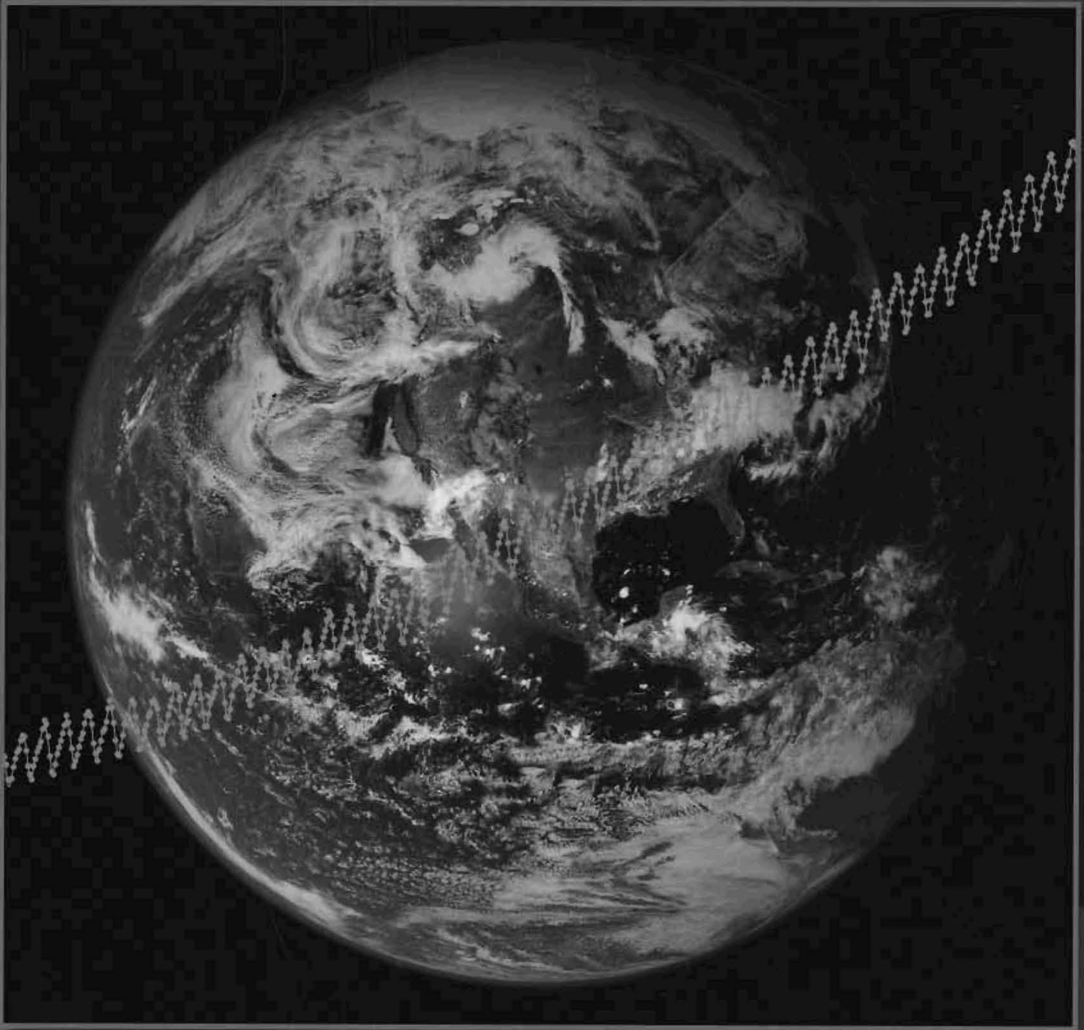
Carbon Sequestration and Its Role in the Global Carbon Cycle



Brian J. McPherson and Eric T. Sundquist
Editors

AGU

Library of Congress Cataloging-in-Publication Data

Carbon sequestration and its role in the global carbon cycle / Brian J. McPherson, Eric T. Sundquist, editors.
p. cm. -- (Geophysical monograph ; 183)
Includes bibliographical references.
ISBN 978-0-87590-448-1
1. Carbon sequestration. 2. Carbon cycle (Biogeochemistry) I. McPherson, Brian J., 1965- II. Sundquist, E. T. (Eric T.)
SD387.C37C3695 2009
577'.144--dc22
2009044559
ISBN: 978-0-87590-448-1
ISSN: 0065-8448

Cover Photo: NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group. Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing, Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights). (http://visibleearth.nasa.gov/view_rec.php?id=2429) Overlying the globe is a graphic of the Keeling Curve, an illustration of the increasing monthly average CO_2 concentrations measured by Charles David Keeling at the Mauna Loa Observatory, Hawaii, over the past 50 years.

2000 Florida Avenue, N.W.
Washington, DC 20009

Printed in the United States of America.

Integrating Terrestrial Sequestration Into a Greenhouse Gas Management Plan

Joel R. Brown and Neil Sampson

USDA Natural Resources Conservation Service, Jornada Experimental Range and The Sampson Group, Las Cruces, New Mexico, USA

Terrestrial sequestration has the potential to contribute to national and global greenhouse gas management strategies. However, spatial and temporal variability in sequestration potential and in the implementation of sequestering technologies introduces serious questions about how to resolve uncertainties and raise the credibility of terrestrial sequestration. Carbon flux in terrestrial ecosystems without land use change generally is less than one ton CO_2e/ha and driven primarily by precipitation. Land use and management changes are relatively common and are driven by economics and social considerations both in the private and public sectors. Implementing a credible greenhouse gas management program that integrates terrestrial sequestration along with other sources and sinks requires a systematic approach to identify and quantitatively monitor changes in the drivers of terrestrial sequestration. A credible terrestrial sequestration monitoring program will require close attention to integrating direct measurement of soils and vegetation, statistically valid scaling, remote sensing, and computer modeling. Predicting changes at a level of confidence useful to policy development will also require an understanding of how land owners and managers respond to private sector price signals and government conservation initiatives.

1. INTRODUCTION

Terrestrial sequestration is the deliberate process of storing carbon in the soil or vegetation via the net effect of naturally occurring processes (photosynthesis, leading to storage in plants; humification and aggregation, leading to conversion of plant carbon to soil carbon; and respiration, which returns some plant and soil carbon to the atmosphere as CO_2). Removing carbon from the atmosphere via terrestrial sequestration has been proposed by many scientists and policy makers as a critical element in the portfolio of actions to stabilize greenhouse gases (GHG) in the atmosphere and avoiding undesirable climate change. *Pacala and Socolow* [2004] identified the potential for land use and management to provide up to two of seven proposed "wedges" in a stabilization "triangle" describing the integrated area between projected business-as-usual (BAU) emissions and a net GHG emissions trajectory that would stabilize atmospheric CO_2 at 500 ppm. Each wedge represents a 1 PgC/year reduction of emissions or increased sequestration to be achieved gradually over the next 50 years. Adopting this stabilization approach could, in principle, result in CO_2 concentrations being reduced in 50 years from >700 ppm under a BAU approach to the 500 ppm stabilization target. The feasibility of this goal depends on the combined rates of CO_2 mitigation achieved by the adopted portfolio of emission reductions and

Carbon Sequestration and Its Role in the Global Carbon Cycle
Geophysical Monograph Series 183

10.1029/2006GM000354

sequestration activities. Thus, one benchmark for integrating terrestrial sequestration into a GHG management plan might be to increase sequestration beyond BAU levels by an average of about 1–2 PgC/year during the next 50 years. Assuming this benchmark is accomplished by a linear increase in sequestration rates, the integrated total over 50 years would be 25–50 PgC. Achieving this level of performance will require (1) improvements in existing understanding of sequestering processes, (2) more focused incentive programs to accelerate adoption and maintenance of sequestering practices, and (3) an enhanced monitoring and verification effort to insure credibility.

Although the processes that determine rates of terrestrial sequestration occur widely in nature and are relatively well understood [*IPCC*, 2000; *CAST*, 2004], the management of these processes to achieve specific objectives requires deliberate decision-making, planning, implementation, maintenance, and monitoring. The complexity of these policy, program and land-management challenges is compounded by two factors: (1) most land is already being used for purposes other than carbon sequestration, and (2) tracking of sequestered carbon is difficult due to seasonal and interannual variability (especially the susceptibility of typically low yearly rates to potential rapid disturbance and loss of stored carbon) and spatial variability over vast acreages. Overcoming these constraints to develop more reliable predictions and estimates of carbon stocks will require improved measurement technologies, monitoring systems, and more systematic approaches to interpreting a wide variety of data.

A very attractive aspect of terrestrial carbon sequestration is that, for most land uses, increasing soil and vegetation carbon is highly consistent with widely accepted practices that have other environmental benefits [*Lal et al.*, 1998; *ADB*, 2003]. However, achieving carbon benefits as part of a larger package of environmental benefits is not without costs [*Elbakidze and McCarl*, 2004; *Stavins and Richards*, 2005]. Costs can generally be broken into two categories: adoption costs and opportunity costs. Adoption costs are associated with implementing new practices to increase carbon storage (e.g., new equipment for conservation tillage or forest harvest practices). Opportunity costs are costs associated with maintaining carbon stocks or sequestering practices at the expense of foregoing potential income (e.g., changing crop rotations, early harvest of timber). Given that the profit margins associated with most land uses and management schemes are relatively small, both adoption and opportunity costs can represent substantial economic risks. Where land-based enterprises are the basis for subsistence, these risks can be even greater. Although most practices that sequester carbon have been implemented as conservation practices under particular circumstances in the past, the widespread implementation of land use and/or management changes for carbon sequestration may have unintended consequences for other management or environmental priorities. There has been little experience to date with attempting to increase soil carbon storage as the primary focus of land use or land management changes [*Manale*, 2002]. However, extensive experience with existing conservation programs provides a solid basis for designing incentives to accelerate adoption. Conversely, lack of experience in the precise measurement of the effects of these activities over a wide variety of operating and agroecological systems limits the credibility of estimates of success.

Where carbon-based market transactions are involved, transaction costs are also introduced. These include the costs of locating buyers, negotiating contracts, preparing adequate documentation, and providing independent third-party verification of carbon measurements and calculations. If buyers are uncertain as to the accuracy of the carbon amounts claimed, these costs will escalate, as more documentation and verification are required. Thus, reliable estimates of carbon stocks and storage potential are critical to providing cost-effective incentives to private landowners and public land managers.

2. ESTIMATING POTENTIAL FOR TERRESTRIAL SEQUESTRATION

Any estimate of the potential for terrestrial sequestration must have a solid foundation in reliable estimates of how the land base is used and managed. The wide variety of native ecosystems (the soils, vegetation, and animals they contain) and the rapid temporal shifts in land use/management practices make this difficult. Of the 13.4 B ha of ice-free land on the earth's surface, 24% is considered potentially arable or can be cultivated [*FAO*, 2002]. Of this 3.2 B ha that is potentially arable, more than 60% is of low productivity, severely limiting management options, which often results in shifting cultivation. Throughout Africa and Asia, land in cultivation ranges from 60 to 140% (by country) of that defined as suitable for cultivation, indicating that much of the cultivated land is subject to degradation. Cultivated land in North America and Europe only accounts for about 50–55% of the potentially arable land. Of the potentially arable land that is not currently cultivated, much is involved in production or conservation set-aside programs and moves in and out of the cultivated land base depending on government programs and, to some extent, commodity prices. In both the developing and developed worlds, movement of land into and out of cultivation is relatively fluid on a year-to-year time scale. This fundamental characteristic of agricultural land use makes it very difficult to monitor changes in activities that affect carbon sequestration on an annual basis. Forest lands, because of this lack of year-to-year change, may be easier to monitor for changes in land cover, and thus, provide a more reliable estimate of carbon dynamics at large spatial scales.

Another 3.9 B ha of the global ice-free land area (~30%) is classified as forests [*FAO*, 2002]. Forest areas are declining, primarily due to clearing and conversion to cropland and pasture. The global decline in forest area is mainly located in the tropics and in developing countries, having shifted from temperate developed countries early in the 20th century. Forest areas have partly recovered due to abandonment of agriculture in some areas (such as the eastern U.S.), but loss of forests in developed countries remains a substantial problem [*FAO*, 2003]. One of the difficulties in assessing the effects of forest loss on carbon dynamics is the decadal shift in land use that occurs with the replacement of native forests by tree plantations.

The remaining 55% of global land area has relatively low productivity potential and is used for domestic stock grazing, wood harvest, and hunting land [*FAO*, 2002]. Human impacts on land use and management are substantial. Over the past two decades, cropland has increased by 10% at the expense of forests and grasslands, and much of this increase has been in areas that are relatively susceptible to degradation due to erosion and other factors that deplete soil quality [*FAO*, 2002]. Changes in land use and degradation status have a tremendous impact on both the amount of carbon stored and the potential to increase carbon storage in soils and vegetation. Estimates are that as much as 1.2 B ha are severely degraded and another 700 M ha are moderately degraded [*FAO*, 2002].

In a recent estimate of the global potential for terrestrial C sequestration, *Thomson et al.* [2008] calculated potential for agricultural soils, forestry, and pastureland by estimating increases in terrestrial C storage under a range of scenarios defined mainly by targets of atmospheric CO_2 levels (450–750 ppm) over the 21st century. They suggest C storage could increase between 9 and 19 Gt for cropland, 26 Gt for reforestation, and between 4.7 and 10.6 Gt for pastureland. Although these estimates are generally at the low end of the ranges provided by others, they do provide a realistic and integrated approach to the potential contribution of terrestrial sequestration.

In the United States, approximately 70% of the total 770 M ha (contiguous 48 states) is privately owned [*NRCS*, 2006]. The remaining 30% is publicly owned and relatively stable in terms of land use. Approximately 20% of the privately owned land (150 M ha) is cropland, which is assumed to be subjected to some form of tillage annually. In response to federal farm programs, there has been a dramatic shift in recent decades from cropland to perennial cover, mainly through the Conservation Reserve Program [*NRCS*, 2004]. From 1982 to 2002, more than 21 M ha of cropland was planted to perennial trees or grasses via incentives offered through federal conservation programs. In 2002, cropland and conservation reserve lands together represented about 21% of the total land area and about 30% of private land. Most conservation land conversions were based on 10-year agreements with the government, and many parcels have moved back into the cropland base as more land has been moved into set-aside programs. These major shifts in land use are well monitored, providing a good example of the kind of data that are available to support a greenhouse gas management plan.

In the U.S., the National Resources Inventory (NRI) is perhaps the most sophisticated land use monitoring system, utilizing data from more than 800,000 sample sites on nonfederal lands in the conterminous U.S., Puerto Rico, Hawaii, and the U.S. Virgin Islands. Nationally consistent data for all sites are available for the years 1982, 1987, 1992, 1997, with "expansion factors" (sample weights) for projecting areal extent (http://www.nrcs.usda.gov/TECHNICAL/NRI/). The NRI is relatively accurate in tracking the movement of land among use categories at the decadal time scale, but lacks sufficient sampling intensity or frequency to track the year-to-year changes in land use and management, especially tillage patterns, critical to developing accurate estimates of carbon stocks [*Ogle et al.*, 2003]. The design of the NRI is tailored to provide robust statistical estimates at substate or multicounty scale. As such, the NRI is suited to documenting regional and national trends of land use over multiyear intervals, but the NRI is not suitable for tracking localized yearly changes.

Tracking changes in land use and management at relatively short time intervals is critical to estimating changes in terrestrial carbon stocks [*Ogle et al.*, 2003; *Ogle and Paustian*, 2005]. Relatively small changes in management on individual tracts of land can have significant impact when multiplied across large land areas [e.g., *Scurlock and Hall*, 1998; *Follett et al.*, 2001; *Lal*, 2004]. In the past several years, substantial progress has been made in developing a more quantitative and reliable understanding of the effects of land use and management change on carbon fluxes at small (<ha) scales.

2.1. Croplands

Cropland management inherently requires soil disturbance to varying degrees to manipulate ecological processes and optimize yield. In general, soil disturbance is also the primary driver of carbon fluxes in agricultural soils. The more frequently and intensively soil is disturbed, the greater the oxidation and loss of carbon to the atmosphere as carbon dioxide [*Lal et al.*, 1998; Chap 4]. Soil disturbance may also enhance erosion, which contributes to further carbon removal from upland eroding soils and also contributes to carbon burial in downslope depositional environments. Addition of commercial fertilizers and other soil amendments also greatly affects plant growth and, eventually, soil carbon levels. Decisions regarding tillage practices and fertilizer inputs are often made ad hoc or on very short time frames in response to a variety of conditions (i.e., soil moisture conditions, weed populations, crop pathogens, commodity prices, etc). This flexibility is essential to farming profitably anywhere in the world. The ability to rapidly implement farming decisions also greatly confounds the accurate prediction and monitoring of changes in soil carbon fluxes [*Follett et al.*, 2005].

Estimates of the potential for cropland management to increase soil carbon pools and reduce atmospheric levels of CO_2 vary widely. The standard approach is to compile site-specific observations following particular land conversions or changes in management, and to extrapolate from these observations to the total land areas potentially subject to comparable changes. One of the earliest attempts by *Lal et al.* [1998] provided estimates for the U.S. that ranged by a factor of 4 (75–208 Tg C/year) depending upon potential adoption and impact of five major activities (soil erosion management, land conversion and restoration, intensification of prime agricultural land, improving fertilizer use efficiency, and management of rice paddies) in the United States. None of the estimates for the proposed actions had a range of less than a factor of 2. More recent attempts have refined those estimates somewhat, but the uncertainty remains large compared to the potential change. *Franzluebbers and Follett* [2005] separated North America into five major regions and estimated potential changes attributable to changes in tillage, cropping systems, organic matter additions, and fertilizer. Uncertainty estimates ranged from ±15 to 400%, depending on the particular region and land management practice.

The challenge is to partition the uncertainty into components related to measurement technologies (requiring new tools to reduce that uncertainty) versus components related to natural variability (primarily climate) and to management (land-use) variability. Natural and management variability may impose unavoidable practical constraints on accounting procedures.

Without doubt, the greatest potential for increasing carbon sequestration in the agricultural sector is the conversion of existing cropland to perennial vegetation, either grasses or trees [*Gebhart et al.*, 1994]. The rate and magnitude of sequestration are determined by inherent soil fertility, time since conversion, plant species, and management [*Post and Kwon*, 2000]. Although the area of land involved in these conservation programs is relatively well known, most authors are unwilling to refine their estimates of soil carbon sequestration to less than an uncertainty factor of two because of insufficient spatially explicit data.

Ogle et al. [2003] analyzed changes in land use and management over 15 years (1982 to 1997) in the U.S. using methods developed by the Intergovernmental Panel on Climate Change (IPCC) and slightly modified to quantify uncertainties. They found that increased sequestration on soils converted from cropping to perennial cover was a net gain of 10.8 Tg C/year, but the estimates ranged from 6.5 to 15.3 Tg C/year at the 95% confidence level. Losses, primarily due to farming organic soils, were estimated at 9.4 Tg C/year (range = 6.4 to 13.3 at 95% confidence). Although the estimates of net carbon stock change were positive over the period, uncertainty associated with changes in tillage, land use change, and C fluxes from organic soils prevented the conclusion that U.S. agricultural soils were a net sink at the 95% confidence level, ranging from a loss of 4.4 Tg C/year to an increase of 6.9 Tg C/year.

Sperow et al. [2003] conducted a similar analysis of potential U.S. soil C sequestration changes in response to management and land use changes. Their estimate of 66 Tg C/year potential sequestration as a result of widespread adoption of no-till and winter cover crops, elimination of fallow, and conversion of erodible land to perennial cover was near the low end of the range (75 to 208 Tg C/year) suggested by *Lal et al.*, [1998]. *Sperow et al.* [2003] also cited uncertainties based in the variable effects of management practices on soil processes, but more importantly, on the extent of adoption by farmers.

2.2. Forests

While agricultural land presents some challenges for carbon measurement and accounting, many of those barriers have already been overcome in tree-dominated systems. Forestry practices have been among the first to attract attention of investors in private market greenhouse gas trading schemes. The basis for this attraction is the historical expertise in accurately predicting lumber yield from forest ecosystems [*Stavins and Richards*, 2005]. A centuries old need (and incentive system) to quickly and accurately estimate timber growth rates and potential lumber yield from large areas has greatly enhanced the early entry of forestry projects into the global GHG emission reduction market. However, 40–60% of total system carbon in forests is in nontimber components, such as woody debris, roots, and soils [*Barford et al.*, 2001; *Heath et al.*, 2002]. Soil carbon in forest ecosystems responds both to climate and to soil fertility. While climate is difficult to predict, effects of year-to-year variability are damped if soil disturbance is minimized, a circumstance that is relatively common in tree production systems [*Yanai et al.*, 2003]. The effects of soil fertility are more difficult to estimate. Most forests not managed primarily for wood products have poorly understood soil resource descriptions and maps, and soil fertility amendments are seldom part of extensive management systems [*Oren et al.*, 2001].

Intensively managed forests (fertilized, cultivated) are, however, growing in both extent and importance, producing over one third of the world's timber supply today [*FAO*, 2002]. Expanding or improving plantation forests have been one of the common forestry practices proposed for carbon sequestration [e.g., *Watson et al.*, 2000]. Soil surveys and fertility monitoring are more commonly utilized in intensive management systems, but periodic monitoring must still contend with the difficulty of physical sampling in soils containing dense tree root mats, the heterogeneity of soils, and the possibility of sudden disturbances such as fire and pest outbreaks.

Even though the estimation of forest carbon benefits from the more straightforward conversion of wood to carbon, there are still substantial uncertainties associated with forest estimation techniques. The net sequestration of all U.S. forest pools is estimated at approximately 170 Tg C/year from 1990 to 2004, including harvested wood and wood products. This sequestration is largely attributable to an increase in C density rather than an increase in forest acreage [*EPA*, 2006]. Similar to the National Resources Inventory (NRI) described above, the forest estimates are derived from the Forest Inventory Analysis (FIA), a plot-based system that relies on statistical extrapolation of observations via estimates of changes in land use and management from surveys. The uncertainty analysis associated with the most recent FIA report had a ±25% uncertainty level, with those estimates ranging from 12 to 139% for individual states [*EPA*, 2006]. The uncertainty was attributed to sampling error, modeling errors, and errors from converting estimates of tree densities, soil carbon levels, and changes in land use taken from individual state level inventories. Resolving these uncertainties could have important consequences because of the large potential for forest systems to increase carbon storage over current levels. *Stavins and Richards* [2005] estimated that U.S. forests could sequester up to 500 Tg C/year economically.

2.3. *Rangeland and Pastureland*

Because they are typically managed extensively (i.e., with little or no fertilizer or water input or cultivation), rangeland and pastures are subject to a high amount of variability in carbon fluxes. The most widely quoted estimate of U.S. potential for rangeland and pastureland sequestration [*Follett et al.*, 2001] has suggested that these lands could potentially sequester approximately 50 Tg C/year, but that estimate is the midpoint of a large range of 17–90 Tg C/year. Approximately half of this potential is attributed to improved management. Management practices on grazing lands generally involve difficult-to-detect changes in livestock numbers or season of use.

In addition, the effects of management practices on grazing land carbon fluxes are confounded by complex soil and vegetation interactions. Many rangeland ecosystems exhibit a wide range of grass:shrub dominance, which can alter soil C levels, depending on management history [*Scholes and Archer*, 1997]. Similar soil types within the same climatic region may support different vegetation, with significant effects on soil and vegetation carbon [*Hibbard et al.*, 2001]. Fortunately, most of these changes are structural in nature and can be detected by proven remote sensing technologies [*Asner et al.*, 2003]. In addition to structural changes in vegetation, even relatively minor changes in management (stocking rate, fertilization, legume addition) can significantly affect soil carbon stocks in grasslands and pastures [*Conant et al.*, 2001]. Detecting these practices and making reasonable inferences about their impacts on carbon stocks will require direct interactions with individual managers. Substantial variation in year-to-year carbon fluxes is common in rangeland and grassland ecosystems, primarily in response to weather patterns [*Svejcar et al.*, 1997]. Accurately tracking carbon dynamics in these ecosystems will require annual direct measurement of fluxes and pools at selected sites in combination with model predictions to extrapolate to landscape and regional scales.

Regardless of the ecosystem and land cover, the potential for soil carbon loss from natural and agricultural systems could dramatically affect the ability to reduce atmospheric levels via deliberate terrestrial sequestration. *Bellamy et al.* [2005] demonstrated measurable changes in soil carbon levels in response to changes in climate, primarily increased temperatures across a wide variety of soils and climatic regimes in the United Kingdom. In addition to the response to increasing temperatures, soil carbon losses were related to existing carbon pools, indicating that more fertile and mesic soils could lose greater amounts of carbon. Another large source of carbon that could potentially be at risk to land degradation and changes in climatic regime is the inorganic carbon stored as calcium carbonate in arid rangelands [*Monger and Martinez-Rios*, 2001]. The loss of topsoil and exposure of these carbonates to the atmosphere has the potential to contribute substantial quantities of CO_2 to the atmosphere. Other aboveground processes also have the potential to release stored carbon to the atmosphere. *Breshears and Allen* [2002] identified the importance of rapid disturbances and nonlinear behavior (thresholds) that have the potential to release stored carbon. In particular, drought, pest outbreaks, and fire can quickly release carbon stored in the soil or in vegetation, or these disturbances can initiate positive feedback in ecological systems that result in degradation that places carbon at risk of loss to the atmosphere.

In summary, potential terrestrial sequestration represents a viable option for meeting a portion of the total goals for reducing atmospheric greenhouse gas levels. The net result of the U.S. forestland, cropland, and grazing land potential sequestration estimates: [0.5 Gt C/year for forests (reforestation and management), 0.2 Gt C/year for cropland (tillage adoption and land conversion), and 0.09 Gt C/year for grazing lands (improved management and restoration) = ~0.8 Gt C/year] approaches one "wedge" of the mitigation portfolio approach suggested by *Pacala and Socolow* [2004]. Although these estimates are optimistic in terms of the level of adoption by landowners, they are relatively conservative in that they include only existing technologies and exclude practices such as urban forestry, suggesting that adoption could be driven more by incentives than new technology development. On the global scale, *Thomson et al.* [2008] took a much more conservative approach to the adoption of sequestering technologies and suggested that cropland (tillage reduction alone) could sequester 0.21 Gt C/year, forestry (reforestation alone) could sequester 0.31 Gt C/year, and grazing lands (management alone) could sequester 0.15 Gt C/year at peak rates.

All of the estimates cited are based on existing, proven technologies that are compatible with existing forest and agriculture production systems. However, setting realistic goals and measuring progress toward them will be difficult. Terrestrial sequestration is highly variable in space and time and is subject to a wide variety of drivers, both natural and anthropogenic. The sources of potential error are of sufficient magnitude that a systematic approach to improving both prediction and monitoring is required.

3. IMPROVING PREDICTION AND MONITORING OF TERRESTRIAL SEQUESTRATION

Establishing a system that will support both private-sector market development and public-sector policy design and program implementation will require an infrastructure that includes direct measurement of carbon dynamics of representative sites, remote sensing and statistical sampling of land and management attributes, and continual refinement and calibration of models based on changes in climate and management. This approach should integrate critical site-specific measures and spatially distribute them with realistic algorithms designed to meet design criteria sufficient to provide confidence for landowners and managers, policymakers, technical advisors, commodity traders, treaty negotiators, and the public.

3.1. Site and Field-Scale Measurements

The technology for direct measurement of soil and vegetation carbon at a specific point is relatively well developed [*Heath et al.*, 2002; *Lal et al.*, 2001]. In conjunction with advances in statistical techniques, new in situ measurement technologies [e.g., *Cremers et al.*, 2001] provide the elements necessary for obtaining statistically reliable estimates of soil carbon at the hectare scale for cropland, rangeland, and forestland [*Kimble et al.*, 2002], but cost-effective applications are lacking. Flux techniques, such as the Bowen ratio and Eddy covariance methods have also been shown to be reliable methods of estimating the movement of CO_2 between terrestrial and atmospheric pools [*Baldocchi*, 2003], but again, an integrated, accurate, cost-effective system that functions at larger scales has yet to be demonstrated. Integrating direct soil and vegetation measurements and flux estimates made at the point and small plot level to make reliable estimates at the hectare level to determine carbon dynamics and drivers remains a challenge, but one that is achievable [*Barford et al.*, 2001; *Wofsy and Harriss*, 2002]. A critical component of improved scaling of carbon dynamics from point to landscape and regional scales is an improved ability to quantify the spatial and temporal variability associated with the adoption of land use and management practices that affect carbon fluxes.

3.2. Remote Sensing and Statistical Sampling

A constraint on the reliable scaling of point and small plot information to hectare, landscape, regional, and national levels is the need to understand temporal and spatial patterns associated with land use and management. Remotely sensed imagery technology is sufficiently well developed to reliably detect most soil and vegetation attributes that significantly affect carbon stocks [*Running et al.*, this volume]. In the particular application to cropland, the challenge is the temporal frequency required for detection of modifications to tillage systems that influence carbon flux. Integrating remote sensing technologies into geographic information systems that also contain land use, land management, soils, and vegetation information is a substantial logistical challenge that deserves attention. New systems are being designed and field tested in forestry applications that cut the costs of large-area measurement of carbon stocks while providing high-resolution georeferenced data that can readily be incorporated into geographic information systems [*Brown et al.*, 2005]. However, an important aspect of predicting terrestrial carbon responses to management changes is management history. Unfortunately, remote sensing has limited applications for this challenge (especially tillage on croplands and shrub control on rangelands), and other investigative methods to include spatially specific historical changes must be developed.

Remote sensing technologies can be integrated with ground-based statistical sampling to validate and refine estimates and to link current and historical management practices to observations. If management practices or climatic variability at the annual scale drive significant changes in carbon dynamics, then inventory protocols should be adopted to collect spatially explicit information in yearly time steps. These ground-based inventories can provide critical information on historical land use and management to improve the performance of predictive models.

3.3. *Modeling*

Integrating changes in driving variables and the distribution of the terrestrial sequestration outputs in time and space has the potential to greatly improve decision making [see *Liu et al.*, this volume]. The modeling technologies to support this approach are relatively well developed and proven in a limited number of locations where calibration has occurred. However, the need for extending this approach to a wider variety of soils, land uses, and land management practices is critical if a credible terrestrial carbon accounting system is to be developed. The US Department of Agriculture and Colorado State University have developed a robust estimation tool (COMET VR) that would allow individuals to report changes in soil carbon to the Department of Energy's Voluntary Greenhouse Gas Emission Reporting System (http://www.cometvr.colostate.edu/). Reporting guidelines and estimation tools are also available for forest systems (http://www.usda.gov/oce/global_change/Forestryappendix.pdf). However, early testing of these tools indicates that there is a wide variety in their utility depending primarily on management systems used to calibrate the models and where the potential user is located [*CAST*, 2004]. Improving the credibility and utility of these types of tools is critical if the movement of carbon among private sector interests is to become an incentive for land owners to adopt sequestering practices or for state and federal agencies to develop a realistic national accounting system for carbon in terrestrial ecosystems. *Follett et al.* [2005] have summarized U.S. regional scale estimates of potential for mitigation via agricultural management and developed a comprehensive list of research needs, including: understanding of carbon storage changes in response to management changes, economics of competing practices, impact of practices on other environmental attributes, and effectiveness of competing policies.

It is unrealistic to believe that there will emerge a system for tracking terrestrial carbon dynamics with any credibility that is not supported by (1) an enhanced understanding of the response of carbon dynamics to land use and management (including climate change), (2) a network of representative monitoring sites upon which to determine the driving factors and indicators of change, (3) a remotely sensed imagery acquisition and analysis program and a statistically valid inventory system, and (4) a comprehensive modeling approach that includes all potential sources and sinks. Improving and refining the accuracy and reliability of estimates of carbon change in terrestrial ecosystems at multiple scales will require a substantial ongoing effort to continually update inputs in response to changes in land use, management, and climatic variability.

REFERENCES

ADB (2003), Asian Development Bank—Forest Policy Working Paper, Asian Development Bank, www.adb.org/Documents/Reports/Forest_Policy/working_paper_fp.pdf

Asner, G. P., S. R. Archer, R. F. Hughes, R. J. Ansley, and C. A. Wessman (2003), Net changes in regional woody vegetation cover and carbon storage in North Texas rangelands, 1937–1999, *Global Change Biol.*, *9*, 316–335.

Baldocchi, D. D. (2003), Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates for ecosystems: Past, present and future, *Global Change Biol.*, *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.

Bellamy, P. H., P. J. Loveland, R. I. Bradley, R. M. Lark, and G. D. Kirk (2005), Carbon losses from all soils across England and Wales 1978–2003, *Nature*, *437*, 245–248.

Breshears, D. D., and C. D. Allen (2002), The importance of rapid, disturbance-induced losses in carbon management and sequestration, *Global Ecol. Biogeogr.*, *11*, 1–5.

Brown, S., T. Pearson, D. Slaymaker, S. Ambagis, N. Moore, D. Novelo, and W. Sabido (2005), Creating a virtual tropical forest from three-dimensional aerial imagery to estimate carbon stocks, *Ecol. Appl.*, *15*, 1083–1095.

CAST (2004), Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture, 120 pp., *Task Force Report No. 141*, Council for Agricultural Science and Technology, Ames IA, USA.

Conant, R. T., K. Paustian, and E. T. Elliott (2001), Grassland management and conversion into grassland: Efects on soil carbon, *Ecol. Appl.*, *11*, 343–355.

Cremers, D. A., M. H. Ebinger, D. D. Breshears, P. J. Unkefer, S. A. Kammerdiener, M. J. Ferris, K. M. Catlett, and J. R. Brown (2001), Measuring total soil carbon with laser-induced breakdown spectroscopy [LIBS]: Results from initial testing, *J. Environ. Qual.*, *30*, 2202–2206.

Elbakidze, L., and B. A. McCarl (2004), Should we consider the co-benefits of agricultural GHG offsets, Choices, (Available at http://www.choicesmagazine.org), 3rd Quarter.

EPA (2006), Inventory of U.S. greenhouse gas emissions and sinks: 1990–2004, Chapter 7, *Land Use Change and Forestry*, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html.

FAO (2002), FAOSTAT Land Use Database, Food and Agriculture Organization, Rome, Last updated with 2002 data, Available at www.fao.org.

FAO (2003), State of the World's Forests, 2003, Food and Agriculture Organization of the United Nations, Rome, http://www.fao.org/DOCREP/005/Y7581E/Y7581E00.HTM.

Follett, R. F., J. M. Kimble, and R. Lal (2001), The potential of U.S. grazing lands to sequester soil carbon, in *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*, edited by R. F. Follett, J. M. Kimble, and R. Lal, pp. 401–430, CRC Press, Boca Raton FL, USA.

Follett, R. F., S. R. Shafer, and A. J. Franslucbbers (2005), Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA, *Soil Tillage Res.*, *83*, 159–166.

Franzluebbers, A. J., and R. F. Follett (2005), Greenhouse gas contributions and mitigation potential in agricultural regions of North America: Introduction, *Soil Tillage Res.*, *83*, 1–8.

Gebhart, D. L., H. B. Johnson, H. S. Mayeux, and H. W. Polley (1994), The CRP increases soil organic carbon, *J. Soil Water Conserv.*, 49, 488–492.

Heath, L. S., R. A. Birdsey, and D. W. Williams (2002), Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001, *Environ. Pollut.*, *116*, 373–380.

Hibbard, K. A., S. Archer, D. S. Schimel, and D. V. Valentine (2001), Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna. *Ecology*, *82*, 1999–2011.

IPCC (2000), Summary for policy makers, *Land Use, Land Use Change and Forestry, A Special Report of the Intergovernmental Panel on Climate Change*.

Kimble, J. M., R. Lal, and R. F. Follett (2002), *Agricultural Practices and Policies for Carbon Sequestration in Soil*, 512 pp., CRC Press, Boca Raton, FL, USA.

Lal, R. (2004), Carbon sequestration in dryland ecosystems, *Environ. Manage.*, *33*, 528–544.

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole (1998), *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, 128 pp., Ann Arbor Press, Chelsea, MI, USA.

Lal, R., J. M. Kimble, R. F. Follett, and B. A. Stewart (2001), *Assessment Methods for Soil Carbon*, 696 pp., CRC Press, Boca Raton, FL, USA.

Manale, A. P. (2002), Public policy issues in soil carbon trading, in *Agricultural Practices and Policies for Carbon Sequestration in Soil*, edited by J. Kimble, R. Lal, and R. Follett, pp. 361–365, CRC Press, Boca Raton, FL, USA.

Monger, H. C., and J. J. Martinez-Rios (2001), Inorganic carbon sequestration in grazing lands, in *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*, edited by R. F. Follett, J. M. Kimble, and R. Lal, pp. 87–118, CRC Press, Boca Raton, FL, USA.

NRCS (2004), *National Resources Inventory—2002 Annual NRI*, USDA Natural Resources Conservation Service, Washington, D. C., USA.

NRCS (2006), *National Resources Inventory, 2003 Annual NRI—Land Use*, USDA Natural Resources Conservation Service, Washington, D. C., USA, http://www.nrcs.usda.gov/TECHNICAL/land/nri03/Landuse-mrb.pdf.

Ogle, S. M., and K. Paustian (2005), Soil carbon as an indicator of environmental quality at the national scale: Inventory monitoring methods and policy relevance, *Can. J. Soil Sci.*, *85*, 531–540.

Ogle, S. M., F. J. Breidt, M. D. Eve, and K. Paustian (2003), Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agricultural lands between 1982 and 1997, *Global Change Biol.*, *9*, 1521–1542.

Oren, R. et al. (2001), Soil fertility limits carbon sequestration by forest ecosystems in a CO_2 enriched environment, *Nature*, *411*, 469–472.

Pacala, S., and R. Socolow (2004), Stabilization wedges: Solving the climate problem for the next 50 years with current technologies, *Science*, *305*, 968–972.

Post, W. M., and K. C. Kwon (2000), Soil carbon sequestration and land-use change: Processes and potential, *Global Change Biol.*, *6*, 317–328.

Scholes, R. J., and S. Archer (1997), Tree-grass interactions in savannas, *Annu. Rev. Ecol. Syst.*, *28*, 517–544.

Scurlock, J. M. O., and D. O. Hall (1998), The global carbon sink: A grassland perspective, *Global Change Biol.*, *4*, 229–233.

Sperow, M., M. D. Eve, and K. Paustian (2003), Potential soil C sequestration on US agricultural soils, *Clim. Change*, *57*, 319–339.

Stavins, R. N., and K. R. Richards (2005), *The cost of U.S. forest-based carbon sequestration*, Pew Center for Global Climate Change, Arlington, VA, USA.

Svejcar, T., H. Mayeux, and R. Angell (1997), The rangeland carbon dioxide flux project, *Rangelands*, *19*, 16–18.

Thomson, A. M., R. C. Izaurralde, S. J. Smith, and L. E. Clarke (2008), Integrated estimates of global terrestrial carbon sequestration, *Global Environ. Change*, *18*, 192–2003.

Watson, R. T., I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken (Eds.) (2000), *Land Use, Land-Use Change, and Forestry: Special Report to the Intergovernmental Panel on Climate Change*, Cambridge University Press, UK.

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, US Global Change Research Program, Washington, D. C.

Yanai, R. D, W. S. Currie, and C. L. Goodale (2003), Soil carbon dynamics after forest harvest: An ecosystem paradigm reconsidered, *Ecosystems*, *6*, 197–212.

J. R. Brown and N. Sampson, USDA Natural Resources Conservation Service, Jornada Experimental Range and The Sampson Group, Las Cruces, NM, USA. (joelbrow@nmsu.edu)