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Grand challenges in biogeoscience

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Introduction

> "The term 'holistic' refers to my conviction that what we are concerned with here is the fundamental interconnectedness of all things".... "I see the solution to each problem as being detectable in the pattern and web of the whole. The connections between causes and effects are often much more subtle and complex than we with our rough and ready understanding of the physical world might naturally suppose..."

These quotes are from *Dirk Gently's Holistic Detective Agency* (1987) by the late Douglas Adams (author of *The Hitchhiker's Guide to the Galaxy*). Mr. Gently is a "holistic detective," a fictional character dwelling in a fantasy world, but in many ways he bears all the hallmarks of a biogeoscientist, as we too, seek answers to multidimensional, multifaceted—and interconnected—problems! (Adams, 1987).

In addition to its broad scope, the remit of biogeoscience constitutes a fundamental scientific endeavor that is of critical importance for our understanding of the Earth system, and especially its response to natural and anthropogenic perturbations. It appears clear that we are now well into the Anthropocene (e.g., Crutzen and Steffen, 2003), and we urgently need to understand better how our world operates if we are to define the limits of human existence on this planet (Rockstrom, 2009; Running, 2012; Steffen et al., 2015), and predict, and possibly mitigate, future change. Life is a pervasive force, orchestrating or widely participating in a myriad of processes at the Earth's surface, and the field of biogeoscience, focused on the interaction between life and the physical environment (Martin and Johnson, 2012), is thus central to this issue. This is perhaps most grandly articulated in the "Gaia" hypothesis—namely that physical and biological processes are closely interwoven, forming a self-regulating system with feedbacks that keep the Earth in balance (Lovelock and Margulis, 1974). While Gaia theory remains controversial, and indeed other hypotheses argue for a more sinister role for life on this planet (e.g., Ward, 2009), the concept has come to symbolize the Earth as a highly complex, interconnected system.

Biogeoscience epitomizes fields of science that witness exciting advances at the interfaces with other scientific disciplines. Indeed, biogeoscience is all about interfaces—the interface between the biotic and abiotic world (the lithosphere, hydrosphere, and atmosphere), between organic and inorganic realms, and between processes that span enormous spatial and temporal scales. It is a nexus where numerous perspectives meet under a common theme of seeking to understand how biotic processes are influenced by and shape today's world, how they have operated and co-evolved in the past, and how they may respond to and influence future conditions and human pressures on this planet. Intermingled anthropogenic and natural forces add yet another layer of complexity and dynamism. Here, I highlight a few crosscutting themes that present common grand challenges.

Working at the Boundaries

Numerous interfaces form the focal points of different themes in biogeoscience. The term "critical zone" was coined to describe the interface between soils and the underlying rock substrate where biological activity plays a crucial role in regolith formation (Brantley et al., 2007). This term has been more broadly used to highlight other interfaces where biological and biogeochemical processes exert key controls. The land-ocean interface strongly influences the fate of biogeochemically important constituents carried by rivers and groundwaters (e.g., Cole et al., 2007; Aufdenkampe et al., 2011). River networks, termed the "arteries of the planet," are focal points for, and have also been modified by human activity (Vorosmarty et al., 2010; Syvitski and Kettner, 2011). The concept of a "boundless carbon cycle" (Battin et al., 2009) emphasizes the interconnected nature of continental and ocean processes. Enormous challenges remain in understanding and quantifying processes at this broad and dynamic interface.

Redox boundaries also constitute major focal points for biogeoscientists, ranging from very small-scale or ephemeral features to large-scale phenomena such as coastal hypoxia (Rabalais et al., 2010) and widespread oxygen deficient zones in the oceans (Keeling et al., 2010). These interfaces are characterized by complex redox chemistry and are hotspots of biological activity influencing biogeochemical cycles over diverse spatial and temporal scales. There are undoubtedly more interfaces to be discovered, some presumably that take place on scales, or over gradients, that we currently cannot measure.

In addition to their biogeochemical and ecological importance, larger-scale physical and chemical boundaries (e.g., isobars, isopycnals, chemoclines) can provide a powerful work framework for imaging or visualizing key properties. In this context, the concept of isoscapes, which exploits isotopic gradients in the environment for understanding natural and human-related phenomena (West et al., 2010), may serve as a model for mapping of other relevant parameters. As we continue to identify and understand the importance of key interfaces, we need to develop tools for displaying and manipulating this information in two-, three- and even four dimensions.

A Matter of Scale

Biogeoscientists deal with processes and phenomena occurring over a huge range of spatial and temporal scales—from atomic to global and even planetary, and from fractions of a second to eons. A major challenge lies in improving our ability to quantify processes over this range of scales, and to "upscale" fluxes and inventories from scales we can observe and measure to those compatible with regional and global modeling approaches. Temporal scales present particular challenges, especially for processes occurring over timescales that are either too short, or too long, to observe readily.

Powerful methods now exist for examining mineral-organism interactions through numerous advances in microscopy and imaging techniques that can map chemical and other variations on minute scales and can reveal specific microbial metabolisms (e.g., Musat et al., 2008; von der Heyden et al., 2012). Such techniques shed light on processes taking place at the organismal, molecular, and even atomic level, and inform about the spatial disposition between life and its abiotic substrates. However, deriving robust quantitative information is challenging. For example, our ability to quantify chemical interactions between the surface of a cell and its environment, or between organic matter and mineral phases in soils and sediments remains limited. Furthermore, much of the organic matter occurring in soils, waters, and sediments remains uncharacterized at the molecular level (e.g., Hedges et al., 2000; Hansell, 2013), yet molecule-molecule interactions are "ground zero" for many key biogeochemical processes.

At the other end of the scale spectrum, global biogeochemical cycles are typically and necessarily described and modeled (given computational demands) in terms of elemental (e.g., C, N, P, O, S), molecular (e.g., CO_2, CH_4, NO_3^-, PO_4^{3-}), or operationally-defined (e.g., dissolved or particulate inorganic and organic C, nutrients etc.) properties. While these "bulk" measures can generally be measured precisely and extensively, enabling derivation of large-scale inventories and fluxes, they fail to capture the complexity of the underlying smaller-scale processes. The non-linearity of many biogeochemical processes also hinders extrapolation across scales. If we take the critical zone in a regolith as an example, it remains a challenge to extrapolate chemical fluxes resulting from microbe-mineral interactions on a micron scale to weathering rates and processes on the scale of an outcrop. Moreover, many microbially-mediated reactions occur so rapidly that it is challenging to elucidate underlying mechanisms. While organism-substrate interactions are evident in many other environments, such as hydrothermal vents, soil microrhizomes, and subsurface petroleum reservoirs, we are not readily able to quantify scales and rates of processes. Sophisticated measurement, observation, experimentation, and modeling approaches need to be developed that adopt common metrics and allow processes to be captured at the relevant spatial and temporal scales.

Integrating "Omics" and Geochemistry

As for all biologically-oriented sciences, biogeoscience has embraced the revolution in molecular biology and the technological innovations that have fueled it. These advances are yielding unprecedented insights into the diversity of life, as well as the metabolic capabilities and strategies that allow life to exist in a vast array of natural and perturbed ecosystems. The capacity to acquire and decipher information has advanced at lightning pace, and the scientific literature is replete with studies illustrating the complexity of life, unusual or unexpected metabolisms, and the existence of, or potential for, life in environments hitherto considered inhospitable (e.g., Holland et al., 2013). We can now say much about who is there (*genomics*), what functions organisms are capable of performing (*transcriptomics*), whether they are expressing this functional capacity (*proteomics*), and what natural products organisms use to proliferate, survive and communicate in their environment (*metabolomics*). Cultivation-independent approaches (e.g., *metagenomics*) now enable direct extraction of information from complex environmental matrices.

Major challenges remain, such as how to cope with and efficiently utilize the vast and multidimensional lines of information emanating from these advanced techniques. We also need to be aware of methodological limitations. For example, large information gaps may exist where unique functions and physiologies are absent or underrepresented in "omics" databases due to sampling and analytical biases. An additional pressing challenge is how to quantitatively link "omics" information to specific geochemical processes and fluxes. For example, we are now frequently able to recognize the genes responsible for orchestrating a specific biological process, such as uptake of specific nutrients. We can even recognize when this capability is expressed, as well as detect the specific metabolites involved. However, linking these phenomena to actual fluxes of materials into and out of cells, and providing quantitative constraints on nutrient cycling on larger spatial and temporal scales are formidable challenges. The wealth of information emerging from the "omics" world thus needs to be translated into metrics and proxy measures for integration into quantitative biogeochemical models.

The Human Dimension

Perhaps the greatest challenge for our discipline is to understand how biogeochemical processes, and the biodiversity and ecosystems they support, will change as we progress through the Anthropocene (e.g., Jackson, 2008; Walther et al., 2009). Embedded in this challenge is the need to understand mean state (baseline) conditions and the Earth's natural rhythms, and to distinguish them from those that are the product of human activity. Unfortunately, our realization of the scope and magnitude of changes that we have induced, or have set in motion, has severely lagged the onset and pace of these changes. Furthermore, capabilities for autonomous, sustained measurements of key parameters have been developed only recently. As we increasingly engineer our planet's solid, aqueous and atmospheric surface environments, it becomes a pressing imperative to define and understand natural systems, and biotic responses to environmental change.

The challenges confronting us are formidable. On one level, we must detect and evaluate the consequences of subtle, gradual, and predominantly unidirectional changes (e.g., warming, intensification of the hydrological cycle, attrition of glaciated areas, sea-level rise, and stratification, acidification and deoxygenation in the oceans). Superimposed on these gradual changes are more abrupt and episodic phenomena (e.g., earthquakes, volcanic eruptions, droughts, fire, floods on land, tropical cyclones) that may have equally profound effects on biogeochemical cycles (e.g., Reichstein et al., 2013). The 2010 Deepwater Horizon oil well blowout in the Gulf of Mexico, and the release of radioactivity from the Fukushima nuclear power plant following the Tôhoku earthquake off Japan in 2011 are recent examples of major direct anthropogenic perturbations. Assessing consequences of extreme events and gradual change brought on by anthropogenic activity constitutes a crucial challenge.

Sustained observations are essential for establishing long-term trends and identifying anomalous departures from these trends, as epitomized by the iconic atmospheric CO_2 record at Mauna Loa (e.g., Keeling et al., 1995). Indeed, they require concerted and sustained measurements spanning generations, transcending disciplines and crossing international borders or physical boundaries (Wunsch et al., 2013). Coordination at numerous levels is needed to develop networked observation programs at the scales that match the processes under scrutiny, such as Critical Zone Observatories (http://criticalzone.org/national; http://www.czen.org/), the terrestrial CO_2 flux observation network (Baldocchi et al., 2001; fluxnet.ornl.gov), ocean observatories (www.oceansites.org) and Ecological Observatory Networks (http://www.neoninc.org). Similarly, broad biogeochemical surveys (e.g., http://www.geotraces.org; Johnson et al., 2009) are essential for assessing spatial variability. There are many successes and highlights, such as satellite-based remote sensing of terrestrial and ocean biogeochemistry (e.g., Zhao and Running, 2010; Siegel et al., 2014). Yet, we need to do much more, including implementation of new technologies for autonomous observation and sampling of environmental and ecosystem properties (Honjo et al., 2014). In addition, deliberate perturbation experiments have proven useful for prediction of responses to anticipated future conditions, and potentially mitigating change (e.g., FACE and soil warming, ocean iron fertilization experiments). Such experiments can also lead to a much broader understanding of the underlying natural processes, as well as defining thresholds, tipping points, and resilience and adaptability in terms of biogeochemical processes and ecosystems.

As current and future observation and experimental strategies are necessarily superimposed on a period of on-going change, we need to explore biogeochemical processes and ecosystem dynamics in pre-anthropogenic times, beyond our window of direct observations, in order to characterize longer-term natural variability. Many facets of biogeoscience seek to understand the origin and evolution of life, and its relationship to and influence on past environments and climate throughout Earth history. Novel archives are continuing to emerge and our ability to interrogate them is advancing rapidly through molecular, isotopic and other proxies and tracers. Further efforts are needed to broaden our view of the evolution of the Earth's surface environments and ecosystems, in both spatial and temporal domains.

A natural consequence of observatory science and expansive measurement programs is a proliferation of datastreams, both in terms of diversity and volume. This flood of data has also led to a rapid expansion in databases and merged datasets (e.g., Kattge et al., 2011), which are proving tremendous resources for researchers and educators, as well as for policy makers. However, these databases create their own non-trivial challenges, such as optimal ways of entering, accessing, visualizing and reducing data, and forging seamless links across datasets. For biogeoscience, these challenges are particularly acute, due to the multidimensional nature of the information we seek.

Finally, in tandem with the ever-growing tidal wave of data that we try to digest, there is concomitant demand for models that can work with, and make sense of these data. Modeling approaches are also needed to better design observation programs in terms of critical variables to be monitored, and to upscale observations (e.g., Arndt et al., 2013; Carvalhais et al., 2014). Similarly, experimental programs can be better designed using modeling-based sensitivity analyses to determine those properties that are most prone to, or likely to promote change. The challenge of understanding interlocked processes operating over different spatial and temporal scales requires development of biogeoscience-specific modeling techniques. Hand-in-hand with these challenges is a need for much more transparent and systematic reporting of measurement uncertainties and limitations in the assessment of model performance and output.

Concluding Remarks

There undoubtedly will be enormous public pressure for bioengineering solutions as climate and environmental change really begin to bite. Biogeoscientists will be in the front line, bombarded with questions seemingly impossible to answer given the complexity and interconnectiveness of the processes at work around us. Additional insults to our environment through deliberate and inadvertent release of pollutants will further confound predictions. Biogeochemical cycles do not respect international boundaries and we may be thrown out of our usual "comfort zone" in providing interpretations and advice. However, by the same token, many exciting new discoveries lie ahead as we meet and surmount these grand challenges. We must be open to unexpected outcomes that undermine current paradigms and overturn prevailing hypotheses.

As Dirk Gently puts it, "Only a child sees things with perfect clarity, because it hasn't developed all those filters which prevent us from seeing things that we don't expect to see."

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