Mountains, Fire, Fire Suppression, and the Carbon Cycle in the Western United States[1]

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Most mountain regions in the western United States are covered by forests, which are for the most part recovering from historical harvesting and have been experiencing active fire suppression over approximately the past 100 years (Tilman and others 2000). Whereas many western landscapes are currently perceived as pristine natural systems, the Rockies, Sierra Nevada, and Cascades were essentially deforested between 1860 and the end of the 20th century, during the era of mining, railroad building, and settlement. Currently, the fraction of old-growth forest remaining in the West is variously estimated at 5 to 15 percent; however, these numbers must be interpreted with caution. In some regions, high-elevation forests of limited current economic value are excluded from the analysis. In other cases, young, naturally disturbed stands are included in the disturbed category, even in forests with normally short disturbance cycles. Forest harvest has generally occurred preferentially in areas of relatively high productivity and standing biomass, so much of the regrowth is occurring in regions with relatively high carbon accumulation potential. Also, in some areas of active fire suppression adjacent to urban corridors, particularly at lower elevations with relatively productive conditions of soil, moisture and light, forests are becoming denser. Although the proportion of total forest land is probably higher than that quoted (taking into account regional variation, high-elevation forests), it remains that a very considerable fraction of the more productive forest lands have experienced some degree of historical disturbance.

Fire exclusion tends to increase carbon accumulation in soils and dead plant material. Since the initial harvesting of Western forests, fire suppression has been actively and for the most part successfully implemented. The average annual area burned in the Sierra Nevada in the 1990s was approximately 15 percent of the area burned annually in the pre-settlement period. Fire suppression does not favor healthy long-term carbon storage in large mature trees, but it does create ecosystems with large quantities of carbon stored in litter, dead wood, and small trees. Thus, the carbon budget of the western United States and the health of Western forests are best understood in terms of:

- climate, with favorable water balance permitting productivity at higher elevations;
- historical land use, with past forest disturbance setting the stage for widespread forest regrowth, especially in the more productive areas; and
- current land use, with fire suppression favoring high carbon storage but creating at-risk ecosystems.

Wildfire suppression in regrowing stands is thought to have a significant effect on carbon sequestration in western U.S. forests. Pacala and others (2001) estimate significant sinks as a

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result of fire suppression in Western pine forests. Schimel and others (2000) also showed significant sinks in mountain biomes. The fire regime before the European settlement 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 because of lightning strikes and land management practices of the indigenous peoples. As a result of ground fires, forests were broadly maintained in healthy, but relatively low-carbon states (Tilman and others 2000). Current fire-suppression efforts have reduced the annual area burned to 10 to 15 percent of pre-settlement levels (Pyne 1982, Tilman and others 2000). Incorporation of fire-suppression activity into predictive models suggests massive consequences for carbon storage in Western landscapes (Houghton and others 1999, Pacala and others 2000). In the most comprehensive effort to date to reconstruct national carbon budgets, Pacala and others (2000) concluded that about 25 percent of annual U.S. carbon uptake (0.12 gigatons of carbon per year) could be due to fire suppression in Western coniferous forests.

Fire suppression is not the only factor responsible for carbon uptake in mountain environments. In the United States and Europe, as recreational, watershed, and other nonconsumptive land uses have increased in the mountains, forest harvest and pasture maintenance practices have decreased. In Europe, the abandonment of high pastures, formerly used for livestock husbandry, is allowing 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. The largest global sink of carbon is found in the mid-latitudes of the Northern Hemisphere, and much of this sink is located in mountainous or hilly terrain *(fig. 1)*.

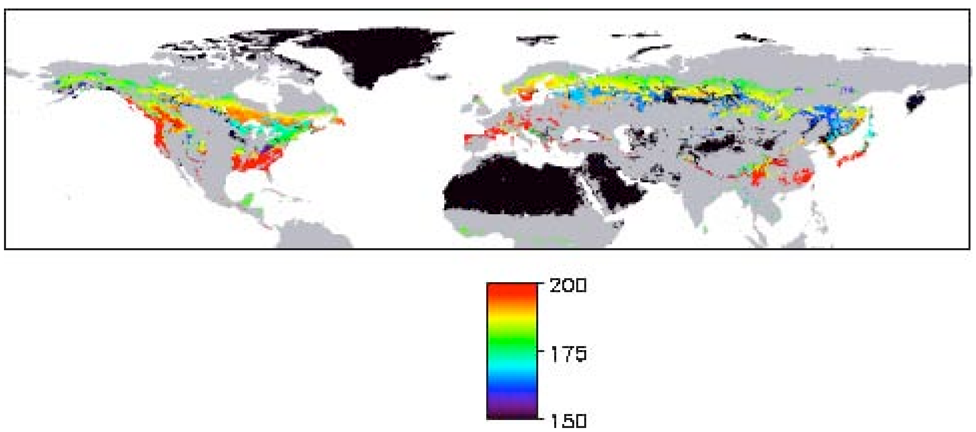

Figure 1— Regions of high carbon storage for the Northern Hemisphere, indicating that in Europe, North America, and China most of the mid-latitude "hot spots" are in mountain ranges. Exceptions to this are found in the boreal (which contributed relatively little globally to carbon uptake) and in parts of the southeastern United States.

The carbon budget of the United States has been the focus of recent scientific debate (Fan and others 1999, Pacala and others 2001). Most researchers suggest that U.S. ecosystems take up a large amount of carbon (Houghton and others 1999, Pacala and others 2001, Schimel and others 2000). Substantial research is being planned to quantify carbon uptake and understand the processes and mechanisms (Wofsy and Harris 2002). The strategy relies on atmospheric measurements from ground-based micrometeorological techniques, concentration networks and airborne sampling to quantify carbon fluxes, complemented by remote sensing, process studies, and operational inventories (Wofsy and Harris 2002). However, because a significant fraction of U.S. carbon uptake is in complex and mountainous terrain, existing atmospheric measurement techniques cannot be used directly. To achieve the goals of the North American Carbon Program in mountain landscapes, meteorological, hydrological, and biogeochemical approaches must be tightly integrated.

Quantifying carbon sequestration in the mountains will require extensive model-data integration: using measurements to calibrate and constrain models and using models to interpolate observations. Effective 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 variability and change, fire management alternatives, pest outbreaks, and timber harvesting on carbon sequestration.

Mountain environments have rarely been addressed specifically in studies of terrestrial carbon dynamics. The International Geosphere Biosphere Program 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 was first suggested that the U.S. sink was localized in eastern U.S. forests (Fan and others 1998), more recent studies that partition the U.S. sink into specific regions suggest that a significant fraction is in the western United States (Pacala and others 2001, Schimel and others 2000).

In the semi-arid western United States, a large fraction of the carbon uptake occurs in complex terrain and montane environments. Most low-elevation areas are dry and dominated by low-carbon density ecosystems, and historical harvest and fire management regimes favor net carbon accumulation in today's Western mountains. Imperatives to preserve forests for watershed management, natural area preservation, and hillslope stabilization actually make mountainous regions a good prospect for long-term carbon sequestration, emphasizing the need for a solid scientific understanding of mountain biogeochemistry. However, our ability to measure carbon exchange is currently limited in the mountains.

Modeling and Remote Sensing of Mountain Biogeochemistry

Using Biome-BGC and Century biogeochemistry models, we explored potential carbon uptake patterns in the United States *(fig. 2).* The results are drawn from the Vegetation and Ecosystem Modeling and Analysis Project (VEMAP) (Schimel and others 2000). These model experiments were driven by historical climate, reconstructed from 1895 to 1993 using more than 8000 long- and short-term weather stations, as well as about 700 high-elevation stations from the SNOTEL 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 statistically corrected for elevation, aspect, and mountain valley inversions. The ecosystem models were "spun up" and then run from 1895 to 1993. The models also included the effect of increasing atmospheric carbon dioxide. Vegetation definitions were fixed and based on reconstructed actual vegetation. Agriculture was treated explicitly, using USDA county-level information (Schimel and others 2000) and 18 crop-management combinations simulated using Century. 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 indicate that 70 percent of the Western U.S. carbon sink occurs at elevations above 750 meters *(fig. 2),* an elevation range dominated by hilly or mountainous topography (50 to 85 percent complex terrain: *fig. 2).* This comprises 20 to 40 percent of total uptake for the lower 48 states. 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 *(fig. 2);* foci of high carbon uptake are found in the Sierra Nevada and Rocky Mountains.

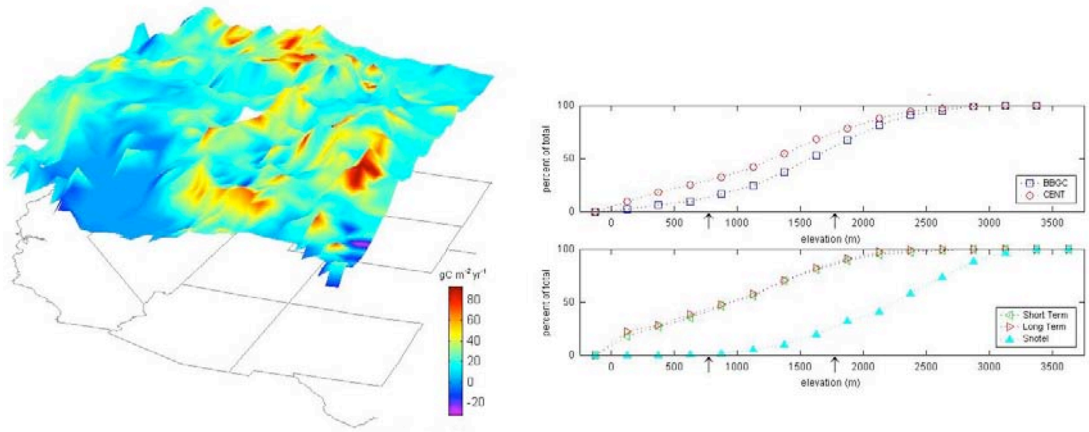

Figure 2— *Left:* Mapped net ecosystem exchange in the western United States, draped over topography (1980–1989 simulations: Schimel and others 2000) is mainly in the mountains (see draped map of modeled Net Ecosystem Exchange [NEE] Biome-BGC). Fluxes in the Pacific Northwest and California are depressed for this decade because of drought. *Right:* Models agree on the basic distribution with elevation (upper line graph) with 75 percent in complex high-elevation topography. Arrows indicate approximately 50 and 85 percent complex terrain at 750- and 1750-m elevations, respectively. A flat high-elevation flux site would represent only 15 percent of the topographic landscape. Meteorological data (lower line graph) used in developing the VEMAP data sets are shown plotted against elevation. Note that data from long-term (10+ years of records) are sparse in the elevations of maximum NEE, and only a small number of SNOWTEL (approximately 700) sites provide high-elevation coverage.

The VEMAP results are probably at least qualitatively correct. These simulations were run without detailed disturbance and management regimes, however. The Western mountains have been intensively managed over the past century. Despite the impression visitors receive of vast wilderness areas, most of the mid- and low-elevation montane forests have been logged or otherwise disturbed, beginning in the pioneer mining era with intensive harvesting during the railroad era. After the early period of forest utilization for construction and fuelwood, industrial harvesting began and continues to this day (Veblen and Lorenz 1991). In the VEMAP simulation illustrated, only a very simple land use and natural disturbance history was applied, consistent with broad-scale statistics but likely wrong in many details. Model results thus do not take into account all of the factors acting to modify spatial patterns of carbon exchange in the western United States.

Remote sensing provides wall-to-wall coverage of ecosystems but does not provide direct estimates of NEE, a measure of the net exchange of carbon between ecosystems and the atmosphere. However, a new operational satellite product provides regular estimates of fractional intercepted photosynthetically active radiation (FPAR) from the MODerate Resolution Imaging Spectroradiometer instrument on NASA's TERRA and AQUA spacecraft. FPAR has been shown to be highly correlated with Gross Primary Productivity (GPP), the gross flux of carbon into the biosphere via photosynthesis and Net Primary Productivity (NPP), the balance of carbon uptake and respiration in vegetation and provides an additional check on our model simulations. The GPP image from MODIS *(fig. 3)* shows a pattern clearly corresponding to the model results shown in *figure 3* and supports the argument that most highly productive and high-carbon–storage potential systems in the western United States are in montane forests and complex topography. High rates of GPP can support significant amounts of carbon storage although much of the annual GPP is respired or burned each year.

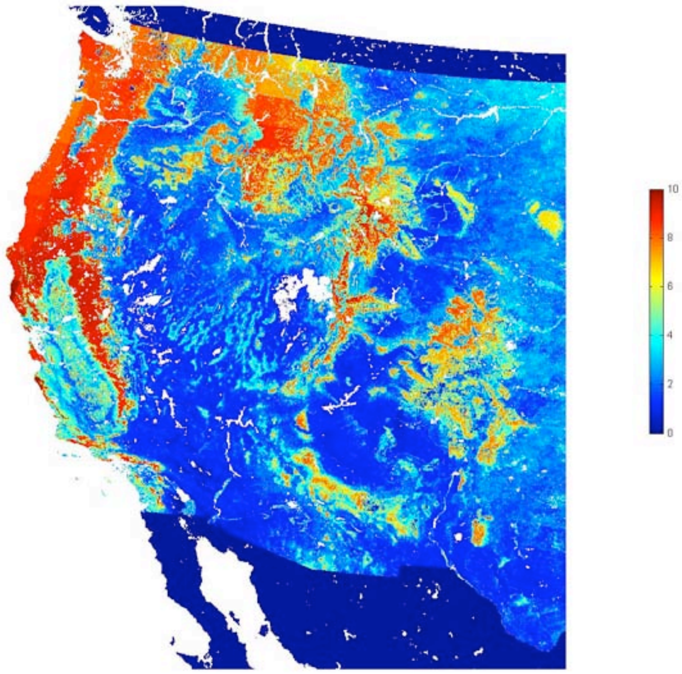

Figure 3— Mapped GPP for the United States, from the MODIS instrument aboard the NASA TERRA satellite for growing season 2001.

Conclusions

Mountains are important contributors to carbon uptake in the Western United States as a result of their unique climate within a semi-arid to arid region and historic and current management emphasis on fire suppression.

Fire management strategies must reflect a balance between hazard management, long-term risk management, and preservation of forest health. Any changes to fire regime or fire management practices are likely to have widespread impacts on forest ecosystem function, affecting carbon storage and tightly linked water resources.

Whereas fire suppression has probably led to a larger carbon sink in the West, much of this sink is present in the fine and coarse fuel categories (dead plant material) or in dense stands of small trees and thus contributes to increased wildfire risk in drought years. Improved carbon management must consider both the amount of carbon stored and the stability of that storage as climate and fire regimes evolve.

Carbon storage in the mountains is largely fed by snowpack moisture, and improved understanding of snowpack and high-elevation water dynamics will be important for forecasting anticipated future ecological conditions in montane forests.

References

Becker, A.; Bugmann, H., editors. 1997. **Predicting global change impacts on mountain hydrology and ecology: Integrated catchment hydrology/altitudinal gradient studies.** IGBP Report No. 43. Stockholm, Sweden.

Fan, S.; Gloor, M.; Mahlman, J.; Pacala, S.; Sarmiento, J.; Takahashi, T.; Tans, P. 1998. **A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models.** Science 282: 442-446.

Gurney, K.R.; Law, R.M.; Denning, A.S.; Rayner, P.J.; Baker, D.; Bousquet, P.; Bruhwiler, L.; Chen, Y.H.; Ciais, P.; Fan, S.; Fung, I.Y.; Gloor, M.; Heimann, M.; Higuchi, K.; John, J.; Maki, T.; Maksyutov, S.; Masarie, K.; Peylin, P.; Prather, M.; Pak, B.C.; Randerson, J.; Sarmiento, J.; Taguchi, S.; Takahashi, T.; Yuen, C. W. 2002. **Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models.** Nature 415: 626-630.

Pacala, S.W.; Hurtt, G.C.; Baker, D.; Peylin, P.; Houghton, R.A.; Birdsey, R.A.; Heath, L.; Sundquist, E.T.; Stallard, R.F.; Ciais, P.; Moorcroft, P.; Caspersen, J.P.; Shevliakova, E,; Moore, B.; Kohlmaier, G.; Holland, E.; Gloor, M.; Harmon, M.E.; Fan. S.M.; Sarmiento, J.L.; Goodale, C.L.; Schimel, D.; Field, C.B. 2001. **Consistent land- and atmosphere-based U.S. carbon sink estimates.** Science 292: 2316-2320.

Pyne, S. 1982. **Fire in America**: **A cultural history of wildland and rural fire.** Seattle, WA: University of Washington Press; 630 p.

Schimel, D.; Melillo, J.; Tian, H.Q.; McGuire, A.D.; Kicklighter, D.; Kittel, T.; Rosenbloom, N.; Running, S.; Thornton, P.; Ojima, D.; Parton, W.; Kelly, R.; Sykes, M.; Neilson, R.; Rizzo, B. 2000. **Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States.** Science 287: 2004-2006.

Tilman, D.; Reich, P.; Phillips, H.; Menton, M.; Patel, A.; Vos, E.; Peterson, D.; Knops, J. 2000. **Fire suppression and ecosystem carbon storage.** Ecology 81: 2680-2685.

Turnipseed, A.A.; Blanken, P.D.; Anderson, D.E.; Monson, R.K. 2002. **Energy budget above a high-elevation subalpine forest in complex topography.** Agricultural and Forest Meteorology 110: 177-201.

Veblen, T.T.; Lorenz, D.C. 1991. **The Colorado Front Range: A century of ecological change.** Salt Lake City: University of Utah Press; 186 p.

Wofsy, S.C.; Harris, R., editors. 2002. **The North American Carbon Program.** UCAR, Boulder, CO: UCAR; 56 p.