FORUM

The Need for "Apples-to-Apples" Comparisons of Carbon Dioxide Source and Sink Estimates

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The global land-based carbon dioxide (CO_2) sink can be derived from the difference between fossil fuel emissions and the sum of estimated increases of CO_2 in the atmosphere and in the ocean [*Houghton*, 2010]. For the purposes of developing policy to limit CO_2 emissions, it is necessary to refine scientific understanding of the land CO_2 flux in terms of its spatial and temporal patterns, as well as the underlying drivers.

Net ecosystem exchange (NEE) is the commonly used measure of the land flux and is defined as the net vertical exchange of CO_2 between a specified horizontal surface and the atmosphere above it over a given period of time. NEE estimates are reported from the atmospheric perspective, such that a positive value represents emissions (a land source) and a negative value represents removals (a land sink). This term represents a seemingly simple concept, and it was given a clear definition as one of the key carbon cycle variables by *Chapin et al.* [2006]. However, considerable confusion still arises around its usage, and the ambiguity is traceable primarily to the suite of different approaches used to estimate it.

Our objective here is to offer a clarified and expanded conceptual view of NEE, particularly in light of the information content and various caveats associated with the main scaling approaches. This is a necessary and timely discussion considering ongoing efforts to make model-model and model-data intercomparisons for assessing carbon balance at the scale of landscapes, regions, and the planet [*Canadell et al.*, 2011; *Huntzinger et al.*, 2012].

What Is and What Is Not Included in NEE?

A commonly applied definition of NEE is that it is equal to the balance between the gross uptake of CO_2 by plants through photosynthesis—gross primary production (GPP)—and the total release of CO_2 back into the atmosphere through ecosystem respiration (ER, the sum of autotrophic and heterotrophic respiration). While such a definition limited to these biogenic flux components approximates NEE at fine spatial scales and short time intervals, larger-scale and longer-term assessments require an expanded definition that includes other key components, namely, the pyrogenic, product (from harvested wood and crops), and aquatic fluxes. All of these components need to be partitioned into fluxes that are included in NEE, particularly those with vertical CO_2 exchange, while removing from the calculation those not included, such as non-CO_2 and/or nonvertical exchanges.

Biogenic fluxes include those vertical CO_2 flux components controlled directly by vegetation and microbial processes, i.e., GPP and ER. Pyrogenic fluxes refer to the direct emission of greenhouse gases to the atmosphere from the combustion of ecosystem (vegetation and soil) carbon. These are also vertical fluxes, but, in addition to CO_2, organic matter combustion results in the emission of other carbon-containing gases (e.g., methane (CH_4) and carbon monoxide). Product fluxes impact NEE via direct emissions of CO_2 from the decay and combustion of carbon in harvested wood products (HWP) and the respiration of CO_2 (by humans and livestock) resulting from the consumption of harvested crop products (HCP). Product fluxes have important nonvertical components (i.e., "lateral" transfers) in that carbon in HWP and HCP is typically not returned to the atmosphere in the same time or place that it was originally taken up by plants. Product fluxes also have non-CO_2 emission components, e.g., CH_4 from decay of HWP in landfills and digestive fermentation of HCP consumed by livestock. Aquatic fluxes are considered in NEE where direct CO_2 evasion from water bodies occurs within the defined time and space. Aquatic fluxes also have important non-CO_2 and nonvertical fluxes (examples include CH_4 emissions from lakes and the lateral, down-stream transfer of dissolved organic and inorganic carbon).

A conceptual understanding of NEE is aided by considering how its definition relates to the other integrated flux indicators defined by *Chapin et al.* [2006]. Net ecosystem production (NEP) is a measure of the biogenic flux, i.e., the balance of GPP and ER, and is thus a subset of NEE. Net ecosystem carbon balance (NECB) integrates all ecosystem carbon gains and losses (whether vertical or lateral and CO_2 or non-CO_2 forms) between two points in time, and thus, NEE is a subset of it. We note that volcanic emissions and mineral weathering are also land fluxes, but these geologic-scale fluxes are not typically included in the time scale of most assessments. CO_2 emissions from fossil fuel burning and cement production represent a substantial flux to the atmosphere but are generally considered separate from the land flux in ecosystem studies.

Reconciling Estimates Among Different Approaches

Driven by international treaties and other policy concerns, as well as a more general scientific interest, there has been in recent years a proliferation of terrestrial carbon budget estimates at global, national, and regional scales. The NASA Carbon Monitoring System (NASA, 2012, http://carbon.nasa.gov/) and the National Oceanic and Atmospheric Administration (NOAA) CarbonTracker system (NOAA, 2012, http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/) are prominent examples. Model-model and model-data comparisons of flux estimates across alternative approaches are a key part of these analyses. Approaches to estimating NEE over large domains typically involve a combination of measurements and modeling and can be generally categorized as either "top-down" (atmosphere-based) or "bottom-up" (biosphere-based). Because each approach focuses on different components of the carbon cycle over different spatial and temporal scales, it is imperative that comparisons consider differences in methodology, particularly with respect to fluxes that are, or are not, included in the estimation of NEE.

Top-down approaches rely on measurements of spatial and temporal patterns in CO_2 concentration observations. NEE estimates can be derived from these observations using an array of techniques ranging from simple boundary layer budget approaches to more complex modeling of atmospheric transport. Atmospheric inversion models (AIMs) use initial estimates of the land flux combined with an atmospheric transport model, with the posterior pattern of land sources and sinks optimized by comparing inferred CO_2 concentrations to observations. These atmosphere-based approaches estimate NEE directly and comprehensively, i.e., they "see" all surface-atmosphere CO_2 exchange as one integrated flux. AIMs [e.g., *Peters et al.*, 2007] may prescribe the spatial and temporal pattern of fossil fuel and pyrogenic emissions based on other data sets but otherwise do not distinguish between the biogenic, product, and aquatic flux components individually.

The eddy covariance flux (ECF) technique is a special case of top-down approach that measures ecosystem-scale CO_2 exchange using tower-based instrumentation with footprints on the order of 1 or more square kilometers [*Baldocchi*, 2003]. ECF measurements are most appropriate in comparisons with modeled estimates of biogenic fluxes (i.e., NEP) over shorter time periods and finer spatial scales. Scaling ECF measurements to broader-scale estimates of NEE is a challenge, however, because they tend to undersample age-specific variation in forest NEP and typically do not capture fluxes related to the pyrogenic, product, and aquatic components.

Plot-level biometric measurements are the basis for bottom-up approaches, either serving directly as input to inventories or indirectly by way of their use in calibrating terrestrial biosphere models (TBMs). One accounting approach to flux estimation is based on the difference between complete inventories at two points in time, thus capturing the total change in ecosystem C (i.e., NECB) [*Heath et al.*, 2011]. Alternatively, a complete inventory can be used for the starting point and updated by modeling forward the components of change (i.e., growth, mortality, decomposition, and disturbance in forests) [*Stinson et al.*, 2011]. TBMs always simulate the biogenic fluxes but vary widely in whether and how they account for the CO_2 and non-CO_2 and vertical and lateral components of the pyrogenic, product, and aquatic fluxes. Bottom-up approaches can be applied at broad scales and estimate flux components individually, allowing for process-level attribution. However, these approaches are often not comprehensive of all components needed to calculate NEE, as there are pools and fluxes thought to be important that are undersampled, of large or unknown uncertainty, and/or not inventoried or modeled at all [*Hayes et al.*, 2012].

As such, additional flux components have to be included with standard, bottom-up NECB results to obtain more true estimates of NEE for comparison with the top-down approaches.

The Path Forward

Several studies have undertaken comparisons of broad-scale flux estimates among alternative scaling approaches, and although convergence has been found in some cases [*Janssens et al.*, 2003], there is often wide disagreement [*Desai et al.*, 2010; *Turner et al.*, 2011]. The initial comparisons have often been somewhat opportunistic and hence not strongly controlled for driver data, spatial and temporal domain, processes included, and uncertainties associated with each approach. More precisely defined comparisons can be achieved through formal model intercomparison projects (e.g., Multi-Scale Synthesis and Model Intercomparison Project, http://nacp.ornl.gov/MsTMIP.shtml, 2012) that involve multiple model simulations run under a common protocol. It is essential that model intercomparison protocols use universally accepted definitions of key carbon cycle variables as they pertain to the results of each different approach. This is particularly true for NEE, as it is the one integrated flux indicator that can be compared between both top-down and bottom-up estimates across all spatial and temporal scales. Thus, researchers must pay due attention to making true "apples-to-apples" comparisons across these different approaches to estimating the net vertical exchange of CO_2 between the surface and the atmosphere.

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