Managing the Carbon Cycle Requires Strong Science

For future climate change mitigation strategies to be effective, carbon cycle science must receive a major boost.

Researchers study terrestrial ecological processes by measuring land-to-air carbon dioxide fluxes using instrumented towers like this flux tower scanning Lake Superior from Granite Island. Credit: John Lenters, Limnotech (Ann Arbor, Mich.). Used with permission.

By Galen A. McKinley, Craig A. Carlson, Arlyn Andrews, Daniel G. Brown, Paty Romero-Lankao, and Gyami Shrestha 25 November 2015

Anthropogenic carbon emissions have substantially perturbed the natural global carbon cycle, which includes the atmosphere, biosphere, lithosphere, and hydrosphere. Because humans inhabit the atmosphere and hydrosphere and depend on food, fiber, and fuel products from the biosphere and our dominant energy source is fossil fuels from the lithosphere, carbon is now integral to all human activities, infrastructure, and built environments.

Nations are beginning to realize the extent of carbon's impact on the global climate, and they are responding to the need for long-term climate stabilization with pledges to reduce their emissions of carbon dioxide and other greenhouse gases. The bilateral U.S.-China agreement in October 2014 exemplifies movement toward international commitments and represents a step that may pave the way for a multinational agreement at the upcoming Conference of the Parties (http://www.cop21paris.org/about/cop21) (COP21, Paris, 2015) or at some later date. Implementation of local- to national-level carbon mitigation policy is quickly evolving toward targets within specific categories of human activity, including transportation, agriculture, and forestry.

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Current and future advances in climate policy depend on a robust infrastructure for science and observation of the carbon cycle at multiple scales. The global and national-level policy arenas are ripe for greater dialog between scientists and policy makers about mitigation approaches and about the advances that scientists must make in order to monitor, measure, and verify that mitigation actions are working.

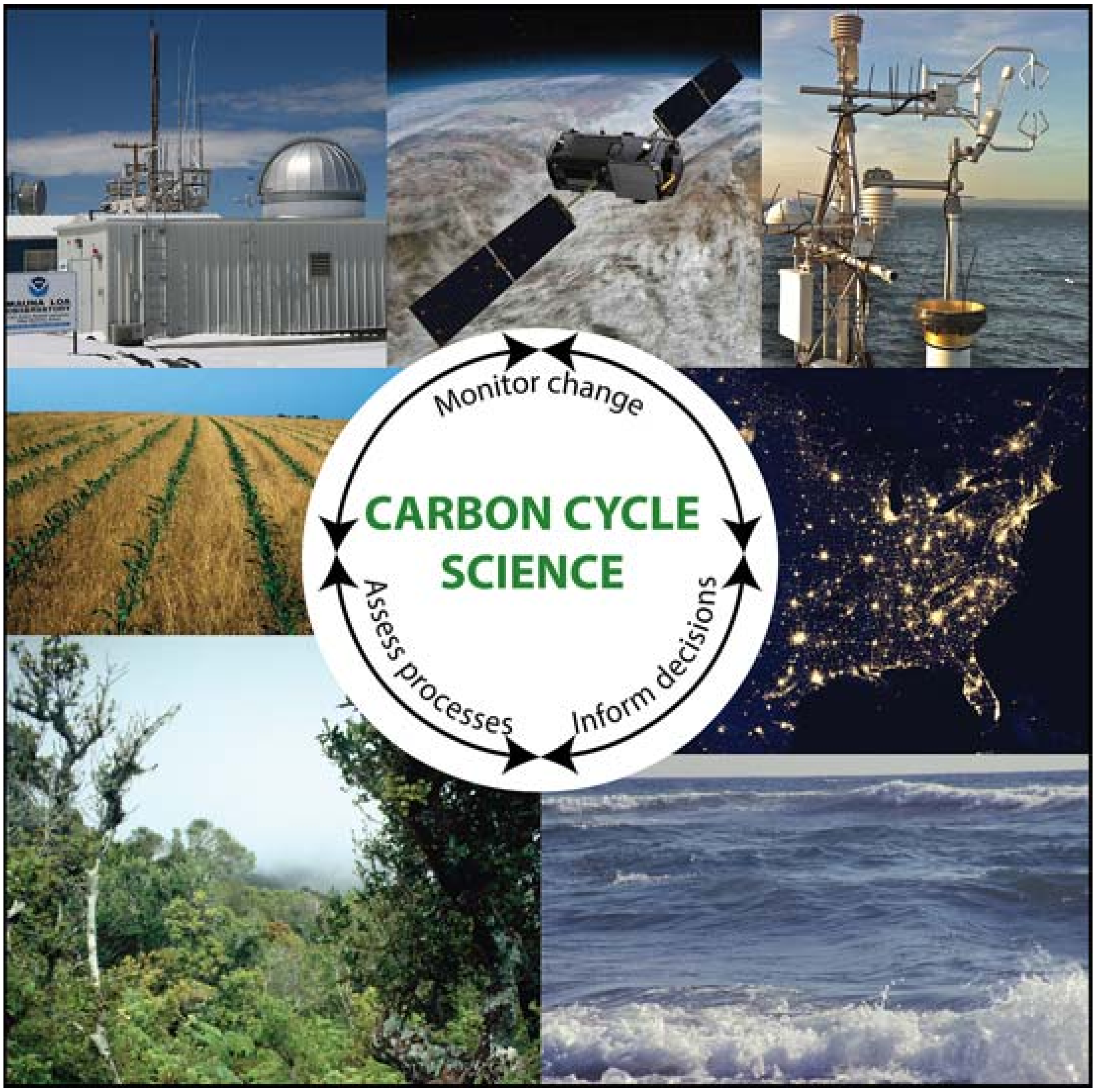
Developing the most effective, efficient, and targeted approaches for carbon emission reductions requires continued improvement in understanding of carbon cycle mechanisms across the physical science, ecological science, social science, and engineering communities. At the same time, the effects of mitigation efforts must be monitored using observations spanning scales from local to global. Nations and agencies within national governments must continue to coordinate observations and science to get the most from limited resources.

Carbon Cycle Science: Local to Global

To begin to address the vast complexity of the carbon cycle, scientists study processes at carefully selected locations. At a few ocean sites, scientists have observed carbon and associated variables monthly for decades.

Researchers study terrestrial ecological processes by measuring land-to-air carbon dioxide fluxes using instrumented towers and, more recently, satellites. To quantify relationships between energy use and emissions, scientists use laboratory studies of combustion to determine "emission factors" that can be applied to fossil fuel use data to estimate emissions.

Scientists use their understanding of the processes and empirical relationships derived from these types of studies to estimate carbon stocks and fluxes at regional to global scales (Figure 1). To independently verify such large-scale estimates, additional observations are also needed. In the oceans, ship-based surveys precisely quantify the oceans' carbon content and document how it changes over decades. On land, inventories of forests and soil carbon biomass illustrate long-term change.



(https://eos.org/opinions/managing-the-carbon-cycle-requires-strong-science/attachment/15-2042_mckinley_ccssg_8_f01_web)

Fig. 1. Researchers study terrestrial ecological processes by measuring land-to-air carbon dioxide fluxes using surface-based instruments, satellites, and laboratory studies. They use their understanding of the processes and empirical relationships derived from these types of studies to estimate carbon

stocks and fluxes at regional to global scales. Photo credits: Clockwise from top left: NOAA, NASA, John Lenters, NASA, Juan Botella, Juan Botella, USDA-NRCS

Clearly, it is impossible to directly observe all fluxes and reservoirs at all times. Thus, scientists have also developed approaches that provide integrated estimates of carbon fluxes to and from the atmosphere across the continents and the oceans. These top-down approaches use observations of atmospheric carbon concentrations together with atmospheric transport and mixing to quantify surface fluxes. These estimates, in turn, place a critical constraint on estimates of national net carbon fluxes [*King et al.*, 2015].

Current Understanding

On timescales relevant to current policy, the global carbon cycle can be considered a closed system in which anthropogenic carbon put into the atmosphere must either remain there or be absorbed into the terrestrial biosphere or the oceans. Since 2007, the Global Carbon Project, an international partnership of carbon cycle scientists, has used this closed-system approach to produce annual global carbon budgets [*Le Quéré et al.*, 2014].

Combining this principle with the multilayered observations and analyses discussed above reveals that the atmosphere has accumulated only about 60% of all anthropogenic carbon emissions since 1750, and the ocean has absorbed the remaining 40% [*Ciais et al.,* 2013]. (In the terrestrial biosphere, carbon emissions from deforestation and other land use changes have approximately balanced carbon uptake from processes including forest regrowth on previously agricultural land on a cumulative basis from 1750 through 2011.)

Estimating regional carbon fluxes and budgets and their temporal change, however, is much more challenging [*Schuster et al.*, 2013; *King et al.*, 2015], largely because many processes occurring in human, terrestrial, and oceanic systems are poorly understood. For example, urban areas are responsible for up to 76% of humans' carbon dioxide emissions, but much uncertainty remains regarding how these urban contributions are regionally distributed and connected with rural emissions [*Romero-Lankao et al.*, 2014].

A Moving Target

Spatial disaggregation of the carbon cycle is also difficult because of how readily human and natural processes cause lateral carbon movements. Carbon can be embodied in international trade, with the carbon emissions in one country arising from the manufacture of goods to be consumed elsewhere.

Terrestrial and aquatic environments also move carbon laterally. Some carbon absorbed by the terrestrial biosphere is deposited in groundwater, streams, and lakes, of which a significant portion may ultimately be reemitted downstream back to the atmosphere [*Battin et al.*, 2009]. Similarly, river-borne carbon entering the coastal ocean may be buried in sediments, exported to the open ocean, or released to the atmosphere. Complex coastal environments create major uncertainties in continental carbon budgets [*Regnier et al.*, 2013].

Translating Science to Emissions Policy

There is no doubt that the observed atmospheric accumulation of carbon is due primarily to fossil fuel burning and thus that reducing fossil fuel use will reduce emissions. Although this general principle is clear, targeted policies and interventions to reduce carbon emissions risk being ineffective if scientists and the decision makers they inform don't fully understand the underlying mechanisms that drive emissions.

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To properly assess carbon flow and transformation by humans, we need to understand how energy and land use associated with human activities modify carbon stocks and fluxes. This includes understanding how economic development may provide opportunities for shifts to infrastructure with a lower carbon footprint.

Given how much cities contribute to total emissions, planners should take advantage of urban economies of scale and make connections between planning and fuel use. More precise monitoring should help regulators identify the most polluting facilities, which likely have the greatest potential for emissions reductions [*Gurney*, 2015].

Management Opportunities for Carbon Sinks

Because plants take up carbon through photosynthesis, smart ecosystem management may be able to increase how much carbon is stored in forests, soils, coasts, and wetlands. But incorporating carbon into land and water management decisions will require better knowledge of how carbon moves through and is transformed within these systems. We must also know how to keep carbon within these systems for the long term and how to quantify "lateral flux" losses.

Uncertainty in the mechanisms of carbon sinks must be low enough to provide confidence that a policy will lead to sufficient carbon storage, especially if a price is placed on carbon. The mechanistic understanding required for effective support of such policy developments remains a major step beyond globally integrated budgets, which the carbon cycle community has only just begun to produce annually. If we want to modify and manage the carbon cycle, we need improved process knowledge with respect to carbon cycling on land, in water, and in human systems.

Living with Uncertainty

In addition to implementing science-based policies that effect meaningful reductions in emissions and increase carbon sinks, we must monitor the natural and human components of the carbon cycle across local to global scales to determine if our policies are accomplishing their goals. At the same time, the complexity of the carbon cycle and the human systems with which it interacts means that the effectiveness of any policy will always have some uncertainty.

Minimizing this uncertainty requires advancing the current top-down approaches to include as many data streams as possible, including satellite data, in situ measurements, inventories, social indicators, and process models. Carbon is long-lived in the atmosphere, so accurately quantifying national net carbon budgets and any policy-driven changes will always require constraining estimates of carbon fluxes on land, in the oceans, and in the connecting surface waters.

Time to Act

It would not be an exaggeration to say that major advances in carbon cycle science will be required to plan and monitor our civilization's path to a sustainable future. As policy makers formulate decisions based on our current level of knowledge (for example, President Obama's Climate Action Plan [*Executive Office of the President*, 2013]), they must also invest in critical scientific and technological advancements for carbon cycle research and monitoring capabilities.

Comprehensive plans that include both short- and long-term interdisciplinary strategies for the carbon cycle science needed to support climate policy already exist [e.g., *Michalak et al.*, 2011; *Ciais et al.,* 2014]: Now is the time for their implementation.

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