ENSO variations change the basic state wind fields over the Atlantic at interannual time scales, altering environmental conditions that may affect hurricane formation. This relationship offers some accuracy in predicting the number of hurricanes that may occur in a given year. Variations of tropical winds and precipitation on intraseasonal time scales associated with the MJO (*13, 19*) are at least as large as the interannual variations associated with ENSO, and they may offer the possibility of predicting which periods during the hurricane season are most likely to produce hurricanes. The slow evolution of the MJO may be forecast up to 2 weeks or more into the future (*27*). An accurate MJO forecast, combined with knowledge of how the MJO affects Gulf of Mexico and Caribbean hurricanes, can be used to improve extended-range forecasts of tropical cyclone activity. The tendency of tropical cyclones over the Gulf of Mexico and Caribbean to cluster in time (*28*) may be explained at least in part by the interactions with the MJO described here.

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15. The first PC has a zero-lag correlation of −0.6 with an MJO index in a previous study (*29*) that is dominated by western Pacific and Indian Ocean zonal wind variability.
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Contribution of Increasing CO_2 and Climate to Carbon Storage by Ecosystems in the United States

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The effects of increasing carbon dioxide (CO_2) and climate on net carbon storage in terrestrial ecosystems of the conterminous United States for the period 1895–1993 were modeled with new, detailed historical climate information. For the period 1980–1993, results from an ensemble of three models agree within 25%, simulating a land carbon sink from CO_2 and climate effects of 0.08 gigaton of carbon per year. The best estimates of the total sink from inventory data are about three times larger, suggesting that processes such as regrowth on abandoned agricultural land or in forests harvested before 1980 have effects as large as or larger than the direct effects of CO_2 and climate. The modeled sink varies by about 100% from year to year as a result of climate variability.

Recent analyses of the global carbon cycle suggest a significant role for terrestrial uptake of CO_2 in the overall budget (*1–4*). Analyses of atmospheric CO_2 have persistently suggested that this terrestrial uptake is largest in the Northern Hemisphere (*2, 3*), and one atmospheric analysis suggests that the United States may play a disproportionate role (*2*). Currently, a number of phenomena contribute to enhanced carbon uptake by ecosystems, including CO_2 fertilization of photosynthesis, climate, nitrogen deposition, recovery from historical land use, and erosion/sedimentation (*4–6*). Although preliminary attempts have been made to partition the terrestrial sink among these processes globally, this quantification is currently extremely crude. It is essential to understand the mechanisms controlling carbon exchange today as a basis for prediction and management interventions (*7*).

Here we present results from the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) aimed at understanding the contribution of ecosystem physiological mechanisms to terrestrial sinks in the conterminous United States during the period 1980–1993. Specifically, we consider how changes in climate and CO_2 concentration affect ecosystem physiology. Three ecosystem models [Biome-BioGeochemical Cycles (Biome-BGC), Century, and the Terrestrial Ecosystem Model (TEM)] that dynamically calculate net carbon storage at a 0.5° × 0.5° resolution (*8*) were used. All three models simulated changes to soil and vegetation carbon in natural ecosystems. Century simulated both natural and simulated agricultural ecosystems. To compute complete regional car-

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bon budgets, we identified those grid cells dominated by agriculture (about 40% of the United States) and used the Century agricultural results to simulate net carbon storage in these grid cells for all models. We analyzed the period 1980–1993 to compare our results with spatial atmospheric inverse calculations (*2, 3*) and inventory-based estimates of forest carbon storage (*4, 9, 10*). The period spans a range of climatic conditions and includes three El Niño events and the global cooling that followed the eruption of Mount Pinatubo (June 1991).

We used climate information for 1895–1993. Climate information was derived from the National Oceanic and Atmospheric Administration (NOAA) Historical Climate Network (HCN) database (*11*). Monthly precipitation and mean minimum and maximum temperature information was derived from the NOAA HCN database and other primary, cooperative, and snowpack telemetry (SNOTEL) station data sets (*11*). Because few station records spanned the entire period, we estimated the spatial autocorrelation structure around each station for its period of record and created a continuous record for 1895–1993 for all stations by geostatistically computing missing anomalies from nearby stations (*12*). The station data were gridded at 0.5° (latitude by longitude) with a terrain-following algorithm (*12*). Forest types and soils data were as described in VEMAP 1995 (*7*) with forest distributions remapped with a database derived from satellite observations (*13*). Agricultural regions were determined from a 1990 land cover inventory of the United States (*13*) and land management practices (fertilization, planting and harvest dates, irrigation, tillage intensity) from U.S. Department of Agriculture National Resource Inventory data (*14, 15*). Atmospheric CO_2 data were from Enting *et al.* (*16*).

Our ensemble of means for the U.S. CO_2/climate sink in ecosystems for the period 1980–1993 is 0.08 Pg of carbon per year (Table 1). The three models agree within 25% in estimating the continental mean. Comparison of model experiments with observed versus constant CO_2 shows that the bulk of the increase is due to CO_2 fertilization, with the rate of uptake varying with and modulated by climate. Annual net carbon storage per unit area is relatively evenly distributed over the conterminous United States, ranging from 100 kg ha^{-1} in the Great Plains and the Northeast to 150 kg ha^{-1} in the Southeast (Fig. 1). As expected, intermodel variability is higher at the regional level than in the continental total, but the model results remain similar within a factor of 3 and are comparable to inventory-based estimates (*9, 10*). Agriculture plays a negligible role in modeled current carbon storage, but Century simulations suggest that, with best management

Table 1. Net carbon storage in the terrestrial ecosystems of the United States as estimated by three biogeochemical models (petagram of carbon per year).

	Biome-BGC	Century	TEM
1980–1993*			
Mean	0.081	0.068	0.086
CV† (%)	108	108	157
1988–1992‡			
Mean	0.050	0.047	0.046
CV† (%)	249	172	293

*The period 1980–1993 is consistent with the inverse analysis of Rayner *et al.* (*3*). †Coefficient of variation. ‡The period 1988–1992 is consistent with the inverse analysis of Fan *et al.* (*2*).

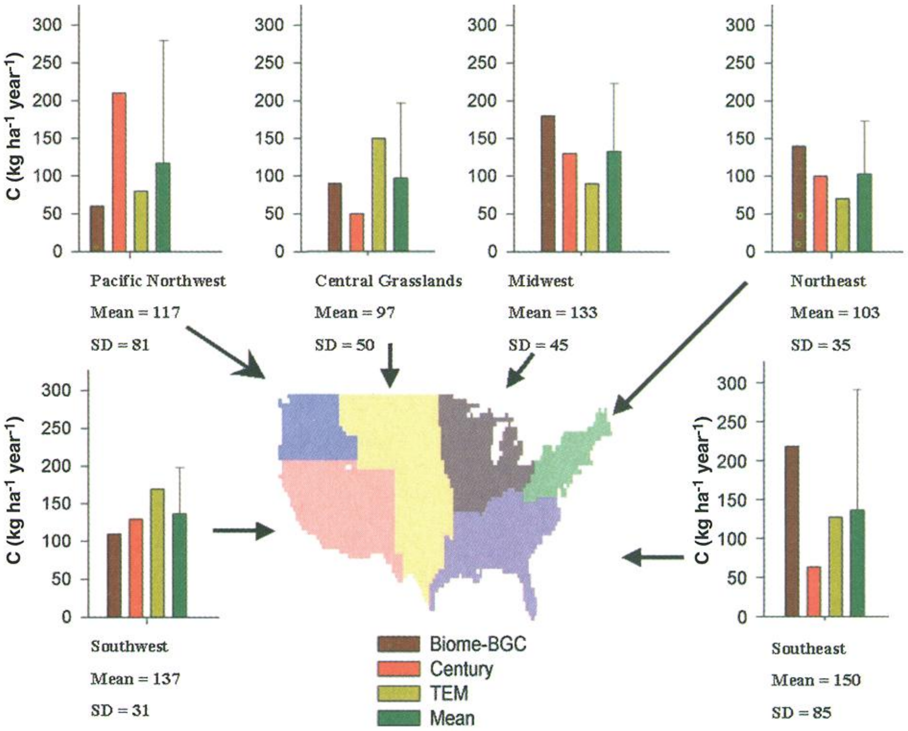

Fig. 1. Net carbon storage for different bioclimatic regions of the United States estimated with all three models for natural ecosystems, with Century results applied in agricultural cells. Histograms show specific model results and the mean (95% confidence interval).

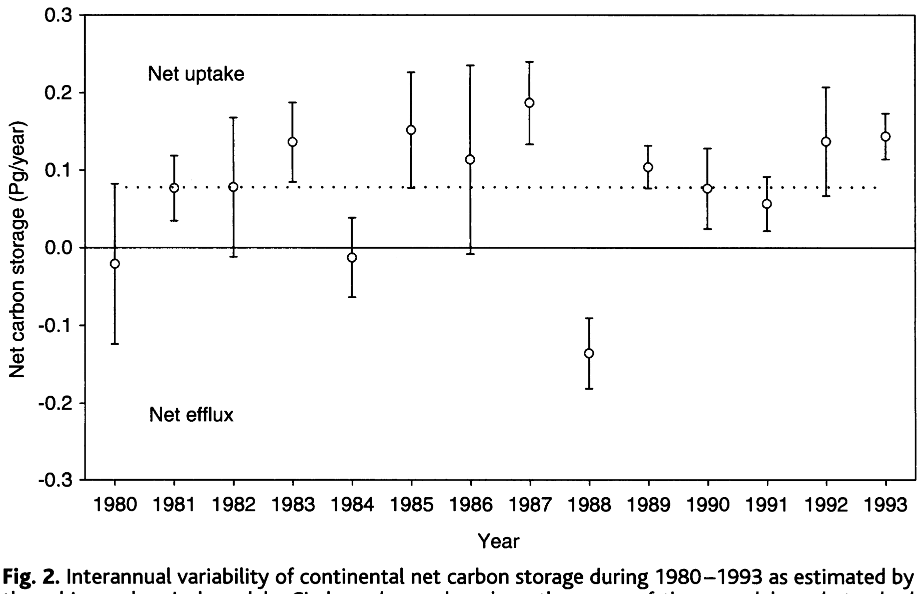

Fig. 2. Interannual variability of continental net carbon storage during 1980–1993 as estimated by three biogeochemical models. Circle and error bar show the mean of three models and standard deviation (±) across three models. Dotted line shows mean of three models for the period 1980–1993.

practices, U.S. agriculture can remain a modest sink for decades to come.

The modeled annual carbon sink is highly variable from year to year, ranging from <0.1 Pg of carbon net efflux to >0.2 Pg of carbon uptake, or more than 100% (Fig. 2). The modeled carbon sink for the period 1988–1992 shows much larger year-to-year variations than the entire period (Table 1). The large modeled variation in continental carbon storage is consistent with site-specific flux measurements and atmospheric studies (*17*), all of which suggest that terrestrial sinks differ dramatically from one year to the next.

This high variability of net carbon storage has several practical implications. First, atmospheric inverse analyses gain in statistical power when they use multiyear averages. In the future, such analyses must be done recognizing that both the magnitude and the subregional spatial distribution of fluxes will vary with the spatiotemporal distribution of climate anomalies. This is especially true if, as is likely, temperature-precipitation anomalies covary with processes (for example, convection) that affect atmospheric transport of CO_2. Second, any use of annual net carbon storage estimates from eddy covariance or other atmospheric techniques (*18*) in policy instruments to mitigate climate change or for land management must be cognizant of the volatile nature of this measure. This will certainly affect the notion of commitment periods (*18*). Third, our results highlight the need for sustained ecological research. Any 2- to 3-year sample within this period could have given a misleading picture of the decadal trend and might have even shown a different sign from the decadal mean. Long-term observations are not merely monitoring, but are needed to recognize fundamental ecological phenomena.

The region we simulated is not geographically identical to the regions defined in atmospheric inverse models (*2, 3*). For perspective, in global simulations with VEMAP models, net carbon storage in the conterminous United States is typically about 60% of the total we model for the region equivalent to the North American domain of Fan *et al.* (*2*). Also, the atmospheric signal results from the outcome of all processes, including processes we do not model such as forest regrowth, erosion, and nitrogen deposition. Therefore, we expect, a priori, the atmosphere to show a somewhat larger sink than we model (Table 1). Our estimate is close in magnitude to inventory-based estimates (*9, 10*) and to some atmospheric estimates (*3*).

Despite high uncertainty, the inventory estimates tend to be larger than the VEMAP estimate for a CO_2/climate sink of 0.08 Pg of carbon per year. For example, Brown and Schroeder (*10*) estimated 0.17 Pg of carbon per year for eastern U.S. forests (compared with our value of 0.04) (Fig. 1). Birdsey and Heath (*9*) estimated a U.S. sink of 0.3 Pg of carbon per year, whereas Houghton *et al.* (*4*) estimate a range of 0.15 to 0.35 Pg of carbon per year. The effects of intensive forest management and agricultural abandonment on carbon uptake in the United States are probably as large as or larger than the effects of climate and CO_2. If the total sink is about 0.3 Pg of carbon per year, and the CO_2/climate sink is about 0.1 Pg of carbon per year, other processes such as regrowth on abandoned agricultural and harvested forest lands must cause a sink of about 0.2 Pg of carbon per year.

This is a different perspective from that given in many global analyses (*1, 19*). A large role for land use effects is consistent with suggestions from the ecological community in the wake of the Kyoto Protocol (*18*). The relative roles of physiological (climate, CO_2) changes compared with the direct effects of human domination of ecosystems need to be reassessed as a basis for understanding how the carbon cycle will change in the future.

Despite the discrepancies, the estimates from the VEMAP models are an order of magnitude less than the high atmospherically based estimates of Fan *et al.* (*2*). Inventory data also suggest a sink of the order of 0.3 Pg of carbon per year. Thus, the best current information suggests that CO_2 and land use contribute a few tenths of a petagram of carbon uptake each year in the United States. The other hypothesized processes for ecosystem carbon storage (nitrogen deposition and sedimentation) are thought to be of a similar magnitude or smaller in this region (*5*). Inventory and model results are in conflict with high estimates from atmospheric inverse estimates. The next steps in the quantification of the North American carbon sink will require additional observations (*20*).

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