

Carbon Sequestration Studied in Western U.S. Mountains

The U.S. carbon budget has been the focus of recent scientific debate [Fan *et al.*, 1998; Pacala *et al.*, 2001; Gurney *et al.*, 2002]. Even conservative estimates suggest that U.S.

ecosystems take up a significant amount of carbon, largely as a result of historical land use practices [Houghton *et al.*, 1999; Schimel *et al.*, 2000; Pacala *et al.*, 2001]. In the western United States, a key cause of carbon sequestration is fire suppression. Fire suppression, of course, also sets the stage for the catastrophic losses that are occurring during fire season 2002. Increases in fire due to the effects of fire suppression, increased prescribed burning and thinning, and climate change could significantly affect the national carbon budget. At the continental scale, a comprehensive research approach—the North American Carbon Program (NACP)—is planned to quantify carbon exchange and improve our understanding of the contributing processes [Wofsy and Harriss, 2002].

The program relies heavily on atmospheric measurements from ground-based eddy correlation towers, concentration networks, and airborne sampling to quantify carbon fluxes. It is complemented by remote sensing, process studies, and operational inventories [Wofsy and Harriss, 2002]. However, significant fractions of both U.S. carbon sequestration and wildfire losses are likely to be in the western United States, where complex and mountainous terrain prevents the use of existing atmospheric measurement techniques.

To achieve the goals of the NACP in mountain landscapes, meteorological, hydrological and biogeochemical approaches must be tightly integrated. Quantifying carbon sequestration in the mountains requires extensive model-data integration, measurements to calibrate and constrain models, and models to interpolate observations. Foreseeable measurement approaches will allow the development of accurately calibrated models and algorithms for extrapolating carbon fluxes over complex terrain. As we develop confidence in simulated carbon budgets of mountain ecosystems, we will be able to explore issues such as the effects of climate on fire frequency and behavior and subsequent regrowth and sequestration, along with effects of pest outbreaks, timber harvesting, and other management activities. In addition, the effects of current and future wildfire management must be considered in estimating the U.S. carbon budget.

Mountain environments have rarely been addressed specifically in studies of terrestrial

carbon. The International Geosphere-Biosphere Programme (IGBP) report on mountain ecosystems makes no mention of a key role for mountainous regions in the Earth's carbon cycle [Becker and Bugmann, 2001]. Although it has been suggested that the U.S. sink is localized in eastern U.S. forests [Fan *et al.*, 1998], recent studies partitioning the U.S. sink into regions suggest that a significant fraction is in the mountains of the western United States [Schimel *et al.*, 2000; Pacala *et al.*, 2001].

In the semi-arid western United States, a large fraction of the carbon exchange occurs in complex terrain and montane environments, where historical harvest and fire management regimes have favored net carbon accumulation. Most low elevation areas are dry and dominated by low-carbon density ecosystems. Imperatives to preserve forests for watershed management, natural area preservation, and hill slope stabilization actually make mountainous regions a good prospect for long-term carbon sequestration, emphasizing the need for a solid scientific understanding of mountain biogeochemistry.

The NACP plan identifies the need for measurements in complex terrain, but the current plan calls for sparse coverage of the montane west [Wofsy and Harriss [2002]; Figure A1.1]. The plan states that "at least one third of North America is topographically too complex for eddy flux measurements and gaps will have to be filled..." using indirect techniques including remote sensing and modeling. Given that these regions account for 25%, or possibly much more of national carbon uptake, new measurement techniques to calibrate and validate models and algorithms in complex terrain must be developed.

Background on Mountain Ecosystems

Many western U.S. mountain regions are covered by forests, which are, for the most part, recovering from historical harvesting and experiencing active fire suppression [Tilman *et al.*, 2000]. Pacala *et al.* [2001] estimate significant sinks as a result of fire suppression in mountainous western pine forests. Schimel *et al.* [2000] also showed significant sinks in mountain biomes. In dry years, the western U.S. mountain ranges are also the focus of severe wildfire losses of carbon.

Wildfire suppression has had a significant effect on carbon sequestration in western U.S. forests. The fire regime prior to European settle-

ment of the western United States was dominated by frequent, low-intensity fires and sporadic, stand-replacing fires [Pyne, 1982]. These fires occurred mainly in dry seasons and were due to lightning strikes and the land management practices of the indigenous people. As a result of ground fires, forests were broadly maintained in healthy, but relatively low carbon states [Tilman *et al.*, 2000]. Current fire suppression efforts have reduced the average annual area burned to 10–15% of the pre-settlement levels [Pyne, 1982; Tilman *et al.*, 2000]. Incorporation of fire suppression activity into models suggests massive consequences for carbon storage in western landscapes [Houghton *et al.*, 1999; Pacala *et al.*, 2001]. In the most comprehensive effort to date to reconstruct national carbon budgets, Pacala *et al.* [2000] concluded that about one-quarter of U.S. carbon uptake (0.12 Gt C year) could be due to fire suppression in western coniferous forests.

Fire suppression is not the only mechanism responsible for carbon uptake in mountain environments. In the United States and Europe, as recreational, watershed, and other non-consumptive land uses have increased in the mountains, forest harvest and pasture maintenance practices have decreased. In Europe, the abandonment of high pastures that were formerly used for livestock husbandry has led to significant expansion of high and mid-elevation forests, creating significant carbon sinks. In temperate Asia, where large populations impose a high demand for agricultural land, remaining forests are largely in mountainous areas.

Modeling and Remote Sensing of Mountain Biogeochemistry

We used the Biome-BioGeochemical Cycles (Biome-BGC) and Century biogeochemistry models to explore potential carbon uptake patterns in the United States (Figure 1). The results are drawn from the Vegetation and Ecosystem Modeling and Analysis Project (VEMAP) [Schimel *et al.*, 2000]. These model experiments were driven by historical climate, reconstructed from 1895 to 1993 using over 8000 long- and short-term weather stations, as well as about 700 high-elevation stations from the SNOTEL (SNOpack TElemetry) network. Short-term stations were linked geostatistically to long-term stations to create a complete pseudo-network of 98-year-long records, which were then gridded to obtain a spatially distributed climate record. In the gridding procedure, temperature and precipitation were corrected for elevation, aspect, and mountain valley inversions.

The ecosystem models were initialized and then run from 1895 to 1993. The models also included the effect of increasing atmospheric

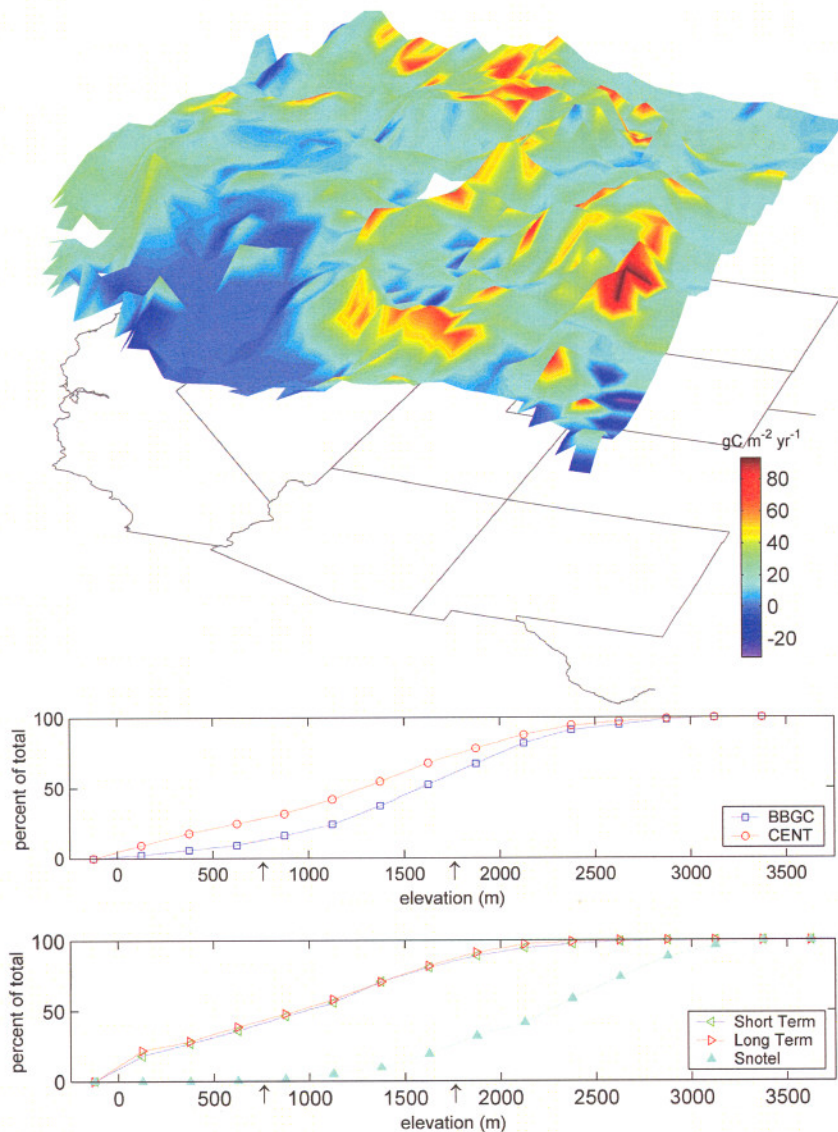


Fig. 1. (top) Mapped net ecosystem exchange in the western United States, draped over topography (1980–1989 simulations, Schimel et al. [2000]), is mainly in the mountains (see draped map of modeled NEE (Biome-BGC)). (bottom) Models agree on the basic distribution with elevation (upper line graph) with about 75% in complex, high-elevation topography. Arrows indicate approximately 50% and 85% complex terrain at 750 m and 1750 m elevation, respectively. A flat high elevation flux site would only represent 15% of the topographic landscape. Meteorological stations for the western United States (lower line graph) used in the VEMAP data sets are shown plotted against elevation. Note that long-term data (10 years of record +) are sparse in the elevations of maximum NEE, and only SNOTEL sites provide high-elevation coverage.

CO₂. Vegetation definitions were fixed and based on remote sensing. Agriculture was modeled using Century in 18 crop-management combinations based on U.S. Department of Agriculture county-level information [Schimel et al., 2000]. Century agricultural results were blended on an area coverage basis into both the Century and Biome BGC results. The VEMAP results have been independently compared to observations for validation and agree reasonably well with data.

Our results show that 70% of the western U.S. carbon sink occurs at elevations above 750 m, an elevation range in which 50–85% of land is dominated by hilly or mountainous

topography (Figure 1). The pattern is striking in the semi-arid western United States, in which most low-elevation ecosystems are dry and dominated by biomes with low carbon density (Figure 1); foci of high carbon uptake are found in the Sierra Nevada and Rocky Mountains. Modeled fluxes in the Pacific northwest and California are depressed for this decade because of drought, but they are high during most decades.

Despite the impression of vast wilderness areas, most western forests have been logged since the mining era. Industrial harvesting for construction and fuel wood began after the early period of forest utilization and continues to this day [Veblen and Lorenz, 1991]. Current

estimates suggest that only 1–10% of western forests are undisturbed. As a result of this, most western forest stands are relatively young—less than 100 years old. The VEMAP spatial pattern is at least qualitatively correct, but these simulations were run without detailed disturbance and management regimes.

Remote sensing provides wall-to-wall coverage of ecosystems but does not provide direct estimates of net ecosystem exchange (NEE), a measure of the net exchange of carbon between ecosystems and the atmosphere. However, the MODerate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's TERRA and AQUA platforms provides regular estimates of gross primary productivity (GPP). MODIS radiances form the basis for estimating GPP, together with climate and other ancillary data; GPP, the gross flux of carbon into the biosphere via photosynthesis, provides a check on model simulations (Figure 2). While GPP and NEE are not always linked, flux measurements generally show GPP and NEE to be related in recently (~100 years) disturbed ecosystems, such as those that dominate western landscapes. Figure 2 shows a pattern of GPP corresponding clearly to modeled NEE (Figure 1).

Improved MODIS GPP and eventual NEE estimates for mountain regions will require more refined measurements of mountain weather and improved correction of satellite reflectances for complex terrain, along with land use histories.

Preliminary Flux Measurements in the Mountains

Testing models and satellite measurements requires rigorous calibration data sets in the mountains. Initial measurements of NEE, GPP, and ecosystem respiration dynamics have been established in an aggrading sub-alpine forest in the Rocky Mountains of Colorado [Turnipseed et al., 2002]. The Niwot Ridge Ameriflux site is locally level, with a 5–6° slope, to accommodate traditional micrometeorological techniques (Figure 3). The site is located at 3050 m elevation and consists of three towers; two are used to make continuous eddy correlation measurements of CO₂ and H₂O fluxes, and wind and scalar concentrations are measured on all three. Prevailing winds are from the west, with fetch consisting of spruce-fir forest for 1.5 km. Continuous flux measurements are in the fourth year of data collection. A description of the site and the data is available at <http://spot.colorado.edu/~monsonr/Ameriflux.html>.

The mountainous terrain at the Niwot Ridge Ameriflux site would deter most micrometeorological purists from attempting flux measurements. To assess the impact of non-ideal conditions, we examined the influence of horizontal mean and turbulent fluxes, which are often assumed to be negligible on flat terrain, non-zero mean vertical fluxes due to divergence in the face of vertical concentration gradients, the forcing of horizontal winds across sloping terrain, and mesoscale influences on flux

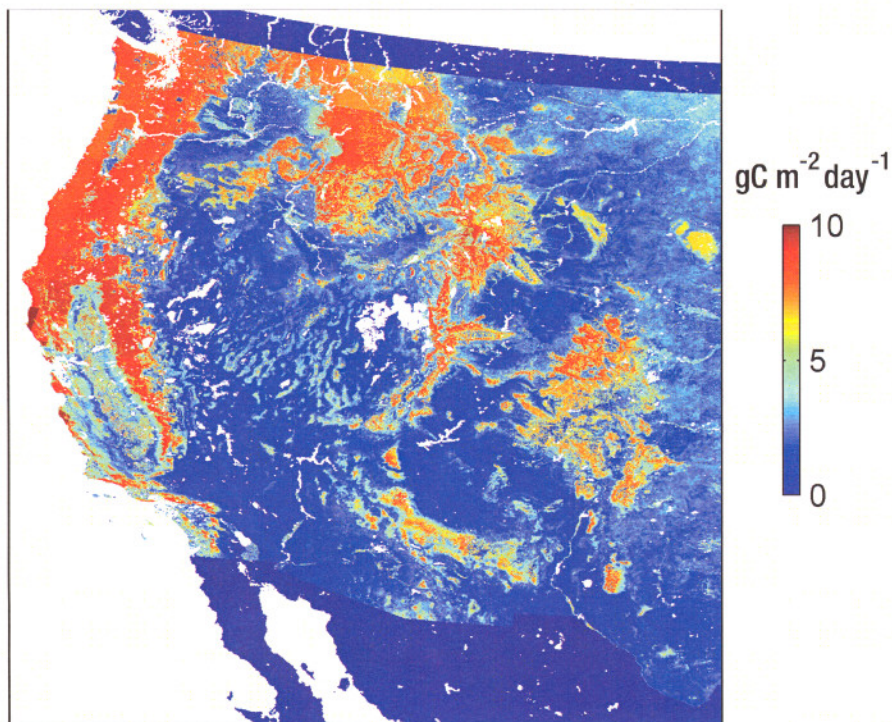


Fig. 2. Mapped gross primary productivity (GPP) for peak growing season 2001 is shown, as estimated from the MODIS instrument aboard the NASA TERRA satellite, with ancillary data on ecosystem type and meteorology. The results clearly show the dominance of high-elevation areas in photosynthetic uptake. Units are $\text{g m}^{-2} \text{day}^{-1}$.

measurements. Based on these data, the situation may be better than initially supposed.

One key test is balancing the energy budget. Two years of flux measurements show that turbulent fluxes of sensible and latent heat at Niwot Ridge account for 84% of the available energy during the summer and 88% during the winter. At high friction velocities $> 1.5 \text{ m s}^{-1}$, the energy budget was closed. When the wind came from the east, over 300 m of consistent terrain, we observed 80–90% closure of the energy budget, not substantially different from studies on near-ideal terrain. This bodes well for future flux studies in mountainous terrain. It is likely that the high level of closure for fluxes involving the eastern fetch is helped by the tendency for greater buoyancy, associated stronger updrafts, and the rough surface of coniferous forest canopies, all of which help shrink the footprint of the flux measurements and relax the uniformity and distance requirements for fetch.

Meso-scale phenomena such as rotors can affect turbulent flux estimates. Rotors are regional wind rotations that occur when high-speed westerlies blow over the continental divide in the presence of a well-defined upper stable layer 8–18% of the time during winter. When west winds are compressed between a stable layer and the surface, they spread out and form a rotor-type wake on the eastern side of the Continental Divide. During a rotor, the wind speed and friction velocity at the surface drop dramatically and σ_z/u^* (the ratio of the standard deviation of vertical wind speed to the friction velocity) increases significantly. We have not observed rotors during the summer.

Mountain ecosystems exhibit high rates of nighttime radiational cooling that lead to strong inversions and cold air drainage, or gravitational flows, that cause downslope flows at night. Horizontal, nighttime CO_2 concentration differences of 10 ppmv were frequently measured across the 150 m distance between towers. Significant advective fluxes of CO_2 can occur beneath the eddy flux sensors located at the top of the towers. Also measured were nighttime advective fluxes during the summer of 2001 calculated from the product of mean horizontal wind speed and mean CO_2 concentration between an upslope tower and a downslope tower. The difference in CO_2 concentration is due to the accumulation of CO_2 , largely from soil respiration, at the downslope tower in the drainage flow.

Average advective fluxes for the night were $5\text{--}10 \mu\text{mol m}^{-2} \text{s}^{-1}$; compared to daytime NEE of $7\text{--}12 \mu\text{mol m}^{-2} \text{s}^{-1}$ and nighttime respiratory fluxes of $2\text{--}6 \mu\text{mol m}^{-2} \text{s}^{-1}$. For nights with consistent drainage flows, maximum advective flux values occurred within 2–4 hours of onset of the flow and diminished through the remainder of the night. The reductions in advective flux occurred despite increases in the velocity of drainage flow as the night progressed. The decrease in advective flux reflects a decrease in soil respiration rate through the night, perhaps due to a decrease in soil temperature. We observed distinct seasonality in respiration, perhaps reflecting variations in soil temperature and moisture.

The Niwot Ridge results, while still uncertain in terms of carbon budgets for the site, provide hope that the complexities and

uncertainties associated with flux measurements in mountainous terrain can be resolved through careful experimental design and intensive analysis. Gently sloping terrain such as that represented by the Niwot Ridge site reflects no more than 15–50% of the western U.S. mountain landscape, with the proportion dropping with increasing elevation. Extension of studies like the Niwot Ridge observations into steeper, more complex terrain is crucial.

Stepping off the Micrometeorological Cliff: Future Flux Studies

Carbon flux measurements can be made in the mountains by adapting micrometeorological techniques to the unique conditions of steep terrain. Organized flows of air and water in sloping terrain provide measurement opportunities that are absent in level terrain. Given the importance of mountain carbon fluxes to regional and national inventories, these efforts are strongly justified. Nighttime advective CO_2 fluxes may be ideal for quantifying soil respiration rates. We propose the concept of “mountain carbonsheds,” which are analogous to “mountain watersheds” in that they are thin sheets of cold air draining off the mountains that carry respired CO_2 downslope, where it accumulates at points of low relief.

By characterizing carbonshed dynamics, we will gain unique insight into respiration. Within watersheds, carbon and water cycles are tightly coupled. At the Niwot Ridge Ameriflux site, early-season ecosystem CO_2 uptake rates—which account for 30–40% of the total growing season carbon uptake—are tightly coupled to soil moisture derived from the springtime snowpack. Wintertime ecosystem respiration, which accounts for carbon losses that total 50–60% of the growing season carbon gain, is sensitive to snowpack depth and its influence on soil temperature; this provides a link between the ecosystem carbon cycle and wintertime hydrology. Well-measured local snowpack and watershed H_2O fluxes, when used with carbon-water stoichiometry, provide independent constraints on CO_2 fluxes.

Using the tight coupling between hydrology and carbon exchange, it may be possible to characterize mountain carbon exchange dynamics from water budgets on a regional basis. By combining watershed and carbonshed measurements and a systems approach to carbon-water coupling, we may come to understand carbon fluxes in the mountains as well as or even better than carbon fluxes in level terrain. Carbonshed/watershed studies are needed to provide the basis for accurate models and remote sensing algorithms that can be used to address the goals of the NACP for the non-level parts of the United States.

Acknowledgments

The authors' work is supported by the Wildland Fire Collaboratory of the National Center for Atmospheric Research (NCAR), the NASA Earth Observing System program, the U.S. Department of Energy (DOE) and the DOE National Institute for Global Environmental

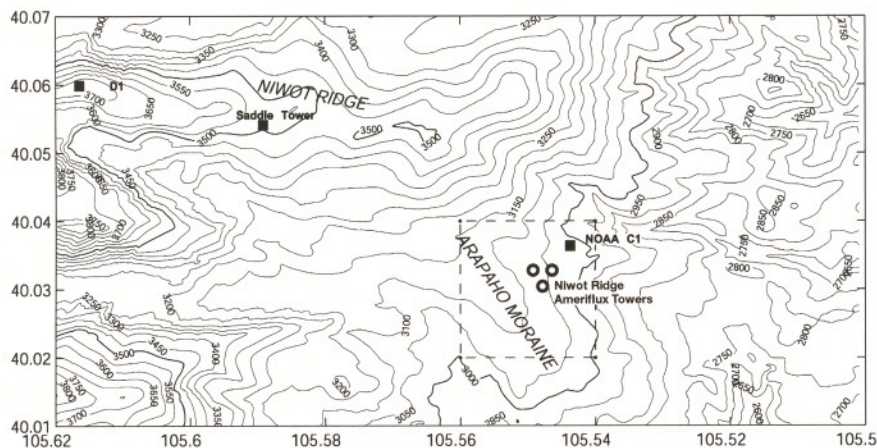


Fig. 3. The topography and tower arrangement for the Niwot Ridge flux study are shown with the placement of the tower array relative to the terrain. Prevailing winds come from the west and east. In addition to these towers, ecological, hydrological, and meteorological studies are also made at this site. Ongoing studies are using carbonshed techniques to quantify respiration and to compare carbonshed estimates to traditional techniques.

Change Program, the U.S. National Science Foundation, the Electric Power Research Institute, and the U.S. Geological Survey. NCAR is sponsored by the National Science Foundation.

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