Forest carbon storage: ecology, management, and policy

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The objective of this review is to give ecologists and policy makers a better understanding of forest carbon dynamics and recent policy and management activities in this arena. The ecology of forest carbon is well understood, but measurement and projection of carbon sequestration at small scales can be costly. Some forest management activities qualify as offsets in various carbon markets. To promote wider use, a system is needed that will provide inexpensive and standardized approaches to forest carbon accounting that are not prone to dishonest handling. The prospects are fairly promising for development of such a system, but first, technical and organizational constraints must be overcome. In contrast, the benefits – in terms of greenhouse-gas reduction – of substituting wood for other building materials, and in displacing fossil fuel energy, could be realized immediately, if standards for calculations can be developed.

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Emissions of the principal greenhouse gas (GHG), carbon dioxide (CO_2), are driven primarily by the burning of fossil fuels, but the Earth's biosphere also plays a major role in the global carbon (C) budget. Forest biomes are an important component of the global C budget, because of the large quantities stored in live biomass, detritus, and soil organic matter, and because forest conversion to other land uses releases C to the atmosphere. Globally, terrestrial ecosystems are currently a major net sink for atmospheric CO_2 (about 1 gigaton C per year); this sink mostly represents the difference between C accumulation in forests and CO_2 emissions from tropical deforestation (Canadell and Raupach 2008). Particular forest landscapes can be either net C sources or net C sinks, depending on their management and dynamics. Forests can therefore play an important role in regulating the future rate of increase of atmospheric CO_2, and management of forests for this purpose is receiving increased attention from national and global policy makers. In this paper, we summarize the key processes of forest C storage and flux and how forest management and land-use activities affect these processes. We review the existing policy framework for forest C management, current approaches for quantifying forest C, and prospects for expanding forest C abatement in the future. We hope that this contribution will help to inform scientists, educators, and policy makers about the role of forest and C storage in global climate change mitigation.

In a nutshell:

- Aboveground biomass of living trees is the most dynamic forest carbon (C) pool
- This C pool can be accurately measured, whereas other pools are less dynamic and more costly to quantify
- Projection of biomass C pools is possible with automated tools, but additional refinements are needed before they can be applied in forest C offset projects
- Forest product substitutions can immediately contribute to C abatement, but standardized approaches are needed for any accounting system

Forest management and carbon storage

Carbon (C) is stored in forest ecosystems in the form of living tree biomass and dead organic matter. In most forests, the largest C pools are aboveground live biomass and mineral soil organic matter, with lesser amounts in roots and surface detritus (Figure 1). The rate at which C accumulates in the ecosystem – net ecosystem productivity (NEP) – represents the sum of changes in each of these pools. Biologically, NEP is the difference between net primary productivity (NPP, the annual net carbon fixation by plant photosynthesis) and heterotrophic respiration (CO_2 emission by non-photosynthetic organisms). Both NEP and the size of these C pools are highly sensitive to forest management activities. The most rapidly changing pool is usually aboveground live biomass, which can be estimated accurately through allometric approaches (Jenkins *et al.* 2003; Kloeppel *et al.* 2007). Quantifying changes in the other C pools is more difficult. Root biomass is hard to measure directly, but it is usually closely correlated with aboveground biomass (average root:shoot biomass ratio = 0.26; Cairns *et al.* 1997), permitting reasonably accurate, indirect estimates.

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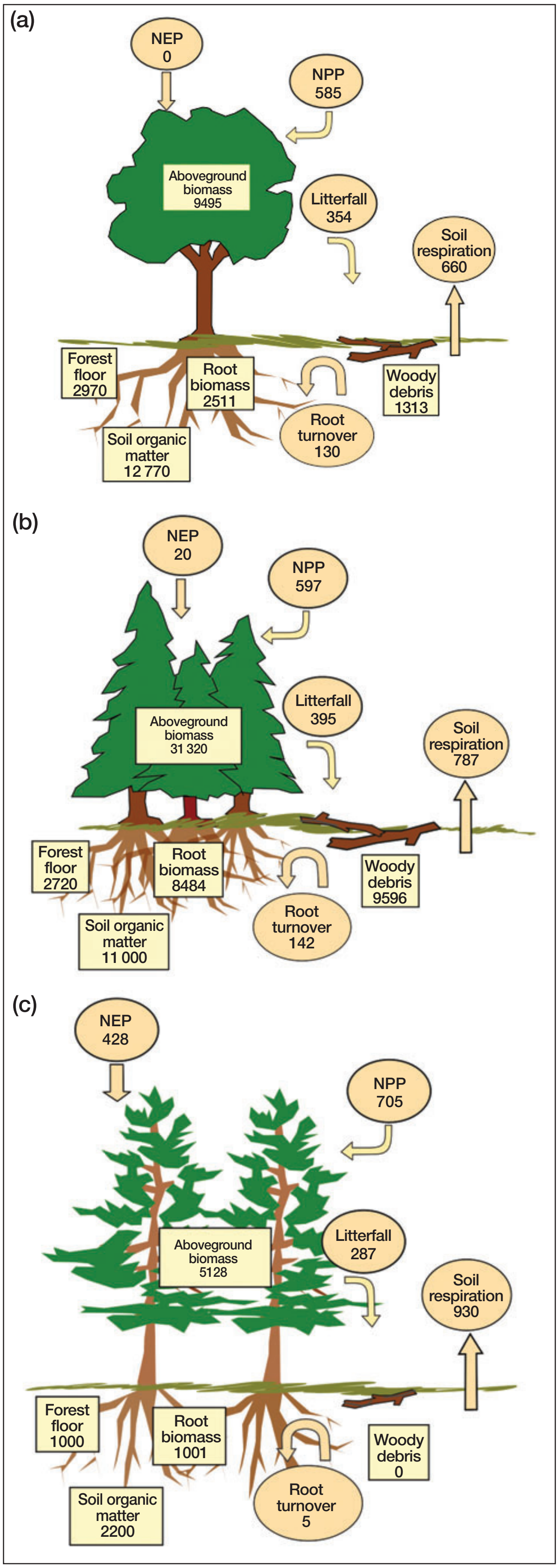

Figure 1. *Major pools (boxes; g C m^{-2}) and fluxes (ovals; g C m^{-2} yr^{-1}) of carbon for three forest ecosystems in different regions of the US. (a) A 100-year-old northern hardwood forest in New Hampshire (Fahey* et al. *2005). (b) Old-growth coniferous forest in western Oregon (Harmon* et al. *2004). (c) A 15-year-old loblolly pine plantation in North Carolina (Hamilton* et al. *2002).*

Soil organic matter comprises the largest C pool in many forests, but changes in soil C pool size are difficult to detect because of high spatial variability. Soil C pools exhibit complex responses to changes in land use, such as deforestation and afforestation (Paul *et al.* 2002), with the magnitude and direction of response depending upon vegetation, soil properties, and climate (Guo and Gifford 2002). Thick litter layers develop on the surface of some forest soils, storing smaller amounts of C than do mineral soils, but with larger and more predictable temporal fluctuations (eg after fires or forest harvest). Finally, in many forests, large quantities of C accumulate in the form of coarse woody debris. Unfortunately, the size of this pool is not closely related to aboveground biomass or forest age (Keeton *et al.* 2007; Woodall *et al.* 2008).

Forest management can greatly affect net C exchange with the atmosphere, both by changing the amount of C stored in various pools and by altering the trajectory of NEP at a location. Because much of the C in wood products removed during forest harvest is not returned immediately to the atmosphere, but rather remains stored in durable products, forest management can increase total C sequestration. Surprisingly, among the fastest growing C pools in the US are landfills, where paper and construction waste break down very slowly (Miner and Perez-Garcia 2007; Skog 2008). Net C sequestration can theoretically be maximized by maintaining the landscape in the maximal stages of NEP; this is accomplished by managing for maximum tree stocking and by using the harvested wood for durable products or as a substitute for fossil fuels (Figure 2). For example, high-intensity silviculture (eg combined pulp and sawtimber production) can maximize total C sequestration in some settings, such as southern pine plantations (Markewitz 2006). The overall effect of forest management on GHG emissions depends on the type of forest and its management, the type of wood products produced, and the efficiency of biomass conversion, as well as assumptions about how the wood and wood residues will substitute for other products with greater GHG emissions and for fossil energy (Eriksson *et al.* 2007). A life-cycle analysis for a secondary-growth Pacific Northwest forest indicated that allowing a harvested stand to grow and sequester carbon resulted in less emission of CO_2 than did that from harvest and storage in wood products; however, when the effect of substituting wood for concrete and steel was also accounted for, then harvest scenarios resulted in less CO_2 emission than did that from the no-harvest scenario (Perez-Garcia *et al.* 2005). This discrepancy emphasizes that the boundary conditions for such analyses must be specified, because they have a considerable effect on the results (Schlamadinger *et al.* 1997).

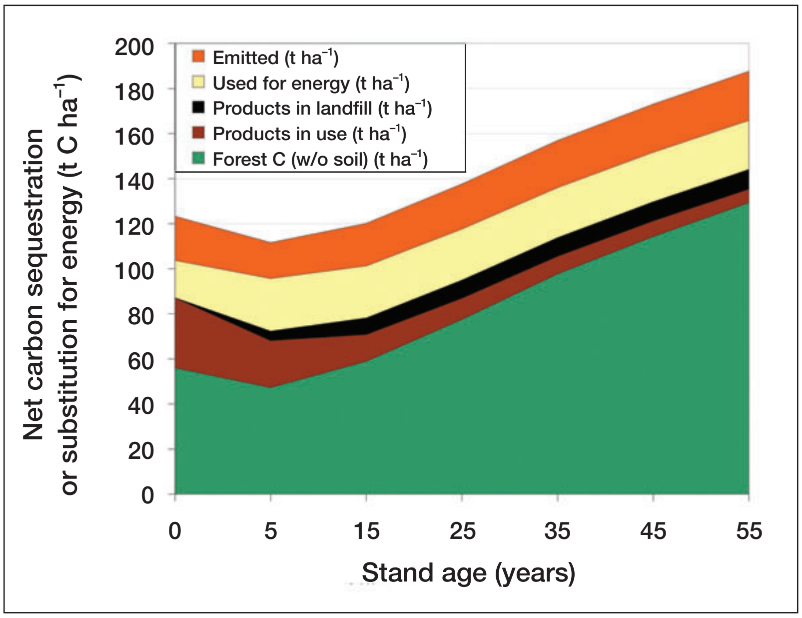

Figure 2. *Aboveground C pools and cumulative aboveground C sequestration for a northern hardwood forest stand and associated wood products in the northeastern US: cumulative C stocks and net sequestration during one harvest rotation, including losses to the atmosphere associated with management.*

Forest harvest can mitigate C emissions by replacing fossil fuel sources of power and heat (Figure 2). The overall C balance for both durable products and wood energy depends upon fossil fuel use associated with harvest, transport, and processing (White *et al.* 2005), as well as how wood products are used and disposed of after their useful life. For example, houses constructed primarily of wood have 20–50% lower emissions of GHGs over their entire life cycle than those built with concrete and steel (Miner and Perez-Garcia 2007). However, such results are sensitive to several assumptions, including the fate of forestland that is taken out of production due to reduced demand for wood and the disposition of wood building materials. Land filling can produce both CO_2 and methane (CH_4), and the net impact depends strongly on assumptions about the fate of the CH_4 as a result of its high global-warming potential (Borjesson and Gustavsson 2000). These observations highlight the complexity of the effects of forest management activities on GHG emissions and underscore the importance of standardizing approaches to such calculations for designing policy guidelines.

Land-use change plays a major role in the global C balance. In the tropics, deforestation associated with agricultural development results in large net emissions of C to the atmosphere (Ramankutty *et al.* 2007). In the temperate zone, land-use change associated with real estate development and with agricultural abandonment alters C storage in forested regions. Afforestation on abandoned agricultural land has acted as a major C sink in the north temperate zone (Woodbury *et al.* 2007a,b), and most secondary forests continue to sequester C; however, this sink will weaken as these forests mature and as further agricultural abandonment is constrained (Hurtt *et al.* 2002). The magnitude and direction of the real estate development effect depend on both the pre-existing vegetation cover and the intensity of development. Suburban development on agricultural land usually increases C storage by increasing tree cover, whereas on forested lands it will reduce C storage, because of both vegetation removal and soil disruption. For example, we observed that residential development in northern hardwood forests resulted in C emissions for typical house lots that ranged from 25–68 Mg C per lot over 50 years. Over the past 30 years, about one-third of US real estate development has occurred on agricultural lands (http://landcovertrends.usgs.gov/index.html), where growth of planted trees partly compensates for the emissions associated with development on forested lands.

In the absence of active management, the maximum C storage that could be achieved and maintained in a large forest landscape depends upon site characteristics and species composition, as well as on the frequency of disturbance to the canopy trees that actively sequester most of the C. Recent analyses of old-growth forests illustrate that C storage in many unmanaged landscapes is not at equilibrium, but rather is increasing (Smithwick *et al.* 2002; Luyssaert *et al.* 2008). Thus, protected areas provide the climate-related ecosystem service of both avoiding the release of stored C and some continued C sequestration.

■ Policy overview for forests and carbon

Under the Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC), most industrialized countries agreed to legally binding reductions in GHGs, and the mechanisms for achieving these reductions are the subject of continuing policy development. European countries established a cap-and-trade system to help achieve compliance, and the UNFCCC also allows C offsets that enlist indirect actions to contribute to emission reduction targets (see Panel 1). Moreover, the UNFCCC authorized the Clean Development Mechanism (CDM), which allows industrialized countries to invest in projects that reduce emissions in developing countries, to help meet their own emission reduction commitments. Several key criteria have been established to assure the integrity of offset projects (Panel 2). Afforestation projects can contribute to meeting emissions targets under the CDM, but the rules are complex and, to date, only one such project has been certified. Of course, the US has not ratified the Kyoto Protocol, and, in the absence of a mandatory federal program, a variety of voluntary and state or regional strategies for emissions reductions have been developed, some including forest initiatives. For example, 10 northeastern states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York,

Panel 1. Glossary of terms in forest carbon

Afforestation and reforestation: Human-induced conversion of non-forest land through planting, seeding, or human promotion of natural seed sources. Afforestation differs from reforestation only in that the former applies to land that has not been forested for at least 50 years, whereas the latter applies to land that was not forested in 1990. (Afforestation is a subset of reforestation using these working definitions.) Both could qualify for carbon offset credits in compliance and voluntary carbon markets.

Avoided deforestation: An action that results in forest not being cleared, when the absence of that action would have led to clearing.

Carbon offset: A financial instrument, measured in units of CO_2 equivalents, that is used by an entity (individuals, companies, or governments) to meet required or voluntary greenhouse-gas (GHG) reductions through actions not directly linked with the actions of that entity. All offsets are expected to meet five criteria: real, additional, verifiable, permanent, and enforceable (see Panel 2). Some forest management activities qualify as carbon offset projects under various emission control agreements.

Carbon Online Estimator (COLE) and Carbon Calculation Tool (CCT): Computer-based tools, developed by the USDA Forest Service, that use FIA data to estimate forest carbon stocks at scales from county to state and national (Proctor *et al.* 2005; Smith *et al.* 2007).

Clean Development Mechanism (CDM): An emissions-trading arrangement under the Kyoto Protocol that allows industrialized countries to invest in projects that reduce emissions in developing countries as an alternative to more expensive measures in their own countries.

Compliance and Voluntary Carbon Markets: Trading of allowances or credits in programs involving either mandatory (compliance; eg RGGI, CDM) or voluntary (eg Chicago Climate Exchange) GHG reductions.

Forest inventory and analysis (FIA) of USDA Forest Service: Periodic census of all forest lands in the US. Permanent plots are dispersed at a density of one plot per 6000 acres, providing a broad-scale assessment of forest conditions. These census data cover several decades, varying among geographic regions.

Forest Vegetation Simulator (FVS): A free and open access (www.fs.fed.us/fmsc/fvsl) forest management model based on tree growth and yield data that projects the effects of silvicultural manipulation on forest conditions. The FVS can also be used to estimate changes in carbon storage in live trees in various regions of US.

Leakage: The general concept that emissions reductions associated with changes in activities (eg limiting timber harvest, increasing harvest rotation lengths) will be replaced by compensating emissions by the displacement of the activities to another location. Leakage is a particular problem for avoided deforestation carbon offset projects if there has been no concurrent reduction in demand for wood products.

Reducing Emissions from Deforestation and Degradation in Developing Countries (REDD): A term used in UNFCCC negotiations to develop financial mechanisms that could complement afforestation and reforestation in the domain of existing forested lands.

Voluntary Carbon Standards (VCS): A program that attempts to standardize the approval of voluntary carbon offsets. The VCS includes standards for crediting a range of forest management activities.

Rhode Island, and Vermont) established a cap-and-trade system called the Regional Greenhouse Gas Initiative (RGGI), which includes forestry offset projects that can be used as a credit toward a power plant's compliance target.

In addition to these compliance markets for C trading, various voluntary programs have been developed. For example, the Chicago Climate Exchange (CCX) is a voluntary North American emission reduction and trading system that also promotes forest offset projects. The Voluntary Carbon Standard (VCS; Panel 1) provides a program for approving credible voluntary offsets that conform to high standards of integrity and seeks to promote investment in C emission reductions. Provisions for assuring that forest offset projects conform to the general criteria for offset projects have been established under both the compliance C market (eg CDM and RGGI) and the voluntary market (eg VCS and CCX), but the guidelines for the compliance market remain more stringent and restricted than those for the voluntary market.

In general, afforestation projects (Panel 1) are the only forest management activities that are eligible as offsets in compliance markets, but provisions for including management of standing forests as offset projects have been developed in voluntary markets (eg VCS) and are being considered in some compliance markets (eg RGGI). Forest management can promote net C sequestration, either by increasing C density or by contributing durable products or fossil fuel substitutes, but a better basis for quantifying management effects is needed. The protection of existing forest ("avoided deforestation") could also be influenced by C markets, but any system for awarding credits for such activities will be complicated. For example, the additionality criterion (Panel 2) would seem to restrict the crediting of avoided deforestation as an offset, because it would require decreased demand or increased C efficiency in making products derived from forested lands. Nevertheless, the VCS recognizes a wide range of forest management activities, including reduced impact logging, extended rotation lengths, and avoided deforestation; however, the ability to meet strict additionality and leakage criteria might limit their application in compliance markets. A financial mechanism for reducing GHG emissions from deforestation and forest degradation in the tropics (Reducing Emissions from Deforestation and Degradation in Developing Countries, REDD; Panel 1) is also being negotiated under the UNFCCC and has been recognized by the VCS. Similar issues of leakage will need to be confronted by REDD (Miles and Kapos 2008). Moreover, integrating other conservation values besides C (eg biodiversity, water) will be challenges because of the complexity of multicriteria analysis. Finally, if policies are implemented that reduce wood harvest, an unintended consequence could be to increase the use of more C-intensive materials, such as steel and concrete.

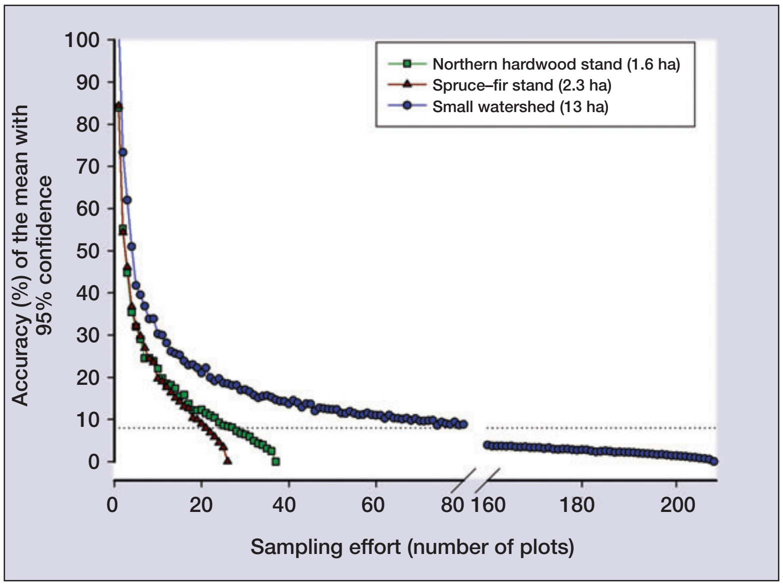

Figure 3. *Accuracy of live-tree-biomass estimates as a function of sampling effort for a northern forest. Estimates provided for two similar areas, but with different species composition and biomass, and for an entire watershed that includes multiple stands at Hubbard Brook, NH. For a given sampling effort, percent accuracy of the estimate was calculated as: (97.5th percentile – 2.5th percentile)/population mean. The percentiles were taken from 1000 biomass estimates calculated from resampled (with replacement) data for each sampling effort (ie number of random plots sampled). The population mean was calculated from a complete inventory of all trees ≥ 10 cm in diameter at 1.37-m height. The dotted, horizontal line represents the required sampling error rate (8%) in the RGGI afforestation protocols. Plot size for subsampling (0.06 ha) was similar to that in current FIA protocols.*

The challenge of forest C accounting has stimulated the development of standardized guidelines for estimating C pools and providing baseline conditions for sequestration crediting (eg for VCS, see http://v-c-s.org; for USDA Forest Service, see Smith *et al.* 2006). For instance, afforestation projects in the compliance markets (eg RGGI) must complete a detailed application that explains how C sequestration will be quantified, monitored, and verified, and general guidelines describe requirements for calculating baseline C storage and sequestration. The project area is divided into relatively homogeneous subpopulations (ie tree species, age, soil, slope, etc); C pools are quantified within each subpopulation, via sample plots sufficient to achieve >95% confidence that results are within 10% of the true mean, and sequestration is estimated by stock changes at least every 5 years (www.rggi.ord/modelrule.htm). The C pools that must be quantified include above- and belowground biomass, as well as coarse woody debris and soil C. The transaction costs for such projects could be high relative to the limited revenue provided by forest C sequestration in the cap-and-trade market.

We quantified the relationship between sampling effort and accuracy in biomass estimates for a typical northern hardwood forest in New Hampshire (Figure 3). We used a complete inventory of trees (≥ 10 cm diameter at breast height) to calculate accuracy using the definitions and standards listed in RGGI protocols. Sampling effort increased markedly above 20–30% accuracy and depended primarily on the scale of the project, as well as forest composition. Measurement costs would also depend on sampling approach and would escalate markedly if soil and coarse woody debris pools were included. Revision of policies for forest C offset projects will need to accommodate such effects on transaction costs if investment in this area is to increase.

■ Prospects and challenges for expanding forest C abatement

From a carbon policy perspective, a low-cost forest C accounting system is needed – one that will provide accurate estimates of changes in forest C pools while assuring that players are not able to cheat the system. Moreover, because C trading will be conducted on a global scale, the accounting system eventually must accommodate international

Panel 2. Criteria for carbon cap-and-trade offset projects, elaborated for the context of forestry

Real: Means that quantified GHG reductions represent actual reductions and not accounting artifacts.

Additional: Refers to the need to ensure that a forestry offset project does not take credit for some forest management activity that would have happened anyway. Similarly, in the case of protection of C in newly created forest preserves, additionality would not be achieved if wood harvest consequently occurred in a different forest tract (ie "leakage").

Verifiable: The need for accurate monitoring programs; although C storage in forests usually changes so slowly that frequent (< 5 yr) remeasurements are pointless, the importance of periodic data collection, in tandem with the awarding of credits, is emphasized by this criterion.

Permanent: Specifies that the sequestered carbon is not re-emitted to the atmosphere, or that some guarantees against this risk are provided. The time scale of "permanence" remains a controversial issue. Mechanisms to address this criterion include risk pooling and banking a percentage of credits as risk insurance. Also, schemes have been proposed to guarantee forest C storage for limited time periods, long enough for alternative technologies to reduce C emissions in other sectors.

Enforceable: The need for contracts or other legal instruments to back the forest offset project and ensure exclusive ownership.

forest C abatement options. What existing and future tools can contribute to such a system?

In the US, the Forest Inventory and Analysis (FIA) program of the USDA Forest Service provides an online database (http://fia.fs.fed.us) that summarizes the inventory information collected from thousands of permanent sampling plots on both private and public lands (Alerich *et al.* 2004). The demand for standardized estimates of forest C stocks has stimulated the development of procedures and tools for the use of FIA data, including two computer-based tools that convert FIA data to C pools and fluxes (the Carbon Online Estimator [COLE] and the Carbon Calculation Tool [CCT]; see Panel 1). However, three key limitations restrict the use of FIA tools for C offset projects: (1) the sampling interval and status of data summaries vary regionally; (2) low sampling density of FIA plots reduces the spatial resolution, so that C stocks at the scale of forestry offset projects may not be accurately represented; and (3) limited information is available on coarse woody debris, soils, and understory vegetation. Thus, although the FIA data sets are large and the tools efficient, they are not yet appropriate for project-scale purposes in forestry offset programs that must now rely on repeated on-the-ground sampling.

For purposes of investment planning and C crediting in forestry offset projects, standardized projections of C accumulation associated with afforestation and forest management activities are needed. Empirical observations provide a strong basis for estimating aboveground biomass accumulation in afforestation projects (Winjum and Schroeder 1997); however, the rate and temporal pattern of detrital and soil C accumulation are difficult to predict (Paul *et al.* 2002). Because the rate of C accumulation in these detrital pools is typically much slower than for aboveground biomass (Post and Kwon 2000), the loss in value of an offset project that ignores these changes is likely to be much smaller than the cost of accurate measurement (Pearson *et al.* 2007). Roots present a challenge, because C storage is substantial and roots are left behind after harvest. For C accounting, the most practical approach might be to exclude soil organic matter and roots in C credit calculations, as long as it can be shown that such exclusion will not overestimate sequestration (Hamburg 2000) or underestimate C losses associated with site preparation (eg plowing or burning).

Verifiable estimates of the C sequestration potential of forestry projects will be required in both voluntary and compliance markets, and both CCX and the California Climate Action Registry (CCAR) already specify these requirements. Standardized projections of C accumulation in existing forests and responses to silvicultural manipulations may be feasible by employing tools such as the USDA Forest Service's Forest Vegetation Simulator (FVS; Dixon 2003). The FVS is a forest management model that consists of a suite of growth and yield models that have been calibrated by exhaustive empirical data to accommodate regional differences encountered in forests across the US. A recent extension to FVS (Reinhardt and Crookston 2007) includes a C submodel that uses the allometric approach to calculate the C stored in live trees. Given its history, scope, and availability, FVS has the potential to provide a quantitative, national platform for projecting near-term (< 50 yr) trends in C pools in forests across the US and their response to silvicultural manipulations. It has been approved for use by CCX and CCAR, to meet their criteria for providing verifiable estimates of C sequestration for forestry projects (Call and Hayes 2007).

To illustrate the potential and limitations of such a national-scale model, we compared long-term inventories for three common forest types in the northeastern US to FVS projections of C dynamics (Figure 4). Aboveground tree biomass was predicted accurately over 37-yr and 50-yr measurement intervals, respectively, for northern hardwood forests in New Hampshire and Allegheny hardwoods in New York State. For the spruce–fir–birch forest in New Hampshire, projections were accurate from 1965–1987, but pollution-induced decline of red spruce (*Picea rubens*; Driscoll *et al.* 2001) resulted in a substantial departure relative to model projections after 1987 (Figure 4a). We also evaluated model projections of forest response to whole-tree harvest in New Hampshire. The FVS model strongly underestimated biomass accumulation, largely because it does not predict the occurrence of pin cherry (*Prunus pensylvanica*), the fast-growing tree species that dominates initial biomass accumulation in some northern forests (Fahey *et al.* 1998). These observations suggest that the FVS has the potential to serve as a standardized platform for forest C projections, but further assessment and refinement are needed, and coordination of model projections with other aspects of C accounting must be completed. In particular, no model simulation can anticipate unexpected events (like the decline of a dominant species), and patterns of tree regeneration following silvicultural manipulations are more difficult to predict than those of tree growth. The FVS requires baseline inventory data and specification of site quality. These requirements would increase the transaction cost and create the potential for cheating or error unless empirical data – or robust and standardized protocols – are available for specifying these baselines at the scale of an offset project.

■ Conclusions

Forests play a major role in the Earth's C balance, and considerable potential for abatement of GHG accumulation in the atmosphere exists in the forestry and land-use sector in the US and beyond (Nabuurs *et al.* 2007). Although the basic principles underlying the effects of forest management on net C emission to the atmosphere are well understood, attempts to incorporate forests into C management schemes will be difficult. Forest management activities can promote C sequestration, but calculations of the GHG mitigation potential of forestry are highly sensitive to the assumptions of the analysis and

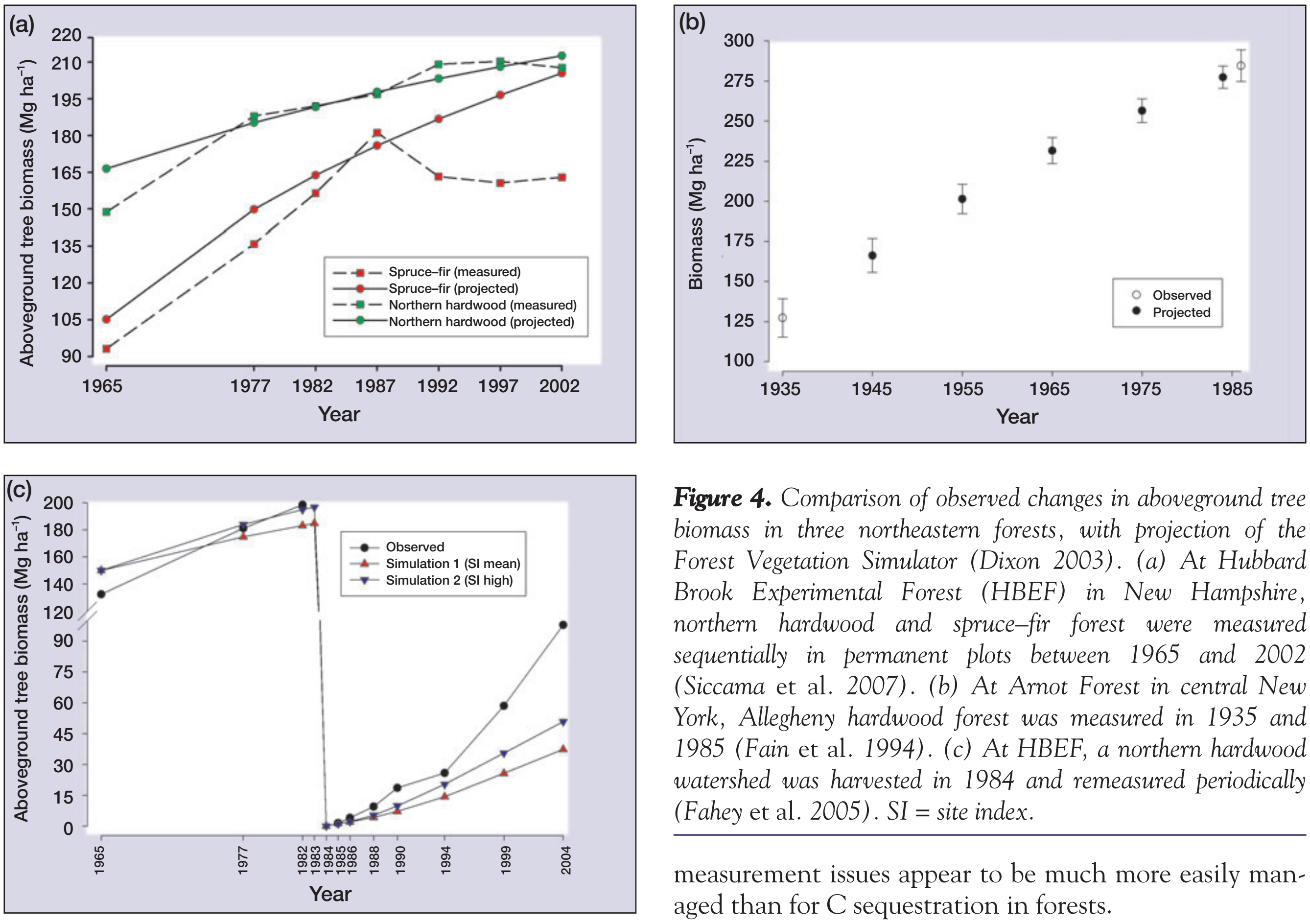

Figure 4. *Comparison of observed changes in aboveground tree biomass in three northeastern forests, with projection of the Forest Vegetation Simulator (Dixon 2003). (a) At Hubbard Brook Experimental Forest (HBEF) in New Hampshire, northern hardwood and spruce–fir forest were measured sequentially in permanent plots between 1965 and 2002 (Siccama* et al. *2007). (b) At Arnot Forest in central New York, Allegheny hardwood forest was measured in 1935 and 1985 (Fain* et al. *1994). (c) At HBEF, a northern hardwood watershed was harvested in 1984 and remeasured periodically (Fahey* et al. *2005). SI = site index.*

vary markedly among forest types, sites, and management systems. Investment in forestry projects as C offsets in compliance markets may be restricted by verification, additionality, and permanence criteria (see Panel 2) of international and regional cap-and-trade agreements. One challenge at hand for stimulating investment in forest C management is to devise a standardized system through tools that are reasonably inexpensive, accurate, and not easily manipulated to create the appearance of forest C sequestration when it is not actually taking place. We envision a global forest C accounting system that would combine FVS-type models with a network of FIA-type plots for calibration, and satellite-based remote sensing for project verification. For example, light detection and ranging (LiDAR) systems on fixed-wing aircraft are capable of accurately estimating forest C density remotely (Lefsky *et al*. 2002; Hurtt *et al*. 2004), and satellite deployment of LiDAR would reduce cost constraints and make the implementation of a global forest accounting system feasible.

In contrast to the difficulties associated with accurately quantifying the GHG benefits of forest management strategies, there is immediate potential for substantial and verifiable substitution of wood products for building materials and fossil fuel energy. Although there are still issues of leakage that must be dealt with in accounting for such substitution, the issue of permanence and many measurement issues appear to be much more easily managed than for C sequestration in forests.

In closing, we emphasize that it is critical to assure both policy makers and potential investors that forest C offset projects address the full range of social and environmental issues that can result from forest management activities. Although there is considerable scope for C mitigation, the danger of encouraging mismanagement is real, and an acceptable "gold standard" for forest C offset projects should be the ultimate goal.

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