Carbon dynamics in response to climate and disturbance: Recent progress from multi-scale measurements and modeling in AmeriFlux

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Summary. The CO_2 flux network, AmeriFlux, aims to quantify and understand the role of terrestrial ecosystems in the global carbon cycle. The network has grown to over 100 sites, with about 25 cluster sites in different disturbance classes or different vegetation types within a climate zone. This paper summarizes the network objectives, recent findings of AmeriFlux research, and future directions necessary to meet global climate change research goals. The information gained from flux sites, multi-factor experiments on processes, and multi-observation networks can help to improve and parameterize models that are applied to quantify and understand carbon budgets across regions and continents.

Key words. Carbon budgets, Ecosystem fluxes, Remote sensing, Process modeling

1. Introduction

About half of the CO_2 emitted by human activities accumulates in the atmosphere, and half is taken up by oceans and land systems. We lack quantitative understanding of where the sinks are, how they function, and whether there is anything we can do to enhance carbon sequestration to counter emissions long enough for technological improvements to have a significant effect by reducing emissions.

The AmeriFlux network was established in 1996 to understand the role of terrestrial systems in the global carbon cycle (Law et al. 2002; AmeriFlux Strategic Plan; http://public.ornl.gov/ameriflux/about-strat_plan.shtml). The network consists of over 100 sites (Fig. 1), which make continuous meteorological and micrometeorological measurements using the eddy covariance method, core biological measurements (e.g. photosynthesis, respiration) for understanding processes that control fluxes, participate in intercalibration activities with a roving system to ensure high quality data are collected, submit their data to a central archive, and participate in synthesis activities across sites. About 25 of the research teams have cluster sites in different disturbance classes or vegetation types within climate zone to examine the effects of disturbance and climate on carbon stocks and fluxes. A Science Chair is responsible for leading scientific activities of the network, such as coordination and quality assurance of measurements across sites, leading cross-network data analysis and synthesis of results, and communicating AmeriFlux results to the scientific community and other users. A Steering Committee of

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Fig. 1. Map of active research sites in the AmeriFlux network (as of September 2004). Many of the sites are clusters in different disturbance classes or vegetation types within a climate zone. The inactive sites have data in the AmeriFlux archive (http://public.ornl.gov/ameriflux/).

lead scientists and agency program managers works with the Science Chair by providing technical and policy advice. The science questions of AmeriFlux are:

- What is the spatial and temporal variability in CO_2 and H_2O exchange and how does this vary with disturbance history, land use, and climate?
- What is the spatial and temporal variation in continental CO_2 and how does this vary with topography, vegetation, and climate?
- What is the relative effect of these factors?

AmeriFlux plays a key role in the North American Carbon Program (NACP), which was recently developed to meet goals of the US Global Change Research Program (USGCRP; http://www.usgcrp.gov). Science questions of the NACP Implementation Strategy include (1) What is the carbon balance of North America and adjacent oceans? What are the geographic patterns of fluxes of CO_2, CH_4, and CO? How is the balance changing over time? (*Diagnosis*); (2) What processes control the sources and sinks of CO_2, CH_4, and CO, and how do the controls change with time? (*Attribution/Processes*); (3) Are there potential surprises (changes in sources or sinks)? (*Prediction*); (4) How can we enhance and manage long-lived carbon sinks, and provide resources to support decision makers? (*Decision support*). AmeriFlux sites are actively participating in the development of the NACP, and in developing new approaches to estimating stocks and fluxes at relevant temporal and spatial scales.

This chapter describes some recent highlights from AmeriFlux research, and the future directions of the network in support of global climate change research.

2. Highlights from AmeriFlux research

2.1 Strong correlation between ecosystem exchange of carbon dioxide and water vapor

Tower flux data from 37 AmeriFlux and CarboEurope sites in different biomes showed a strong correlation between monthly gross photosynthesis and water vapor exchange (transpiration plus evaporation) at the ecosystem scale, consistent with leaf-level physiological control (Law et al. 2002). The water-use efficiency (WUE = slope of relation between GPP and water vapor exchange) was ranked highest to lowest: evergreen coniferous forests (4.2 g CO_2/kg H_2O) > grasslands (3.4) > deciduous broadleaf forests (3.2) > crops (3.1) > tundra vegetation (1.5). Thus, evergreen coniferous forests took up more carbon per unit of water loss than other biomes, and three of the biomes had lower but similar efficiencies (grasslands, deciduous broadleaf forests, and crops).

2.2 An average of 83% of gross photosynthesis is respired to the atmosphere

Among 37 sites in different biomes, an average of 83% of the total amount of carbon taken up by the terrestrial systems in photosynthesis was respired back to the atmosphere (Law et al. 2002). The ratio of annual ecosystem respiration to gross photosynthesis averaged ranged from 0.55–1.2, with lower values for grasslands, presumably because of less investment in respiring plant tissue compared with forests. Values >1 were observed for boreal forests (i.e., net loss of CO_2), ecotonal temperate/boreal forests, some northern temperate forests, and a cropland. The ratio includes effects of both short- and long-term processes. Some of the variation is from differences in heterotrophic respiration, which is strongly influenced by labile carbon pools (Ryan and Law 2004).

2.3 Site water balance and temperature are primary abiotic controls on GPP

Across biomes, mean annual temperature and site water balance explained about 65% of the variation in gross photosynthesis (Law et al. 2002). Water availability limits leaf area index over the long term (Waring and Running 1998), and inter-annual climate variability can limit carbon uptake below the photosynthetic capacity of the ecosystems. The simple correlations, as well as biome-specific water-use efficiencies may be useful for large-scale atmospheric modeling of land surface influences on variation in atmospheric CO_2.

2.4 Ecosystem net carbon uptake is greater when the diffuse fraction of incident radiation is high

Volcanic aerosols from the 1991 Mt. Pinatubo eruption greatly increased diffuse radiation worldwide for the following two years (citation). Long-term flux data in a deciduous forest showed that the increase in diffuse radiation enhanced noontime photosynthesis by 23% the year following eruption (1992) and 8% in the second year (Gu et al. 2003). This finding indicates that the aerosol-induced increase in diffuse radiation contributed to the enhanced terrestrial carbon sink and the temporary decline in the growth rate of atmospheric carbon dioxide (CO_2) following the eruption. It points to the need for investigation of the roles of variability of cloudiness and aerosol concentrations in global carbon cycle dynamics.

2.5 Soil respiration is strongly linked with labile pools

Soil respiration is the combination of root and rhizosphere respiration, and microbial respiration. It has become the focus of many process studies at flux sites because tower flux studies have shown that soil respiration accounts for 60 to 70% of ecosystem respiration (Law et al. 1999; Goulden et al. 1996; Janssens et al. 2001), and it is strongly linked to photosynthesis (Irvine et al. 2004; Bowling et al. 2002; Janssens et al. 2001), fine root mass (Campbell et al. 2004), and litterfall (Davidson et al. 2002). Experiments at flux sites have shown that roots and associated mycorrhizae produce roughly half of soil respiration (Law et al. 2001a), with much of the remainder derived from decomposition of recently produced litter, which confirms a synthesis of earlier work (Hanson et al. 2000).

Recent flux site studies have shown that there is a large increase in soil respiration following pulse rain events that occur when soils are relatively dry (Lee et al. 2004; Kelliher et al. 2004). A question is whether or not this has a significant effect on annual net carbon uptake by the ecosystem (balance between photosynthesis and respiration).

A synthesis across biomes showed that the lowest to highest rates of soil respiration averaged over the growing season were grassland and woodland/savanna < deciduous broadleaf forests < evergreen needleleaf, mixed deciduous/evergreen forests with growing season soil respiration significantly different between forested and non-forested biomes. This is the inverse of trends in water-use efficiency by biome (Law et al. 2002), and the results of the synthesis suggest that we need to put more effort into investigating the effects of seasonal changes in aboveground and belowground labile pools on soil respiration (Ryan and Law 2004; Hibbard et al. 2004). A synthesis of the current state of our knowledge on soil respiration, and future research needs is presented in Ryan and Law (2004).

3. A case study on combining measurements and modeling for regional estimates of carbon stocks and fluxes

The NACP implementation strategy identifies a priority of development of “bottom-up” designs that use multiple scales of observations and process modeling to quantify carbon

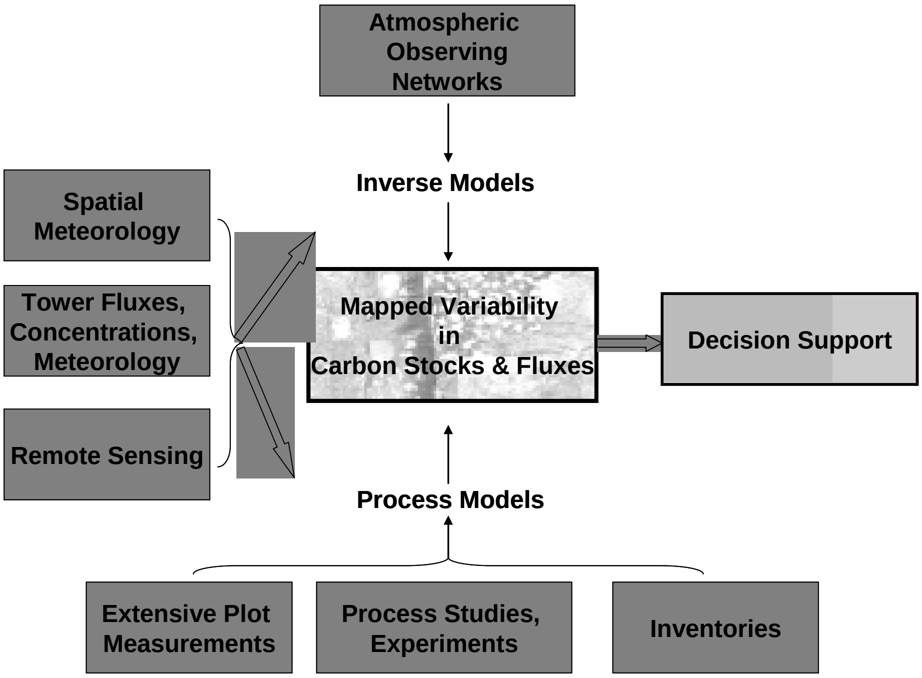

Fig. 2. A conceptual model of the major components of the North American Carbon Program, which will rely on a variety of data sets, remote sensing data and modeling to map variation in carbon stocks and fluxes across North America.

fluxes and understand the influence of climate and disturbance on stocks and fluxes(Denning et al. 2004). It also recommends top-down approaches to quantify and spatially resolve continental CO_2 fluxes (Fig. 2). The various approaches are to be developed and compared to reduce uncertainty in estimates of stocks and fluxes.

In Oregon, a regional scaling study was conducted using a spatially nested hierarchy of observations (flux measurements, inventories, remote sensing data) and a biogeochemistry model, Biome-BGC, to map carbon stocks and net ecosystem production (NEP) across western Oregon (Law et al. 2004a,b). Observations of forest age, LAI, and vegetation type were used to develop and test Landsat ETM+ remote sensing algorithms (Law et al. 2004b). The Biome-BGC model was parameterized with some of the observations (e.g. foliar C:N, remote sensing LAI), and tested with others (e.g. NEP, GPP from flux data, NPP from extensive sites, ANPP from inventories) to iteratively improve model performance before final application of the model. Spectral regressions with half of the field data and various spectral bands reduced uncertainty in remote

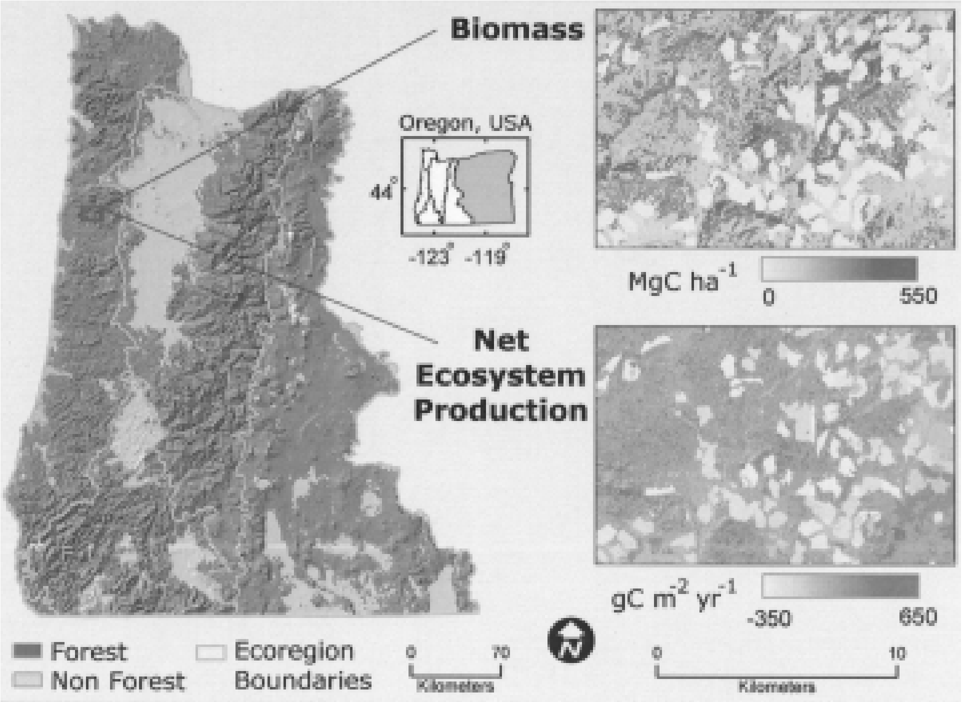

Fig. 3. Mapped forest biomass and net ecosystem production (NEP) in western Oregon, where a bottom-up approach was tested for applications of a spatially nested hierarchy of observations, including satellite remote sensing data, and a process model, Biome-BGC to provide realistic estimates of carbon stocks and fluxes across regions (From cover image of September 2004 issue of Global Change Biology).

sensing estimates of LAI, which were used to control the water balance (soil depth) in the model for each pixel. Field data were also used to evaluate remote sensing estimates of stand age and land cover type that are needed for model input. The inventory data were used to determine changes in carbon allocation to wood with forest age.

Western Oregon forests grow across a strong climatic gradient where annual rainfall ranges from 2100mm in the coastal forests to 300mm in the eastern Oregon juniper woodlands. For the forested part of the region (8.2 million hectares), simulated NEP was 168 g C m^{-2} yr^{-1}, with the highest mean uptake in the Coast Range ecoregion (226 g C m^{-2} yr^{-1}), and the lowest mean NEP in the Eastern Oregon ecoregion (88 g C m^{-2} yr^{-1}) (Law et al. 2004a; Fig. 3). Carbon stocks averaged 33.7 Kg C m^{-2}, with wide variability among ecoregions. This information was combined with harvest records and forest fire information to estimate net biome production (NBP) for western Oregon. The study suggested that averaged over 5 years, the forest NBP of western Oregon offset about 50% of fossil fuel CO_2 emissions in the state, and this was reduced by half in the year of a historically-large and severe wildfire. The estimates will be refined when new data on carbon transformations from the forest fires in the region have been analyzed (Campbell et al. in prep.). The study cautions that losses of carbon stocks and fluxes in wildfires are not well quantified in some regions, and that assumptions of carbon losses and transformations by modelers will need to be improved with new data where they are currently lacking.

In developing and testing the prognostic version of the model, Biome-BGC, we found that we need to better characterize the changes in carbon stocks and fluxes following forest stand replacing disturbance for parameterizing the model. In terms of ecosystem processes represented in the model, the dynamics of carbon allocation patterns through forest stand development should be addressed, and these change with climate zone and biome. We also need to characterize successional species mixes in forests following stand replacing disturbance, rather than assume that the disturbed areas are solely a uniform regrowth of the same tree species, and we need better representation of respiration processes (Law et al. 2001b; Thornton et al. 2002; Law et al. 2003). For other biomes, remote sensing land cover should distinguish crop type for improving model estimates; this isn't currently available in commonly used land cover products.

While there is room for improvement in the model and data assimilation approaches, this demonstrates the value of multiple data sources for model ingestion to ultimately quantify variation in the carbon balance. Likewise, the information gained from flux sites, multi-factor experiments on processes, and multi-observation networks can help to improve and parameterize models that are applied to quantify and understand carbon budgets across regions and continents.

4. Future directions

AmeriFlux and other flux networks provide multi-year data on half-hourly micrometeorology and meteorology, and they are the focal points of intensive process studies and thorough carbon accounting (e.g. biometric estimates of multi-annual NEP). These data should be collected at sites that represent the major biomes and ecoregions of a network (Hargrove et al. 2003). The data are critical for model development, testing, and parameterization.

Process studies are needed to improve modeling of respiration across landscapes. Although temperature and moisture data have been used to model soil respiration within a site, the relationships do not hold across sites. This requires knowledge about the labile pools, and flux sites will need to measure these pools more rigorously in the future. Long-term experimental manipulations at flux sites will also advance understanding of interactive effects of water, nitrogen and increased atmospheric CO_2 for improving carbon cycle models (e.g. Free Air CO_2 Enrichment sites that are also measuring whole ecosystem fluxes) (Oren et al. 2001).

Data assimilation methods are relatively new to the flux and biological community, and there is a need to develop and test such methods for regional and continental estimates of stocks and fluxes. The methods are challenging, and rely on both short-term (e.g. eddy flux data, seasonal changes in leaf area index) and long-term process data (e.g. soil carbon pools measured every 5 years). Early tests of these approaches show that more frequent measurements of pools and reduced uncertainty in field biological data and eddy flux data are critical for applying these methods (Williams et al. 2004). In the North American Carbon Program, it is expected that data assimilation methods will be applied in both top-down and bottom-up approaches, and that the approaches will be iteratively compared and improved to reduce uncertainty in carbon balance estimates. To be successful, this requires modelers and field researchers to work together to determine the minimum set of measurements needed with specificity on methods (e.g. soil C pools, acceptable uncertainty levels) and acceptable temporal frequency of measurements.

There is more emphasis now on quantifying and reducing uncertainty for making policy decisions that rely on robust estimates of carbon stocks and fluxes. The various networks, CarboEurope, AsiaFlux, AmeriFlux, and OzFlux, need to work together to improve data quality, data management and data sharing to advance the science that relies on flux network data (Baldocchi et al. 2001).

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