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A synthesis of current knowledge on forests and carbon storage in the United States

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Abstract. Using forests to mitigate climate change has gained much interest in science and policy discussions. We examine the evidence for carbon benefits, environmental and monetary costs, risks and trade-offs for a variety of activities in three general strategies: (1) land use change to increase forest area (afforestation) and avoid deforestation; (2) carbon management in existing forests; and (3) the use of wood as biomass energy, in place of other building materials, or in wood products for carbon storage.

We found that many strategies can increase forest sector carbon mitigation above the current 162–256 Tg C/yr, and that many strategies have co-benefits such as biodiversity, water, and economic opportunities. Each strategy also has trade-offs, risks, and uncertainties including possible leakage, permanence, disturbances, and climate change effects. Because ~60% of the carbon lost through deforestation and harvesting from 1700 to 1935 has not yet been recovered and because some strategies store carbon in forest products or use biomass energy, the biological potential for forest sector carbon mitigation is large. Several studies suggest that using these strategies could offset as much as 10–20% of current U.S. fossil fuel emissions. To obtain such large offsets in the United States would require a combination of afforesting up to one-third of cropland or pastureland, using the equivalent of about one-half of the gross annual forest growth for biomass energy, or implementing more intensive management to increase forest growth on one-third of forestland. Such large offsets would require substantial trade-offs, such as lower agricultural production and non-carbon ecosystem services from forests. The effectiveness of activities could be diluted by negative leakage effects and increasing disturbance regimes.

Because forest carbon loss contributes to increasing climate risk and because climate change may impede regeneration following disturbance, avoiding deforestation and promoting regeneration after disturbance should receive high priority as policy considerations. Policies to encourage programs or projects that influence forest carbon sequestration and offset fossil fuel emissions should also consider major items such as leakage, the cyclical nature of forest growth and regrowth, and the extensive demand for and movement of forest products globally, and other greenhouse gas effects, such as

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methane and nitrous oxide emissions, and recognize other environmental benefits of forests, such as biodiversity, nutrient management, and watershed protection. Activities that contribute to helping forests adapt to the effects of climate change, and which also complement forest carbon storage strategies, would be prudent.

Key words: afforestation; avoided deforestation; carbon emission offsets; carbon storage and sequestration; disturbance risk; greenhouse gas mitigation; intensive silviculture; substitution; urban forestry; wood biomass energy; wood products.

Introduction

Carbon dioxide (CO_2) and other greenhouse gases (GHGs) have increased markedly since the Industrial Revolution because of the combustion of fossil fuels for energy and from changes in land use, such as deforestation for agriculture. Because CO_2 emissions from fossil fuels have a long residence time in the atmosphere and because the Earth will take centuries to come into thermodynamic equilibrium with higher GHG concentrations, the effects of elevated GHGs on global climate and ecosystems will last for a millennium or more (Archer 2005, Solomon et al. 2009).

We examine how forests and products from forests could be managed to sequester more carbon and slow the release of carbon to the atmosphere, with a focus on the United States. We review the available literature to answer two questions: (1) Can forest management and use of wood products provide carbon sinks that will last for a defined period of time? (2) What are the major trade-offs, risks, uncertainties, and co-benefits of using forests and wood products to help reduce or slow the increase in GHG concentrations?

To answer these questions, we first examine the global and forest carbon cycles, the role that forests have in the global carbon cycle, and how human activities have influenced these cycles. Next, focusing on the biological and biophysical processes, we examine the major strategies for forest carbon storage, including: land use change, forest management, biomass energy, wood products, urban forest management, and fuel treatments to decrease loss of carbon stocks. We then discuss some methods to measure forest carbon. We also briefly discuss the economics and policy features surrounding forest carbon storage. Finally, we then identify major risks, uncertainties, trade-offs, and synergies with other ecosystem and societal values. We conclude with considerations for policy.

Human alteration of the global carbon cycle

Since the Industrial Revolution, atmospheric CO_2 concentration ([CO_2]) has increased from 280 parts per million (ppm) to over 385 ppm as a result of over 400 petagrams (Pg) of carbon (C) (1 Mg C = 3.67 Mg CO_2) released to the atmosphere from human activities (Siegenthaler et al. 2005, IPCC 2007). Currently, human activities contribute CO_2 to the atmosphere through the combustion of fossil fuels (totaling 8.7$\pm$ 0.5 Pg C/yr in 2008) and from deforestation and changes in land use (1–2 Pg C/yr) (Houghton 2005, IPCC 2007, CDIAC 2009, Le Quere et al. 2009). The current rate of increasing atmospheric CO_2 concentration would be greater if it were not for the absorption of about one-half of the fossil fuel emissions by the terrestrial biosphere (3.0 Pg) and the oceans (2.3 Pg) (Schimel et al. 2001, Gurney et al. 2002, Le Quere et al. 2009). Plants and soil store ~2000 Pg C, ~60% of which is contained in forests and forest soils (Winjum et al. 1992). Because forests comprise a large and active portion of the terrestrial carbon stocks and flows (Fig.1), altering human activities to maintain forest carbon stocks and promote greater CO_2 uptake and storage has gained much attention as an option for reducing atmospheric CO_2 concentrations.

The Forest Carbon Cycle

The exchange of CO_2 between forests and the atmosphere is complicated. Live and dead trees store ~60% of the carbon in forest ecosystems. Trees are long-lived and forests can accrue carbon over a long time. Disturbance periodically kills some or all of the trees and changes the balance between production and decomposition, the consequences of which occur over large temporal and spatial scales (Figs. 2 and 3).

Forest stands are vulnerable to natural disturbances such as fire, disease, fungal infections, insect infestations, and weather damage (Kurz et al. 2008*a*, *b*, Balshi et al. 2009, van Mantgem et al. 2009, Metsaranta et al. 2010). Outbreaks of mountain pine beetle in western North America, for example, have caused extensive tree mortality over millions of hectares from western Canada to Arizona. Stand-replacing fire is very common in the United States, and many forest types are well adapted to and depend on fire. Natural disturbances affect forests on different temporal and spatial scales (Pickett et al. 1989); some forests experience significant mortality due to disturbance in average intervals of less than 100 years, while disturbance intervals in some forests can be much longer.

Disturbance such as stand-replacing fire can release large amounts of CO_2 from forests, but forest carbon stocks will usually fully recover over the life cycle of the forest (Kashian et al. 2006). Fire causes tree death and reduces total carbon stocks initially (Fig. 2). However, most of the aboveground carbon stocks are retained after fire in dead tree biomass, because fire typically only consumes the leaves and small twigs, the litter layer or duff, and some dead trees and logs (Rothstein et al. 2004; Fig. 2). Trees killed by fire retain their carbon initially but then gradually lose carbon to the atmosphere as they decompose over decades. Soon after disturbance, new trees begin to grow and store carbon while dead trees decompose. The ratio of carbon in

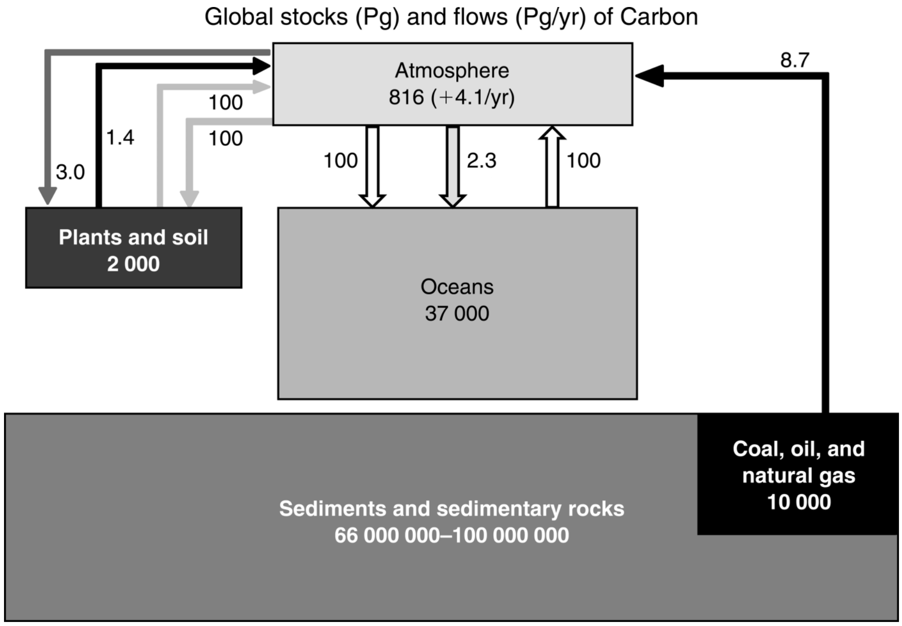

FIG. 1. Plants and soil play a large role in the global carbon cycle as shown by the stocks and annual fluxes (values are in petagrams, Pg). Non-filled and solid light-gray arrows are the historical fluxes between the oceans and the atmosphere, and plants and soil and the atmosphere (100 Pg/yr), that would have occurred without human influence. The filled light gray arrow is the additional ocean absorption of CO_2 (3.2 Pg/yr) resulting from increased CO_2 in the atmosphere since the Industrial Revolution. The black arrows are the fluxes to the atmosphere from fossil fuel combustion (8.7 Pg/yr) or deforestation (1.4 Pg/yr). The solid dark gray arrow is the flux from the atmosphere to the land, mostly from forest regrowth (3 Pg/yr). The measured atmospheric increase of 4.1 Pg C/yr is not equal to the sum of the additions and withdrawals because they are estimated separately and with associated uncertainties (le Quere et al. 2009). For perspective, U.S. fossil fuel emissions are ~1.6 Pg C/yr, and forests in the conterminous United States contain ~41 Pg C and a net carbon storage rate of ~0.2 Pg C/yr. Globally, forests contain ~1100 Pg C but only have a net carbon storage rate of ~1.0 Pg C/yr due, in large part, to deforestation globally (Dixon et al. 1994).

living-to-dead biomass increases over time, as do total ecosystem carbon stocks, until the forest and carbon stocks are fully recovered (Fig. 2).

Although disturbances subject forests to boom and bust cycles in carbon stocks over time, this effect is moderated over large spatial scales because a single disturbance rarely affects an entire landscape at the same time (Harmon 2001). Forested landscapes often resemble a mosaic of many stands in different stages of recovery, due to different types and timing of disturbance. Over large spatial and long temporal scales, the average forest carbon stocks are relatively stable over time (Fig. 3; Harmon 2001, Kashian et al. 2006, Smithwick et al. 2007). However, changes in the frequency and severity of disturbance regimes, including synchronized stressors, over large areas compared to the historical norm, such as through human intervention or climate change, can increase or lower the average forest carbon stocks over time (Kashian et al. 2006, Smithwick et al. 2007).

Human alteration of the U.S. forest carbon cycle

Human activities directly influence carbon uptake and storage in U.S. forests in dramatic ways. From 1700 to 1935, large-scale forest use for wood fuel and timber and forest clearing for agriculture resulted in a loss of ~60% of the total forest carbon stocks, with carbon emissions from forest clearing peaking at 400–800 Tg C/yr around 1900 (Fig. 4; Birdsey et al. 1993, 2006, Houghton et al. 1999). Beginning in the early 20th century, choice of energy source and building materials shifted from wood

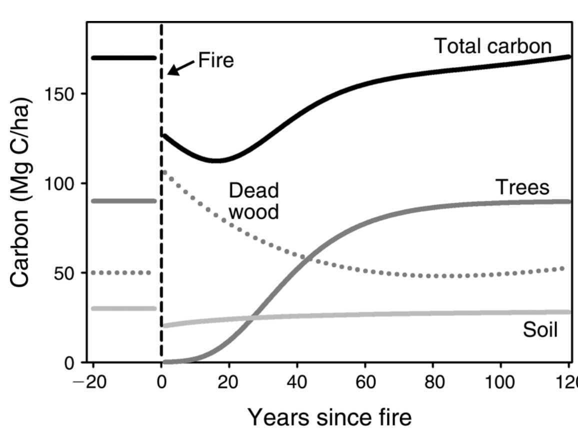

FIG. 2. If a forest regenerates after a fire and the recovery is long enough, the forest will recover the carbon lost in the fire and in the decomposition of trees killed by the fire. This concept is illustrated here by showing carbon stored in forests as live trees, dead wood, and soil and how these pools change after fire. Model output is from an analysis published in Kashian et al. (2006).

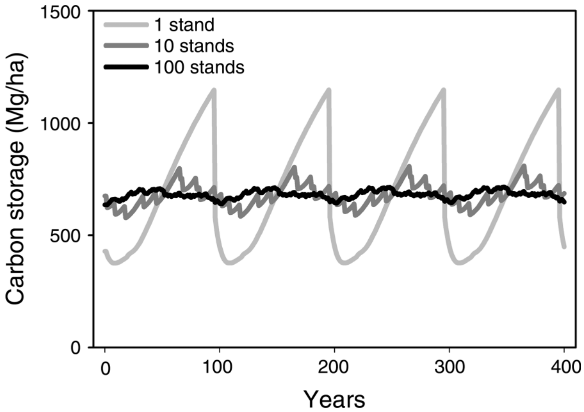

Fig. 3. Management actions should be examined for large areas and over long time periods. This figure models how the behavior of carbon stores changes as the area becomes larger and more stands are included in the analysis under normal disturbance regimes. As the number of stands increases, the gains in one stand tend to be offset by losses in another, and hence the flatter the carbon stores curve becomes. The average carbon store of a large number of stands is controlled by the interval and severity of disturbances. That is, the more frequent and severe the disturbances, the lower the average becomes (not shown).

to fossil fuels, steel, and concrete, and agriculture was abandoned in many areas. As a result, forest regrowth in the United States has recovered ~40% of the carbon lost to the atmosphere through the deforestation and harvesting before 1935 (Birdsey et al. 1993, 2006). Because a significant portion of former forestland is now cropland or pastureland (Smith et al. 2007), U.S. forests will not recover all of the forest carbon stocks present prior to European settlement without drastic reductions to U.S. agricultural output.

How much longer U.S. forests will continue to be carbon sinks as a result of this recovery is unclear. Forests in the conterminous United States and derived forest products currently store 216–313 Tg C/yr, which is equivalent to about 10–20% of U.S. fossil fuel emissions (Table 1; SOCCR 2007, USEPA 2010). Continued human population growth and exurban development will continue to exert pressure to reduce existing forests and associated carbon benefits.

Humans also affect forest carbon dynamics indirectly by altering disturbance regimes, increasing atmospheric CO_2 and nitrogen deposition, and changing global and regional climate (Pastor and Post 1988, Scheffer et al. 2001, Denman et al. 2007, Canadell et al. 2007*a*, Magnani et al. 2007, Lenihan et al. 2008, Janssens and Luyssaert 2009). Fire suppression, land use change, and climate change in the United States have altered the fire-return intervals in many forests (Fellows and Goulden 2008, Mitchell et al. 2009). As a result, tree densities and carbon stocks in some forests are often greater than before (Houghton et al. 1999), but large stand-replacing fires are also more common (Covington and Moore 1994, Hurtt et al. 2002, Westerling et al. 2006). Where soil nutrients and water are not strongly limiting, increased atmospheric [CO_2] attributed to human activities can enhance tree growth (Schimel et al. 2000, McCarthy et al. 2009, McKinley et al. 2009, Norby et al. 2010). Similarly, release of biologically reactive nitrogen from human activities into ecosystems can increase plant growth where nitrogen availability constrains plant growth and potentially decrease plant growth in some sensitive forest ecosystems (Townsend et al. 1996, Aber et al. 1998).

Biophysical Effects of Forest Cover

Forest cover influences albedo (the amount of radiation that is reflected from the Earth's surface) and evapotranspiration, potentially changing regional climate (Bala et al. 2007, Jackson et al. 2008). Forests generally absorb more solar radiation (have lower albedo) compared to other land cover; so, when forest area increases, more radiation is absorbed resulting in warming air masses (Bonan 2008). The strongest potential warming effect occurs when boreal forest cover replaces snow-covered ground, which has very high albedo (Bonan 2008). Forests can also reduce air temperatures relative to other cover types because forests typically support high rates of evapotranspiration, which increases evaporative cooling, cloud formation, and precipitation (Bonan 2008). Tropical forests have high evapotranspiration and the strongest cooling effects, while boreal forests, with relatively little evapotranspiration, have weak cooling effects. The effects of albedo and evapotranspiration rates are generally less than the carbon effects of land use change, but they are the highest when land use changes between forest and non-forest cover (Jackson et al. 2008). The net effect of these biophysical processes on climate are not well understood, particularly for temperate forests, which comprise most of the forests in the United States (Bonan 2008).

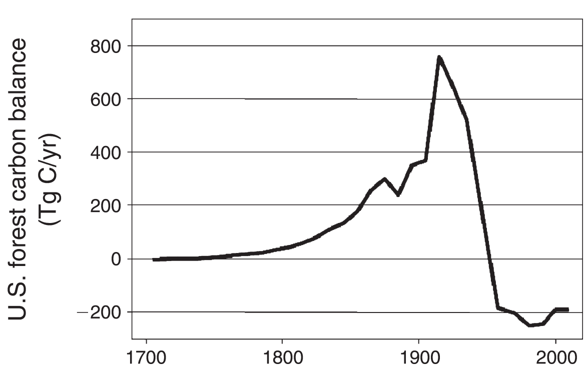

Fig. 4. The carbon balance of the U.S. forest sector shows that clearing for agriculture, pasture, development, and wood use released ~42 000 Tg of carbon from 1700 to 1935, and recovered ~15 000 Tg of carbon from 1935 to 2010. Adapted and reprinted from Birdsey et al. 2006, with permission from the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

TABLE 1. U.S. forest carbon storage and flux estimates and some published potential mitigation estimates for various activities.

Category and item	Estimate (Tg C/yr)	Source
Forest growth		
Net growth	184	Smith et al. (2007: Table 36), summary line, assuming wood density of 400 kg/m^3 for softwoods and 600 kg/m^3 for hardwoods and a carbon content of 50%; excludes interior Alaska.
Removals	110	Same as for net growth.
Mortality not removed	55	Same as for net growth.
Gross growth	349	(Net growth + Mortality + Removals)
Current forest sector carbon storage		
Forest annual net carbon storage change	192	2008, USEPA (2010), Table 7-7; excludes interior Alaska.
Harvested wood annual net carbon storage change	24	Same as above.
Total	216	
Forest annual net carbon storage change	256	SOCCR (2007), Table ES-1.
Harvested wood annual net carbon storage change	57	Same as above.
Total	313	
Mitigation potential		
Afforestation	1, 37, 119, 225	USEPA (2005), Table 4-5 for carbon prices of $18, $55, $110, $183 per Mg C, respectively. 1 Tg C/yr requires 262 000–1 133 000 ha of crop or pastureland suitable for tree growth.
Forest management	29, 60, 86, 105	Same as above. Activities include longer harvest interval, increasing growth, establishing preserves. 1 Tg C/yr requires 479 000–707 000 ha of forestland suitable for management.
Forest sector total	30, 97, 205, 330	Same as above.
Biomass energy	190	Perlack et al. (2005)
Biomass energy	130	Zerbe (2006)
Avoided deforestation	Unknown	
Forest management	Unknown	
Product substitution	Unknown	
Urban forestry	Low	
Fuel treatments	Unknown	
Urban forests		
Urban forest net annual carbon stock change	26	2008, USEPA (2010), Table 7-42.
Fire emissions		
Annual emissions from forest fires	67	USEPA (2010), Table 7-9. Averaged over 2000, 2005–2008.
CO_2 emissions		
U.S. CO_2 emissions	1615	2008, USEPA (2010), Table ES-2.
U.S. non-CO_2 GHG emissions	282	2008, CO_2 equivalent, USEPA (2010), Table ES-2.
Total	1897	

Note: Mitigation potential is in addition to some baseline projection of forest sector carbon storage. The multiple values in the "estimate column" correspond to the dollar values in the "source" column. For example, under afforestation we could sequester 1, 37, 199, and 225 Tg C/yr if we provide subsidies in the amount of $18, $55, $110, and $183, respectively.

DISTRIBUTION AND FLUX OF FOREST CARBON IN THE UNITED STATES

The United States including Alaska supports 303 million ha of forestland, ~7.7% of the world's total, with forest carbon stocks varying greatly in response to the wide ranges in environmental conditions, land use history, and current human influences (Figs. 5 and 6; FAO 2007, Woodbury et al. 2007*a*). Forests of the conterminous United States, most of which are classified as temperate forests, cover an area of ~251 million ha and contain ~41 000 Tg C, most of which (63% or 25 800 Tg C) is contained in the eastern United States (Smith and Heath 2004, 2008, Woodbury et al. 2007*b*, USDA 2008; Fig. 5A). Publicly owned forests, primarily found in the West, comprise ~40% of all forestland in the conterminous United States and contain ~19 000 Tg C (Smith and Heath 2004). Forests occupy the greatest fractions of land area in the southern and northeastern regions (Figs. 5A and 6A), while the largest total forest carbon stocks are found in the southern and Pacific regions (Fig. 6B), which also have the highest forest carbon density (Fig. 6C). The Great Plains states have the lowest forest carbon stocks of any region; however, on their eastern edge, increasing tree density and woody plant encroachment

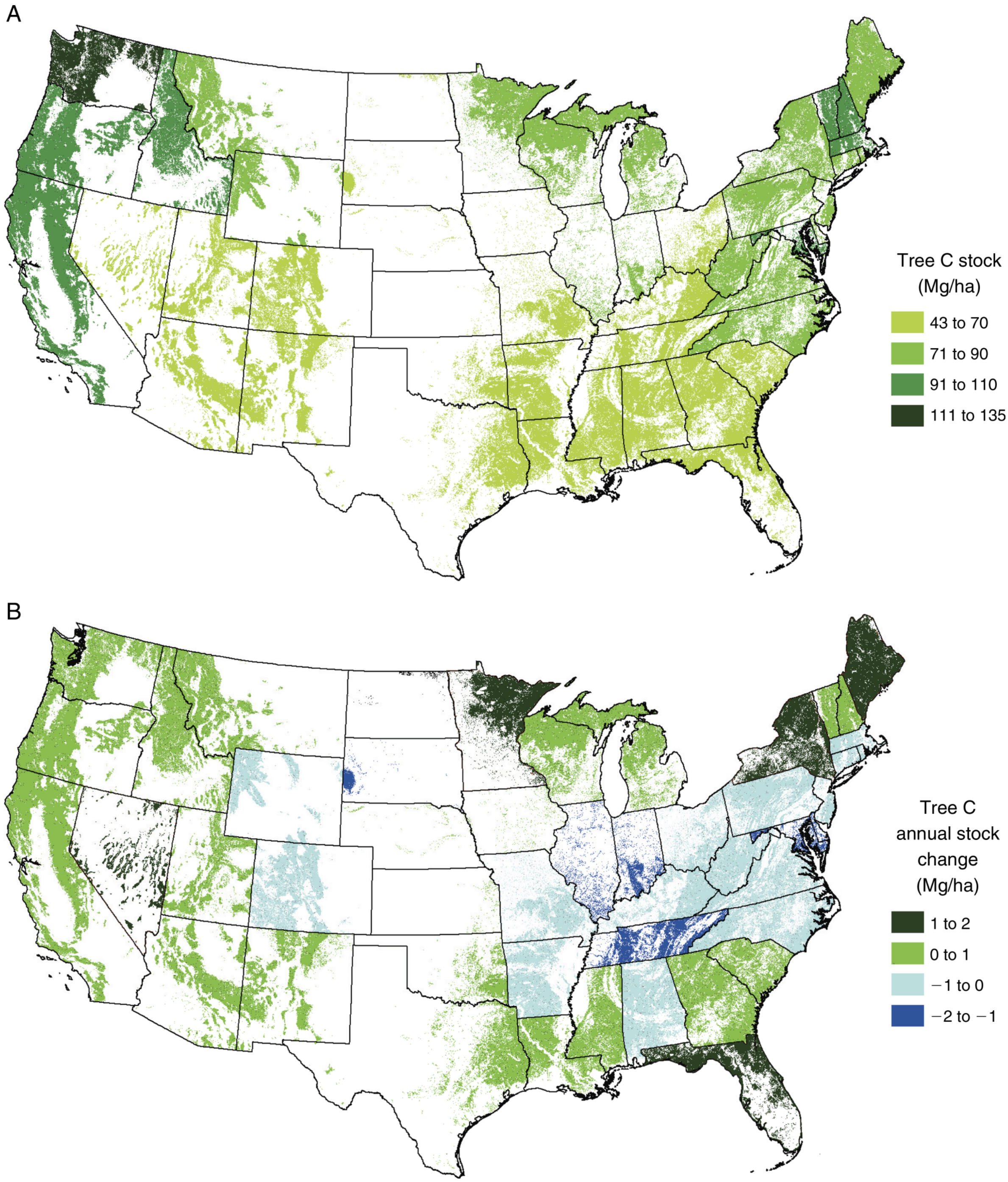

FIG. 5. (A) Average statewide forest carbon stocks (Mg C/ha) in live and dead trees in the conterminous United States and (B) changes (Mg C ha/yr) in forest carbon stocks from 1990 to 2005. Dark green represents the states with forests having the greatest carbon stocks or most carbon gain; light green represents the least. These maps were generated using data from the Forest Inventory and Analysis National Program (FIA). (Adapted from Woodbury et al. 2007*b*.)

are increasing carbon stocks (Briggs et al. 2005). Southern forests cover the greatest area in the conterminous United States and form a strong carbon sink because of their young age structure (resulting from past human disturbance) and very active forest management in this region (Turner et al. 1995, Johnsen et al. 2001; Figs. 5 and 6). About 13 million ha of southern forests are in pine plantations and include some of the more intensively managed forests in the world (Fox et al. 2007*b*).

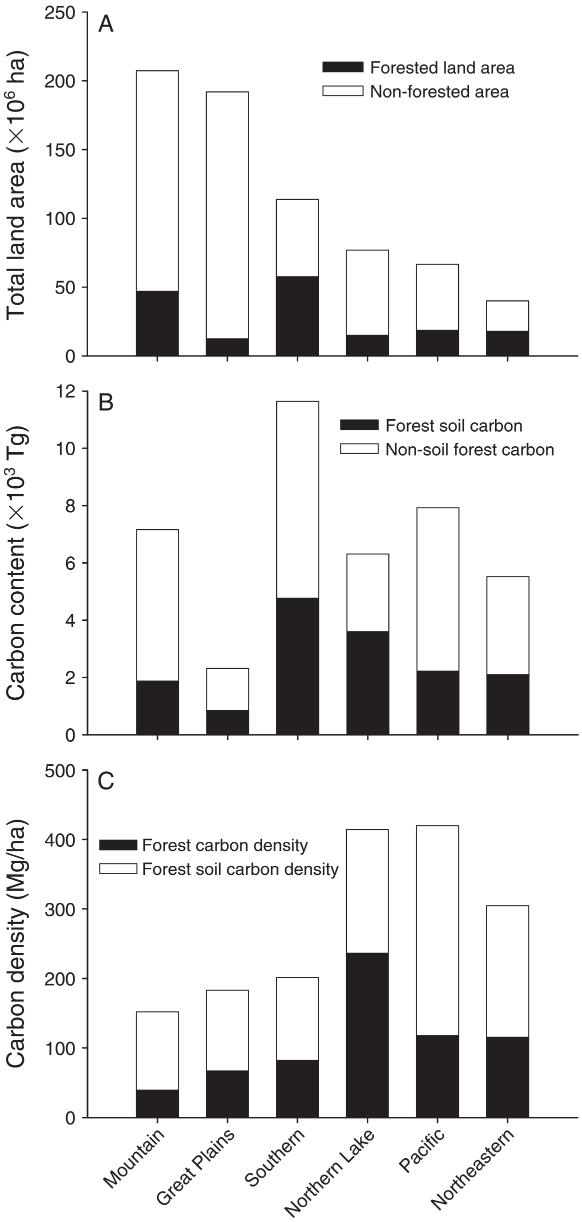

FIG. 6. (A) Total land area and forested area, (B) forest carbon in aboveground (non-soil forest carbon) and soil carbon stocks, and (C) carbon density of aboveground and soil carbon, including coarse roots of each region in the conterminous United States. Included states in each region are: Mountain (Arizona, New Mexico, Colorado, Utah, Wyoming, Montana, Idaho, Nevada); Great Plains (Texas, Oklahoma, Kansas, North Dakota, South Dakota, Nebraska, Missouri, Iowa); Southern (North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Arkansas, Kentucky, West Virginia, Virginia, Tennessee); Northern Lake (Wisconsin, Michigan, Illinois, Minnesota, Indiana, Ohio); Pacific (Washington, Oregon, California); and Northeastern (Massachusetts, New Hampshire, Maine, Rhode Island, Vermont, Connecticut, New York, New Jersey, Pennsylvania, Maryland, Delaware). Data source for carbon stocks and changes in U.S. forests is USDA (2008).

Current net forest growth in the United States (excluding interior Alaska) is 184 Tg C/yr, while 110 Tg C/yr is harvested annually and 55 Tg C/yr is lost to mortality and not harvested, giving gross forest growth of 349 Tg C/yr (Table 1; Smith et al. 2007: Table 36). Estimates of current annual net carbon storage change for U.S. forests are 192 Tg C/yr (USEPA 2010) and 256 Tg C/yr (SOCCR 2007). Differences among the estimates arise from differences in area included and different assumptions about carbon accumulation in pools that are difficult to measure. For example, the SOCCR (2007) estimate uses a much greater estimate for soil carbon accumulation (from Pacala et al. 2001) and includes carbon accumulation in urban forests. Although USEPA (2010) includes an urban tree category, we have not included that amount in the forest estimate we are using. For reference, U.S. CO_2 emissions in 2008 were 1615 Tg C/yr with another 282 Tg C/yr from other greenhouse gases such as methane and nitrous oxides (converted into CO_2 using "global warming potentials") (USEPA 2010).

MANAGING FORESTS FOR CARBON: PROJECT SYSTEM BOUNDARIES AND KEY CONCEPTS

Defining system boundaries is critical for evaluating the carbon impact of any carbon project. However, because CO_2 is well mixed in the atmosphere, important processes that control atmospheric CO_2 could be outside of the system boundary but remain unknown because they are too difficult to measure. For example, if system boundary for a project is a forest area, then decreasing harvests can influence activities outside of this boundary owing to a societal need to compensate for lowered supply of wood products by increasing supply elsewhere. Given a particular system boundary these so called "leakage" effects can be difficult to estimate. Other processes that are often not incorporated into the system boundary for a project include: possible emissions from disturbance or from planting, thinning, and harvesting; emission offsets (defined later in *Carbon offsets, credits, and additionality*) from wood energy use; and emission offsets from use of wood in place of alternate materials that emit more CO_2 in their manufacture. Economic market processes that influence the contribution of emission offsets from avoiding use of wood substitutes, use of biomass energy, and change in imports and exports of carbon in harvested wood products may have a notable influence on carbon stocks and offsets, and are discussed more in *Expanding the Role of Forests in Mitigating Climate Change*.

For our review of forests and carbon, we consider the forest project boundary (Fig. 7) to include one or more of the following: carbon stored in the forest, carbon stored in wood products in use and in landfills (Micales and Skog 1997, Skog 2008, Heath et al. 2010, Werner et al. 2010), and fossil fuel emissions that may be reduced by increases in wood biomass energy use (Schlamadinger et al. 1995) or reductions in fossil fuel emissions from

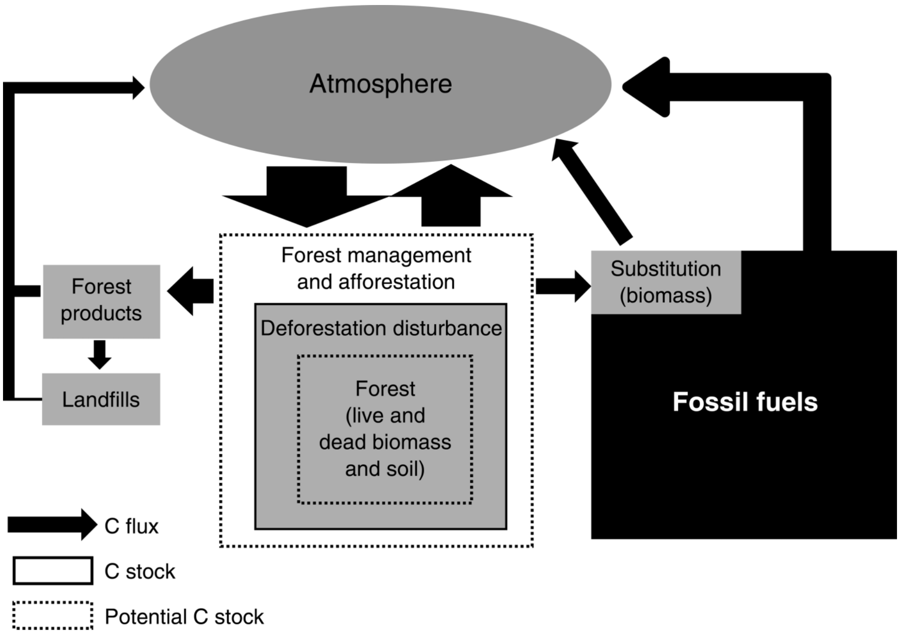

FIG. 7. Carbon stocks (boxes) and fluxes from those stocks (arrows) are shown as a conceptual model illustrating carbon dynamics within the system boundaries of a hypothetical forest system. The width of the arrows roughly approximates the magnitude of the flux (for conceptualization purposes only). The boundaries of the forest system include carbon stored in living/dead biomass and in soils, in which the carbon stocks can increase or decrease owing to afforestation or deforestation, respectively. A forest system includes carbon harvested from forest stocks to produce forest products (some of which enter landfills) as well as forest products used as substitutes for products that use significantly more energy in their production or are used as a direct substitute for fossil fuel in energy generation. Substitution "stores" carbon only in the sense that unused fossil fuel carbon remains in the ground. Per unit mass, more carbon can be emitted from the combustion of biomass than that of fossil fuels to produce the same energy equivalent, because some fossil fuels are more energy dense (i.e., more energy can be generated per unit carbon).

the substitution of wood for products such as steel and concrete that emit higher amounts of GHGs in their manufacture (Lippke et al. 2004, Perez-Garcia et al. 2005, Zerbe 2006). Conclusions about the effect of a carbon project will be influenced by the choice of the carbon storage and emission processes that are included within the system boundary.

Carbon offsets, credits, and additionality

A carbon offset is a reduction in greenhouse gas emissions (or an increase in carbon sequestration) by one individual or organization that can compensate for (or offset) emissions made by another individual or organization. The latter can thus use the former's offset to manage emissions. Offsets can refer to either carbon physically stored in forests and forest products or a reduction in fossil fuel carbon emissions as a result of the use of forest products (Fig. 7). Offsets are financial instruments that could be traded (bought and sold) as "carbon credits." Carbon offsets require additionality, that is, the carbon benefits occur as a result of an action deliberately taken to increase carbon sequestration above some reference level or "baseline" value (Vine et al. 2001). Estimates of additionality and timing of offset can be uncertain as in the case of offsets due to the effects of substitution of wood products for other building materials, substitution of wood biomass energy for fossil fuels, and changes in land use due to changes in management or product use. The baseline can differ with different system boundaries for a project. The baseline depends on estimates of the initial and forecasted carbon stocks and fluxes in the scenario of no proposed project action. Some metrics of additionality must make assumptions about future consumption and use of wood products and land use, which are determined by market forces over time.

The chosen baseline will influence and can even determine if a project will be carbon positive. For example, afforestation can noticeably increase ecosystem carbon stocks by growing trees, which store more carbon than either crops or grassland (Fig. 8A), assuming this would not have happened without human intervention. However, if the starting point is a mature forest with large carbon stocks (Cooper 1983, Harmon et al. 1990), then harvesting this forest and converting it to a young forest will reduce carbon stocks and result in a net increase in atmospheric [CO_2] for some time (Fig. 8B; Harmon and Marks 2002). Even if the mature forest is converted to a very productive young forest, it could take several harvest intervals to equal the amount of carbon that was stored in the mature forest, even with 100% utilization efficiency, biomass for energy and substitution (Harmon et al. 1990; Fig. 8A).

Permanence and leakage

Many recent forest carbon sequestration projects also consider "permanence" and "leakage" metrics. Permanence requires that the sequestered carbon will remain for the length of the project. Both natural and human disturbances can reduce permanence and anticipated gains for carbon sequestration projects. Negative leakage occurs when carbon sequestration projects cause changes to carbon stocks outside of the system boundary for a project, reducing or canceling the project's carbon benefit. Leakage in the form of harvest or land use change outside a system boundary can be quite significant (Murray et al. 2004, Meyfroidt et al. 2010), but is very difficult to measure because of the complexity of societies reliance on the forest system and forest use, rapid and global nature of market adjustments, and the difficulty of identifying cause and effect. Nonetheless, appropriate accounting of leakage and permanence is necessary to provide integrity to carbon sequestration projects.

Strategies for Increasing Forest Carbon

Avoiding deforestation

Between 1850 and 1998, global land use change released some 156 000 Tg C to the atmosphere, with most of this release resulting from deforestation (Houghton 2005). Currently, global deforestation results in the gross annual loss of nearly 90 000 km^2, or 0.2% of all forests (FAO 2007, IPCC 2007), which is estimated to release 1400–2000 Tg C/yr, with about two-thirds of the deforestation occurring in tropical forests in South America, Africa, and Southeast Asia (Houghton 2005, IPCC 2007).

Forests in the United States provide a strong carbon sink, partially from increases in forested area and forest regrowth (SOCCR 2007, USEPA 2009*b*, Crevoisier et al. 2010; Fig. 4, Table 1). The gross deforestation rate between 2000 and 2005 in the United States was ~600 000 ha/yr, but there was a net increase in forested area during this period of ~400 000 ha/yr because some 1 000 000 ha/yr of land reverted to forests (Birdsey et al. 2006, FAO 2007). These dynamics will change, with the balance of future land use expected to decrease total forested area in the United States by more than nine million ha by 2050 (Alig et al. 2003). Development and conversion of forest to pasture or agricultural land are responsible for much of the current and expected loss of U.S. forests. Fire disturbance regimes that increasingly fall outside of the ecological history of an ecosystem can result in the large-scale conversion of forests to shrublands and meadows. By contrast, regeneration of forests in these areas of the western United States will help retain forest carbon.

Afforestation

The term afforestation is generally defined as the establishment or planting of forests in areas where there have not been forests (e.g., grasslands) or where forests have not been present for some time (usually more than 20 years). In the United States, estimates suggest that afforestation could sequester between 1 and 225 Tg C/yr from 2010 to 2110, depending on federal policy and the valuation of carbon (USEPA 2005, SOCCR 2007; Table 1).

Proposed afforestation projects in the United States have focused on establishing forest plantations on marginal agricultural land to decrease potential interference with food production and reduce soil erosion. However, afforestation might require substantial human intervention in the form of irrigation or fertilization in areas that do not naturally support forests. In 2005, about one-half of the carbon sink in the conterminous United States (216–313 Tg C/yr; SOCCR 2007, USEPA 2010) was from forest regrowth on abandoned cropland (Pacala et al. 2001). Using 2005 data (SOCCR 2007) as an example, an effort to offset U.S. fossil fuel emissions of 1615 Tg C/yr by 10% (or 160 Tg C) per year, would require that one-third of U.S. croplands, or 44 million ha, would need to be converted to tree plantations (Jackson and Schlesinger 2004), requiring large changes in current land use. Texas, Minnesota, Iowa, Illinois, and Missouri have the greatest potential for afforestation of agricultural lands, and Texas, California, Montana, New Mexico, and Colorado have the greatest potential for afforestation of rangelands (Potter et al. 2007). The greatest gains in carbon storage through afforestation with the least human input in the form of irrigation and fertilization will occur where productive forestland once existed because climatic and edaphic conditions favor forest growth.

Afforestation can also affect soil carbon stocks (Dixon et al. 1994, Jandl et al. 2007), especially in degraded agricultural lands, which have lost as much as two-thirds of their original soil carbon (Lal 2004). Reviews of afforestation of former agricultural land found an average net increase in soil carbon of 0.14–0.34 Mg C ha/yr (Post and Kwon 2000, Paul et al. 2002), with a large variability across sites that differed by climate, age of the stand, tree type, and soil depth. A different analysis showed that soil carbon decreased 6.9% when trees were grown on grasslands, pasture, or shrublands (Berthrong et al. 2009). Soil carbon is typically lost in the first decade after forest establishment, but most forests eventually recover most of the lost soil carbon after 30 years (Paul et al. 2003). There is substantial evidence that most locations could expect a modest gain of soil carbon from afforestation over at least several decades.

Tree and shrub encroachment into grasslands, rangelands, and savannas, which may also be called unintentional afforestation, is estimated to sequester an estimated 120 Tg C/yr, more than one-half of what existing U.S. forests sequester annually (SOCCR 2007). Because tree growth estimates are sparse in these areas, this estimate is very uncertain (95% confidence bounds

>100%). Tree and shrub encroachment results from changing land use, overgrazing, and fire suppression (Van Auken 2000). The land area of woody encroachment in the United States is estimated to be 2.24 million km^2 (224 million ha), with the majority in the Rocky Mountain region (Houghton et al. 2000). Encroachment by *Juniperus* into native grasslands in the eastern Great Plains has increased ecosystem carbon stocks by as much as 100 Mg/ha in <50 years, or ~2 Mg C ha/yr (McKinley and Blair 2008, Strand et al. 2008). This estimate shows results similar to a grassland afforestation project with planted trees in China, which increased aboveground carbon stocks by 1.06–2.75 Mg C ha/yr (Hu et al. 2008). We do not include encroachment as a strategy because it is unintentional.

Forest management: decreasing forest harvests

Forest management can increase the interval between harvests or decrease harvest intensity and thereby increase forest carbon stocks (Schroeder 1992, Thornley and Cannell 2000, Liski et al. 2001, Harmon and Marks 2002, Jiang et al. 2002, Seely et al. 2002, Kaipainen et al. 2004, Balboa-Murias et al. 2006, Harmon et al. 2009). Some old growth forests in Oregon, for example, store as much as 1100 Mg C/ha (Smithwick et al. 2002), which would take centuries to recoup if these stocks were liquidated and replaced, even with fast growing trees (see Fig. 8B). Generally, harvesting forests with high biomass and planting a new forest will reduce overall carbon stocks more than if the forest were retained, even counting the carbon storage in harvested wood products (Harmon et al. 1996, Harmon et al. 2009). Thinning increases the size and vigor of individual trees, but generally reduces net carbon storage rates and carbon storage at the stand level (Schonau and Coetzee 1989, Dore et al. 2010). The estimates of harvest effects on soil carbon are mixed. A meta-analysis of forest harvest impacts showed a nonsignificant average loss of 8% of mineral soil carbon stocks and significant 30% loss of the organic layer (forest floor) carbon (Nave et al. 2010), whereas another review found no effect (Johnson and Curtis 2001). Low intensity or partial harvests maintain forest carbon stocks compared to clearcuts (Harmon et al. 2009) while possibly reducing the risk of disturbance, such as fire and damaging storms, and concurrently allowing forests to be used for wood products or biomass energy.

Forest management: increasing forest growth

Increasing growth rates in existing or new forests increases the carbon storage on the landscape, provided that the harvest interval is kept the same, and increases the supply of forest products or biomass energy. Practices that increase forest growth include fertilization; irrigation; switch to fast-growing planting stock; and weed, disease, and insect control (Albaugh et al. 1998, 2003, 2004, Allen 2001, Nilsson and Allen 2003, Borders et al. 2004, Amishev and Fox 2006).

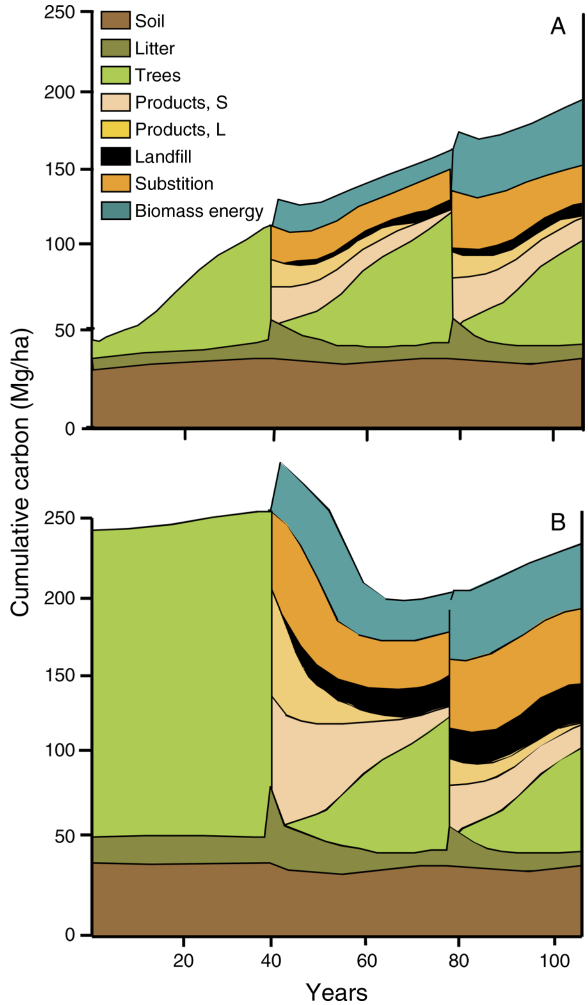

Fig. 8. Carbon balance from two hypothetical forest management projects with different initial ecosystem carbon stocks. Cumulative carbon stocks in both ecosystems, carbon removed from forest for use in wood products (long [L]- and short-lived [S]), substitution, and biomass energy (bio-energy) are shown for two scenarios: (A) land that has been afforested and (B) a forest with high initial carbon stocks. Carbon stocks for trees, litter, and soils are net carbon stocks only. Both scenarios are harvested in 40-year intervals. This diagram assumes that all harvested biomass will be used and does not account for logging emissions. Gains in carbon sequestration occur in two ways; (1) increasing the average ecosystem carbon stock (panel A; tree biomass), and (2) accounting for carbon stored in wood products in use and landfills, as well as preventing the release of fossil fuel carbon (counted as stored carbon) via product substitution or biomass energy (panel A; landfill, short- and long-lived products, and bio-energy). However, carbon can be lost for some time (panel B) when forests with substantial carbon stocks are harvested (e.g., some old-growth forests) until carbon stocks can accrue via sequestration in landfills, products, and with substitution effects. (The figure is adapted from the 2007 IPCC report.)

Yield gains from these practices can be impressive. In pine forests in the southern United States, tree breeding has improved wood growth, and thus carbon accumulation rate, by 10–30% (Fox et al. 2007*a*, *b*), and increased pest and stress resistance (McKeand et al. 2006) reduces losses to mortality. For southern U.S. pines, operational plantations using improved seedlings, control of competing vegetation, and fertilization grow wood four times faster than naturally regenerated second-growth pine forests without competition control (Carter and Foster 2006). Fertilization can show 100% gains for wood growth (Albaugh et al. 1998, 2004). Nitrogen and phosphorus fertilizers have been used in ~6.5 million ha of managed forests in the Southeast to increase wood production (Liski et al. 2001, Seely et al. 2002, Albaugh et al. 2007, Fox et al. 2007*a*). Many U.S. forests are nitrogen limited and would likely respond to fertilization (Reich et al. 1997). The potential to increase forest growth varies by site and depends on the specific climate, soil, tree species, and management. Where fertilization is used to increase carbon production and storage, careful accounting of the carbon cost of producing, transporting, and applying fertilizers, as well as any additional increases in other potent GHGs such as nitrous oxide (N_2O), is required.

Using wood products to reduce emissions from fossil fuels and store carbon

Biomass energy.—Increased wood biomass used in place of fossil fuels can lower atmospheric CO_2 over time depending on the forest growth or wood emissions that would have occurred without the increased use of wood for energy (Marland and Marland 1992, Schlamadinger et al. 1995, Searchinger et al. 2009). The degree and time path of emission offsets will also depend on its effects in changing forest harvest and forest products use elsewhere (Searchinger et al. 2008, 2009, Melillo et al. 2009, Meyfroidt et al. 2010). For biomass from existing forests, the CO_2 benefit balance is influenced by the time period considered, forest growth rate, initial stand carbon density, and the efficiency with which wood offsets fossil fuel emissions (Schlamadinger et al. 1995).

In 2008, biomass energy made up 28% of the U.S. renewable energy supply and 2% of the total U.S. energy use (U.S. Energy Administration 2009); estimates suggest that this could be increased to 10% through increased use of wood for energy generation (Zerbe 2006). If prices for biomass energy increase, short-rotation forest crops such as poplars could become a significant feedstock source (Solomon et al. 2007). Expansion of wood biomass energy is currently limited by high transportation costs, technology development, the low price of fossil fuels, and uncertainty as to how long forest resources will take to renew (Maness 2009).

Carbon in forest products

Wood and paper continue to store carbon when in use and also in landfills. The rates of change depend on the rates of additions, disposal, combustion, and open air or landfill decay. The half-life for single-family homes made of wood built after 1920 is about 80 years (Skog 2008, USEPA 2008), while the half-life of paper and paperboard products is less than three years (Skog 2008). About two-thirds of discarded wood and one-third of discarded paper go into landfills (Skog 2008). Decay in landfills is typically anaerobic and very slow (Barlaz 1998) and, because of this, 77% of the carbon in solid wood products and 44% in paper products will remain in landfills for a very long time (Chen et al. 2008, Skog 2008). About 2500 Tg C accumulated in wood products and landfills in the United States from 1910 to 2005 (Skog 2008), with ~700 Tg C (in 2001) in single- and multifamily homes (Skog 2008). In 2007, net additions to products in use and those in landfills combined were 27 Tg C/yr (USEPA 2009*c*), with ~19 Tg C/yr from products in use (Skog 2008).

Methane release from anaerobic decomposition of wood and paper in landfills reduces the benefit of storing carbon because methane has about 25 times more global warming potential than CO_2. For some paper, the global warming potential of methane release exceeds its carbon storage potential, but high lignin paper and wood have a positive carbon benefit, even considering methane emissions (Skog 2008). Using discarded products for energy generation would likely provide a better carbon benefit than landfill burial.

Substitution.—Using wood as a substitute for steel and concrete lowers fossil fuel emissions because the energy needed for production is considerably lower (Schlamadinger and Marland 1996). In some cases, using wood from fast-growth forests for substitution can be more effective in lowering atmospheric CO_2 than storing carbon in the forest where increased wood production is sustainable (Marland and Marland 1992, Marland et al. 1997, Baral and Guha 2004, Werner el al. 2010). The carbon storage effect of wood can be multiplied by as much as two or more times when wood is substituted for more energy-intensive building materials such as steel and concrete (Sathre and O'Connor 2008). Opportunities for substitution in the United States are largely in nonresidential buildings (McKeever et al. 2006, Upton et al. 2008) because most houses are already built with wood. Some other opportunities to increase the substitution effect in residential buildings do exist, however, by using wood for walls in houses, for example (Lippke and Edmonds 2006).

Urban forestry

Urban forestry (the planting and management of trees in and around human settlements) offers limited potential to store additional carbon, but we cover urban forests here because of the large interest in using them to offset carbon emissions and because urban trees provide many co-benefits. The carbon density of some urban ecosystems in the conterminous United States rivals that of tropical forests. In 2000, total carbon stocks of U.S. urban areas, including infrastructure, was 18 000 Tg C based on a small number of direct measurements

(Churkina et al. 2010), with a net accumulation rate of 26 Tg C/yr (USEPA 2010).

The potential for urban forestry to help offset GHG emissions is limited for two reasons: (1) urban areas make up only a small fraction of the U.S. landscape (3.5%; Nowak and Crane 2002), and (2) urban forests require intensive management. When urban landscapes are irrigated or fertilized, the carbon benefits may be reduced by the energy required for the synthesis of fertilizer, by the extraction and application of irrigation water, and by soil nitrous oxide emissions (Pataki et al. 2006). Urban forests have important indirect effects on climate (Akbari 2002), however, by cooling with shading and transpiration, potentially reducing fossil fuel emissions associated with air conditioning. When urban forests are planted over very large regions, the climate effects are less certain, as trees have both warming effects (low albedo) and cooling effects, and may result in complex patterns of convection that can alter air circulation and cloud formation (Jackson et al. 2008).

Fuel treatments

Fuel management uses thinning to lower foliage biomass to reduce the risk of crown fire because crown fires are difficult, if not impossible, to control (Finney 2001, Ager et al. 2007). Fuel management occurs in forests with a variety of historical fire regimes, from forests where historical forest density was lower and the natural fires were mostly surface fires, to forests with stand-replacing fire regimes in which crown fires naturally occurred (Finney 2001, Peterson et al. 2005, Ager et al. 2007, Mitchell et al. 2009). Fuel management temporarily lowers the carbon stored in forest biomass and dead wood because the thinned trees are typically piled and burned or mulched and then decompose (Stephens et al. 2009). If a crown fire burns through a forest that was thinned to a low density, the fire may change from a crown to a surface fire in which many of the trees can often survive the fire. By contrast, many or all of the trees in an unthinned stand are often killed by a crown fire. This contrast in survival has led to the notion that fuel treatments offer a carbon benefit: removing some carbon from the forest may protect the remaining carbon (Finkral and Evans 2008, Hurteau et al. 2008, Mitchell et al. 2009, Stephens et al. 2009, Dore et al. 2010).

There are two views regarding the science on carbon savings through fuel treatments. Some studies have shown that thinned stands have much higher tree survival and lower carbon losses in a crown fire (Hurteau et al. 2008) or have used modeling to estimate lower carbon losses from thinned stands if they were to burn (Finkral and Evans 2008, Hurteau and North 2009, Stephens et al. 2009). However, other stand-level studies have not shown a carbon benefit from fuel treatments (Reinhardt et al. 2010), and evidence from landscape-level modeling suggests that fuel treatments in most forests will decrease carbon (Harmon et al. 2009, Mitchell et al. 2009) even if the thinned trees are used for biomass energy. Because the occurrence of fires cannot be predicted at the stand level, treating forest stands without accounting for the probability of stand-replacing fire could result in lower carbon stocks than in untreated stands (Hanson et al. 2009, Mitchell et al. 2009). More research is urgently needed to resolve these different conclusions because thinning to reduce fuel is a widespread forest management practice in the United States (Battaglia et al. 2010). We recommend that such research focus on the landscape scale because carbon loss in thinning needs to be placed in the context of the expected fire frequency and extent and the potential for regeneration after fire. Regardless of the outcome of such research, the carbon benefits of fuel treatments might be improved by using the harvested trees for wood or energy generation.

Measuring Forest Carbon

Carbon in forests

At the scale of individual forest stands, standard inventory methods are used to estimate the carbon stored in trees, plants, dead wood, and in forest floor litter (Gibbs et al. 2007). These approaches use mathematical formulas (allometry) to calculate tree biomass from simple measurements (e.g., tree diameter at 1.4 m), which can be converted to carbon using a simple ratio. Forest carbon estimates can be enhanced by measuring other pools, such as dead wood and soil (Bradford et al. 2008). Repeated measurements or models are used to estimate changes in carbon over time. Estimates of belowground carbon stocks are more difficult because of limited data on root biomass, the high spatial variability of soil carbon, and the high cost of sampling (Davis et al. 2004).

Remote sensing can measure or verify aboveground pools of carbon at landscape scales. Radar and lidar are effective at monitoring of vegetation structure, tree height, cover, and disturbance (Hese et al. 2005, Sherrill et al. 2008, Asner 2009, Helmer et al. 2009). Satellite-based observation can also be used to obtain coverage of large areas (Nabuurs et al. 2010). These techniques can be combined with inventory-based methodologies to increase statistical certainty when extrapolating to large spatial scales (Dubayah and Drake 2000, Brown 2002).

Monitoring at the regional or national scale will require information from combinations of methodologies obtained at different spatial scales. In the United States, the official forest carbon statistics are based on field plots from the Forest Inventory and Analysis National Program combined with remotely sensed changes in forest age, cover types, and disturbance (see Fig. 5; Smith and Heath 2008, USEPA 2008). Regional gaps in inventory data can be addressed using remotely sensed data combined with modeling (Birdsey 2004). A more complete discussion on general methodologies to estimate forest carbon stocks can be found in Gibbs et al. (2007).

Carbon in wood products, substitution, and biomass energy

The carbon stored in wood products is difficult to measure directly because no direct measurement system exists and imports and exports must be tracked. Monitoring of carbon accumulation in wood products is currently conducted at the national scale (Aalde et al. 2006, USEPA 2009*c*) using models to track the quantity of wood in different uses over time. These estimates can be verified by comparison to census-based estimates of carbon stored in housing and to the U.S. Environmental Protection Agency's estimates of wood and paper discarded to landfills and the resulting methane emission rates (Skog 2008, USEPA 2009*c*). Estimates of wood product decomposition can be made using regional or local data on timber use and national estimates of decay for those uses (Smith et al. 2006). This procedure was used in accounting for the carbon in wood products adopted by the California Air Resource Board (Climate Action Reserve 2009). Industrial use of biomass energy can be tracked through sales records and self-reporting (Hillring 2006). Unlike measures of carbon storage or "carbon offsets" using forests and forest products, there are no direct measures for carbon offsets resulting from product substitution or biomass energy.

Expanding the Role of Forests in Mitigating Climate Change

To increase forest carbon storage, carbon storage in harvested wood products, offset of emissions by alternate use of steel and concrete vs. wood, and offset of fossil fuels with wood of wood energy, societies will need to assign a high value to carbon to make these activities economically viable through market mechanisms (USEPA 2005, Maness 2009). For example, direct subsidies paid to landowners (as in the current Conservation Reserve Program for agriculture) could also provide an incentive to maintain or increase carbon stocks. Voluntary markets and registries are emerging, and current proposals being debated include a carbon tax, a "cap-and-trade" market, and land use regulation (Lippke and Perez-Garcia 2008).

Several studies have estimated the potential for increased forest sector carbon mitigation (Table 1). Jackson and Schlesinger (2004) estimate that one-third of current U.S. cropland would need to be afforested to offset 10% of U.S. fossil fuel emissions (160 Tg C/yr). Perlack et al. (2005) estimate that U.S. forests could provide ~190 Tg C/yr for energy generation, using residue from logging and land clearing operations, fuel treatments, fuelwood, unutilized wood and pulping liquors in processing mills, and urban areas. Zerbe (2006) estimates that forest biomass energy could provide 130 Tg C/yr for energy generation. With the use of only harvest residue, forests could provide ~20 Tg C of dry wood annually, producing ~4 billion gallons (15×10^9 L) of biofuel per year by 2022 (BRDI 2009). The U.S. Environmental Protection Agency (USEPA 2005) estimates that U.S. forests could offset an additional 30–330 Tg C/yr above current levels between 2010 and 2110 with economic incentives of $18–$183 US$ per Mg carbon; for an economic incentive of $110 US$ per Mg of carbon, afforestation supplied 58% of the carbon savings and forest management 42% (this report did not evaluate avoided deforestation). Jackson and Baker (2010) estimate that afforestation, forest management, and forest biomass fuels could offset an additional 90–200 Tg C/yr, with afforestation (46%) and forest management (50%) supplying most of the benefit.

Estimates of the economic potential for forest carbon for different strategies are generally highly uncertain due, in part, to the large scale necessary for some activities. For example, utilizing the unused and currently used residue from forest harvest for biomass energy (Perlack et al. 2005) would be roughly equivalent to 40% of the gross annual forest growth in the United States (Table 1), growing to roughly 54% by 2030. Also, to achieve the higher range of carbon storage (200–330 Tg C/yr) estimated in the USEPA (2005) report would require improved forest management on 34–60 million ha and afforestation of 25–46% of U.S. cropland (based on afforestation carbon storage potentials reported in Jackson and Schlesinger 2004). Such large-scale land use change could lead to increased deforestation in other countries to replace the lost crop production in the absence of global mitigation measures.

Using economic incentives within the forest sector to lower atmospheric CO_2 will have a significant monetary cost (USEPA 2005). The estimated cost of the USEPA (2005) high-end estimates of 200–330 Tg C/yr in the United States is $110–$183 per Mg of carbon, for a total annual cost of $23–60 billion US$. However, economic modeling consistently shows that forest carbon storage (including afforestation) can significantly lower the cost of complying with the proposed regulations and meeting emissions targets (Xu 1995, Huang et al. 2004, Richards and Stokes 2004, Niu and Duiker 2006, Strengers et al. 2008, Maness 2009, USEPA 2009*a*) compared to the same reductions in the energy or transportation sectors.

Uncertainty, Risk, and Trade-offs

Each forest carbon storage strategy mentioned previously has trade-offs and can be affected by systemic factors, increasing uncertainty and risk. It is impossible to make changes to the forest and forest products system that are large enough to have an impact on atmospheric [CO_2] without also having large effects on other ecosystems or ecosystem services. In addition, population increase and exurban development will decrease the general amount of forested area while increasing demand for forest products. The potential to increase carbon storage in forests needs to be weighed against the projected increases in disturbances promoted by a changing climate that may lower carbon storage. Recognizing such issues will be vital to any effort to promote forest carbon storage.

Disturbance

Increasing carbon sequestration in forests also increases the risk and impact of losing some of these carbon stocks to forest fires, insect outbreaks, and storms (Girod et al. 2007, Kurz et al. 2008*b*, Balshi et al. 2009, Metsaranta et al. 2010). Although most disturbances have little effect on forest carbon stocks over long temporal and large spatial scales, our knowledge of how more extreme future disturbances (those outside of the observed range of variability) will affect carbon management and sequestration is limited (Breshears and Allen 2002).

Climate change threatens to amplify risks to forest carbon stocks by increasing the frequency and severity of disturbances such as wildfires, insect outbreaks, hurricanes, and drought, lowering the potential productivity and long-term storage capacity of some forests, and threatening the ability of some forests to remain as forests (Dale et al. 2000, 2001, Barton 2002, Breshears and Allen 2002, Westerling et al. 2003, Running 2006, Canadell et al. 2007*b*, Chambers et al. 2007, Strom and Fule 2007, Kurz et al. 2008*a*, Littell et al. 2009, Metsaranta et al. 2010). Changes in forest structure caused by fire suppression, harvest of large trees, and interactions with climate change have been implicated in creating larger and more severe wildfires in some fire-adapted ecosystems in the western United States (Covington and Moore 1994, Dale et al. 2001, Westerling et al. 2003, 2006, Brown et al. 2004, Breshears et al. 2005, Kashian et al. 2006, Allen 2007, Fellows and Goulden 2008, Miller et al. 2009). Since 1990, CO_2 emissions from wildland forest fires in the conterminous United States have ranged between 11and 85 Tg C/yr (USEPA 2009*b*). The annual area of U.S. forests burned has been increasing over the last 60 years (Stephens 2005, Westerling et al. 2006, Littell et al. 2009), and projections using future climate suggest that the annual area burned is likely to double by 2100 (McKenzie et al. 2004). High-severity fires can increase soil erosion, alter nutrient cycling, decrease post-fire seedling recruitment, which can shift forests to meadows or shrublands and cause long-term losses of carbon, compromising carbon offset projects (Barton 2002, Savage and Mast 2005, Allen 2007, Strom and Fule 2007, Galik and Jackson 2009, Metsaranta et al. 2010). Increases in the frequency and intensity of storms and insect outbreaks, as well as changes in climate may also affect site productivity and the range of forests. Many forests could release significant amounts of carbon to the atmosphere during the next 50–100 years, which coincides with the period when reducing CO_2 emissions is most critical. Climate change adaptation strategies for forests are being developed to anticipate necessary management changes in a changing climate (Joyce et al. 2008).

Strategies for increasing forest carbon storage and offsets

We define uncertainty as the extent to which an outcome/result is not known and risk as the potential for harm resulting from the mitigation activity. Risk can refer to harm to both the forest and climate system (e.g., elevated GHGs). The following strategies are discussed in order of increasing uncertainty and risk (see Table 2 for summary).

Avoided deforestation.—Avoided deforestation protects existing forest carbon stocks with low risk and many co-benefits. Important risks are the potential for leakage (deforestation can move elsewhere with no lowering of atmosphere [CO_2]) and lost economic opportunities for timber, agriculture, pasture, or urban development (Meyfroidt et al. 2010). Leakage estimates (percentage of carbon benefit lost) for avoided deforestation, without allowing harvest, range from 9% to 92% for different U.S. regions (Murray et al. 2004). In the United States, regenerating forests after severe wildfires may be important for avoiding conversion of forest to meadow or shrubland (Keyser et al. 2008, Donato et al. 2009).

Afforestation.—Afforestation stores carbon and has some benefits (including erosion control and improving water quality), few risks and uncertainties, but some trade-offs. Afforestation on historical forestland generally has the greatest co-benefits, lowest risk, and fewest trade-offs. The benefits of afforestation are enhanced where seedlings established, whether by planting or natural regeneration, include a substantial proportion of native species appropriate to the site. This will enhance species diversity, and possibly wildlife habitat, with the lowest risk for unintended consequences if done on lands that were formerly forests. Planting monocultures of nonnative or native improved-growth species on historical forestland will likely yield greater carbon storage rates, but fewer benefits in terms of biodiversity.

Planting trees where they were not present historically can lower species diversity (if trees are planted in native grassland), lower the water table, cause soil erosion on hill slopes, and absorb more solar energy (lower albedo) compared to the native ecosystem (Jobbagy and Jackson 2004, Farley et al. 2008, Jackson et al. 2008, McKinley and Blair 2008, Schwaiger and Bird 2010). Conversion of agricultural or grazing lands to forest reduces revenue from agricultural products and may lead to deforestation elsewhere to compensate; this type of leakage can be significant (18–43%; Murray et al. 2004). Afforestation generally reduces streamflow because trees use more water than do grass or crops (Farley et al. 2005, Jackson et al. 2005). Irrigation might be necessary in some arid and semiarid regions, which might compete with agricultural water supply and other uses. If afforestation efforts include the addition of nitrogen fertilizer, emissions of nitrous oxide (a greenhouse gas with roughly 300 times more global warming potential than CO_2) may increase.

Decreasing carbon outputs.—Decreasing removal of carbon from forests through longer harvest intervals or less intense harvests will increase forest carbon stocks. Benefits of the decreased outputs strategy include an

TABLE 2. Uncertainty, co-benefits, and trade-offs of proposed carbon mitigation strategies.

Mitigation strategy	Uncertainty about strategy	Co-benefits	Trade-offs
Avoided deforestation	low: uncertainty about leakage; uncertainty about risk of disturbance	any watershed protection, biodiversity, wildlife habitat, recreation opportunities depend on type of avoided deforestation	lost economic opportunities affecting farmers or developers directly
Afforestation	low-moderate: depends on where afforestation is done; uncertainty about biophysical effects, leakage, and risk of disturbance	erosion control, improved water quality; any biodiversity and wildlife habitat improvements depend on type of afforestation	lower streamflow, lost revenue from agriculture, demand for agricultural water; increased release of N_2O reduces the carbon benefit
Management			
Decreasing C outputs (harvest)	moderate: uncertainty about how to influence landowner behavior efficiently to decrease harvest; leakage effects could be significant	increased old-growth seral stage; structural and species diversity, wildlife habitat; effects on benefits depend on landscape condition	displaced economic opportunities affecting forest owners, forest industry, and employees
Increasing forest growth	low	higher wood production, potential for quicker adaptation to climate change	lower streamflow, loss of biodiversity; release of N_2O reduces the carbon benefit; greater impacts of disturbance on carbon storage
Biomass energy	moderate: uncertain technology	increased economic activity in forest products industries, could reduce costs of forest restoration efforts	intensive forest management on larger area, lower carbon storage in forests
Product substitution	moderate: difficulty demonstrating additionality, limitations in expanding wood use in construction applications	increased economic activity in forest products industries	active forest management on larger area, lower carbon storage in forests
Urban forestry	high: net carbon benefit depends on many factors	any shading, reducing energy use for cooling, wildlife habitat, recreation projects depend on type of project	high maintenance requiring inputs of water, energy, and nutrients, particularly if forests were not the native ecosystem and with poor species choice; release of N_2O reduces the carbon benefit
Fuel treatments	high: benefits have not yet been examined at landscape scale; large unknowns remain about carbon benefits	lower risk from fire and insects; increased economic activity; possible offsets from use of wood	lost economic opportunities to firefighting businesses and employees; lower carbon on site

Notes: We define uncertainty as the extent to which an outcome/result is not known. All the listed mitigation strategies have a risk of leakage and reversal, which could compromise carbon benefits and permanence, respectively.

increase in structural and species diversity. Increased risks include carbon loss due to disturbance and the potential for increased harvesting elsewhere (leakage) to compensate for the reduction in forest products.

Increasing forest growth.—The benefits of increasing forest growth include the opportunity to increase wood production, possibly greater carbon stocks, and opportunity to plant species and genotypes adapted to future climates. Risks include reducing the carbon benefit by emissions of nitrous oxide from forest fertilization, reduced water yield (faster growth uses more water), which is more pronounced in arid and semiarid forests in the western United States, and a loss of biodiversity if faster growth is accomplished by replacing multispecies forests with monocultures (limited diversity can make some forests vulnerable to rapid environmental change and to insect and disease epidemics).

Biomass energy, carbon storage in products, and substitution.—The carbon benefits of increasing the use of wood for biomass energy and for product substitution might require more intensive forest management over a much broader area than currently occurs in the United States, depending on how and to what extent wood products are utilized. For example, the aforementioned 130–190 Tg C/yr of potential biomass energy (Perlack et al. 2005, Zerbe 2006) would involve using estimated sustainable and recoverable portions of unused and currently used residue from logging and land clearing operations, along with amounts from estimated fuel treatments, fuelwood, unutilized wood and pulping liquors in processing mills, and urban wood waste. To the extent that wood energy use exceeds use of these residues or forest harvesting is expanded beyond current usage to meet demand for biomass energy, there would be reductions in carbon stored in the forest. If additional forest harvest were necessary to produce wood for energy, the result would be a near-term emission that would again require time to offset with forest regrowth (Marland and Marland 1992). If branches and foliage were to be removed for biomass energy beyond a limited fraction, fertilization could be needed to replace the nutrients removed to maintain productivity (Patzek and Pimentel 2005). Additionally, dead wood will decrease and soil carbon may decrease under harvesting. Displacing agriculture for afforestation or energy crops could lead to deforestation elsewhere, and those carbon emissions can negate any climate benefit or cause more carbon emissions (Searchinger et al. 2008, Melillo et al. 2009, Meyfroidt et al. 2010), as well as reduce food production and security (Campbell et al. 2008). Last, because reductions in fossil fuel carbon emissions resulting from product substitution and biomass energy are difficult to demonstrate and subject to leakage, these efforts may only partly decrease fossil energy use.

Urban forestry.—Urban forestry has a relatively small role in storing carbon with both significant trade-offs and co-benefits. The higher the maintenance required for urban trees, the less likely they will help mitigate climate change. Urban trees can have high mortality rates in all regions (Nowak et al. 2004). Where cities are located in what would naturally be forested areas, urban forests serve to restore these lands, and trees will likely have lower maintenance requirements. In cities located in grasslands and deserts, however, urban forests require large amounts of irrigation water for maintenance.

Fuel treatments: mitigating fire risk to prevent carbon loss.—The carbon benefits of fuel treatments are uncertain.

Conclusions and Recommendations

U.S. forests and forest products currently store the equivalent to 10–20% of U.S. fossil fuel emissions (SOCCR 2007, USEPA 2008), largely because of continued forest recovery from past deforestation and extensive harvesting. Increased nitrogen deposition and atmospheric CO_2 compared to historical levels may also be contributing to increased forest growth, but the science supporting their contribution is uncertain (Hurtt et al. 2002, Canadell et al. 2007*b*).

How much longer U.S. forests will continue to be a carbon sink is unclear because forests are still growing and future land use is difficult to predict. Forest regrowth in the United States has recovered ~40% of the carbon lost to the atmosphere through deforestation and harvesting before 1935 (Fig. 4; Birdsey et al. 1993, 2006). Because a significant portion of former forestland is now in agriculture or pasture (Smith et al. 2007), it is unlikely that U.S. forests will recover all of the forest carbon stocks present prior to European settlement. Population growth and the resulting exurban development, and an increase in disturbance in a changing climate will also reduce existing forests and carbon stocks.

Perhaps the most difficult and yet most important question is: will the carbon that we deliberately sequester remain stored long enough to allow society to reduce its dependence on fossil fuels and/or to find a means to remove and permanently store CO_2 from the atmosphere? The answer is: it depends. Forest management can increase average forest carbon stocks through a variety of mechanisms, but the length of time in which carbon will be sequestered will depend on the length of carbon sequestration projects, consistency of management techniques over space and time, and our capacity to anticipate and adapt to changing disturbance regimes, climate change, and offset effects influenced by market forces. Each forest carbon storage strategy should be evaluated in terms of its effect on storage and emissions within and outside of the forest, the cost of implementation, the timing of net carbon benefit (Marland et al. 1997), the capacity to offset CO_2 emissions, and the risks and uncertainties.

There are some notable opportunities to expand the use and increase the effectiveness of some forest carbon storage strategies. Wood and paper currently being placed in landfills could be used as energy in place of fossil fuel and also reduce methane emissions from landfills. Wood use could be expanded in nonresidential building construction and for walls in residential housing. Natural disturbances (fire and beetle kill) offer an opportunity to use dead trees for biomass energy (Kumar 2009). The potential of forest soils to sequester carbon are high, particularly in forests that are restored on former agricultural land (Heath et al. 2003). Planting trees after certain catastrophic fires can increase carbon storage in areas that will not regenerate naturally.

Each strategy we examined has trade-offs. Avoiding deforestation and increasing the harvest interval in the United States may move timber harvesting elsewhere, resulting in no net benefit for carbon in the atmosphere. Reestablishing forests (afforestation) can store large amounts of carbon on a unit of land but will also displace current land uses such as farming and pasture. Longer harvest intervals may initially lower the amount of available forest products, but could foster a move toward higher-value forest products that are locally sourced. Intensive silviculture can increase growth but decrease streamflow and biodiversity. Increasing forest product use and forest biomass energy will require more active forest management over larger areas than currently occurs and may lower forest carbon stores. Although the carbon consequences are still largely unknown, the use of biomass for energy from forest thinning might help lower fire risk and suppression costs and reduce fossil fuel use. Forests offer many benefits besides carbon, so managers should consider all benefits and trade-offs associated with each activity before deciding on specific land management practices.

Knowledge gaps

Further research would fill a number of knowledge gaps that span scientific disciplines. Although we have a good knowledge of forest carbon at the plot level, we lack knowledge of natural and human influences on forest carbon at the landscape scale. Problems such as the carbon effects of fuel treatments, the effects of disturbance, and changes in land use can only be understood at the landscape scale. Other unknowns at this scale are the interactions of climate change, disturbance, and species shifts with carbon balance. Also, a greater comprehensive understanding of carbon flows among different processes and their interactions within large or complex system boundaries is necessary. How land cover change alters albedo and evapotranspiration is only generally understood, but could be very important. Methods to assess and measure additionality, leakage, permanence, and substitution are needed, particularly for long temporal and large spatial scales. Carbon life-cycle analyses are largely absent in assessments of forest carbon storage strategies and are vitally needed to determine net benefits to atmospheric [CO_2]. Closing these knowledge gaps will help carbon accounting efforts and the market viability of forest carbon.

Considerations for forest carbon policy

National policy, market forces, public will, and biological potential will determine how much more carbon U.S. forests can store through forest management or offset fossil fuel use via substitution and biomass energy (Maness 2009). If carbon were assigned a high monetary value, U.S. forests could roughly double their current annual carbon benefit (USEPA 2005, Nabuurs et al. 2007, Fujimaki et al. 2009). Such large offsets would require substantial trade-offs, such as lower agricultural production, diminished non-carbon ecosystem services from forests, and higher risk for increasing forest carbon loss in forests. Decision-makers will need to weigh the potential carbon and other benefits of these activities against the considerable uncertainties surrounding their carbon consequences (i.e., leakage effects and risks), negative impacts on other ecosystem services, some large negative societal and monetary trade-offs, enormous scale needed for proposed activities, and uncertainty in how future climate will affect forests.

A policy decision on the timing of carbon benefits will influence which strategies to employ. One strategy would be to seek near-term carbon benefits by maintaining and enhancing growth and carbon storage in forests. Near-term carbon benefits could also be achieved by optimizing forest management and the use of wood products and biomass energy where it yields near-term offsets, as well as accumulates offsets over time that would exceed near-term accumulation in forest. By contrast, the carbon benefits of some strategies may be deferred for some time; in particular, strategies that involve the use of forests with large carbon stocks (e.g., old growth forests) or those that are not efficient. Any policy to encourage programs or projects that influence forest carbon sequestration and offset fossil fuel emissions should: (1) promote the retention of existing forests; (2) account for other greenhouse gas effects, such as methane and nitrous oxide emissions and biophysical changes; (3) account for leakage, such as harvest moving elsewhere indirectly caused by changes in management with the project system boundary; (4) recognize other environmental benefits of forests, such as biodiversity, nutrient management, and watershed protection; (5) focus on the most robust and certain carbon storage benefits in any compensation scheme; (6) recognize the cyclical nature of forest growth and regrowth, the extensive movement of forest products globally, and the difficulty and expense of tracking forest carbon; (7) recognize that the value of any carbon credit will depend on how well the carbon can be measured and verified; (8) acknowledge that climate change and population growth will increase the potential for forest loss and may keep large-scale projects from reaching their full potential; (9) recognize the trade-offs involved in the various forest carbon storage strategies, and (10) understand that the success of any carbon storage strategy depends on human behavior and technological advances in addition to forest biology.

Realistic, science-based assumptions should be used to establish baselines to assess additionality, that is, providing reasoning and evidence that the carbon benefit is the result of actions deliberately taken. Identification and delineation of the system boundary for various activities is critical for comprehensive understanding and optimizing carbon benefits. Protocols that estimate carbon credits should appropriately discount carbon storage estimates for uncertainty in measurement, effects beyond the system boundary of the project, and permanence. Sound methods with adjustments for uncertainty are also needed to estimate leakage (a project indirectly causing carbon loss outside of the project's boundaries) and permanence (a specified minimum length of time that carbon is to be stored) concerning forest carbon, wood products carbon, and the effects of substitution and biomass energy use.

Because forest carbon loss poses a significant climate risk and because climate change may impede regeneration following disturbance, avoiding forest loss and promoting regeneration after disturbance should receive high priority as policy considerations. Avoiding loss of forests should be a strong policy consideration owing to very low risk and little uncertainty compared to other strategies discussed in this report. Forest loss moves carbon from forests to the atmosphere, particularly where the loss includes not only trees but also the decomposition of soil carbon. Because of climate change, increasing forest disturbance, and continued population growth and exurban development, we cannot assume that existing forests will remain. Focusing on adaptation to the effects of climate change (Joyce et al. 2008) to protect existing forests and as a complement to implementing forest carbon storage strategies would be prudent.

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