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Data Gaps for Monitoring Forest Carbon in the United States: An Inventory Perspective

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ABSTRACT / There is increasing interest in accurate estimates of regional carbon fluxes, and identification of the causes of land/atmosphere/ocean exchange of carbon. Improved information will lead to better policies for managing greenhouse gas emissions and sequestration. The goals of this paper are to review the capability of ongoing operational inventory programs for estimating forest carbon stocks and stock changes, and to identify opportunities to improve forest carbon monitoring by enhancing these programs and supplementing them with new monitoring capability. Carbon in forest ecosystems and wood products cannot be measured directly. Ongoing forest monitoring programs provide a statistical basis for estimating carbon stocks and stock changes, based on data already collected, with a temporal resolution of about 5 years. Improvements in inventories will shorten the reporting cycle and add some variables that enhance the content with respect to carbon estimation, but it will take about a decade for full implementation. Meanwhile, there is an important role for remote sensing measurements, modeling, and imputation techniques to fill gaps in spatial coverage and content. Elements of the proposed North American Carbon Program, if implemented, will improve the estimates of forest ecosystem carbon.

There is increasing interest in accurate estimates of regional carbon fluxes, and identification of the causes of land/atmosphere/ocean exchange of carbon (National Research Council 1999, Sarmiento and Wofsy 1999). Because forests store large quantities of carbon and these stocks are affected by many factors, accurate monitoring of forest carbon stocks and fluxes is a critical component of a national strategy to manage greenhouse gas emissions and sequestration. Long-term operational forest monitoring programs are the basis for estimating and reporting carbon stocks and stock changes for forests of the United States. These estimates are comparable to similar estimates from other approaches (Pacala and others 2001). Because the uncertainty of the inventory approach is difficult to quantify, and there are known data gaps, identification of opportunities to fill data gaps is an important step in improving the estimates.

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 and others 2001, Goodale and others 2002, Körner 2000, Schimel and others 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.

The U.S. Global Change Research Program is currently undergoing a strategic review of research activities (US Climate Change Science Program 2003). Improving the accuracy of regional estimates of carbon stocks and fluxes, and improving the estimation of the relative magnitude of various causal factors are generally considered high-priority goals of the carbon cycle element of the draft research plan. Improved information will lead to better policies for managing greenhouse gas emissions and sequestration, and will help in evaluation of the effectiveness of implementing carbon sequestration projects.

The purpose of this review paper is to consider the capability of ongoing operational inventory programs for estimating forest carbon by various accounting categories, and to identify opportunities to improve forest carbon estimates by enhancing these programs and supplementing them with new monitoring capability. This review is primarily from the forest inventory perspective, which includes an element of remote sensing and linkage to intensive ecosystem research sites, but does not fully consider other emerging approaches such as systematic sampling of atmospheric CO_2 concentrations.

KEY WORDS: Carbon cycle; Forest inventory; Remote sensing; Ecosystem research

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Current Programs for Monitoring Forest Carbon

Forest Inventory and Analysis and Forest Health Monitoring

The United States Department of Agriculture (USDA) Forest Service, Forest Inventory and Analysis (FIA) Program conducts a continuous inventory and assessment of U.S. forests (Smith and others 2001). This national inventory provides periodic estimates of area, timber volume, tree biomass, and wood products (Alig and others 1990, Smith and others 2001). The forest inventory data are the basis for reporting statistics about carbon in U.S. forests (Birdsey and Heath 1995, U.S. Environmental Protection Agency 2002).

Until very recently, individual states were surveyed sequentially within regions, on a cycle averaging about 10 years. National statistics were compiled from these inventories every 5 years. For long-term trend monitoring and projections, 5-year intervals are sufficient and consistent with requirements to report greenhouse gas emissions and sinks by 5-year periods. Within the last few years, the implementation of state inventories has begun changing to a more continuous process. Data are collected in many states every year, with all of the sample plots scheduled for measurement over a 5- to 10-year period. These changes will facilitate annual reporting of basic inventory statistics, which in turn will facilitate reporting of carbon stock changes on an annual basis.

Forest inventories use multiphase sampling designs involving remote sensing and ground measurements (Birdsey and Schreuder 1992). Until recently the phase-one sample typically consisted of interpretation of high-altitude color infrared photography. Current research involves techniques to switch from high-altitude photography to satellite imagery for the first sample phase. The phase-one sample is used to stratify the land base for sampling and for making periodic area estimates. The estimates of area change from forest inventories, which include all forest land regardless of ownership, must be reconciled with data on private lands of all cover/use categories collected by the USDA Natural Resources Conservation Service (2000).

The phase-two sample consists of about 150,000 permanent field sample locations that are remeasured periodically to provide statistics on harvest, growth, mortality, damage, species composition change, and a host of observed and calculated site descriptors such as ownership and forest type. At each sample location, a rigorous protocol is followed to select and measure a representative sample of trees. This sample is the basis for estimating volume and mass of live and dead trees. Methods have been developed to estimate biomass directly from the sample trees and to convert tree volume to carbon for developing long-term trend estimates (Jenkins and others 2003, Smith and others 2003). These estimates are then expanded to the population level using the area statistics from the phase-one sample.

A subsample of the phase-two plots (known as Forest Health Monitoring (FHM) plots or phase-three plots) is the basis for more intensive ecosystem measurements (Stolte and others 2002). Data on soils, down woody debris, understory vegetation, and other ecological indicators are collected on this subsample, which is linked statistically to the phase-one and phase-two samples. The subsample of phase two consists of approximately 5000 sample plots. Successive measurements have been initiated on about one half of this subsample of field plots.

Intensive Ecosystem Studies

The most comprehensive ecosystem measurements available are from intensive, long-term ecosystem studies such as those comprising the Long-Term Ecological Research (LTER) site network sponsored by the National Science Foundation. The LTER network and other intensive research sites typically have a long history of repeated measurements of a common and comprehensive suite of ecological variables, such as soil and litter carbon, that are unavailable from extensive statistically based forest inventories. In recent years, another network of monitoring sites (known as AmeriFlux) with a focus on land/atmosphere CO_2 flux has been implemented by the Department of Energy and other agencies (Baldocci and others 2001). At these sites, towers extend through the forest canopy to monitor the exchange of CO_2 and water vapor between the land and the atmosphere, and energy flux, on a continuous basis.

Unlike statistically based forest inventories, intensive ecosystem studies are concentrated on purposely selected sites (usually without recent disturbance) and therefore do not represent the full range of landscape conditions. Some intensive ecosystem studies include control conditions and selected treatments to simulate disturbance effects, but collectively these do not represent the majority of ecosystem and disturbance conditions found in U.S. forests. A well-known bias of the AmeriFlux network is that the monitoring technology does not perform well in the hilly terrain that is typical of forested lands in many regions, and so the flux towers tend to be located in relatively flat areas. Furthermore, the location of flux towers is usually well away from edge conditions that are known to affect both microclimate and ecosystem processes (Chen and others 1995, Riitters and others 2002). The North American Carbon Program (discussed below) may provide an opportunity to integrate these ecosystem monitoring networks and establish comparable though less intensive CO_2 flux monitoring on conditions that represent much larger landscapes.

The North American Carbon Program

The North American Carbon Program (NACP) addresses fundamental questions about the buildup of greenhouse gases in the atmosphere (Wofsy and Harriss 2002). More specifically, the NACP is designed to monitor sources and sinks of CO_2, CO, and CH_4, and to attribute observations to a variety of human and natural causes. What is the role of land use and management? How much of fossil fuel emissions is taken up by ecosystems? How can we enhance carbon sinks? These questions were 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. To improve forest carbon monitoring, the NACP recommends enhanced ecosystem carbon measurements at a large and diverse network of experimental forests (forests set aside for research purposes) selected to represent a variety of sites and management practices. These experimental forests would become baseline sites to (1) integrate existing and proposed monitoring systems; (2) evaluate the effectiveness of management for increasing carbon sequestration; (3) develop monitoring and accounting protocols; and (4) develop and demonstrate forest management practices.

A new monitoring protocol (described as "tier 3" in the NACP) is proposed that will link extensive monitoring (FIA and FHM) with the intensive flux sites and ecosystem process studies. Conceptually, tier 3 is the third level of monitoring in association with remote sensing (tier 1) and extensive inventory (tier 2). Tier 3 locations comprise clusters of monitoring sites that represent typical conditions over large landscapes. The locations would be associated with existing flux towers or ecosystem research sites, or with established treatments at experimental forests, to take advantage of existing infrastructure and long-term measurements. An important function of tier 3 is to augment the geographic coverage of the land surface by flux towers, which have limited representation of mountainous terrain and highly disturbed landscapes.

Measurements at tier 3 sites will include key components of the carbon balance that will facilitate scaling, in time and space, of intensive ecosystem measurements to the larger landscape. Key measurements at tier 3 include (1) representative measurements of soil carbon flux, which is strongly regulated by climate and disturbance, and may account for one third or more of the total forest/atmosphere carbon flux (Goodale and others 2002); (2) methane flux, an important greenhouse gas with potential for release from forested peatlands and wetlands (Dlugokencky and others 2001, Updegraff and others 2001), (3) variables such as litterfall and decay rates of down dead wood that complement data collected during extensive inventories and comprise more complete ecosystem carbon accounting (Ehman and others 2002) (4); basic meteorological and site (e.g., soil, physiography) parameters to enable linkage with similar AmeriFlux sites and to facilitate scaling with remote sensing and models; and (5) tier 2 measurements to facilitate scaling to larger landscapes by linking with extensive inventory data. These suggested measurements would require that tier 3 sites be sampled much more frequently than typical tier 2 sites. The new sites will have value for parameterizing or validating the outputs of ecosystem process models, and may be useful as sites where the influence of disturbances and management on ecosystem processes can be studied relative to a previously established baseline carbon budget.

Options for Filling Forest Carbon Data Gaps

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).

In the following sections, individual components of the forest carbon cycle are reviewed with respect to the availability of monitoring data. The geographical coverage of forest land by current monitoring programs is also discussed. Selected options to improve current monitoring capability are discussed within the context of the current and proposed monitoring programs reviewed earlier.

Biomass

The FIA Program has produced national-scale biomass estimates for U.S. forests since the 1980s (Cost and others 1990, Smith and others 2001). These estimates are based on tree measurements from the large statistical sample of U.S. forests, and biomass regression models from special studies (Birdsey and Schreuder 1992). In the 1990s, these biomass estimates were converted to carbon for national reports (Birdsey and Heath 1995). A recent comprehensive compilation of biomass regression models by tree species resulted in a consistent set of national biomass estimators (Jenkins and others 2003). The new biomass equations are now applied directly to the national tree-level database from FIA, or applied to volume estimates at the sample plot level, to estimate carbon in biomass for U.S. forests (Heath and others 2003, Smith and others 2003).

The current estimates of carbon in biomass from FIA data are limited primarily by the sampling error of the inventory data (Phillips and others 2000), the validity of the biomass equations (Jenkins and others 2003), and the geographic coverage of the inventory (discussed below). The application of aggregate biomass equations to FIA data is appropriate at large spatial scales, but errors are likely to be unacceptable at smaller scales where local equations may be more appropriate. In either case, it is difficult if not impossible to precisely quantify the magnitude of all sources of biomass estimation error. A Monte Carlo simulation approach to estimating errors of forest carbon estimates suggests that estimates of change in biomass carbon are within 10% of the true value (Smith and Heath 2000). This level of accuracy is probably sufficient for most information needs at large scales (groups of states); accuracy of estimates at smaller scales will depend on sample size and validity of available biomass equations. Alternate approaches to biomass estimation based on remote sensing are under development (e.g., Myneni and others 2001). Alternate estimation approaches can provide important independent validation of the ground-based estimates (or vice versa).

Soils

There is no long-term, comprehensive soil carbon monitoring data available for U.S. forests. The Forest Service FHM Program has partially implemented soil carbon monitoring (Palmer and others 2002, Stolte and others 2002). Sampling protocols have not been in place long enough for remeasurement of a sufficient number of sample plots to detect changes for most of the United States. Sampling protocols may be inadequate for monitoring changes in soil carbon because only one point per location is sampled to a limited depth. Typically, soils are spatially variable and several sample points would be needed characterize any given FIA or FHM sample plot area. Changes in soil carbon mass, although potentially significant, are small relative to the size of the measured carbon stocks and therefore require a large number of samples to attain a useful precision. Current estimates of soil carbon for large areas do not utilize the sparse, relatively new FHM data but rather are made using a variety of modeling techniques and several data sets that only partially represent the range of forest conditions and disturbances (Heath and others 2003, Johnson and Kern 2003). The "STATSGO" base map of soil taxonomy is linked to soil attribute data, but the soil attributes for forestland may be inadequate for characterizing carbon stocks or changes in carbon stocks after disturbance (Heath and others 2002). Compilations of soil carbon estimates from literature reviews are available to address responses of soil carbon to several important disturbances: deforestation, afforestation, harvesting, forest management, and fire (Guo and Gifford 2002, Hoover 2002, Post and Kwon 2000). These data compilations are useful as input to models that can simulate carbon changes for large forested landscapes, but include unknown sources of error because the literature data may not represent all landscape conditions.

The Forest Service FHM Program continues to expand coverage across the United States. It is likely to be a decade or longer before enough remeasurement takes place using the current protocols to detect soil carbon changes for large regions. The Forest Service FIA and FHM Programs need to evaluate the data collection methods (particularly the protocol of one sample point per sample plot) for soil carbon to determine whether they are sufficiently precise to provide useful data within a reasonable time frame. The Forest Service FIA and FHM Programs also need to continue to implement Forest Health Monitoring over all forestlands of the United States.

Emerging research may point to widespread application of new soil carbon monitoring techniques. For example, laser-induced mass spectrometry can determine age of soil carbon constituents (Magrini and others 2001). Also under consideration are methods to directly measure soil CO_2 flux over large areas as an alternative to measuring stock changes over long remeasurement periods (O'Neill and others 2002).

Implementation plans for the NACP include large-scale deployment of soil CO_2 flux monitoring at experimental forest sites that represent typical landscape conditions, with particular attention to disturbances that are likely to have a significant effect on soil carbon (Wofsy and Harriss 2002). Pilot studies are needed to develop cost-efficient methods for monitoring soil CO_2 flux at tier 3 sites, and to integrate these measurements with ongoing operational monitoring activities (FIA and FHM).

In addition to the Forest Service experimental forests, research and demonstration areas managed by universities and the private sector (particularly forest industry) could be included in the tier 3 network. Many of these sites have enough history of measurements and known treatments to develop soil carbon baselines and treatment effects for improvement of modeling approaches to estimating soil carbon changes.

Forest Floor and Down Woody Debris

There is no long-term, comprehensive monitoring data available for carbon in forest floor and down woody debris (FF & DWD) of U.S. forests. The Forest Service FHM Program has partially implemented monitoring of FF & DWD, but protocols have changed and have not been in place long enough for remeasurement of sufficient sample plots to detect changes (Stolte and others 2002). Recent studies indicate that there is a great deal of heterogeneity in FF & DWD, suggesting that a limited number of sample plots may not provide reasonable estimates, particularly if forest disturbance history is unknown (Idol and others 2001, Pedlar and others 2002, Smith and Heath 2002, Yanai and others 2000). Current estimates are made using a variety of modeling techniques supported by various data sets that partially represent the range of forest conditions and recovery from forest disturbances. Modeled estimates of changes in FF & DWD are continually improving as FIA/FHM data collection covers more areas, as special studies of the decay rates of woody debris are completed, and as modeling techniques are improved. Modeled estimates have unknown errors when extrapolated to areas and conditions not represented by the underlying data.

The Forest Service FHM Program continues to expand coverage of the United States. It is likely to be a decade or longer before enough remeasurement takes place to enable reporting of FF & DWD carbon changes for all regions of the United States based on direct measurements rather than relying almost exclusively on modeling techniques. The Forest Service FIA and FHM Programs need to evaluate the data collection methods for FF & DWD to determine whether they are sufficiently precise to provide useful data within a reasonable timeframe. The Forest Service FIA and FHM Programs also need to continue to implement Forest Health Monitoring over all forestlands of the United States.

Recent research sponsored by the Joint Fire Science Program is making a significant contribution to estimates of FF & DWD mass, which is also a major constituent of fire fuels (Joint Fire Science Plan Drafting Committee, USDA Forest Service, personal communication 2002, web site: http://jfsp.nifc.gov/JointFire.html). A variety of techniques are being investigated to develop maps of fuel loads, including application of remote sensing and Geographic Information System (GIS) modeling techniques. However, the underlying data for these studies are still inadequate for representing all areas, forest conditions, and decay rates.

When fully implemented, the NACP would include comprehensive monitoring of forest/atmosphere carbon exchange. According to the implementation plan, enhancements to land inventories would include large-scale deployment of FF & DWD monitoring at sites that represent landscape conditions with particular attention to disturbances that are likely to have a significant effect on ecosystem carbon.

Wood Products

Carbon in wood products is not directly monitored. Data on volume of harvested wood is available from the FIA database and statistical reports (Smith and others 2001). The volume estimates of harvested wood can be converted to carbon estimates using the procedures for estimating biomass from volume. Once the wood leaves the forest, statistics on wood production and consumption are collected by the Forest Service and Department of Commerce (May 1998, Haynes 2003). These data are used as input to simulation models that estimate, over time, the mass of carbon in four harvested wood pools: wood in use, wood in landfills, wood burned for energy, and wood burned or decomposed without generation of energy (Heath and others 1996, Skog and Nicholson 1998).

Regional mill studies, primarily conducted by the Forest Service Forest Products Laboratory and the FIA Program, have documented the utilization of harvested wood through product manufacturing, use, and disposal. Through periodic assessments, the utilization factors are updated and reported as part of the compilation of national forest resource statistics (Smith and others 2001).

Estimation models need refinement to keep pace with changes in utilization technology and to address regional differences in harvesting, utilization, and disposal of wood products. There is also a need to assess imports and exports of roundwood and wood products to achieve global understanding of harvested carbon flows.

Alternately, a monitoring system could be developed to directly inventory the stock of carbon in wood products (houses, furniture, landfills, etc.) and track the changes in these carbon pools. The inventory could be linked with statistics already available about harvesting, housing starts, changes in landfill areas and technology, and use of wood products and wood waste for energy.

Non-Timberland Forests

Non-timberland forests include forest lands that cannot produce more than 20 cu ft/ac/yr of timber, forest lands reserved from timber utilization by legal designation, and urban forests (lands that would meet the definition of forest if not developed). For many years, the FIA and FHM programs either did not include these lands in the inventory sample, or did not sample and remeasure these lands with the same intensity as timberlands. Thus, the basic inventory data are lacking for developing estimates of carbon stocks and stock changes using the same techniques that are applied to timberland. Modified techniques based primarily on area statistics by forest type and productivity class have been used to provide complete coverage for U.S. forest lands, but the lack of sample plot data and especially remeasurement of sample plots makes these estimates of unknown accuracy and precision.

The FIA and FHM Programs are in the process of implementing monitoring on all forest lands including non-timberland forests. Previous gaps are being filled as increased funding allows states to be added to the new annualized inventory system. However, it will likely be more than a decade before enough remeasurement data are available to fill in this large gap for most of the United States, and in particular, much of interior Alaska and the Intermountain West. Meanwhile, the individual FIA units are compiling all available information about volume and biomass on these lands for national reporting purposes, and using imputation techniques to simulate data based on mapped variables (Ohmann and Gregory 2002).

Because of the need for comprehensive estimates, there is a need to apply improved techniques to generate monitoring information on non-timberland forests. This should include increased use of remotely sensed data since much of the area of non-timberland forest is located in remote areas that are difficult and expensive to measure on the ground.

An important aspect of filling these data gaps is coordination among agencies, both to ensure that critical gaps are filled and to avoid double counting of transition areas. Transition areas include primarily those lands in the Western United States that meet the definition of forestland but that may also be extensively grazed, making it difficult to determine whether the land should be classified as forest land or rangeland. This is primarily a technical issue within USDA being addressed by the Forest Service and the Natural Resources Conservation Service.

Summary and Conclusions

Carbon in forest ecosystems and wood products cannot be measured directly. Ongoing forest monitoring programs provide an improving statistical basis for estimating carbon stocks and stock changes with a temporal resolution of about 5 years. The ongoing transition to annual inventories will facilitate reporting on an annual basis. Geographical coverage by sampling of the most productive forests, classified as timberland and comprising two thirds of all U.S. forest land, is very good. Sampling gaps are being filled for some large areas of less productive forest land and reserved forest land. Because of the length of time required to implement land inventories and remeasure sample plots, modeling approaches will be required to fill in data gaps for perhaps another decade. Meanwhile, there is an important role for remote sensing and imputation techniques to fill in gaps in spatial coverage.

Methods have been developed and applied to convert forest inventory data to carbon estimates. Estimates of carbon in biomass are directly related to data collected by the forest inventory, and are limited primarily by applicability of biomass equations. Other carbon pools are less directly related to above-ground inventory data, and the collection of more direct measures of carbon mass is only just beginning as part of the regular inventory process. Knowledge of these carbon pools and their changes requires use of a variety of estimation methods and models to provide comprehensive coverage for U.S. forest lands. The ongoing forest inventory and forest health monitoring programs include subsampling of carbon in soils, down woody debris, and forest floor. When fully implemented and remeasured in about a decade, the database for monitoring forest ecosystem carbon will be greatly improved.

Elements of the proposed North American Carbon Program, if implemented, will improve the estimation process for forest ecosystem carbon. These elements include cluster sampling with intensive measurements at disturbed sites, advances in remote sensing observations, and improvements in models for estimation.

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