Biogeoscapes: **Ocean Metabolism and Nutrient Cycles on a Changing Planet**

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Introduction: In an effort to explore and develop international community interest for a potential future "Biogeotraces-like" program, a working group of 28 scientists from 9 nations met in Woods Hole in November 2018. There was strong interest in continuing this effort among the international participants, who agreed to act as ambassadors to communicate these discussions to their respective national communities. This report describes ideas put forward, including a new name: *Biogeoscapes*, to help stimulate further dialogue within national and international communities towards the long-term goal of developing a global program that aspires to combine detailed biological and chemical investigations of the oceans.

Concept: *Biogeoscapes* aims to improve our understanding of the functioning and regulation of ocean metabolism[1] and its interactions with nutrient cycling[2] within the context of a hierarchical seascape perspective[3]. This is needed in order to better quantify the role of biological feedbacks on a changing planet. Ocean metabolism is a useful organizing concept as it operates at an intracellular scale for each organism, which then collectively interact to shape net metabolism at the assemblage level across ocean biomes. Ultimately, ocean metabolism is at the heart of our planetary life support system, as it couples biochemical processes and ecosystem-scale cycling of carbon, oxygen and nutrients, especially during periods of environmental change. However, the understanding of ocean metabolism that underpins current predictive models emphasizes a simple link between ocean resources and biogeochemistry, with a dominant control for physical mechanisms. This ignores feedbacks and interactions,

[1] Here we refer to metabolism as the chemical processes that occur within individual organisms and populations, as well as among communities and ecosystems
[2] Considered to include both major (e.g. nitrogen, phosphorus and silica) and micro (e.g. iron, zinc, manganese, cobalt, copper and nickel) nutrients
[3] See e.g. Kavanaugh, et al (2016) https://doi.org/10.1093/icesjms/fsw086

newly discovered from a growing set of omics[4], physiology and nutrient datasets, both within and between organisms and the chemical environment, over different time and space scales. *Biogeoscapes* will reveal how metabolisms in the ocean are structured and regulated, at multiple levels of biological and biogeochemical organization, by linking new tools across observations and models within a standardized framework.

Scale: *Biogeoscapes* will provide a multi-dimensional global vision of the ocean at multiple time and space scales, by exploiting three main tools: i) our new ability to efficiently measure, characterize and map nutrients and metabolites (including macro- and micro-nutrients, gases, and organic compounds), ii) insights into the composition and function of ecological communities from omics and physiology, and iii) the integrative potential of new modelling platforms and artificial intelligence/machine learning. By linking these tools within a coherent framework, *Biogeoscapes* provides the opportunity to reveal the forcings and functioning of the ocean metabolism, along with its resilience to changes in the ocean environment, as a whole.

Approach: We envisage full water-column ocean sampling, including a temporal component in two ways. Firstly, using augmented observatories that leverage existing national activities at sea to provide core measurements of a set of key parameters. Secondly, via hybrid approach to conducting ocean surveys that can deliver complementary measurements of chemical and biological pools, as well as rate processes at larger spatial scales. We also see a role for laboratory experiments (to provide rate measurements and reference genomes) that will aid in field interpretation and for novel numerical modelling at different levels of complexity. Crucial to *Biogeoscapes* will be the coupling of omics to nutrient cycling via a suite of physiological linkages within a standardized analytical framework (that includes samples, data collection and interpretation), with a clear numerical pipeline that integrates computational biology and ocean biogeochemical modelling. This range of potential activities will likely change, as we incorporate inputs from the larger community, following broader national and international discussions of scientific goals, research priorities and funding opportunities.

Expected Outcomes: Generate a baseline understanding of the major microbial communities in the ocean and their metabolic function. Produce tools for the visualization and analysis of data. Quantify the biological and biogeochemical hierarchies that structure ocean metabolism at different scales. Develop protocols and pipelines to intercalibrate and manage data across different disciplines. Address the representation of key biological feedbacks within ocean ecosystem models. Train a new generation of scientists worldwide and build capacity in the fields of omics, physiology, chemical oceanography, bioinformatics and modelling. Build the foundation for the study

[4] Here we consider omics as (meta)genomics, (meta)transcriptomics, (meta)bolomics and (meta)proteomics

of future anthropogenic impacts on the ocean, the Earth's primary life support system, and its resilience to change. Develop links to UN 2030 Sustainable Development Goals, G7 Future of the Seas and Oceans and drive future projections of ecosystem change and fisheries.

Background to the *Biogeoscapes* meeting and a timeline for further action:

Background: In November 2018, approximately 28 international scientists from the fields of chemical oceanography, omics, physiology and modeling met to explore the need and scope of a new international program loosely aimed around coupling the potential insight onto ocean ecosystems from new advances from different fields (primarily arising from the Tara Oceans and GEOTRACES efforts). The meeting was sponsored by the Scientific Commission on Ocean Research, the Ocean Carbon and Biogeochemistry program and the Moore Foundation. Four invited speakers highlighted the insight and added value gained from integrating observations of micronutrients and omics. Reflection on previous programs identified the importance of intercalibration and data management, and the need for omics intercalibration efforts and investment in novel data management and open access, user friendly platforms. Equally, the need for new ecosystem modelling approaches, capable of integrating the mechanisms and feedbacks emerging from omics datasets was noted. Time was spent discussing the potential extent and impact of a new program, as well as choosing *Biogeoscapes* as the name. The role of different types of contributions from different nations, including the routes to funding *Biogeoscapes* activities were discussed, and the overall outcome of the meeting is summarized in the broad mission statement above. This preliminary broad mission of *Biogeoscapes*will be improved by further input and feedback from the international community. It is anticipated that feedback from the wider community will occur first via national meetings during 2019 and then in a larger international forum, which would shape the preliminary science plan in much more detail.

Timeline: During 2019, we encourage all nations to bring together the chemical oceanography, biological and microbial oceanography, omics, physiology and modelling communities to showcase *Biogeoscapes* preliminary research goals and vision, disseminate information, solicit feedback and build a national steering group. At these meetings, the following topics could be considered for discussion: What kinds of science questions do scientists in your nation see as being important within the broad goal of *Biogeoscapes* on a 10 year timescale? How would you see your nation contributing to *Biogeoscapes* efforts – e.g. fieldwork, laboratory work, modelling, project coordination, data management? Are there any impediments that the program could seek to mitigate via training or collaboration? Please inform us of your plans and progress using the email address info@biogeoscapes.org.

During 2019, a series of intercalibration efforts will also get underway and the progress of these activities will be disseminated through the program website.

In 2020, we aim to have a larger international meeting to begin to scope more specific science and implementation plans, including the development of an international steering committee. Please sign up at www.biogeoscapes.org to remain informed about all activities.

Biogeoscapes meeting attendees:

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