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Carbon Cycling and Biosequestration

Integrating Biology and Climate Through Systems Science

Report from the March 2008 Workshop

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Executive Summary

One of the most daunting challenges facing science in the 21st Century is to predict how Earth's ecosystems will respond to global climate change. The global carbon cycle plays a central role in regulating atmospheric carbon dioxide (CO_2) levels and thus Earth's climate, but our basic understanding of the myriad of tightly interlinked biological processes that drive the global carbon cycle remains limited at best. Whether terrestrial and ocean ecosystems will capture, store, or release carbon is highly dependent on how changing climate conditions affect processes performed by the organisms that form Earth's biosphere. Advancing our knowledge of biological components of the global carbon cycle is thus crucial to predicting potential climate change impacts, assessing the viability of climate change adaptation and mitigation strategies, and informing relevant policy decisions.

Global carbon cycling is dominated by the paired biological processes of photosynthesis and respiration. Photosynthetic plants and microbes of Earth's landmasses and oceans use solar energy to transform atmospheric CO_2 into organic carbon. The majority of this organic carbon is rapidly consumed by plants or microbial decomposers for respiration and returned to the atmosphere as CO_2. Coupling between the two processes results in a near equilibrium between photosynthesis and respiration at the global scale, but some fraction of organic carbon also remains in stabilized forms such as biomass, soil, and deep ocean sediments. This process, known as carbon biosequestration, temporarily removes carbon from active cycling and has thus far absorbed a substantial fraction of anthropogenic carbon emissions.

Results from first-generation climate–carbon cycle models suggest that the capacity of the terrestrial and ocean biosphere to absorb anthropogenic CO_2 is likely to peak by mid-century. In some scenarios, large amounts of organic carbon currently locked in high-latitude permafrost, tropical forests, and other ecosystems may in fact be released back to the atmosphere. The rate and magnitude of photosynthesis and respiration, as well as the stability of carbon stored in ecosystems, are heavily influenced by climate variables such as temperature, CO_2 levels, availability of water and nutrients, and disturbances such as fire and pests. Given the immense quantities of carbon cycled by Earth's biosphere (210 gigatons annually), even relatively small shifts in the rates of carbon cycle processes and amounts of carbon biosequestered in ecosystems could have major impacts on atmospheric CO_2 levels.

Although it is critical to more accurately predict the impacts of shifting climate conditions on carbon cycling and biosequestration in ecosystems, most carbon cycle processes are either minimally represented or altogether absent from current climate models. Different models supplied with nearly identical human emissions scenarios have produced dramatically different projections for carbon uptake, storage, or release by land and ocean ecosystems. This problem is compounded by the limited set of experimental approaches aimed at validating the predictions of climate models. Resulting uncertainties diminish the models' predictive capabilities, decrease their level of resolution, and limit their general utility for anticipating and responding to climate change scenarios.

Understanding and predicting processes of the global carbon cycle will require bold new research approaches aimed at linking global-scale climate phenomena; biogeochemical processes of ecosystems; and functional activities encoded in the genomes of microbes, plants, and biological communities. This goal presents a formidable challenge, but emerging systems research approaches provide new opportunities to bridge the knowledge gap between molecular- and global-scale phenomena. Systems-level research emphasizes studies on the underlying principles of intact, complex systems and facilitates scaling of concepts and data across multiple levels of organization. Applying this approach to the global carbon cycle will require multifaceted but highly integrated research that incorporates experimentation on model organisms and systems, collection of observational data on communities and ecosystems, and mechanistic modeling of processes ranging from metabolic to global scales.

In March 2008, the U.S. Department of Energy's Office of Biological and Environmental Research (OBER) held the Carbon Cycling and Biosequestration Workshop. Operating within DOE's Office of Science, OBER is uniquely positioned to lead new national research initiatives aimed at understanding the interlinked systems that form the underpinnings of the global carbon cycle. OBER supports fundamental research and technology development aimed at achieving predictive, systems-level understanding of organisms, biological communities, ecosystems, and global climate. OBER research has been crucial in advancing modern genomics-based systems biology, understanding community and ecosystem-scale responses to climate change variables, and developing increasingly sophisticated models of global climate processes.

At the DOE Carbon Cycling and Biosequestration Workshop, researchers at the forefront of microbiology, plant biology, ecological research, and biogeochemical modeling identified research requirements necessary to (1) advance understanding of the biological processes that drive the global carbon cycle, (2) achieve greater integration of experimental biology and biogeochemical modeling approaches, (3) assess viability of potential carbon biosequestration strategies, and (4) develop novel experimental approaches to validate climate model predictions.

It is now widely recognized that we must confront expanding global energy needs while simultaneously reducing carbon emissions and minimizing negative climate impacts. Transformational breakthroughs are needed to increase the accuracy and resolution of climate change models that inform policy decisions, open new avenues to innovation in climate change adaptation and mitigation strategies, and assess the validity of potential solutions. Achieving an exponential increase in our understanding of the interwoven systems that control the ultimate fate of carbon in Earth's ecosystems is integral to meeting these challenges.