Landscape Carbon Monitoring and Analysis at the Experimental Forest Network

Richard Birdsey
USDA Forest Service
11 Campus Blvd Suite 200
Newtown Square, PA 19073
rbirdsey@fs.fed.us

Randall Kolka, Marie-Louise Smith, Michael Ryan,
David Hollinger, Linda Heath, Coeli Hoover (USDA Forest Service)

ABSTRACT

Current forest monitoring capability lacks many of the observations needed for complete forest carbon accounting over large areas. An improved observation and monitoring system is undergoing pilot testing at several forest sites in the U.S. This initiative is part of the interagency North American Carbon Program (NACP), and builds on existing capability at the Forest Service network of experimental forests. Three related activities comprise the improved observation system: (1) development and deployment of improved field measurement techniques to enhance ongoing monitoring activities, (2) implementation of an efficient and cost-effective forest carbon monitoring network based on the Forest Service experimental forest network, and (3) development of data analysis and integration methods. Improved estimates of carbon stocks and flows will provide a strong scientific foundation for development and deployment of carbon sequestration technology to mitigate greenhouse gas emissions. Anticipated products include key input data for predictive models and scenario analysis, comprehensive and timely analyses and reports that support an increasing interest in forest carbon management, improved monitoring and estimation methods, and customized studies of opportunities to protect and enhance America's forest productivity. Enhancing observations at experimental forests has additional benefits such as facilitating use of these sites for carbon management research and demonstration projects, and providing the basis for an "early warning" capability to detect the initial impacts of climate change.

THE NORTH AMERICAN CARBON PROGRAM

The U.S. Global Change Research Program recently completed a strategic review of research activities (US Climate Change Science Program 2003). High priority goals include improving the accuracy of regional estimates of carbon stocks and fluxes, and improving the estimation of the relative magnitude of various causal factors. The North American Carbon Program (NACP), a prominent component of the new strategic plan, addresses the causes of and responses to the buildup of greenhouse gases in the atmosphere (Wofsy and Harriss 2002). These issues were also identified by the National Academy of Sciences as critical uncertainties in understanding the global carbon budget and in particular the role of North American lands (National Research Council 1999). The NACP includes enhanced remote sensing of biomass, new sampling schemes for atmospheric and ocean CO_2 concentrations, enhancements to land inventories, and expansion of intensive monitoring sites. An increased effort will be made to integrate these various monitoring programs through synthesis activities, and to develop comprehensive reports and databases.

Significant uncertainties exist in estimates of the magnitude of the U.S. carbon sink, as shown by comparing estimates from land-based measurements with atmospheric approaches (Pacala et al. 2001). For the period 1980-1989, we estimated a carbon sink in the conterminous U.S. between 0.30 and 0.58 PgC y^{-1}. This uncertainty casts doubt on ability to effectively monitor carbon stock changes for domestic accounts and for managing greenhouse gas emissions and sinks. Furthermore, many factors that cause changes in carbon stocks of forests and wood products have been identified, but there is little agreement on the relative magnitude of their influence (Barford and others 2001; Casperson et al. 2001; Goodale and others 2002; Körner 2000; Schimel et al. 2000). The long-term effects of land-use change, timber harvesting, increasing atmospheric CO_2, climate change, N deposition, and tropospheric ozone have all been considered as major factors affecting carbon in forests and wood products. It is particularly difficult,

yet very important, to have the ability to separate the effects of human actions from natural factors that affect land/atmosphere carbon exchange.

Integration of land and atmospheric approaches to monitoring land/atmosphere carbon exchange and quantifying the relative contribution of causal factors shows great promise for reducing the uncertainties inherent in the individual approaches. A study of Europe's terrestrial biosphere clearly demonstrated the benefits of complementary use of data from eddy covariance sites and inventories (Janssens et al. 2003). The integrated approach also includes accounting for C losses from biomass harvesting and water transport. Inclusion of C losses from biomass harvesting and water transport gives the most complete accounting of carbon balance from the land perspective (Randerson et al. 2002).

Enhanced land measurements and remote sensing coupled with ecosystem modeling will have the following impacts as described in the NACP strategic plan:
- Improve ongoing inventory and monitoring of greenhouse gas emissions from land
- Develop well-quantified large-scale estimates of land-atmosphere C exchange
- Improve the ability to attribute observed changes to the full suite of mechanisms, including natural variability as well as direct and indirect human influences
- Provide the information on plant and soil components of ecosystem fluxes necessary to understand and interpret larger-scale regional and continental fluxes
- Provide a source of data for landscape-scale comparison with remote sensing and model results derived from remote sensing.

THE MULTI-TIER APPROACH TO MONITORING

The approach to biophysical measurements for the North American Carbon Program involves hierarchical, multi-tier monitoring that integrates ongoing *extensive* inventory and monitoring programs with *intensive* monitoring and process studies. An intermediate monitoring tier at the *landscape* scale is being implemented to link extensive with intensive monitoring using an intermediate set of biometric measurements.

Extensive monitoring consists of remote sensing of land cover and change detection, and field observations from large networks of inventory sample plots. Extensive measurements represent all of the different land characteristics within the area monitored either through systematic sampling or wall-to-wall detection by remote sensors. *Intensive monitoring* is conducted at a small number of selected sites such as Long-Term Ecological Research (LTER) sites and the growing array of AmeriFlux sites (and those of related networks). These measurements represent the land conditions selected by investigators to answer specific research questions, and therefore represent only a portion of the land conditions found in a land area. *Landscape monitoring* includes clusters of measurement sites that represent the complete range of conditions over selected land areas. One of the main goals of landscape monitoring is to include sites that are managed or disturbed by natural events, and that represent different stages of succession following disturbance.

CURRENT FOREST MONITORING NEEDS

An important aspect of landscape-scale monitoring is to augment the geographic coverage of the land surface by flux towers, which have limited representation of mountainous terrain and highly disturbed landscapes. The current network of flux towers does not consistently represent land that is managed or disturbed, and locations where it is difficult to operate intensive monitoring equipment (mountains, wetlands, etc.).

A limitation of intensive-site monitoring is the inability to reflect the considerable contribution of disturbance events, including both natural disturbances and land management activities, which can cause very rapid carbon losses (Korner 2003). Also, the effects of disturbances on the carbon cycle are poorly captured by ongoing forest inventories because of the distance between sample points and length of remeasurement period. Landscape-scale monitoring has the flexibility to address disturbances opportunistically, by adding sample plots to the existing design to take advantage of disturbance events.

Remote sensing can aid in determining the spatial and temporal characteristics of disturbances, and directing the location of supplemental field sampling.

Extensive monitoring lacks detailed ecosystem measurements needed to represent all the important carbon pools and fluxes (Birdsey 2004). A recent report on ecological indicators addressed monitoring data gaps including gaps for forest carbon indicators (Heinz Center 2002). Targeted indicators included major components of forest carbon accounting: biomass, soils, forest floor and down woody debris, and wood products. Of these, only biomass on timberland was reported; the other components were judged by the Heinz Center to be deficient in data availability through ongoing monitoring programs. None of the four components was reported for forest classifications other than timberland. For reporting carbon statistics in other documents, these monitoring data gaps are filled through research studies and modeling (e.g., Birdsey and Heath 1995; Heath and others 1996, 2003).

AUGMENTING THE "AMERIFLUX" NETWORK OF FOREST SITES

Special conditions required for using the eddy covariance method include steady atmospheric conditions, homogeneous vegetation, and flat terrain for an extended distance upwind (Baldocchi 2003). Biometric measurements can fill this gap. Independent biometric measurements compared with eddy covariance estimates agree (within about 30%) when compared over several years time scale (Baldocchi 2003; Ehman et al. 2002). Typical limitations of biometric measurements are related primarily to use of allometric relationships to convert simple measurements to estimates of mass (Clark et al. 2001; Jenkins et al. 2003), and difficulty with measuring changes in soil carbon (Law et al. 2001). To some extent these biometric deficiencies will be addressed with the landscape-scale sample protocols, which feature soil CO_2 flux measurements and high-precision tree measurements.

Workshops in summer 2003 identified a desired list of variables and a sampling design, and started the process of developing a field manual. A summary list of variables is shown in Table 1. Similar to intensive monitoring, important variables that define the ecosystem "state" such as vegetation type, foliage nitrogen concentration, and soil C:N ratio will be measured along with automated measurements of key "driving variables" such as light, temperature, and precipitation that control the rate of ecosystem carbon uptake and loss. These state and driving variables will be measured at different vegetation conditions within landscapes, allowing estimates of NPP and NEP to be derived as closely as possible from field measurements, supplemented by models of ecosystem C exchange that are parameterized for each landscape monitoring location.

Table 1. Selected land measurement variables and scale of measurement.

Example Variable	Extensive Monitoring	Landscape Monitoring	Intensive Monitoring
Land cover	X	X	X
Leaf area	X	X	X
Disturbance	X	X	X
Live biomass	X	X	X
Litterfall		X	X
Soil CO_2 flux		X	X
Methane flux		X	X
Dissolved Organic C		X	X
Net Ecosystem Exchange of CO_2			X

Six landscape monitoring sites have begun testing the field protocols (in April 2004). The sites were selected to represent a variety of managed and unmanaged forest conditions in different physiographic regions, so that the protocols can be thoroughly tested using a realistic range of applications. Figure 1 shows the locations of the pilot test landscapes along with a representation of existing and potential flux tower sites and other intensive monitoring sites without flux towers. Except for the Southern site, these locations are on public lands and therefore protected from unanticipated human disturbances.
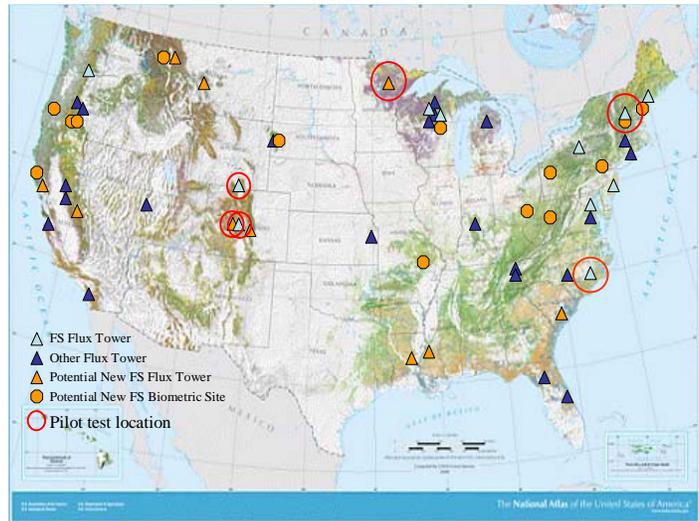

Figure 1. Location of study sites overlaid on existing and potential flux and biometric monitoring locations.

SAMPLING SCHEME FACILITATES SCALING

The proposed sampling scheme augments the basic field data collected at the landscape monitoring sites with remote sensing and additional field measurements for model parameterization and validation. Figure 2 illustrates the sampling scheme for landscape monitoring sites. At the center is a flux tower or other intensive ecosystem monitoring location if no flux tower is available. Core landscape monitoring sample locations are arrayed on a regular grid in a 1x1 km square surrounding the flux tower. The USFS Forest Inventory and Analysis protocol for regional sampling is the basis for vegetation measurements, with the supplemental ecosystem carbon measurements applied to these sample locations. By using the standard protocol for regional inventories, estimates from landscape-scale monitoring can be related to commonly measured variables and extrapolated to similar sites over a larger area using geo-statistical techniques.
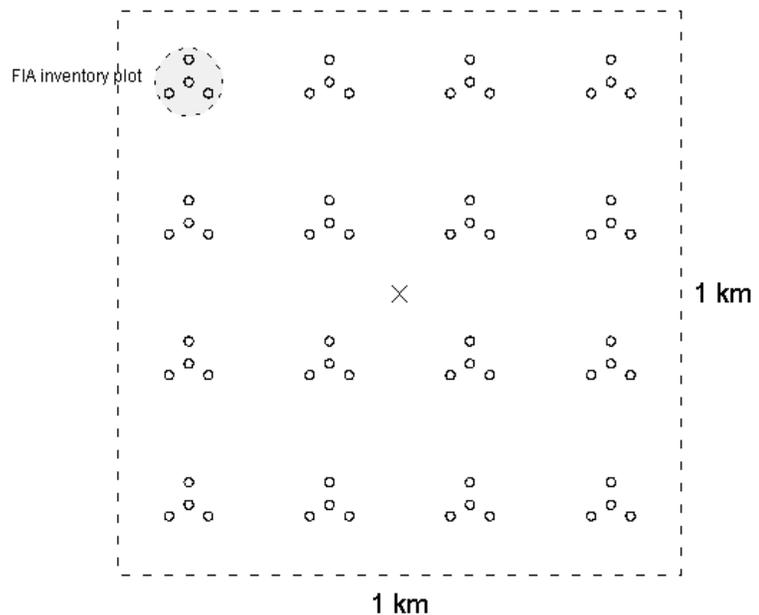

Fig. 2. Proposed Tier-3 sampling design for the U.S. using 16 FIA inventory plots. The exact number of sample plot locations will be determined by variability of the landscape and number of sampling strata. The cross represents a flux or meteorological tower.

OUTPUTS FROM FOREST LANDSCAPE MONITORING

Landscape monitoring will contribute to the NACP in several important ways. First, the wide variety of sites and unbiased sampling designs will provide direct estimates of landscape-level C sequestration (and its uncertainty) via measured changes in terrestrial C pools. These estimates will provide the "ground truth" to atmospherically-derived or remote sensing estimates that can extend beyond the areas covered by landscape monitoring. Secondly, the geographically-dispersed landscape sites combined with their acquisition of continuous meteorological data will provide ecosystem models with spatially explicit estimates of carbon stocks and ecosystem productivity needed to accurately model the dynamics of North American C exchange. The core data outputs will include productivity estimates such as those illustrated in figure 3. It is clear from the literature that such data is in great demand for a variety of applications that require parameter values or validation for the simulations of ecosystem process models. In addition to statistical data, several map products validated with field data will be produced for each landscape monitoring site. Key maps include vegetation structure from Lidar, carbon stocks, and NPP/NEP estimates from a combination of data sources including MODIS, biometrics, and flux towers.
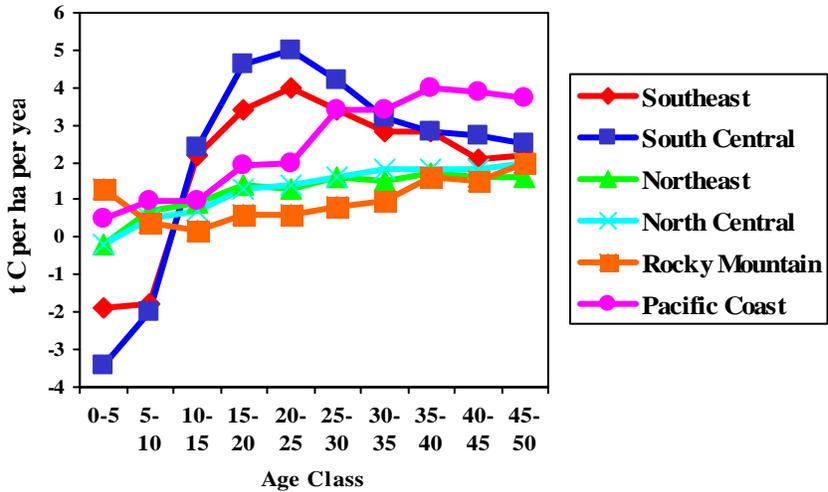
Figure 3. Examples of aggregate NEP curves from forest inventory data and ecosystem studies for regions of the conterminous U.S.

"ROADMAP" LINKING DATA, MODELS, AND DECISION SUPPORT

We envision a multi-component process to link data collection and process models with decision support needs (Figure 4). Our roadmap consists of 3 broad activities as illustrated in Figure 4: (1) develop a consistent set of landscape-scale estimates of carbon stocks and productivity (NPP, NEP) for stands at various stages of succession following land management activities and natural disturbances, and evaluate their uncertainty; (2) develop and validate process models to simulate (a) effects of natural disturbances on carbon stocks and productivity at the ecoregion
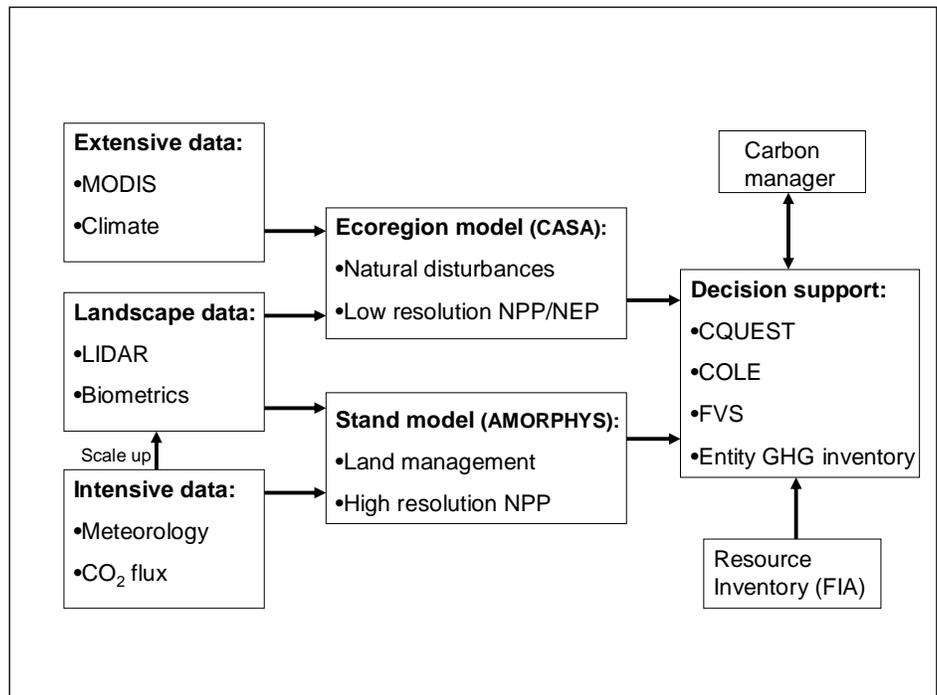
Figure 4. Flow diagram (roadmap) of linkage between data, models, and decision support.

scale, and (b) effects of forest management activities on carbon stocks and productivity at the forest stand scale; and (3) develop and evaluate decision support tools for estimating and reporting carbon stocks and changes in carbon stocks for use by forest carbon managers. Achieving these objectives will constitute a significant advance in availability of relevant and useful ecosystem data for broad application by the scientific, policy, and land management community, and lead the way toward implementation of landscape monitoring on a much broader scale than currently possible.

A physiologically-based individual tree modeling component (AMORPHYS) will facilitate using the field data to estimate NPP and NEP for managed tree stands in various stages of development, and will provide the ability for land managers to update or project stand-level inventories of carbon stock for project evaluation and reporting to greenhouse gas registries. We plan to strengthen our ability to map and characterize landscapes through remote sensing technologies, primarily MODIS and Lidar. Finally, this suite of landscape-scale data will be used to parameterize decision support tools for analysis of carbon cycle impacts of operational forest management and to implement carbon management programs.

SUMMARY AND CONCLUSIONS

The main products of this research include precise statistical estimates and maps of carbon stocks and productivity for a variety of forest landscape conditions; improved process models at ecoregion and stand scales; and decision-support tools for land managers interested in carbon management.

In 2002 the President directed USDA to develop accounting rules and guidelines for reporting and crediting carbon sequestration and emissions reduction by forestry and agriculture. This is a voluntary program designed to establish a fair market for trading carbon credits. The rules and guidelines are needed to provide a basis for consistent estimation of the quantity of carbon sequestered and emissions reduced by different forestry activities, and will be used to determine the value of the credits. The rules and guidelines must be based on solid scientific and technical work to be credible, and must not impose an excessive burden on voluntary reporters. The outcomes of this process are based on the added value that carbon credits can bring to traditional forestry: increased income for landowners, rural development, sustainable forest management, and clean air.

Enhancing observations at experimental forests has additional benefits such as facilitating use of these sites for carbon management research and demonstration projects, and providing the basis for an "early warning" capability to detect the initial impacts of climate change.

LITERATURE CITED

Baldocchi, Dennis D. 2003. Assesing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present, and future. Global Change Biology 9, 479-492.

Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore. 2001. Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science* 294: 1688-1691.

Birdsey, Richard A. 2004. Data gaps for monitoring forest carbon in the United States: an inventory perspective. Environmental Management IN PRESS

Birdsey, Richard A., and Linda S. Heath. 1995. Carbon changes in U.S. forests. In: Productivity of America's Forests and Climate Change, Linda A. Joyce (Ed.). General Technical Report RM-271. U.S. Department of Agriculture, Forest Service, Ft. Collins, CO. 56-70

Casperson, John P., Steven W. Pacala, Jennifer C. Jenkins, George C. Hurtt, Paul R. Moorcraft, and Richard A. Birdsey. 2001. Contributions of land-use history to carbon accumulation in U.S. forests. *Science* 290: 1148-1151.

Clark, D.D., Brown, S., Kicklighter, D.W. et al. 2001. Measuring net primary productivity in forests: concepts and field measurements. Ecological Applications 11: 356-370.

Ehman, J.L., H.P. Schmid, C.S.B. Grimmond, J.C. Randolf, P.J. Hanson, C.A. Wayson, and F.D. Cropley. 2002. An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. *Global Change Biology* 8(6): 575-589.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, S., and A.Z. Shvidenko. 2002. Forest carbon sinks in the northern hemisphere. *Ecological Applications* 12(3): 891-899.

Heath, Linda S., Richard A. Birdsey, Clark Row, and Andrew J. Plantinga. 1996. Carbon pools and flux in U.S. forest products. NATO ASI Series Vol. I 40, ed. by Michael J. Apps and David T. Price. Springer-Verlag Berlin. 271-278.

Heath, L. S., J.E. Smith, and R.A. Birdsey. 2003. Carbon trends in U.S. forestlands: a context for the role of soils in forest carbon sequestration. In: Kimble, John; Heath, Linda S.; Birdsey, Richard A.; Lal, R. The potential of U.S. forest soil to sequester carbon and mitigate the greenhouse effect. Boca Raton, FL: CRC Press: 35-46.

Heinz Center. 2002. The state of the Nation's ecosystems. New York, NY: Cambridge University Press. 270 p.

Janssens, Ivan A., Friebauer, Annette, Ciais, Philippe, and many others. 2003. Europe's terrestrial biosphere absorbs 7 to 12% of Eurpoean anthropogenic CO2 emissions. Science 300, 1538-1542.

Jenkins, Jennifer C., David C. Chojnacky, Linda S. Heath, and Richard A. Birdsey. 2003. National-scale biomass estimators for United Sates tree species. *Forest Science* 49(1): 12-35.

Körner, C. 2000. Biosphere responses to CO_2 enrichment. *Ecological Applications* 10(6): 1590-1619.

Körner, Christian. 2003. Slow in, rapid out – carbon flux studies and Kyoto targets. Science 300, 1242-1243.

Law, B.E., Sun, O.J., Campbell, J., Van Tuyl, S., and P.E. Thornton. 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biology 9, 510-524.

National Research Council. 1999. Global Environmental Change: Research Pathways for the Next Decade. Committee on Global Change Research, National Research Council, National Academy Press, Washington, DC, USA, 616 pp.

Pacala, S.W., G.C. Hurtt, D.Baker, P.Peylin, R.A. Houghton, R.A. Birdsey, and others. 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. 2001. *Science* 292: 2316-2320.

Randerson, J.T., Chapin III, F.S., Harden, J.W., Neff, J.C., and M.E. Harmon. 2002. Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. Ecological Applications 12(4), 937-947.

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

US Climate Change Science Program. 2003. Strategic plan for the climate change science program. Washington, DC: http://www.climatescience.gov/Library/stratplan2003/default.htm

Wofsy, S.C., and R.C. Harriss. 2002. The North American carbon program (NACP). Report of the NACP Committee of the U.S. Interagency Carbon Cycle Science Program. Washington, DC: US Global Change Research Program. 56 p.