Ecosystem metabolism and the global carbon cycle

At present, we employ a large array of tools and approaches that give us some understanding of the carbon cycle. Each of these provides a piece of the carbon-balance puzzle, but there is no single tool or approach that gives the total spatial and temporal resolution that is needed to understand global and regional carbon dynamics, and the control of those fluxes.

As we prepare for an implementation phase of the Kyoto Protocol, agreed by the Parties of the Framework Convention for Climate Change to stabilize the concentrations of atmospheric carbon dioxide (CO_2), nations will need precise information on the variability of background levels of carbon exchange in their biotic systems, and on how humans are modifying these exchanges. In addition, the high economic value of the terrestrial carbon sink, and its associated uncertainties, places a high priority on understanding current and future controls of the carbon source–sink dynamics. Consequently, we need an international integrated research effort to study the metabolism of the earth and the global carbon cycle.

There are two fundamental issues for understanding the Earth's carbon metabolism and the impacts of global change on it: (1) the spatial location and strength of contemporary carbon sources and sinks; and (2) the future metabolic trajectories as climate, atmospheric composition and land-cover change. To address these two key issues, an integrated and multidisciplinary approach involving monitoring at various spatial scales, experimentation and modeling is required.

Several approaches are available for measuring atmospheric CO_2 concentrations and fluxes at various spatial scales. These provide information on the localization of carbon sources and sinks across continents, regions and ecosytems ('top-down' approach). For example, results from the network of gas-sampling sites combined with models of global atmospheric transport provide estimates of carbon fluxes at continental and subcontinental scales. These estimates, although quite coarse, are the first attempt to identify the major source and sink regions of the planet.

Satellite-based data also provide whole-planet coverage for some measurements related to fluxes, such as plant growth phenology (e.g. the 'normalized difference vegetation index', which is related to net primary productivity). More detailed spatial-flux analyses can be obtained by taking measurements (from balloons and aircraft) that provide flux information relevant to regions and landscapes ($\approx$100 km). Eddy covariance towers can then identify the contribution of various components (at scales of $\approx$1 km^2) of the landscape and provide detailed information on the climatic controls over whole-ecosystem fluxes. Eddy covariance measurements in conjunction with results from other studies of ecosystem physiology can provide insights into the relative contribution of various ecosystem components (i.e. soil, microbes and canopies) and fluxes (respiration and photosynthesis), which are the basis for a mechanistic understanding ('bottom-up' approach).

Overall integration will be attempted with the use of biospheric models that will synthesize flux measurements not only from different spatial scales, but also across the various temporal sampling frequencies of each single technique or measurement. Political boundaries can also be resolved with biospheric models.

As well as understanding the spatial localization and strength of carbon sources and sinks, it is critical to be able to predict future dynamics and trajectories of carbon fluxes. Ecosystem responses resulting from annual climatic variation or short-term climate trends will most likely give an ambiguous indication of the future trajectories of carbon fluxes (i.e. ranging from decades to a century), because they ignore long-term metabolic adjustments and biogeochemical feedbacks. For instance, in several field ecosystem experiments where CO_2 concentration has been elevated, initial large increases in carbon storage have declined over time, probably because of long-term nutrient limitation. Therefore, long-term observations and long-term experimental manipulations (such as increasing the concentration of CO_2, warming soil and air, and altering nitrogen deposition) are also required to provide the data to develop and test models of these phenomena and to project carbon fluxes under future climatic and atmospheric scenarios (bottom-up approach).

Finally, novel modelling approaches should be developed to account for metabolic changes associated with biome shifts, plant invasions and changes in land cover (including disturbances regimes). Ultimately, in addition to abiotic factors (e.g. climate), predictive models will have to account for changes in land cover and use as a result of political and economical factors.

The top-down perspective allows us to quantify carbon fluxes over the biosphere at landscape, regional, continental and global scales. The bottom-up approach allows us to examine the dynamics and mechanisms that control these fluxes at the ecosystem level, and provides the necessary data to develop and validate ecosystem and global models that will estimate future carbon fluxes.

Thus, as we understand more of Earth's carbon metabolism, we need an integrated approach that incorporates our existing tools. We also need to ensure that all of the necessary information is being acquired efficiently. It is important that national research efforts and international global-change programs [e.g. the International Geosphere–Biosphere Programme (IGBP) and the Global Change and Terrestrial Ecosystems (GCTE) carbon initiatives] develop strong links to achieve the international coordination necessary to study global carbon metabolism.

At present, nations depend on the Intergovernmental Panel on Climat Change (IPCC) to assess information on the carbon cycle and other elements influencing climate change. This process, coordinated by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), does not direct or coordinate research but summarizes the available information and makes recommendations based on the findings. The research input comes from the normal undirected scientific process, although some nations are developing carbon research programs. At the international level, there are research programs that deal with some parts of the cycle, including carbon dynamics of the ocean, responses of terrestrial ecosystems to global change and modelling the earth system. However, there is no single international program that examines, and more importantly, coordinates carbon-cycle research. Such a program must now be established.

Acknowledgements
This paper contributes to the Global Change and Terrestrial Ecosystems (GCTE) Carbon Initiative.

Josep Canadell

GCTE International Project Office, CSIRO Wildlife & Ecology, PO Box 284, Canberra, ACT 2601, Australia (pep.canadell@dwe.csiro.au)

Harold A. Mooney

Dept of Biological Sciences, Stanford University, Stanford, CA 94305, USA (hmooney@jasper.stanford.edu)

  PII: S0169-5347(99)01601-8