensing is another Earth system monitoring technology that has increasingly employed ICON principles. Efforts to openly disseminate remote-sensing data have grown rapidly, from the opening of Landsat archives and the establishment of data processing and distribution centers like the Land Processes Distributed Archive Center, to the development of user-friendly web portals like Earthdata Search and EarthExplorer. Increased coordination has enabled international orchestration of upcoming missions as well as integrated data products like the Harmonized Landsat-Sentinel dataset which combines NASA and the European Space Agency satellite data. At the application level, user-driven repositories like GitHub have enabled open data and code sharing while cloud-based platforms like Google Earth Engine have made large data sets, complex algorithms, and cloud computing networked and open.

4.2 Challenges

Inter-related issues of data availability, computational, monetary costs, time costs, researcher preferences, and data standards pose key challenges. For example, challenges exist in balancing geographic representativeness and the need for environmental/ecological stratification (Guerin et al., 2020). Geographic gaps are common in data networks, especially for emerging nations, which directly impact data integration and openness (Villarreal and Vargas 2021). While satellite imagery and open-access platforms for data acquisition and processing can partially mitigate these geographic biases, inequity in resources, training, and access due to political restrictions and low funding in emerging nations greatly limit seamless integration. Moreover, despite the potential for existing networks to provide networked research infrastructure for biogeoscience research (Hinckley et al. 2016), mission- and agency-specific protocols can make integrating ICON principles across networks challenging.

Research in biogeosciences is driven by exploration and hypotheses rather than

by integration and networking alone. As such, ICON-driven research ensures transparency and reproducibility, while advancing the investigation of large-scale, context-dependent biogeochemical questions. With the large-scale questions that need to be addressed in biogeosciences today, overcoming the challenges that inhibit ICON principles will be essential.

4.3 Opportunities

Adopting ICON principles in biogeosciences provides many opportunities to expand our understanding of critical ecosystem processes. In particular, paired experimentation and field observations provide coordinated assessments across scales needed to resolve global biogeosciences challenges like ecosystem responses to climate change (Hanson & Walker 2019, Hinckley et al. 2016). First, we advocate accelerating efforts to integrate multiple experiments at single sites and coordinate research efforts across networks to provide integrated data streams. For example, globally-coordinated field campaigns and remote-sensing data networks can advance the quantification of biogeochemical drivers and feedbacks across scales to improve continental assessments of emerging trends. Second, ICON principles should be more thoroughly embraced for real-time data collection by expanding sensor availability, coordinating data standards and tools, and increasing open-access. Especially important in this effort is the goal to increase sampling in underrepresented geographical areas and expand the reach of data networks to researchers in those regions. Third, to optimize these opportunities to incorporate ICON principles across and within all subdisciplines in the biogeosciences, there should be transparency in data, metadata, and methods in open publications (i.e., clear design descriptions, uncertainty estimates) and an effort to achieve standardization while allowing for site- and budget-specific modifications when needed. Finally, the development of easy-to-use forecasting tools (e.g., web dashboards) for non-specialist end-users in conservation and ecological management should be prioritized. Advances in biogeosciences can then be more readily incorporated by practitioners, allowing them to overcome barriers to technology and information where the need is greatest, especially in underrepresented low- and middle-income countries that are critical for expanding ICON science to the global scale.

5 Call to action to work towards ICON science

Great potential exists to better engage stakeholders, community members, and inclusive networks of global scientists in research efforts. We strongly encourage richer involvement with these audiences and more purposeful translation and communication of findings to society (e.g., Arora et al., 2021). ICON-driven science not only will solve scientific gaps but also increase scientific equity, inclusion, and more fluid use of collective scientific knowledge. To implement ICON principles in biogeosciences, we call for a suite of actions on short- and long-term horizons focusing on a people-centric approach toward capacity building, cultural shifts, breaking barriers through reduced entry costs, building research

networks, and promoting community engagement with open and fair research practices. We also suggest developing interoperable methods and instrumentation to confront global challenges and solve key questions in biogeosciences.

6 Acknowledgments, Samples, and Data

DD was supported in part by the Watershed Function Science Focus Area and ExaSheds projects at Lawrence Berkeley National Laboratory funded by the U.S. Department of Energy, Office of Science, and Biological and Environmental Research under Contract No. DE-AC02-05CH11231. MAB acknowledges support from the United States National Science Foundation (OCE 1840715), the United States National Institutes of Health (NIEHS 1P01ES028939), and a Grant-in-Aid of Research from Sigma Xi, the Scientific Research Society (G201903158412545). C.G. acknowledges support from the National Science Foundation (NSF), Awards 1655095 and 1856319. S.N. acknowledges support from the New Zealand Ministry of Business, Innovation and Employment through the Global Change Through Time research program (contract C05X1702). N.T. acknowledges support from the Office of Biological and Environmental Research in the U.S. Dept. of Energy (DOE) Office of Science - Early Career Research program. B.B. was supported as part of the Next Generation Ecosystem Experiments-Tropics, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (DE-AC02-05CH11231). HCQ acknowledges support from the Division of Environmental Biology at NSF award 1749252. SMB acknowledges support from the Spanish Ministry of Science and Innovation (CEX2019-000940-M). RV acknowledges support from NASA Carbon Monitoring System (80NSSC21K0964). LM acknowledges support from the Division of Environmental Biology at NSF award 2034192.

Authors for Section 2: DD, AM, EL, MS, SMB, GK, HSS, FQB, RV, SWL, and JC. Authors for Section 3: MB, TMC, CG, LH, SN, TYC, OP, and NT. Authors for Section 4: ALDS, BB, CH, EG, HCQ, KA, KR, LM, and ZLN.

7 References

Armenteras, D (2021). Guidelines for healthy global scientific collaborations. Nature Ecology & Evolution, pages 1–2.

Arora, B., P. Sullivan, S. Kuppel, X. Yang, and J. Groh (2021), The future of critical zone science: Call for papers, *Eos*, 102, https://doi.org/10.1029/2021EO157965

Besançon, L., Peiffer-Smadja, N., Segalas, C. et al. (2021). Open science saves lives: lessons from the COVID-19 pandemic. *BMC Med Res Methodol 21*, 117. https://doi.org/10.1186/s12874-021-01304-y

Chabbi, A., & Loescher, H. W. (Eds.). (2017). Terrestrial Ecosystem Research Infrastructures: Challenges and Opportunities. CRC Press.

Chief, K., R. E. Emanuel, and O. Conroy-Ben (2019), Indigenous symposium on water research, education, and engagement, *Eos*, 100,

https://doi.org/10.1029/2019EO114313.

- Clobert, J., Chanzy, A., Le Galliard, J. F., Chabbi, A., Greiveldinger, L., Caquet, T., ... & Saint-André, L. (2018). How to integrate experimental research approaches in ecological and environmental studies: AnaEE France as an example. Frontiers in Ecology and Evolution, 6, 43.
- Davies, S. W., Putnam, H. M., Ainsworth, T., Baum, J. K., Bove, C. B., Crosby, S. C., ... and Bates, A. E. (2021). Promoting inclusive metrics of success and impact to dismantle a discriminatory reward system in science. *PLoS biology*, 19(6), e3001282.
- Denny, E.G., K.L. Gerst, A.J. Miller-Rushing, G.L. Tierney, T.M. Crimmins, C.A.F. Enquist, P. Guertin, A.H. Rosemartin, M.D. Schwartz, K.A. Thomas, J.F. Weltzin. (2014). Standardized phenology monitoring methods to track plants and animal activity for science and resource management applications. *International Journal of Biometeorology*, 58:591-601. https://doi.org/10.1007/s00484-014-0789-5.
- Driscoll, C. T., Lambert, K. F., & Weathers, K. C. (2011). Integrating science and policy: A case study of the Hubbard Brook Research Foundation Science Links program. *BioScience*, 61(10), 791-801. https://doi.org/10.1525/bio.2011.61.10.9
- Elmendorf, S.C., Jones, K.D., Cook, B.I., Diez, J.M., Enquist, C.A.F., Hufft, R.A., Jones, M.O., Mazer, S.J., Miller-Rushing, A.J., Moore, D.J.P., Schwartz, M.D., Weltzin, J.F. (2016). The plant phenology monitoring design for The National Ecological Observatory Network. *Ecosphere* 7(4):e01303. https://doi.org/10.1002/ecs2.1303.
- Enquist, C.A., Jackson, S.T., Garfin, G.M., Davis, F.W., Gerber, L.R., Littell, J.A., Tank, J.L., Terando, A.J., Wall, T.U., Halpern, B. and Hiers, J.K. (2017). Foundations of translational ecology. *Frontiers in Ecology and the Environment*, 15(10), pp.541-550.
- Gosz, J. R., Waide, R. B., & Magnuson, J. J. (2010). Twenty-Eight Years of the US-LTER Program: Experience, Results, and Research Questions. In: Müller F., Baessler C., Schubert H., Klotz S. (eds) Long-Term Ecological Research. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-8782-9_5
- Guerin, G. R., K. J. Williams, B. Sparrow, and A. J. Lowe. (2020). Stocktaking the environmental coverage of a continental ecosystem observation network. Ecosphere~11.~https://doi:10.1002/ecs2.3307
- Hanson, P. J., & Walker, A. P. (2020). Advancing global change biology through experimental manipulations: Where have we been and where might we go?. *Global Change Biology*, 26(1), 287-299.
- Hinckley, E. L. S., Anderson, S. P., Baron, J. S., Blanken, P. D., Bonan, G. B., Bowman, W. D., ... & Wieder, W. R. (2016). Optimizing available network

resources to address questions in environmental biogeochemistry. BioScience, 66(4), 317-326.

Hubbard, S. S., Williams, K. H., Agarwal, D., Banfield, J., Beller, H., Bouskill, N., et al. (2018). The East River, Colorado, Watershed: a mountainous community testbed for improving predictive understanding of multiscale hydrological—biogeochemical dynamics. $Vadose\ Zone\ J.\ 17,\ 1–25.$ doi: 10.2136/vzj2018.03.0061

Kothawala, D.N., Kellerman, A.M., Catalán, N. and Tranvik, L.J., (2020). Organic Matter Degradation across Ecosystem Boundaries: The Need for a Unified Conceptualization. *Trends in Ecology & Evolution*.

Krassovski, M. B., Lyon, G. E., Riggs, J. S. and Hanson, P. J. (2018). Near-real-time environmental monitoring and large-volume data collection over slow communication links. *Geoscientific Instrumentation Methods and Data Systems*, 7(4): 289-295.

MBIE - New Zealand Ministry of Business, Innovation and Employment (2007). Vision Mātauranga - Unlocking the Innovation Potential of Māori Knowledge, Resources and People. Wellington, New Zealand. 28 pages.

Márquez, M.C. and Porras, A.M. (2020). Science communication in multiple languages is critical to its effectiveness. *Frontiers in Communication*, 5, p.31. https://doi.org/10.3389/fcomm.2020.00031

M. Mirtl, E. T. Borer, I. Djukic, M. Forsius, H. Haubold, W. Hugo, J. Jourdan, D. Lindenmayer, W.H. McDowell, H. Muraoka, D.E. Orenstein, J.C. Pauw, J. Peterseil, H. Shibata, C. Wohner, X. Yu, P. Haase. (2018). Genesis, goals and achievements of Long-Term Ecological Research at the global scale: A critical review of ILTER and future directions. *Science of The Total Environment*, 626, p.1439-1462, https://doi.org/10.1016/j.scitotenv.2017.12.001.

Perkmann, M., Salandra, R., Tartari, V., McKelvey, M. and Hughes, A. (2021). Academic engagement: A review of the literature 2011-2019. *Research Policy*, 50(1), p.104114. https://doi.org/10.1016/j.respol.2020.104114

Pourret, O., Suzuki, K. and Takahashi, Y. (2020) Our Study is Published, But the Journey is Not Finished!, *Elements*, 16, 229-230.

Roman, D., Reeves, N., Gonzalez, E., Celino, I., Abd El Kader, S., Turk, P., Soylu, A., Corcho, O., Cedazo, R., Calegari, G.R. and Scandolari, D. (2021). An analysis of pollution Citizen Science projects from the perspective of Data Science and Open Science. *Data Technologies and Applications*. https://doi.org/10.1108/DTA-10-2020-0253

Roy, H.E., Pocock, M.J.O., Preston, C.D., Roy, D.B., Savage, J., Tweddle, J.C. and Robinson, L.D. (2012). Understanding Citizen Science & Environmental Monitoring. Final Report on behalf of UK-EOF. NERC Centre for Ecology & Hydrology and Natural History Museum.

Sandbrook, C., Fisher, J. A., Holmes, G., Luque-Lora, R., & Keane, A. (2019). The global conservation movement is diverse but not divided. *Nature Sustainability*, 2(4), 316-323. https://doi.org/10.1038/s41893-019-0267-5

Shirk, J.L., Ballard, H.L., Wilderman, C.C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B.V., Krasny, M.E., and Bonney, R. (2012). Public participation in scientific research: a framework for deliberate design. *Ecology and Society*, 17(2): 29. https://doi.org/10.5751/ES-04705-170229

Stell, E., D. Warner, J. Jian, B. Bond-Lamberty, and R. Vargas (2021). Spatial biases of information influence global estimates of soil respiration: How can we improve global predictions? *Global Change Biology* 27:3923–3938.

Varadharajan, C., Faybishenko, B., Henderson, A., Henderson, M., Hendrix, V. C., Hubbard, S. S., et al. (2019). Challenges in building an end-to-end system for acquisition, management, and integration of diverse data from sensor networks in watersheds: lessons from a mountainous community observatory in East River, Colorado. *IEEE Access* 7, 182796–182813. doi: 10.1109/AC-CESS.2019.2957793

Vargas, R., Alcaraz-Segura, D., Birdsey, R., Brunsell, N. A., Cruz-Gaistardo, C. O., de Jong, B., Etchevers, J., Guevara, M., Hayes, D. J., Johnson, K., et al. (2017). Enhancing interoperability to facilitate implementation of REDD+: case study of Mexico. *Carbon Management*, 8(1):57–65

Verdone, M., & Seidl, A. (2017). Time, space, place, and the Bonn Challenge global forest restoration target. *Restoration ecology*, 25(6), 903-911.

Villarreal, S., & Vargas, R. (2021). Representativeness of FLUXNET sites across Latin America. *Journal of Geophysical Research: Biogeosciences*, 126. https://doi.org/10.1029/2020JG006090

Volkmann Till H. M., Aditi Sengupta, Luke A. Pangle, Katerina Dontsova, Greg A. Barron-Gafford, Ciaran J. Harman, Guo-Yue Niu, Laura K. Meredith, Nate Abramson, Antonio A. Meira Neto, Yadi Wang, John R. Adams, David D. Breshears, Aaron Bugaj, Jon Chorover, Alejandro Cueva, Stephen B. DeLong, Matej Durcik, Ty P. A. Ferre, Edward A. Hunt, Travis E. Huxman, Minseok Kim, Raina M. Maier, Russell K. Monson, Jon D. Pelletier, Michael Pohlmann, Craig Rasmussen, Joaquin Ruiz, Scott R. Saleska, Marcel G. Schaap, Michael Sibayan, Markus Tuller, Joost L. M. van Haren, Xubin Zeng and Peter A. Troch (2018). Controlled Experiments of Hillslope Coevolution at the Biosphere 2 Landscape Evolution Observatory: Toward Prediction of Coupled Hydrological, Biogeochemical, and Ecological Change. in: Hydrology of Artificial and Controlled Experiments (eds. Jiu-Fu Liu and Wei-Zu Gu), IntechOpen, pp. 25-74. https://doi.org/10.5772/INTECHOPEN.72325.

West, H., Quinn, N., Horswell, M. (2019). Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future

opportunities. Remote Sensing of Environment, Volume 232, 111291. https://doi.org/10.1016/j.rse.2019.111291

Wieder, W. R., Pierson, D., Earl, S., Lajtha, K., Baer, S. G., Ballantyne, F., Berhe, A. A., Billings, S. A., Brigham, L. M., Chacon, S. S., Fraterrigo, J., Frey, S. D., Georgiou, K., de Graaff, M.-A., Grandy, A. S., Hartman, M. D., Hobbie, S. E., Johnson, C., Kaye, J., Kyker-Snowman, E., Litvak, M. E., Mack, M. C., Malhotra, A., Moore, J. A. M., Nadelhoffer, K., Rasmussen, C., Silver, W. L., Sulman, B. N., Walker, X., and Weintraub, S.: SoDaH: the SOils DAta Harmonization database, an open-source synthesis of soil data from research networks, version 1.0, Earth Syst. Sci. Data, 13, 1843–1854, https://doi.org/10.5194/essd-13-1843-2021, 2021