Resolving Carbon Budgets in Complex Terrain of the Rocky Mountain Western U.S. – A Proposed NACP Intensive

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Introduction

Our knowledge of biosphere-atmosphere carbon fluxes in complex and mountainous terrain is limited. It has generally been assumed that theory and measurement capabilities are not adequate for accurate mass balance approaches in complex topography and this has diminished efforts to resolve local and regional carbon budgets in the mountains. Western U.S. mountains play a significant role in the US carbon budget. Recent studies that regionalize the U.S. carbon sink suggest that a significant fraction of carbon sequestration occurs in hilly to mountainous terrain (Houghton et al., 1999, Schimel et al., 2000, Pacala et al., 2001). Recently, we used satellite data and ecosystem models to show that Western U.S. montane regions contribute disproportionately to continental U.S. carbon uptake (Schimel et al., 2002: Fig. 1); we estimated that 25 to 50% of total U.S. carbon uptake, and up to 75% of Western U.S. uptake, occurs in mountainous terrain. The recent tendency to ignore ecosystems in complex terrain in favor of simpler systems for the study of CO_2 fluxes has hampered our ability to accurately assess major components of the U.S. carbon sink.

We make the case that intensive studies at several scales (from plot to region) in the Rocky Mountain Front Range would significantly enhance our ability to (1) develop the context of western montane forests within the North American carbon budget, and (2) develop new model-data fusion approaches that accommodate regional carbon budgets for ecosystems characterized by complex topography. We propose a measurement and analysis framework that builds on existing initiatives involving airborne (top-down) and nested arrays of tower-flux and concentration (bottom-up) observations. The overall aim of the effort will be to implement and evaluate the data analysis framework outlined in Fig. 2; an approach that combines forward and inverse modeling to achieve "optimized" estimates of regional biosphere-atmosphere CO_2 fluxes.

Why the Rocky Mountain Front Range?

Several ongoing efforts in the Rocky Mountain Front Range could support an NACP Intensive. The Niwot Ridge Ameriflux site is progressively identified as an intensive focus site for regional carbon sequestration studies. In its current configuration, the site contains a nested design of four towers (within 150 m of each other), each with vertical profiling of CO_2, and two with continuous flux measurements of CO_2, H_2O, and energy. In May 2004, three additional above-canopy towers will be installed at the site as part of the NSF-funded Biocomplexity project on Carbon in the Mountains. The three new towers will be situated along a prominent topographic drainage in the vicinity of the Ameriflux site in an effort to examine localized channels of advective carbon flux. As part of the Biocomplexity project, the Airborne Carbon in the Mountains Experiment (ACME) will be launched with intensive campaigns in May and July 2004; the aim of these campaigns will be intensive aircraft sampling of CO_2 concentrations and fluxes, stable isotopes, and other carbon-containing trace gases within a regional footprint centered on the Niwot Ridge Ameriflux site. Three sites in the Rocky Mountain Front Range (Niwot Ridge Ameriflux, Fraser Experimental Forest, Glacier Lakes Ameriflux) have been chosen as focus sites for an NACP Tier 3 Prototype Project (funded by USDA Forest Service, January 2004). As a result, these sites will be well-characterized in 2004-2006 with regard to fundamental vegetation characteristics, soil respiration dynamics and local scaling of fluxes from plots to tower footprints.

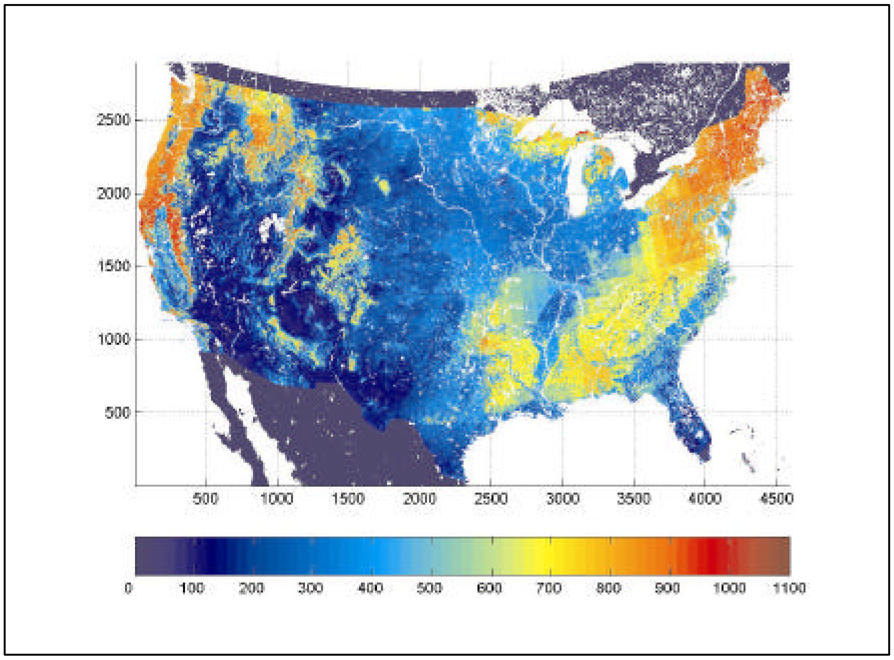

Figure 1. Gross primary productivity (GPP) estimated from the MODIS satellite instrument showing strong correlation between high rates of carbon uptake and montane topography. The bottom color chart reflects GPP in units of gC m^{-2} y^{-1}.

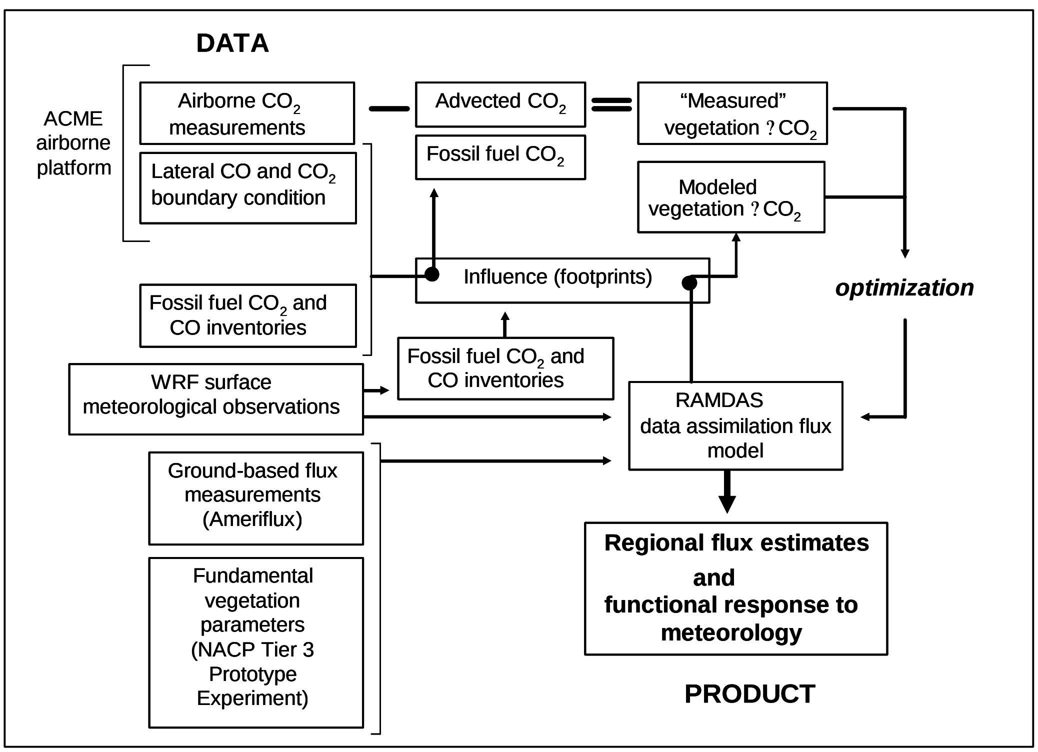

Figure 2. Conceptual scheme for assimilation of tower and airborne data to produce regional estimates of CO_2 flux during an NACP Intensive in the Rocky Mountains. (Based on Gerbing et al. 2003a, 2003b, Lin et al. 2004).

The Carbonshed Concept as an Organizing Principle

We have developed the “carbonshed” approach for the study of the ecosystem carbon balance of montane landscapes. We define a carbonshed within the same context as a watershed – a mountainous tract in which the slopes and valleys cause complex topographic patterns, which directly influence the drainage and accumulation of CO_2. A carbonshed represents all slopes that share a common nighttime drainage of CO_2. We propose the carbonshed as the principal factor forcing the primary and higher-order surface-atmosphere interactions that control ecosystem C fluxes in complex terrain. In mountainous carbonsheds, near-surface dynamics in the flow of CO_2 cause complex patterns of mixing as the CO_2 is vented into the atmosphere.

The Central Organizing Questions to be Addressed in an NACP Intensive

Forested mountain ecosystems may contribute significantly to regional carbon uptake. Flux measurements on micrometeorologically feasible sites within the mountains suggest that controls over carbon exchange are complex and significantly affected by the redistribution of water and energy within carbonsheds. However, to understand the role of mountains in continental carbon budgets, we must be able to scale local fluxes to the carbonshed level, and integrate over carbonsheds that exhibit different topo-edaphic and disturbance characteristics. To do this we propose to focus on the following basic scientific and methodological questions:

1) How do the processes that control surface-atmosphere CO_2 exchange in the mountains differ from those in flat terrain? How does the topographic redistribution of energy, snow, and liquid water affect patterns of surface-atmosphere CO_2 exchange in the mountains? How does disturbance due to forest fires affect the redistribution of energy, snow and liquid water, and how are these affects coupled to surface-atmosphere CO_2 exchange?

2) Can we integrate fluxes of CO_2 over carbonsheds using local measurements of CO_2 concentration and stable-isotope composition in organized flows of air?

3) What variables (e.g., slope, aspect, elevation, land use/disturbance history, H_2O budget) control the scaling of individual carbonshed fluxes to entire mountain ranges? How do mesoscale air flows (e.g., mountain gravity waves, rotors) affect our ability to scale carbonshed fluxes to entire mountain ranges?

4) Can we test model predictions, which are based on carbonshed studies and extrapolated to regional scales, by comparison to large-scale measurements from aircraft and satellite?

Proposed Measurements and Modeling for an NACP Rocky Mountain Intensive

Recognizing that direct annual measurement of C budgets using atmospheric techniques will be impossible in complex landscapes, we focus on model-data integration, assimilating measurements to calibrate and constrain models, and models to interpolate observations and expand predictive capabilities into novel land-use and climate scenarios. Recognizing also that carbon and water exchange are closely coupled, especially in arid and semi-arid Western U.S. ecosystems, we focus on linking carbon and water measurements. We propose to utilize a multiple constraint approach, combining modifications of standard micrometeorological budgeting techniques with independent measurements of the carbonshed water budget and innovative uses of isotopes to additionally constrain estimates of CO_2 exchange. Finally, we propose to challenge process models with data assimilation at multiple time and space scales, utilizing seasonal to interannual flux measurements, carbonshed scale campaigns to scale up to water/airshed scales (10's of km), and regional (100-1000's of km) airborne measurements. The project's modeling would use a coupled ecosystem-atmosphere model, allowing simulated fluxes to be translated into concentration patterns for comparison to surface and airborne observations. We propose a focus on challenging the model's ability to simulate observations to test whether we have correctly identified the critical processes causing variations in biogeochemical processes in complex landscapes. The goal will be to identify the time-space scales over which extrapolation is valid, and those where the paradigm fails.

Eddy and advective flux measurements. Flux measurements in mountainous terrain are complicated by the fact that drainage flows and accompanying advective flux divergence can preclude an accurate mass balance for scalars of interest. We have already established a multiple-tower, triangulated approach at the existing Niwot Ridge Ameriflux site, with vertical profiling of CO_2 concentration and wind speed at each tower, to quantify advective flux divergence and improve the CO_2 mass balance. Planned for 2004 is the addition of three more towers within the Como Creek carbonshed. As part of an NACP Intensive, similar along-slope temporary tower arrays could be located at the Glacier Lakes Ameriflux site in Wyoming and the USDA Forest Service Experimental Forest near Fraser, Colorado. (All three of these sites have been selected for an NACP Tier 3 Prototype Project.) Use of these sites for an expanded NACP Intensive would provide three dispersed sites within the Rocky Mountain Front Range to provide replication of studies at the local scale and broad geographic representation of studies at the regional scale.

Isotopic measurements. We propose the use of isotopic measurements of CO_2 (^{18}O) as an additional tracer for downslope patterns in the drainage of respired CO_2. The isotopic method is based on a simple idea: respired CO_2 will have a distinctive ^{18}O signature. The ^{18}O of soil respiration is determined by exchange with soil water. The ^{18}O of soil water varies with elevation, and so ^{18}O provides information on both respiration rate and the elevational range within which trapped CO_2 was respired.

Modeling and data analysis. A primary aim of the intensive would be to construct a process-based model of the carbonshed CO_2 balance, incorporating spatially-explicit characteristics of the terrain and its effect on eddy and advective fluxes. Measurements from the tower networks and isotope studies could be used to inform algorithm development and constrain model conditions. By 'feeding' model development from the measurement networks, we would be able to generate predictions of CO_2 fluxes at even larger spatio-temporal scales, which can be validated using aircraft sampling as described below. Within an NACP Intensive, multiple groups with independent process-based models would be able to test model performance within the context of challenging terrain using common data sets. A Mountain Model Comparison could be one lasting initiative to emerge from an NACP Intensive in the Front Range.

As one example of a candidate model to test in an NACP Intensive, we propose to utilize a new regional-scale ecosystem-atmosphere assimilation model RAMDAS (RAMS Data Assimilation System), to analyze surface, sonde, airborne and satellite data (Vukicevic 2000, Vukicevic et al., 2001). The model is based on the CSU mesoscale atmospheric model RAMS, which has been widely and successfully used for high-resolution applications in complex terrain. RAMS has a wide variety of physical parameterization options, has been used to study complex terrain (Walko et al., 1992) and runs using a nested grid approach. RAMDAS includes a land surface model and detailed snow redistribution and melt routines, and is ideally suited to the assimilation of CO_2 data and analysis of wind fields and convection in complex, vegetated landscapes. When run at high resolution, RAMDAS could produce optimized analyses of CO_2 flux, advection and mass transport during the field campaigns.

Regional extrapolation and aircraft measurements. As part of an NACP Intensive, we propose aircraft sampling during 2006-2007, building on the studies that are already planned for May and June 2004. The studies in 2004 will provide a good foundation of data and experience that can be used to ensure refined sampling in 2006-2007. For airborne sampling, we propose flights to measure concentration and ^{13}C and ^{18}O in CO_2 at low altitude (1000' agl) in the early morning. The measurements would be targeted at measuring regional variation in carbon content and venting of the nocturnal boundary layer, as a constraint on respiration (and modeled mixing). The flights would cover contrasting land surface types and different slopes and aspects. We would not try to budget respiration fluxes of CO_2 directly from these flights but rather would test modeling of concentrations and biophysical processes. Isotopic measurements would provide markers of respired and tropospheric CO_2, while CO measurements would serve as a pollution tracer. A second mission strategy could employ airborne eddy covariance to measure CO_2 fluxes over contrasting landscape types nearer mid-day when uptake is maximal. Together, these flights would allow the testing of whether CO_2 fluxes can be successfully estimated over different forest types. The third type of mission would measure vertical profiles on the upwind and downwind sides of the domain in a Lagrangian, air-mass following approach. This experiment would have very different goals. The first objective will be to estimate the characteristics and variability of air entering the domain. While the Front Range region is downwind of a large area of low population density and low biological activity, there are a few significant powerplants (Hayden CO), smaller cities (Grand Junction, CO) and biologically productive ranges (eg., Zirkel Mtns). Since our modeling system makes assumptions about the incoming concentrations, these data will be crucial for setting a stochastic noise contribution in initial conditions. Second, we could use this type of mission to generate data for regional-scale surface flux estimates using advanced modeling approaches and data assimilation. Third, complex meteorological phenomena will affect CO_2 profiles over the mountains. Processes such as mountain waves, rotors and thunderstorms will transport the signals of surface exchange to high altitude and far downfield. Measurements of vertical profiles over the mountains and downwind will be useful for understanding the characteristics of surface-exchanged scalars (CO_2, H_2O) over the mountains, as a test of modeled transport and mixing in the montane regime, and for the design of eventual airborne and possible remote sensing techniques in complex terrain.

Conclusions

Accurate budgeting of terrestrial CO_2 fluxes requires the development of new measurement and data assimilation approaches that can be applied to ecosystems in complex terrain. Taking the US as a whole, we estimate that 25-50% of the carbon sink occurs in montane ecosystems; in the western US, this estimate increases to 75%. An NACP measurement campaign in the Rocky Mountains, which combines ground-based and airborne measurements with advanced modeling and data assimilation techniques, can be used as a prototype to develop new carbon budgeting procedures and gain greater insight into the magnitude and dynamics of carbon uptake in ecosystems of complex terrain.

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