https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Biogeosciences Discussions
Open Access

Ideas and perspectives: Biogeochemistry - Its Future Role in Interdisciplinary Frontiers

Thomas S. Bianchi[1], Madhur Anand[2], Chris T. Bauch[3], Donald E. Canfield[4], Luc De Meester[5,6,7], Katja Fennel[8], Peter M. Groffman[9], Michael L. Pace[10], Mak Saito[11], Myrna J. Simpson[12]

[1]Dept. of Geological Science, University of Florida, Gainesville, FL USA
[2]School of Environmental Sciences, University of Guelph, Guelph, Ontario, Canada
[3]University of Waterloo, Department of Applied Mathematics, Waterloo, Canada
[4]Nordcee, University of Southern Denmark, Odense, Denmark
[5]Dept. of Biology, University of Leuven, Leuven, Belgium
[6]Leibniz Institut für Gewässerökologie und Binnenfischerei (IGB), Berlin, Germany
[7]Institute of Biology, Freie Universität Berlin, Berlin, Germany
[8]Dept. of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada
[9]City University of New York Advanced Science Research Center at the Graduate Center, New York, NY USA and Cary Institute of Ecosystem Studies, Millbrook, NY USA
[10]Dept. of Environmental Sciences, University of Virginia, Charlottesville, VA USA
[11]Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA USA
[12]Dept. of Physical and Environmental Sciences, University of Toronto, Toronto, Canada

Correspondence to: Thomas S. Bianchi (tbianchi@ufl.edu)

Abstract. Biogeochemistry has an important role to play in many environmental issues of current concern related to global change and air, water, and soil quality. However, reliable predictions and tangible take-up of solutions offered by biogeochemistry will need further integration of disciplines. Here, we emphasize how further developing ties between biology, geology, and chemistry and social sciences will advance biogeochemistry through: 1) better integration of mechanisms including contemporary evolutionary adaptation to predict changing biogeochemical cycles; 2) better integration of data from long-term monitoring sites in terrestrial, aquatic, and human systems across temporal and spatial scales, including the continental and global scale, for use in modeling efforts; and 3) implementing insights from social sciences to better understand how sustainable and equitable responses by society are achieved. The challenges of 21st century biogeochemists are formidable, and will require both the capacity to respond fast to pressing issues and intense collaboration with government officials, the public, and internationally-funded programs. Keys to its success will be the degree to which biogeochemistry succeeds in making biogeochemical knowledge more available to policy makers and educators, in predicting future changes in the biosphere in response to climate change and other anthropogenic impacts on time scales from seasons to centuries, and in facilitating sustainable and equitable responses by society.

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Biogeosciences Discussions
Open Access
EGU

1 Introduction

Biogeochemistry was one of the first truly inter- or multi-disciplinary sciences (Bianchi 2020, Gorham 1991, Schlesinger 1991, Vernadsky et al. 1926) and the field is now expanding in multiple directions: from small scales via interactions with microbiology and ‘omics approaches (genomics, transcriptomics, proteomics, and metabolomics) (Figure 1) to large scales as a component of Earth System Sciences (Steffen et al. 2020).

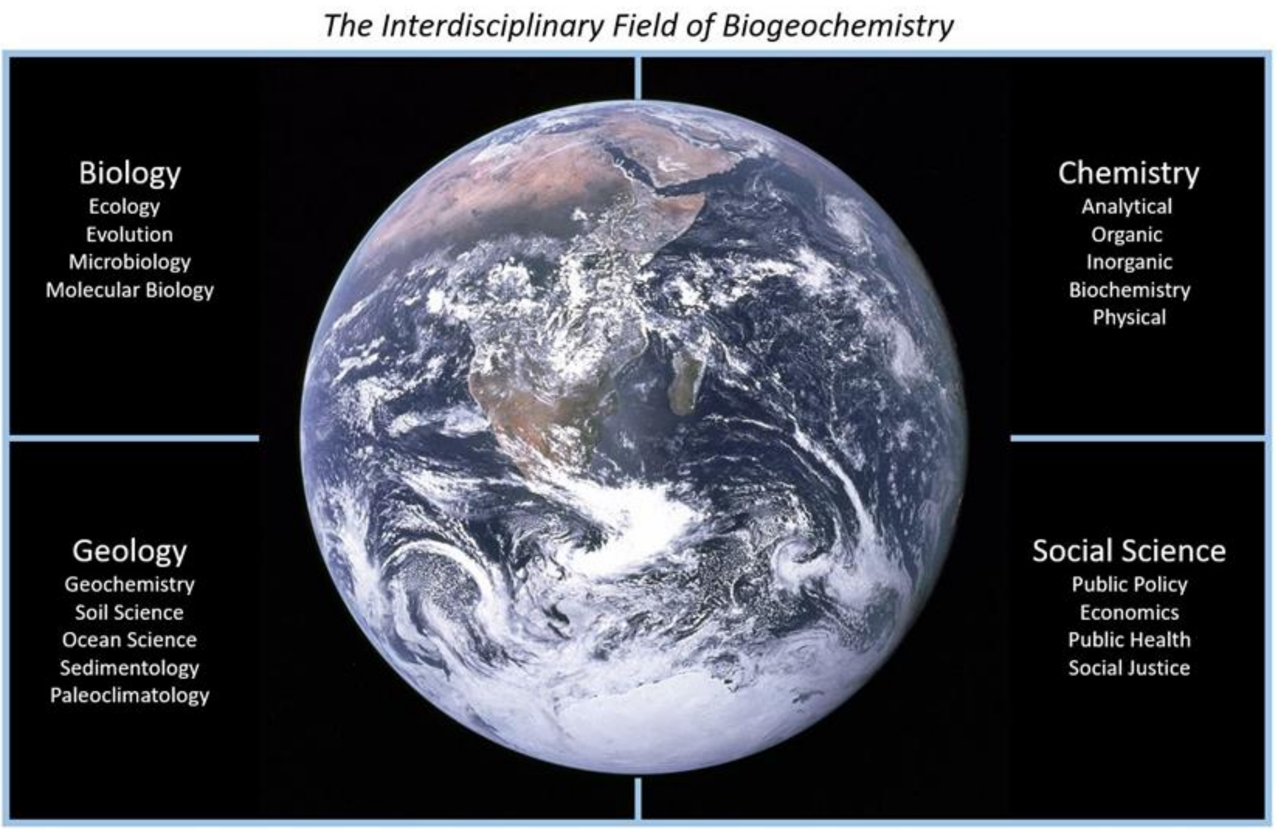


Figure 1: The 21st century now demands new interdisciplinary approaches that involves the integration of the disciplines core to traditional biogeochemistry with social sciences.

A more recent review of Biogeochemistry incudes some of these more nascent linages molecular biology (Bianchi 2020). Biogeochemists will be challenged to better link Earth System Models and biogeochemical cycling with biological trait change and environmental modeling. A better incorporation of mechanistic knowledge from “omic” studies (Coles et al. 2017) and a stronger integration of ecological and evolutionary dynamics will allow more reliable predictions of ecological and

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Biogeosciences Discussions

evolutionary responses to global change (Urban et al. 2016). In this perspective, we emphasize how further developing ties between biology, geology, and chemistry and also with social sciences will advance biogeochemistry through a better integration of: 1) mechanistic insights at multiple levels of biological organization, including the dynamic interactions between contemporary evolution and ecology to predict changing biogeochemical cycles, 2) data from long-term monitoring sites in terrestrial, aquatic, and human systems across temporal and spatial scales, including the continental and global scale, for use in modeling efforts, and 3) insights of social sciences, focusing on the human-natural system as a whole.

2 Understanding Biogeochemistry using 'Omics

In recent decades, the ability to directly track genes and gene functions of organisms in nature, especially in microbes, has greatly contributed to understanding their interactions with biogeochemical cycles (Martiny et al. 2006, Rusch et al. 2010). Measurements of microbial transcripts and proteins in natural environments has allowed direct observation of the cellular functions as adaptive responses to the environment (Bergauer et al. 2018, Gifford et al. 2011). These functional systems include biogeochemically-relevant enzymes, transporters, storage molecules, and regulatory systems, and the quantitation of enzymes can be used to generate 'omic-based potential biogeochemical rates (Saito et al. 2020). This provides mechanistic information about the underpinnings of biological controls on biogeochemistry and allows direct quantification of rate changes along different pathways. There are many knowledge gaps to fill, however: roughly half of all genes have unknown function, the systems biology controlling regulation is poorly characterized (Held et al. 2019), and we know little about how the different biochemical pathways relate to resilience at the ecosystem level. Forging connections between the genetic and biochemical underpinnings to the production of metabolites that contribute to carbon and other element cycling is primed for discovery (Soule et al. 2015). Omics studies will also help understanding how the microbiomes of plants, invertebrates and vertebrates making up the predator-prey and decomposition food webs influence biogeochemical cycles (Macke et al. 2017).

3 Linking Ecological and Evolutionary dynamics

There has been longstanding interest in the co-evolution of life and biogeochemical cycles on Earth, as chemical conditions of this planet have been strongly influenced by the evolving biochemical capabilities of life (Canfield et al. 2007, Lenton et al. 2014, Saito et al. 2003). Earth's life support system is inextricably tied to biogeochemical cycling and evolution. Recently, evidence has accumulated that significant evolutionary trait change can occur over time scales of just a few generations, and the rapidly changing environmental context at local, regional and global scales during the Anthropocene leads to strong selection pressures on populations to adapt (Bell et al. 2008; Hutchins et al. 2015; Kuebbing et al. 2018, Seibel and Deutsch 2020). This contemporary evolution has been shown to impact ecosystem functioning and elemental cycling dynamics (Bassar et al. 2010, Declerck et al. 2015). In one example, evolution of zooplankton within a single growth season has been shown to

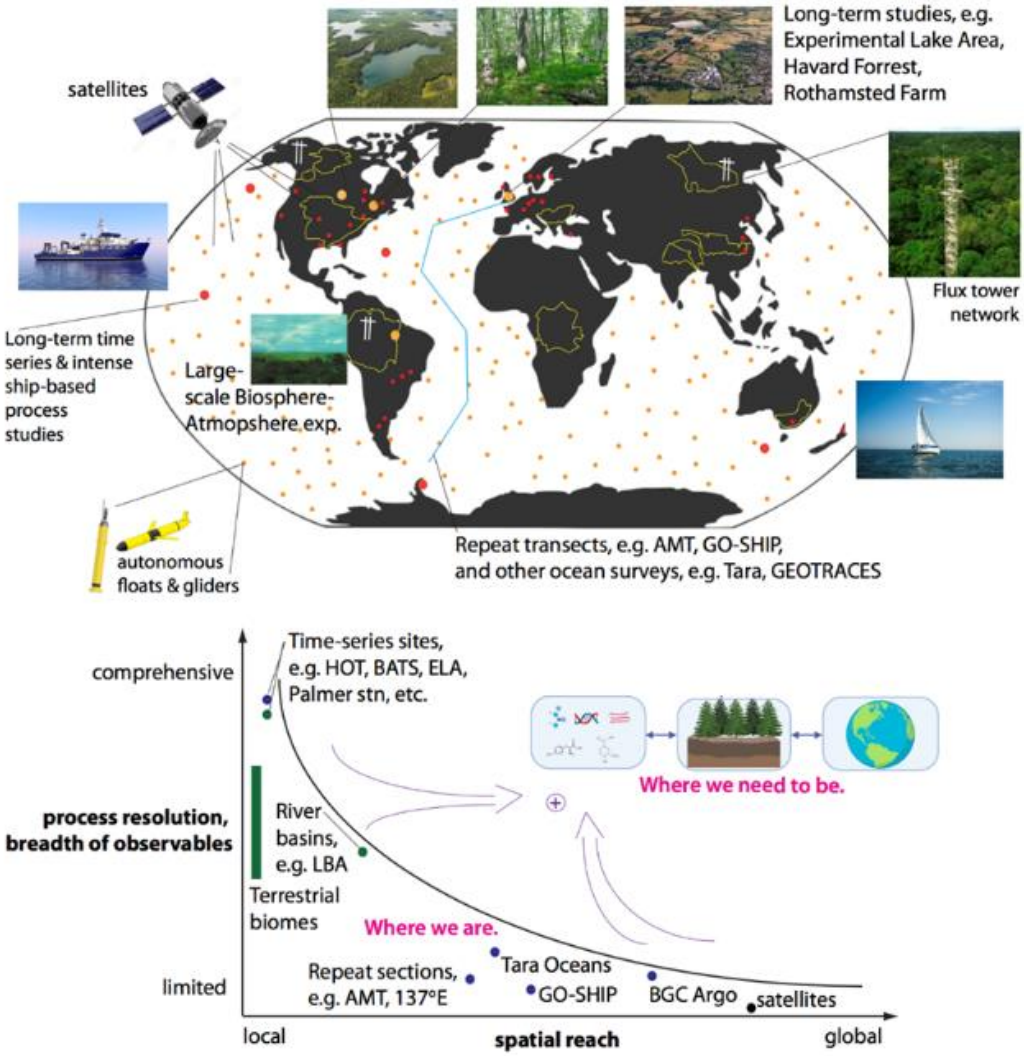
https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

shape the typical seasonal dynamics of phyto- and zooplankton in lakes (Schaffner et al. 2019). In another example, evolution in body size in salmon through its effects on salmon consumption by bears affects nutrient transfer from aquatic to terrestrial systems (Carlson et al. 2011). Many surprising pathways and mechanisms are to be discovered. For example, fear of predation by spiders can alter the elemental composition of grasshoppers, resulting in changes in production and nutrient cycles in ecosystems (Hawlena et al. 2012). Theory indicates that rapid evolutionary trait change can also influence the occurrence and (recovery) trajectory of ecosystem regime shifts (Dakos et al. 2019). Integrating ecological and evolutionary responses is needed to make reliable predictions of how ecosystems respond to climate change (Matthews et al. 2011) and how this impacts biogeochemical cycles.

Biogeochemistry should treat ecosystems and their biota as complex adaptive integrative systems, including population-level genetic adaptation to environmental change (Levin 2003). Due to their short generation times, eco-evolutionary dynamics are expected to be important in microbial communities that are key to determining rates and types of biogeochemical processes (Reed et al. 2014). While the above examples illustrate that short-term evolutionary processes can influence how populations and communities influence biogeochemical cycles on a timescale of years or less, the evolutionary emergence of enzymes with new biogeochemical functionality appears to be rarer, occurring over geologic time scales (David and Alm 2011).

4 A Renewed Holistic Approach in Earth Sciences

Increased understanding of how eco-evolutionary and ecophysiological responses regulate biogeochemical cycling under global change must be matched by an ability to detect the biogeochemical changes and feedbacks on regional to global scales. Therefore, the ability to monitor key biogeochemical parameters and processes across the globe is of fundamental importance, but a formidable challenge (Figure 2).



105 **Figure 2: Illustration of the current trade-off between geographic scope and mechanistic depths and detail of observables in marine, inland water and terrestrial environmental studies. The upper panel indicates selected examples ranging from long-term time series to global programs. The lower panel schematically illustrates the hurdle to achieving comprehensive global understanding that has to be overcome by integrating local, regional and global scale programs.**

Presently, programs integrating microbial communities with their functional environmental impacts are local or regional in geographic scope (Richter et al. 2018). Examples are two programs focused on oceanographic regions (the Hawaii Ocean Time-series [HOT], the Bermuda Atlantic Time-series [BATS]) and a program with a national focus (the U.S. National

Ecological Observatory Network [NEON]). Similarly, molecular-level approaches are most often focused on specific sites (Crowther et al. 2019, Simpson and Simpson 2012). Programs with global reach tend to be limited in their observables and their ability to achieve detailed process resolution. Some of these programs are satellite-based, but also include experiment and modeling networks (Djukic 2018, Stokstad 2011). Some examples include LANDSAT, the Gravity Recovery and Climate Experiment [GRACE] and the Soil Moisture Active Passive [SMAP] missions, and global networks of autonomous ocean profilers (Chai et al. 2020). Both local/regional and global-scale approaches are essential to achieve a comprehensive and global view of how our planet works and how and why our planet's environment is changing. Global geochemical and genomic ocean survey efforts are underway (e.g., GEOTRACES and Tara Ocean), however efforts to thoroughly integrate these approached have been more limited. The international interest in creating a global scale marine microbial biogeochemistry effort, currently called Biogeoscapes, is in line with such needed integrative approaches, and could serve as an important example of an integrative global mechanistic study. Finally, improved flow of information between increasing observational capacity (including both technical capabilities and numbers of study sites) and global modeling efforts will be needed.

To detect and mitigate global environmental change, a mechanistic understanding linking molecular-level data (biological, chemical, and geological) to processes occurring at the scale of entire biomes or the globe needs to be achieved (Crowther et al. 2019). This is a major challenge as it requires connecting cellular and organismal level systems biology with observational and modeling studies of global biogeochemical cycles. Synergies between detailed process-level understanding through local or regional studies and the ability to upscale and detect global change through global-scale observations have already contributed strongly to progress in our field, progressing beyond some its previously conceived shortfalls (Cutter 2005, Likens 2004). Yet, more improvements are needed (Groffman et al. 2017), amongst others to face the challenges of accessibility and sharing of complex data (Saito et al. 2020, Tanhua et al. 2019, Villar et al. 2018), the integration of observations and predictive models (Fennel et al. 2019), and the incorporation of societal factors (e.g., damming, nutrient management) in model projections (Seitzinger et al. 2010).

5. Embracing the Social Dimension

Vernadsky's popularization of a planet-wide "biosphere" defined by the modifying influences of life, and his later expansion of this concept into the "noösphere" defined by human influence, presaged modern Sustainability Science -- "an emerging field of research dealing with the interactions between natural and social systems, and with how those interactions affect the challenge of sustainability" (Kates 2011). Nearly a century after Vernadsky, biogeochemistry is, once again, poised for a burst of even greater interdisciplinary progress and impact, especially if biogeochemists build bridges with the social sciences and propose solutions that recognize Sustainability Science's "triple bottom line" of environment, economics, and equity.

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Biogeosciences Discussions

We argue for a new pathway in biogeochemistry that considers the many dimensions of sustainability throughout the research process, and considers biogeosciences and the social sciences as contributing to a holistic understanding of the human-environment system (Figure 3).

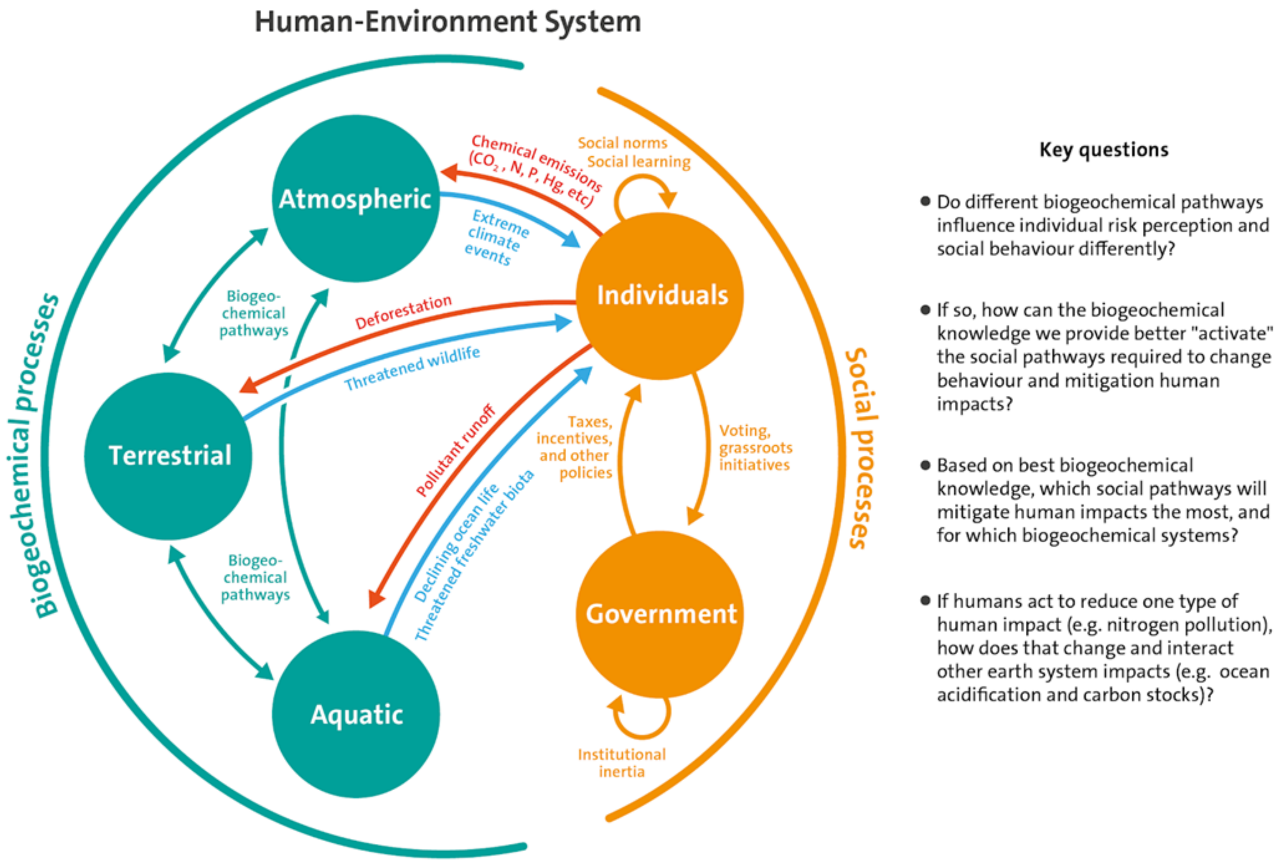


Figure 3: "Translational biogeochemistry" would encompass the two-way feedbacks between human and biogeochemical systems. Understanding human societal pathways will be critical in discerning and mitigating future climate patterns and its biogeochemical consequences.

This is similar to the idea of translational medicine, an interdisciplinary area of research that aims to improve human health by focusing on the relevance of novel research discoveries to actual patient outcomes. We argue that there is a large gap between discoveries in biogeochemistry and their application to improving ecosystem health. For example, biogeochemistry research may present many possible solutions to managing the global carbon budget -- from planting a trillion trees, to carbon taxes

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

and trading, to direct air carbon capture -- but their adoption (or not) by various levels of society are not generally studied scientifically, which could very much hamper the development of solutions.

Integrating human behaviour at several scales is essential because a lack of understanding of social processes can lead to unexpected societal "push back", rendering scientific advances less impactful. For example, the "yellow vest" protests in France emerged in response to a new carbon tax and greatly hindered progress toward carbon management goals in that country. Protestors agreed that climate change is an issue but were not willing to accept socially unjust solutions. While top-down approaches like the Paris agreement, with its ongoing political challenges and limited efficacy in combating climate remains a major issue, scientists are rushing to study how to harness social forces in a polycentric manner in order to tackle global-scale sustainability challenges. Put succinctly, without involving individuals outside of the field in all stages of the research process, biogeochemistry research that seeks to advance sustainability through policy or behaviour change risks answering questions that decision-makers are not asking, or proposing solutions that populations will not adopt. The window of opportunity to protect many of the natural systems we have the privilege of studying is rapidly disappearing. And the primary barrier to adoption of many sustainability solutions are often political and social limitations, not lack of scientific knowledge or availability of technology. Increasing public awareness of how basic science is linked with environmental problems through early education will be key in reducing these limitations.

Does the need for socially conscious, policy-driven research mean that basic science inquiry in biogeochemistry is dead? Are we not allowed to wonder about the origin of the earth and the basic processes that underlie the cycling of energy, water and nutrients across the surface of the earth? We argue that there is a false dichotomy between biogeochemistry and a translational bio-geo-socio-chemistry. Indeed, our goals are consistent with Vernadsky's original vision, as he stated "understanding our planet the way it is." The difference is that human influence on the Earth system is now so pervasive that our challenge has moved from integration of biology, geology and chemistry, to inclusion of social sciences. Indeed, this will make biogeochemical knowledge more available to policy makers and educators; help predict future changes in the biosphere in response to climate change and other anthropogenic impacts on time scales from seasons to centuries; and facilitate sustainable and equitable responses by society. Nevertheless, our knowledge of biogeochemical cycles remains relatively limited compared to other core sciences (biology, chemistry, physics, geology) and thus basic research will be key in understanding and laying the foundation for good policy development.

Biogeochemistry is already an inherent component of Sustainability and Earth System Sciences, which are addressing the overarching challenge of how global change impacts the habitability of our planet and our ability to sustainably use its resources to feed and supply the world population and economy. A pivotal issue is how organismal, environmental, and societal processes cause feedbacks that affect biogeochemical cycles and global change (Seitzinger et al. 2010). A "translational" biogeochemistry would be a natural pathway of research on transformational human-environment processes

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

because (1) both sustainability science and biogeochemistry are systems science approaches, and (2) collaboration between biogeochemists and social scientists could address topical key questions at a scale that is both holistic with respect to social-climate interactions, and suitably fine-grained (Figure 3). A holistic human-environment systems approach to applied biogeochemistry that accounts for social feedback might help winnow down policy recommendations to those that are both effective and likely to be adopted.

Key questions include: Do different biogeochemical systems pathways (e.g. extreme climate events versus ocean acidification) influence risk perception and social behaviour differently (e.g. GHG emission reduction versus dietary change)? If so, how can the biogeochemical knowledge we provide better "activate" the social pathways required to support mitigation behaviour? And, how will feedbacks between different biogeochemical systems hinder or accelerate these social pathways? An example of such an integrative approach is coupled social-climate modelling (Bury et al 2019), in which submodels are developed both for social dynamics and climate dynamics, and the two submodels are then coupled together. As a result of this, socio-economic pathways become a prediction of theoretical models and thus become the subject of scientific study themselves, instead of being assumptions that are simply input into climate models. A human-environment perspective would change not only how we think about the natural world, but how we design our research. A sustainability science approach to research may include stakeholders and policy experts at all stages in the research process.

6 Summary and Recommendations

The regional and global importance of biogeochemical processes for the homeostasis of Earth's life support system necessitates accelerating research to achieve the goal of a sustainable global society. Starting from an awareness of the field's history, new developments and key limitations of current approaches, we aimed at developing a perspective on how biogeochemistry can better serve society.

The challenges and opportunities of 21st century biogeochemists are formidable and will require intense collaboration with government officials, the public, internationally-funded programs, and other fields such as the social sciences. Keys to its success will be the degree to which biogeochemistry succeeds in making biogeochemical knowledge more available to policy makers and educators, in predicting future changes in the biosphere in response to climate change and other anthropogenic impacts on time scales from seasons to centuries, and in facilitating sustainable and equitable responses by society. While Biogeochemistry remains a young field, it will have an important role in bringing about a sustainable future. There are several impediments to fully realizing this role, including the need for further integration across disciplines and spatial scales, the intrinsic challenges of combining increased breadth with mechanistic depth, and the need to strengthen connections to society. While biogeochemistry has made major achievements in the past century describing Earth's global and regional biogeochemical cycles for the first time, we recognize that the field has acquired new societal responsibilities, in particular uncovering how humans are rapidly changing biogeochemical cycles, assessing the impact of these changes on biological communities and feedbacks on society, and effectively communicating this information to policy makers and society-at-large.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements: All authors contributed equally to the conceptualization and writing of this document. Figures 1 and 2 were generated by M.S. and K.F., respectively.

Financial support: T.S.B. was supported in part, by the Beverly Thompson Endowed Chair in Geological Sciences; M.J.S. acknowledges support from a Natural Sciences and Engineering Research Council of Canada Tier 1 Canada Research Chair in Integrative Molecular Biogeochemistry

References

Bassar, R. D., Marshall, M.C., López-Sepulcre, A, Zandonà, E, Auer, S.K, Travis, J., Pringle, C.M., Flecker, A.S., Thomas, S.A., Fraser, D.F., and Reznick D.N.: Local adaptation in Trinidadian guppies alters ecosystem processes. Proc. Natl. Acad. Sci., USA, 107, 3616-3621, https://doi.org/10.1073/pnas.0908023107, 2010.

Bell, G., Collins, S.: Adaptation, extinction and global change. Evol. Appl., 1(1), 3-16, https://doi.org/10.1111/j.1752-4571.2007.00011.x, 2008.

Bergauer, K., Fernandez-Guerra, A., Garcia J.A.L., Sprenger R.R., Stepanauskas, R., Pachiadaki, M.G., Jensen, O.N., and Herndl, G.J.: Organic matter processing by microbial communities throughout the Atlantic water column as revealed by metaproteomics, Proc. Natl. Acad. Sci., 115(3), E400-E408, ; https://doi.org/10.1073/pnas.1708779115, 2018.

Bianchi, T.S.: The evolution of biogeochemistry, revisited. Biogeochemistry (invited paper for special anniversary issue). (In Press).

Bury, T. M., Bauch, C. T., and Anand, M.: Charting pathways to climate change mitigation in a coupled socio-climate model. PLoS computational biology, 15(6): e1007000, https://doi.org/10.1371/journal.pcbi.1007000 2019.

Canfield, D. E., Poulton, S. W. and Narbonne, G.M.: Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life. Science, 315, 92-95, https://doi.org/10.1126/science.1135013, 2007.

Carlson, S. M., Quinn, T. P. and Hendry, A. P.: Eco-evolutionary dynamics in Pacific salmon, Heredity, 106, 438-47, https://doi.org/ 10.1038/hdy.2010.163, 2011.

Chai, F., Johnson, K. S., Claustre, H., Xing, X., Wang, Y., Boss, E., Riser, S., Fennel, K., Schofield, O., and Sutton, A.: Monitoring ocean biogeochemistry with autonomous platforms, Nature Reviews Earth & Environment, https://doi.org/10.1038/s43017-020-0053-y, 2020

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Coles, V. J., Stukel, M.R., Brooks, M.T., Burd, A., Crump, B.C., Moran, M.A., Paul, J.H., Satinsky, B.M., Yager, P.L., Zielinski, B.L., and Hood, R.R.: Ocean biogeochemistry modeled with emergent trait-based genomics, Science, 358, 1149-1154, https://doi.org/10.1126/science.aan5712, 2017.

Crowther, T. W., van den Hoogen, J., Wan, J., Mayes, M.A., A. D. Keiser, A.D., Mo, L., Averill, C., and Maynard, S.: The global soil community and its influence on biogeochemistry, Science, 365, https://doi.org/10.1126/science.aav0550, 2019.

Cutter, G. A.: Biogeochemistry: now and into the future, Palaeogeogr., Palaeoclimatol., Palaeoecol., 219, 191-198, https://doi.org/10.1016/j.palaeo.2004.10.021, 2005.

Dakos, V. Matthews, B., Hendry, A.P., Levine, J., Loeuille, N., Norberg, J., Nosil, P., Scheffer, M., and De Meester, L.: Ecosystem tipping points in an evolving world, Nat. Ecol. Evol., 3, 355-362, https://doi.org/10.1038/s41559-019-0797-2, 2019.

Djukic, I.: Early stage litter decomposition across biomes, Sci. Total. Environ., 628-629, 1369-1394, https://doi.org/10.1016/j.scitotenv.2018.01.012, 2018.

Fennel, K., Gehlen, M., Brasseur, P., Brown, C.W., Ciavatta, S., Cossarini, G., Crise, A., Edwards, C.A., Ford, D., Friedrichs, M.A., Gregoire, M., Jones, E., Kim, H., Lamouroux, J., Murtugudde, R., Perruche, C., and the GODAE Ocean View: Marine Ecosystem Analysis and Prediction Task Team Advancing marine biogeochemical and ecosystem reanalyses and forecasts as tools for monitoring and managing ecosystem health, Front. Mar. Sci., 6, https://doi.org/10.3389/fmars.2019.00089, 2019

David, L. A. and Alm, E. J.: Rapid evolutionary innovation during an Archaean genetic expansion, Nature, 469, 93-96, https://doi.org/10.1038/nature09649, 2011.

Declerck, S. A. J., Malo, A.R., Diehl, S., Waasdorp, D., Lemmen, K.D., Proios, K., and Papakosta, S.: Rapid adaptation of herbivore consumers to nutrient limitation: eco-evolutionary feedbacks to population demography and resource control, Ecol. Lett., 18, 553-562, https://doi.org/10.1111/ele.12436, 2015.

Gifford, S. M., Sharma, S., Rinta-Kanto, J. M. and Moran, M. A.: Quantitative analysis of a deeply sequenced marine microbial metatranscriptome, The ISME J., *5*(3), 461-472, https://doi.org/10.1038/ismej.2010.14, 2011.

Gorham, E: Biogeochemistry: Its origins and development, Biogeochemistry, 13, 199-239, https://doi.org/10.1007/BF00002942, 1991.

Groffman, P. M., Cadenasso, M.L., Cavender-Bares, J., Childers, D.L., Grimm, N.B., Morgan Grove, J., Hobbie, S.E., Hutyra, L.R., Darrel Jenerette, G., McPhearson, T., Pataki, D.E., Pickett, S.T.S., Pouyat, R.V., Rosi-Marshall, E., and Ruddell, B.L.: Moving towards a new urban systems science, Ecosystems, 20, 38-43, https://doi.org/10.1007/s10021-016-0053-4, 2017.

Hawlena, D., Strickland, M. S., Bradford, M. A. and Schmitz, O. J.: Fear of predation slows plant-litter decomposition, Science 336, 1434-1438, https://doi.org/10.1126/science.1220097, 2012

Held, N. A., McIlvin, M. R., Moran, D. M., Laub, M. T. and Saito, M. A.: Unique patterns and biogeochemical relevance of two-component sensing in marine bacteria. MSystems, *4*(1), e00317-18, https://doi.org/10.1128/mSystems.00317-18, 2019.

Hutchins, D.A., Walworth, N.G., Webb, E.A., Saito, M.A., Moran, D., McIlvin, M.R., Gale, J., and Fu, F.X.: Irreversibly increased nitrogen fixation in *Trichodesmium* experimentally adapted to elevated carbon dioxide. Nat. Comm., 6(1), 1-7, https://doi.org/10.1038/ncomms9155, 2015.

Kates, R. W.: What kind of a science is sustainability science? Proc. Nat. Acad. Sciences., 108(49), 19449-19450, https://doi.org/10.1073/pnas.1116097108, 2011.

Kuebbing,S.E., Reimer A.P., Rosenthal, S.A, Feinberg, G., Leiserowitz, A., Lau, J.A., and Bradford, M.A.: Long-term research in ecology and evolution: a survey of challenges and opportunities, Ecol. Monogr., 88, 245-258, https://doi.org/10.1002/ecm.1289, 2018.

Lenton, T.M., Boyle, R. A., Poulton, S. W., Shields-Zhou, G. A. and Butterfield, N. J.: Co-evolution of eurkaryotes and ocean oxygenation in the Neoproterozoic era, Nat. Geosci., 7, 257-265, https://doi.org/10.1038/ngeo2108, 2014.

Levin, S. A.: Complex adaptive systems: exploring the known, the unknown and the unknowable. Bull. Amer. Math. Soc., 40(1), 3-19, https://doi.org/10.1090/S0273-0979-02-00965-5, 2003.

Likens, G. E.: Biogeochemistry: some opportunities and challenges for the future, Wat. Air Soil Pollut., Focus, 4, 5–24, https://doi.org/10.1023/B:WAFO.0000028341.75842.08, 2004.

Macke, E., Tasiemski, A., Massol, F., Callens M., and Decaestecker, E.: Life history and eco-evolutionary dynamics in light of the gut microbiota, Oikos, 126, 508-531, https://doi.org/10.1111/oik.03900, 2017.

Martiny, A. C., Coleman, M. L. and Chisholm, S. W.: Phosphate acquisition genes in *Prochlorococcus* ecotypes: evidence for genome-wide adaptation, Proc. Natl. Acad. Sci., 103(33), 12552-12557, https://doi.org/10.1073/pnas.0601301103, 2006.

Matthews, B., Narwani, A., Hausch, S., Nonaka, E., Peter, H., Yamamichi, M., Sullam, K.E., Bird, K.C., Thomas, M.K., Hanley, T.C., and Turner, C.B.: Towards an integration of evolutionary biology and ecosystem science, Ecol. Lett., 14, 690-701, https://doi.org/10.1111/j.1461-0248.2011.01627.x, 2011.

Reed, D. C., Algar, C. K., Huber, J. A. and G.J. and Dick, G. J.: Gene-centric approach to integrating environmental genomics and biogeochemical models, Proc. Natl. Acad. Sci. USA, 111(5), 1879-1884, https://doi.org/10.1073/pnas.1313713111, 2014.

Richter, A., Schöning, I., Kahl, T. Bauhus, J. and Ruess, L.: Regional environmental conditions shape microbial community structure stronger than local forest management intensity. Forest Ecol. Manag., 409, 250-259, http://doi.org/10.1016/j.foreco.2017.11.027, 2018.

Rusch, D. B., Martiny, A. C., Dupont, C. L., Halpern, A. L., and Venter, J. C.: Characterization of *Prochlorococcus* clades from iron-depleted oceanic regions, Proc. Natl. Acad. Sci., 107(37), 16184-16189, https://doi/org/10.1073/pnas.1009513107, 2010.

Saito, M. A., Saunders, J.K., Chagnon, M., Gaylord, D., Shepherd, A., Held, N.A., Dupont, C., Symmonds, N., York, A., Charron, M., and Kinkade, D.: Development of an ocean protein portal for interactive discovery and education, https://doi.org/10.1101/2020.05.29.124388, 2020.

Saito, M. A., McIlvin, M.R., Moran, D.M., Santoro, A.E., Dupont, C.L., Rafter, P.A., Saunders, J.K., Kaul, D., Lamborg, C.H., Westley, M., Valois, F., and Waterbury, J.B.: Abundant nitrite-oxidizing metalloenzymes in the mesopelagic zone of the tropical Pacific Ocean, Nat. Geosci., 13, 355–362, https://doi.org/10.1038/s41561-020-0565-6, 2020.

Saito, M. A., Sigman, D. M. and Morel, F. M.: The bioinorganic chemistry of the ancient ocean: the co-evolution of cyanobacterial metal requirements and biogeochemical cycles at the Archean-Proterozoic boundary. Inorg. Chim. Acta, 356, 308-318, https://doi.org/10.1016/S0020-1693(03)00442-0, 2003.

Schaffner, L. R., Govaert, L., De Meester, L., Ellner, S.P., Fairchild, E., Miner, B.E., Rudstam, L.G., Spaak, P., and Hairston, N.G.: Consumer-resource dynamics is an eco-evolutionary process in a natural plankton community, Nat. Ecol. Evol., 3, 1351-1358, https://doi.org/10.1038/s41559-019-0960-9, 2019.

Schlesinger, W. H..: Better living through biogeochemistry. Ecology, 85(9), 2402–2407, https://doi.org/10.1890/03-0242, 2004.

Seibel, B. A. and Deutsch, C.: Oxygen supply capacity in animals evolves to meet maximum demand at the current oxygen partial pressure regardless of size or temperature, J. Exp. Biol., https://doi.org/10.1242/jeb.210492, 2020.

Seitzinger, S. P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B.M., Garnier, J., and Harrison J.A.: Global river nutrient export: A scenario analysis of past and future trends. Global Biogeochem. Cycl., 24, GB0A08, https://doi.org/10.1029/2009GB003587, 2010.

Simpson, M. J. and Simpson, A. J.: The chemical ecology of soil organic matter molecular constituents, J. Chem. Ecol., 38, 768-784, https://doi.org/10.1007/s10886-012-0122-x, 2012.

Soule, M. C. K., Longnecker, K., Johnson, W. M. and Kujawinski, E. B.: Environmental metabolomics: Analytical strategies, Mar. Chem., 177, 374-387, https://doi.org/10.1016/j.marchem.2015.06.029, 2015.

Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H.J., Dube, O.P., Dutreuil, S., Lenton, T.M., and Lubchenco, L.: The emergence and evolution of Earth System Science, Nat. Rev. Earth Environ., 54-63, https://doi.org/10.1038/s43017-019-0005-6, 2020.

Stokstad, E.: Open-source ecology takes root across the world, Science, 334, 308-309, https://doi.org/10.1126/science.334.6054.308, 2011.

Tanhua, T., Tanhua, T., Pouliquen, S., Hausman, J., O'Brien, K., Bricher, P., de Bruin, T., Buck, J.J.H., Burger, E.F., Carval, T., Casey, K.S., Diggs, S., Giorgetti, A., Glaves, H., Harscoat, V., Kinkade, D., Muelbert, J.H., Novellino A., Pfeil, B., Pulsifer, P.L., Van de Putte, A., Robinson, E., Schaap, D., Smirnov, A., Smith, N., Snowden, D., Spears, T., Stall, S., Tacoma, M., Thijsse, P., Tronstad, S.,Vandenberghe, T., Wengren, M., Lyborn, L., and Zhao, Z.: Ocean FAIR Data Services, Front. Mar. Sci., 6, 440, https://doi.org/10.3389/fmars.2019.00440, 2019.

Urban, M., Bocedi, G., Hendry, A.P., Mihoub, J.B., Pe'er, G., Singer, A., Bridle, J.R., Crozier, L.G., De Meester, L., Godsoe, W., Gonzalez, A., Hellmann, J.J., Holt, R.D., Huth, A., Johst, K., Krug, C.B., Leadley, P.W., Palmer, S.C.F., Pantel, J.H., Schmitz, A., Zollner, P.A., and Travis, J.M.J.: Improving the forecast for biodiversity under climate change, Science, 353, https://doi.org/10.1126/science.aad8466, 2016.

https://doi.org/10.5194/bg-2020-395
Preprint. Discussion started: 4 November 2020

Biogeosciences Discussions

Vernadsky, V. I.: Biosfera. Leningrad. Seen in abridged English translation, Synergetic Press, Oracle, Arizona (1986), also available in a complete French translation, La Biosphere, by the author, Alcan, Paris (1929) ~ (1945), https://doi.org/10.1017/S0376892900036584, 1926.

Villar, E., Vannier, T., Vernette, C., Lescot, M., Cuenca, M., Alexandre,´A., Bachelerie, P., Rosnet, T., Pelletier, E., Sunagawa, S., and Hingamp, P.: The Ocean Gene Atlas: exploring the biogeography of plankton genes online, Nucl. Acids Res., 46(W1), https://doi.org/10.1093/nar/gky376, 2018.