May 2014

Managing Carbon

Kenneth E. Skog
U.S. Forest Service, Madison, WI, kskog@fs.fed.us

Duncan C. McKinley
U.S. Forest Service, Washington, DC, dcmckinley@fs.fed.us

Richard A. Birdsey
USDA Forest Service, Newtown Square, rbirdsey@fs.fed.us

Sarah J. Hines
Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, CO, shines@fs.fed.us

Christopher W. Woodall
Northern Research Station, U.S. Forest Service, Saint Paul, MN, cwoodall@fs.fed.us

See next page for additional authors

Skog, Kenneth E.; McKinley, Duncan C.; Birdsey, Richard A.; Hines, Sarah J.; Woodall, Christopher W.; Reinhardt, Elizabeth D.; and Vose, James M., "Managing Carbon" (2014). *USDA Forest Service / UNL Faculty Publications*. 274.
http://digitalcommons.unl.edu/usdafsfacpub/274

Authors

Kenneth E. Skog, Duncan C. McKinley, Richard A. Birdsey, Sarah J. Hines, Christopher W. Woodall, Elizabeth D. Reinhardt, and James M. Vose

Chapter 7
Managing Carbon

Kenneth E. Skog, Duncan C. McKinley, Richard A. Birdsey, Sarah J. Hines, Christopher W. Woodall, Elizabeth D. Reinhardt, and James M. Vose

7.1 Introduction

Storing carbon (C) and offsetting carbon dioxide (CO_2) emissions with the use of wood for energy, both of which slow emissions of CO_2 into the atmosphere, present significant challenges for forest management (IPCC 2001). In the United States, there has been a net increase in C in forests and in harvested wood products stocks (Tables 7.1 and 7.2), a result of historical and recent ecological conditions, management practices, and use of forest products (Birdsey et al. 2006). However,

K.E. Skog (✉)
Forest Products Laboratory, U.S. Forest Service, Madison, WI, USA
e-mail: kskog@fs.fed.us

D.C. McKinley
National Research and Development Staff, U.S. Forest Service, Washington, DC, USA
e-mail: dcmckinley@fs.fed.us

R.A. Birdsey
Northern Research Station, U.S. Forest Service, Newtown Square, PA, USA
e-mail: rbirdsey@fs.fed.us

S.J. Hines
Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, CO, USA
e-mail: shines@fs.fed.us

C.W. Woodall
Northern Research Station, U.S. Forest Service, Saint Paul, MN, USA
e-mail: cwoodall@fs.fed.us

E.D. Reinhardt
Fire and Aviation Management, U.S. Forest Service, Washington, DC, USA
e-mail: ereinhardt@fs.fed.us

J.M. Vose
Southern Research Station, U.S. Forest Service, Raleigh, NC, USA
e-mail: jvose@fs.fed.us

D.L. Peterson et al. (eds.), *Climate Change and United States Forests*, Advances in Global Change Research 57, DOI 10.1007/978-94-007-7515-2_7,

Table 7.1 Net annual changes in carbon (C) stocks in forest and harvested wood pools, 1990–2009

C pool	1990	2000	2005	2009
	(Tg C year^{-1})			
Forest				
Live, aboveground	−98.2	−78.3	−122.1	−122.1
Live, belowground	−19.3	−15.7	−24.1	−24.1
Dead wood	−8.6	−3.5	−8.4	−9.1
Litter	−8.8	7.5	−11.4	−11.4
Soil organic C	−14.9	17.6	−53.8	−53.8
Total forest	−149.8	−72.4	−219.9	−220.6
Harvested wood products				
Products in use	−17.7	−12.8	−12.4	1.9
Products in solid waste disposal sites	−18.3	−18.0	−16.3	−16.7
Total harvested wood products	−35.9	−30.8	−28.7	−14.8
Total net flux	−185.7	−103.2	−248.6	−235.4

From USEPA (2011)

Table 7.2 Carbon (C) stocks in forest and harvested wood pools, 1990–2010

C pool	1990	2000	2005	2009
	(Tg C)			
Forest				
Live, aboveground	15,072	16,024	16,536	17,147
Live, belowground	2,995	3,183	3,285	3,405
Dead wood	2,960	3,031	3,060	3,105
Litter	4,791	4,845	4,862	4,919
Soil organic C	16,965	17,025	17,143	17,412
Total forest	42,783	44,108	44,886	45,988
Harvested wood products				
Products in use	1,231	1,382	1,436	1,474
Products in solid waste disposal sites	628	805	890	974
Total harvested wood products	1,859	2,187	2,325	2,449
Total C stock	44,643	46,296	47,211	48,437

From USEPA (2011)

recent projections for the forest sector suggest that annual C storage could begin to decline, and U.S. forests could become a net C emitter of tens to hundreds of Tg C year^{-1} within a few decades (USDA FS 2012a). It is therefore urgent to identify effective C management strategies, given the complexity of factors that drive the forest C cycle and the multiple objectives for which forests are managed. An ideal C management activity contributes benefits beyond increasing C storage by achieving other management objectives and providing ecosystem services in a sustainable manner.

Strategies for effectively managing forest C stocks and offsetting C emissions requires a thorough understanding of biophysical and social influences on the forest

C cycle (Birdsey et al. 1993). Successful policies and incentives may be chosen to support strategies if sufficient knowledge of social processes (e.g., landowner or wood-user response to incentives and markets) is available. For example, if C stocks are expected to decrease owing to decreasing forest land area caused by exurban development, policies or incentives to avoid deforestation in those areas may be effective. If C stocks are expected to decrease owing to the effects of a warmer climate, reducing stand densities may retain C over the long term by increasing resilience to drought and other stressors and by reducing crown fire hazard (Jackson et al. 2005; Reinhardt et al. 2008). Protecting old forests and other forests that have high C stocks may be more effective than seeking C offsets associated with wood use, especially if those forests would recover C more slowly in an altered climate.

If climate change increases productivity in a given area over a long period of time, increasing forest C stocks through intensive management and forest products, including biomass energy, may be especially effective. It is equally important to know which strategies might make some management practices unacceptable (e.g., reducing biodiversity). However, no standard evaluation framework exists to aid decision making on alternative management strategies for maximizing C storage while minimizing risks and tradeoffs.

Here we discuss (1) where forest C is stored in the United States, (2) how to measure forest C through space and time, (3) effectiveness of various management strategies in reducing atmospheric greenhouse gases (GHG), and (4) effectiveness of incentives, regulations, and institutional arrangements for implementing C management.

7.2 Status and Trends in Forest-Related C

Net annual C additions to forests (84 %) and harvested wood products used in human settlements and infrastructure (10 %) account for most of the total annual GHG sequestration in the United States. The two largest C components in forests are aboveground biomass (37 %) and soil organic C (38 %), with the rest distributed among belowground biomass (8 %), litter (11 %), and dead wood (6 %). Because aboveground biomass accumulates, then shifts to dead wood, litter, or wood products in a matter of decades, forest management and land use activities can affect aboveground biomass distribution over decades. In other words, management modifications can potentially increase C accumulation and emission offsets.

Change in forest area and forest C per unit area (C density) determines the change in C stocks over time. Since the 1950s, U.S. forest area has been relatively stable (Fig. 7.1) while C density has been increasing. Large-scale reforestation of the United States since the early 1900s is the primary cause of expansion of forest area over time. Increasing C sequestration is a result of gross growth per year continuing to increase, while mortality has increased slowly and harvest removals have stabilized (Fig. 7.1). Despite national trends of stable forest area and increasing C, it is likely that mortality plus harvest exceeds growth in some areas.

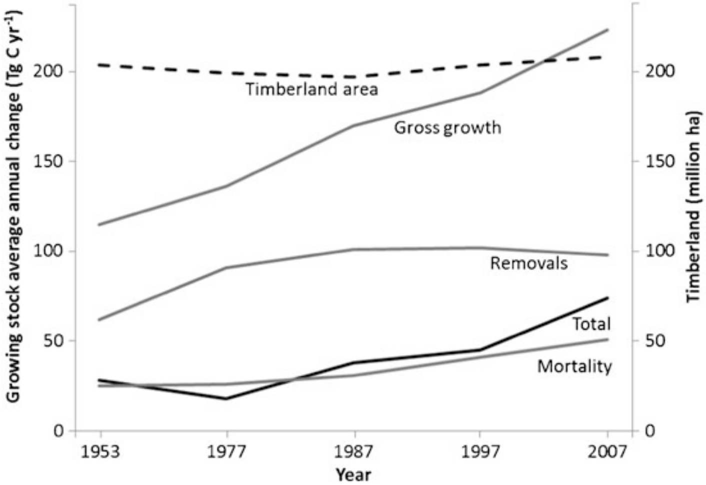

Fig. 7.1 Growing stock carbon change is affected by growth, mortality, and removals, along with timberland area, 1953–2007

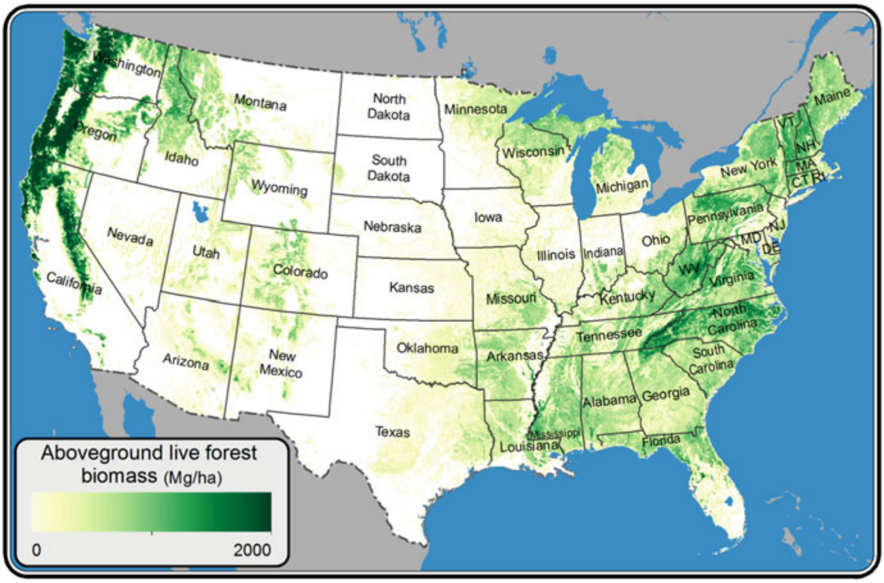

Fig. 7.2 Aboveground live biomass in forests

Aboveground biomass C stocks are largely found in the Pacific coastal region, Appalachian Mountains, Rocky Mountains, Lake States, and central hardwoods (Fig. 7.2). Net annual C sequestration can vary considerably at small spatial scales, and a forest can quickly become a net emitter of C following local disturbances

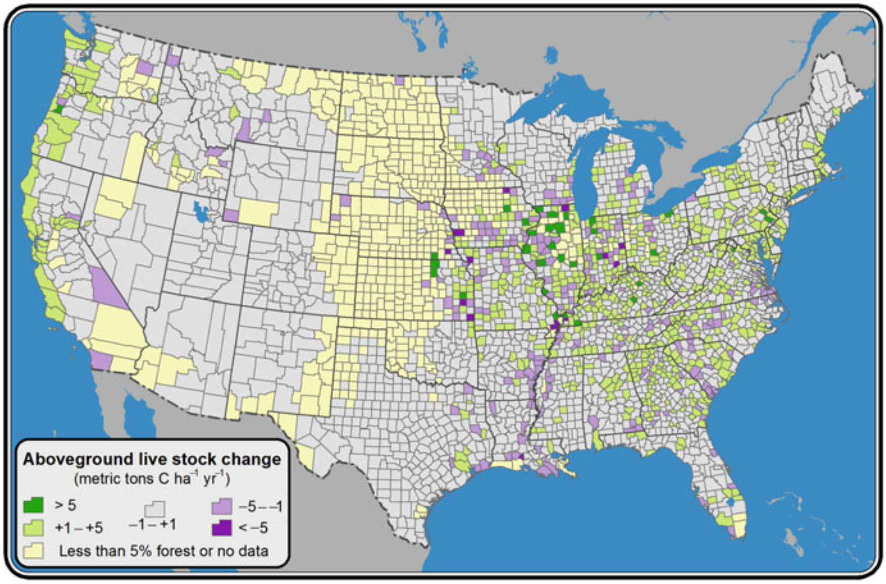

Fig. 7.3 Aboveground live forest carbon change

such as wildfire. Although C stocks have been increasing in most U.S. counties in recent years (Fig. 7.3), uncertainty in annual net sequestration increases greatly as the spatial scale decreases. Given the low density of forest plots that are remeasured each year, estimates of interannual variation in forest C for a local area may be detectable only after major changes in forest structure caused by harvest, wildfire, or other disturbances. Because of inherent variation in C stocks at small spatial scales, it makes more sense to quantify C dynamics at large scales when measuring C sequestration and effectiveness of C management strategies.

7.3 Monitoring and Evaluating Effects of C Management

Effectiveness of C management activities for mitigating GHG emissions is based on forest removal (and retention) of CO_2 from the atmosphere. Figure 7.4 shows C storage and emission processes that can be affected by management of C in forests and wood products. Carbon changes are evaluated by tracking C flows across system boundaries over time. The boundary around the "forest sector" includes forest, wood products, and wood energy processes for a defined forest area. A system can be defined to include only C fluxes to and from forests or wood products, or it may include C fluxes from equipment used to manage forests and manufacture and transport wood products, nonwood products, and fossil fuel feedstocks.

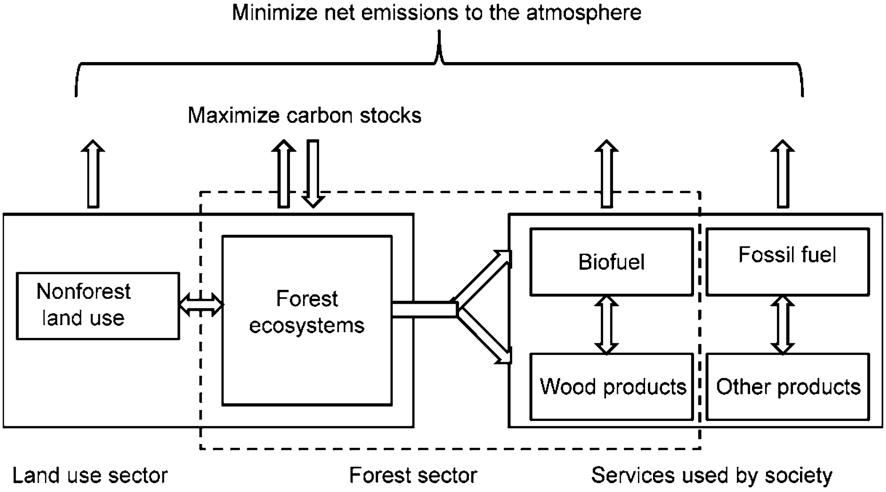

Fig. 7.4 Forest sector and non-forest sector greenhouse gas emissions and stock changes that are influenced by forest management

Forest management can affect GHG emissions beyond the "forest sector." System boundaries can be expanded to include substitution of wood energy for fossil fuels, and substitution of wood products for non-wood products that produce higher levels of GHGs. System boundaries can also be expanded beyond the defined forest area to nonforest areas where actions may cause indirect land use change and associated GHG emissions. System boundaries also include a definition of the time period over which C storage or emissions are evaluated. The effects of altering a C management strategy, storing C, or altering emissions cannot be assessed without clearly defining system boundaries, processes, and time period. Unfortunately, no standard approach exists for evaluating forest biomass as a replacement for fossil fuels.

Evaluating C management strategies associated with forests requires (at a minimum) (1) monitoring C stock changes and emissions over time, and (2) evaluating the effects of altered activities that affect in-forest C (in situ) and associated C storage or emissions outside forests (ex situ). One accounting framework (type A) determines how C fluxes in terrestrial systems and harvested wood products have changed for a current or past period because of management actions and other factors such as natural disturbances. Another accounting framework (type B) determines the degree to which a change in management under various mitigation strategies could increase C storage and decrease emissions.

This accounting approach determines the magnitude of additional C offsets compared to a baseline, where the baseline is the level of C stock, C stock change, level of emissions, or emissions change for a given set of land conditions and activities (e.g., forest management, timber harvest, and disturbances) and off-land activities (e.g., substitution for fossil emissions, as defined by the accounting system and boundaries at a point in time or over a period of time). A baseline can be defined by past conditions or projected future conditions. The effectiveness of a new strategy (e.g., providing an incentive to increase wood use for energy) is determined by changes in landowner behavior. For example, high energy use (high price) may motivate some landowners to convert non-forest land to wood plantations, thus accumulating C and benefiting from wood substitution for fossil fuel. In addition, an increase in wood prices could cause pulpwood to be used for energy rather than for oriented strandboard panel production and associated C storage.

Accounting for the effects of forest management on C must include, explicitly or implicitly, specification of the accounting framework (type A or B) and system boundaries for processes included (e.g., forest sector, service sector, non-forest land use, specific forest area, time period, wood C only, and other GHG emissions). A "common" type A framework defines system boundaries to include current annual C exchange with the atmosphere from forest ecosystems at a given geographic scale, plus C additions and emissions for harvested wood products from those forests (Fig. 7.4). This framework can be used to answer the management question "Are forests and forest products continuing to (collectively) withdraw and store C from the atmosphere?" The framework is also the basis for reporting GHG emissions and sinks in many accounting systems such as that used in annual reports to the United Nations Framework Convention on Climate Change (United Nations 1992).

This framework is not intended to evaluate the full effects on atmospheric CO_2 of a change in strategy, which would require a system boundary that includes changes in non-wood C emissions and C emissions or storage outside the forest. Some excluded changes may include altered fossil fuel use, other land use emissions, and altered no-wood product emissions (Fig. 7.4). Evaluating strategy changes requires a framework that includes all processes that significantly change atmospheric CO_2. If changes in emissions occur over many years, the framework must evaluate CO_2 fluxes over many years. For example, a strategy to increase use of wood for heat, electric power, or biofuels via incentives at a national level would change CO_2 flux estimates compared to a given baseline over an extended time from (1) wood for energy, (2) fossil fuels for energy, (3) land use change (e.g., crops to plantation, or forest to intensive plantation), and (4) flux from forests where wood is removed (including regrowth after removal).

"Leakage" recognizes certain C effects in which the effects of a policy or management change are evaluated with a type B accounting framework. Leakage expressed the C effects of a program change outside the system boundaries defined by a limited set of processes (e.g., C changes for a specific forest area). Leakage includes C changes on land outside of a system boundary (e.g., caused by changes in harvest or land use) (Sohngen et al. 1999; Schwarze et al. 2002; Murray et al. 2004; Gan and McCarl 2007; Pachauri and Reisinger 2007), and differs depending on the mitigation activity (Murray et al. 2004; Gan and McCarl 2007). In the United States, leakage estimates associated with activities on a given land area range from less than 10 % to greater than 90 % (proportion of C benefit lost), depending on the activity and region (Murray et al. 2004). Globally, leakage estimates range between 42 and 95 % (Gan and McCarl 2007). Leakage tends to be highest where programs constrain the supply of forest products (e.g., no harvest is allowed) or constrain land use change (e.g., forest land conversion to agriculture) (Sohngen et al. 1999, 2008; Aukland et al. 2003; Murray et al. 2004; Depro et al. 2008; Sohngen and Brown 2008). In contrast, the indirect effects of a program can increase C benefits outside of a system boundary through "spillover" (Magnani et al. 2009). For example, spillover can occur if an increase in plantation forestry reduces C losses from established forests by increasing C flows in cheaper forest products (Magnani et al. 2009). Defining system boundaries to include indirect effects on C (e.g., multi-national programs) or otherwise accounting for leakage ensures program integrity.

Ineffectiveness of some C storage strategies may be caused by flaws in incentive structures or policies, not by biophysical attributes of the strategy itself. For example, an incentive program might favor harvesting large trees that produce lumber, assuming that lumber would replace building materials that emit more C in manufacturing. If this incentive strategy were implemented, the lumber could go to non-building uses, or an increase in harvest by one landowner could be offset by a decrease by another. This is a flaw of the incentive system, not of the underlying wood substitution strategy. If there were incentives for builders to use wood rather than alternate materials, the strategy could be effective in reducing emissions from manufacturing.

Life cycle assessment (LCA) can be used to evaluate C management strategies by focusing on the change in C storage or emissions associated with producing one unit of wood energy or one unit of wood product. An *attributional LCA*, which is similar to a type A accounting framework, estimates storage and emissions over the life cycle of one unit of product, including specification of forest growth, harvest, manufacturing, end use, disposal, and/or reuse. Attributional LCAs monitor inputs and emissions associated with production and do not include all process that would be affected by a change in production or processes. A *consequential LCA*, which is similar to a type B accounting framework, also estimates storage and emissions over the life cycle of one unit of product, but calculates the *change* in emissions associated with a one-unit change in product production caused by *change* in processes over the life cycle. Consequential LCAs are typically used to analyze the potential response of a change to a system, such as a change in policy, and can include the effects of altered product demand on production and emissions from products across many sectors.

It can be difficult to compare the effectiveness of different C management strategies, because they are often evaluated with different system boundaries, accounting frameworks, models, assumptions, functional units (land area vs. product units), and assumed incentives. However, it is possible to describe the effects of strategies on changing particular processes, uncertainty in attaining specific effects, and timing of the effects.

7.4 Carbon Mitigation Strategies

Carbon mitigation through forest management focuses on (1) increasing forest area (afforestation), avoiding deforestation, or both, (2) C management in existing forests, and (3) use of wood as biomass energy or in wood products for C storage and as a substitute for other building materials. Estimates of CO_2 emissions offset by forests and forest products in the United States (using the type A framework) vary from 10 to 20 % depending assumptions and accounting methods (McKinley et al. 2011), with 13 % (about 221 Tg C year^{-1}) being the estimate as of 2011 (USEPA 2011). The first two mitigation strategies above maintain or increase forest C stocks (using the type B framework with a boundary around forest area and other land capable of growing forests). The third strategy increases C storage or reduces emissions, including C fluxes associated with forests and products removed from the forest (using the type B framework with a boundary around the forest sector, services, and non-forest land processes) (Fig. 7.4). The mitigation potential of these strategies differs in timing and magnitude (Table 7.3).

7.4.1 Land Use Change: Afforestation, Avoiding Deforestation, and Urban Forestry

7.4.1.1 Afforestation

In the United States, estimates of the potential for afforestation (active establishment or planting of forests) to sequester C vary from 1 to 225 Tg C year^{-1} for 2010–2110 (U.S. Climate Change Science Program 2007; USEPA 2005). Afforestation can be done on land that has not been forested for some time (usually more than 20 years). Reforestation refers to establishing forests on land that was previously forested but has been in non-forest use for some time. Mitigation potential, co-benefits, and environmental tradeoffs depend on where afforestation and reforestation efforts are implemented (Table 7.3).

The mitigation potential of afforestation and reforestation is significant and generally has co-benefits, low risk, and few tradeoffs. Forest regrowth on abandoned cropland comprises about half of the additional potential C sink in the United States (Pacala et al. 2001). Sequestering the equivalent of 10 % of U.S. fossil fuel emissions (160 Tg C) would require 44 million ha (or one-third) of U.S. croplands to be converted to tree plantations (Jackson and Schlesinger 2004), with 0.3 to 1.1 million ha needed to sequester 1 Tg C annually (USEPA 2005). Forest establishment on productive, high-value agricultural land is unlikely and may cause leakage (Murray et al. 2004), although establishing forest plantations on less productive, low-value agricultural land is more feasible. Where climatic and soil conditions favor forest growth (over crops), irrigation and fertilization inputs would be low

Table 7.3 Mitigation strategies, timing of impacts, uncertainty in attaining carbon (C) effects, co-benefits and tradeoffs[a]

Mitigation strategy	Timing of maximum impact	Uncertainty about strategy (biophysical risks)	Uncertainty about strategy (structural risks)[b]	Co-benefits	Tradeoffs
Land use change					
Afforestation (on former forest land)	Delayed	Low	Leakage	Erosion control, improved water quality, increased biodiversity and wildlife habitat	Lost revenue from agriculture
Afforestation (on non-forest land)	Delayed	Moderate	Leakage	Biodiversity	Erosion, lower streamflow, decreased biodiversity and wildlife habitat, increased nitrous oxide emissions, competition for agricultural water, local warming from lower albedo
Avoided deforestation	Immediate	Low	Leakage	Watershed protection; maintenance of biodiversity and wildlife habitat, some recreation	Lost economic opportunities affecting farmers or developer directly
Urban forestry	Delayed	High		Reduced energy use for cooling; increased wildlife habitat, possible recreational opportunities	High maintenance might be required in terms of water, energy, and nutrients; possible damage to infrastructure
In situ forest C management					
Decreasing C outputs	Immediate	Moderate	Leakage	Increased old growth; increased structural and species diversity, and wildlife habitat; benefits depend on landscape condition, forest type, and wildlife species (e.g., may not benefit species requiring early sucessional habitat)	Displaced economic opportunities affecting forest owners, forest industry, and employees

Increasing forest growth	Delayed	Low	Leakage	Higher wood production, potential for quicker adaptation to climate change	Lower streamflow, loss of biodiversity, release of nitrous oxide, greater impact of disturbance on C storage
Fuel treatments	Delayed	High		Lower risk from fire and insects, increased economic activity, possible additional offsets from use of wood, climate change adaptation tool	Lost economic opportunities to firefighting business and employees, lower carbon on site, site damage caused by treatment
Ex situ forest C management					
Product substitution	Part immediate, part delayed	Moderate	Leakage	Increased economic activity in forest product industries	Active forest management on larger area, lower C storage in forests
Biomass energy	Immediate to delayed, depending on source	Moderate/high	Leakage	Increased economic activity in forest product industries, possible lower cost of forest restoration	Intensive management on larger area; lower C storage in forests

---

[a] Uncertainty is defined here as the extent to which an outcome is unknown. Most mitigation strategies have a risk of leakage and reversal, which could compromise C benefits. Timing of maximum impact is adapted from Solomon et al. (2007) and uncertainty, co-benefits, and tradeoffs from McKinley et al. (2011)

[b] The potential degree of leakage or other structural risk for a strategy depends on the incentives, regulations, or policy used to implement it. For example, if an incentive program to increase forest growth occurs in only one region, then growth may be decreased in other regions. If the incentive is nationwide, there is little leakage within the United States, but there may be leakage to other countries. Other structural risks can result from improper selection of locations to implement the strategy. For example, fire hazard reduction treatments could be done on land areas where the removals of forest C are larger and of longer duration than the expected avoided emissions from fire. There can also be risk in selecting wood for fuel (e.g., from older forests) where C recovery will be slow

relative to gains in C storage, creating co-benefits such as erosion control, improved water quality, higher species diversity, and wildlife habitat.

Afforestation on lands that do not naturally support forests may require human intervention and environmental tradeoffs. Carbon storage in tree and shrub encroachment in grasslands, rangelands, and savannas could potentially be 120 Tg C year^{-1}, a C sink that could be equivalent to more than half of what existing U.S. forests sequester annually (U.S. Climate Change Science Program 2007), demonstrating the potential (unintentional) effects of land use change and other human activities (Van Auken 2000). However, planting trees (especially non-native species) where they were not present historically may alter the water table, cause soil erosion on hill slopes, and absorb more solar energy compared with a native ecosystem (Jobbágy and Jackson 2004; Farley et al. 2008; Jackson et al. 2008; McKinley and Blair 2008). Irrigation, where necessary, may compete with agricultural water supply and other uses, and water-demanding tree species can reduce streamflow (Farley et al. 2005; Jackson et al. 2005). Use of nitrogen (N) fertilizers may increase emissions of nitrous oxide, a GHG with 300 times greater radiative effect than CO_2.

7.4.1.2 Avoiding Deforestation

Avoiding the loss of forested land can prevent loss of C to the atmosphere. Estimates of potential C mitigation through avoided deforestation are not available for the United States; however on a global scale, deforestation results in the gross annual loss of 90,000 km^2, or 0.2 % of all forests (FAO 2007; Pachauri and Reisinger 2007), which releases 1,400–2,000 Tg C year^{-1}; two-thirds of the deforestation occurs in tropical forests in South America, Africa, and Southeast Asia (Houghton 2005; Pachauri and Reisinger 2007). Over a recent 150-year period, global land use change released 156,000 Tg C to the atmosphere, mostly from deforestation (Houghton 2005). In contrast, forest area in the United States increased at a net rate of 340,000 ha year^{-1} between 2002 and 2007. Increased forest area and regrowth are responsible for most of the current U.S. sink (USEPA 2011). However, land development and conversion of forest to agricultural land is expected to decrease forest area in the United States by 9 million ha by 2050 (Alig et al. 2003). In addition, increased area burned by fire may result in the conversion of some forests to non-forest (McKenzie et al. 2009), or a permanent reduction in C stocks on existing forests if fire-return intervals are reduced (Harden et al. 2000; Balshi et al. 2009). Successful regeneration after wildfires will help avoid conversion of forest to vegetation that retains less C (Keyser et al. 2008; Donato et al. 2009).

Avoided deforestation protects existing forest C stocks and has many co-benefits (Table 7.3), including maintaining the functionality of watersheds, plant and animal habitat, and some recreational activities (McKinley et al. 2011). However, incentives to avoid deforestation in one area may increase forest harvest elsewhere, deriving minimal reduction in atmospheric CO_2. Avoided deforestation may also decrease economic opportunities for timber, agriculture, and urban development in some areas (Meyfroidt et al. 2010). Leakage can be large for avoided deforestation, particularly if harvest is not allowed (Murray et al. 2004).

7.4.1.3 Urban Forestry

Planting and managing trees in and around human settlements offers limited potential to store additional C, but urban trees provide indirect reductions of fossil fuel emissions and have many co-benefits. Although urban C stocks in the United States are surprisingly large (Churkina et al. 2010), the potential for urban forestry to help offset GHG emissions is limited because urban areas comprise only 3.5 % of the landscape (Nowak and Crane 2002), and urban trees require intensive management. Urban forests affect local climate by cooling with shading and transpiration, potentially reducing fossil fuel emissions associated with air conditioning (Akbari 2002). In urban forests planted over very large areas, trees have both warming effects and cooling effects, resulting in complex patterns of convection that can alter air circulation and cloud formation (Jackson et al. 2008). Mortality of urban trees is generally high (Nowak et al. 2004), and they require ongoing maintenance, particularly in cities in arid regions. Risks increase when irrigation, fertilization, and other maintenance are necessary to maintain tree vigor (Pataki et al. 2006).

7.5 *In Situ* Forest Carbon Management

Carbon mitigation through forest management focuses on efforts to increase forest C stock by either decreasing C outputs in the form of harvest and disturbance, or increasing C inputs through active management. Carbon mitigation for a combined effort including increased harvest intervals, increased growth, and preserved establishment could remove 105 Tg C year^{-1}. Achieving these results would require large land areas, because 500,000–700,000 ha of manageable forest land are needed to store 1 Tg C year^{-1} (USEPA 2005).

7.5.1 Increasing Forest C by Decreasing Harvest and Protecting Large C Stocks

Forest management can increase forest C by increasing the interval between harvests or decreasing harvest intensity (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). Increasing harvest intervals have the biggest effect on forests harvested at ages before peak rates of growth begin to decline (culmination of mean annual increment [CMAI]), such as some Douglas-fir

(*Pseudotsuga menziesii* [Mirb.] Franco) forests in the northwestern United States. Increasing rotation age for forests with low CMAI, such as Southern pine species that are already harvested near CMAI, would yield a decreasing benefit per year of extended rotation.

Harvesting forests with high biomass and planting a new forest reduce overall C stocks more in the near term than if the forest were retained, even counting the C storage in harvested wood products (Harmon et al. 1996, 2009). For example, some old-growth forests in Oregon store as much as 1,100 Mg C ha^{-1} (Smithwick et al. 2002), which would require centuries to regain if these stocks were liquidated and replaced, even with fast-growing trees (McKinley et al. 2011). Partial harvests, including leaving dead wood on site, maintain higher C stocks compared to clearcuts (Harmon et al. 2009) while concurrently allowing forests to be used for wood products or biomass energy. Although thinning increases the growth rate and vigor of residual trees, it generally reduces net C storage rates and C storage at the stand scale (Schonau and Coetzee 1989; Dore et al. 2010). Studies on the effects of harvest on soil C provide mixed results (Johnson and Curtis 2001; Nave et al. 2010). Benefits of decreased wood (and C) outputs from forests include an increase in structural and species diversity (Table 7.3). Risks include C loss from disturbance and reduced substitution of wood for more C-intensive materials.

7.5.2 Managing Forest Carbon with Fuel Treatments

Since 1990, CO_2 emissions from wildland forest fires in the conterminous United States have averaged 67 Tg C $year^{-1}$ (USEPA 2009a, 2010). The possibility that fuel treatments, although reducing onsite C stocks, may contribute to mitigation by providing a source for biomass energy and avoiding future wildfire emissions is attractive, especially because fuel treatments have many co-benefits. Fuel treatments are a widespread forest management practice in the western United States (Battaglia et al. 2010) and are designed to alter fuel conditions to reduce wildfire intensity, crown fires, tree mortality, and suppression difficulty (Reinhardt et al. 2008; Scott and Reinhardt 2001). Fuel treatment to reduce crown fire hazard can be done by reducing surface fuels, ladder fuels (small trees), and canopy fuels (Peterson et al. 2005), all of which remove C from the site (Stephens et al. 2009; Reinhardt et al. 2010) and alter subsequent forest C dynamics.

Crown fires often result in extensive tree mortality, whereas many tree species can survive surface fires. This contrast in survival has led to the notion that fuel treatments may offer a C benefit by removing some C from the forest to protect the remaining C (Finkral and Evans 2008; Hurteau et al. 2008; Mitchell et al. 2009; Stephens et al. 2009; Dore et al. 2010). Thinned stands that burn in a surface fire typically have much higher tree survival and lower C losses than similar, unthinned stands that burn in a crown fire, although the net effect of fuel treatment C removal and surface fire emissions may exceed that from crown fire alone, even when materials from fuel treatments are used for wood products (Reinhardt et al.

2010). Because fuel treatment benefits are transient, they may lapse before a wildfire occurs, in which case the C removed by the fuel treatment is not offset by reduced wildfire emissions.

Modeling studies suggest that fuel treatments in most landscapes will result in a net decrease in landscape C over time (Harmon et al. 2009; Mitchell et al. 2009; Ager et al. 2010), because the savings in wildfire emissions is gained only on the small fraction of the landscape where fire occurs each year. The following conditions would be required to yield a substantial C benefit: (1) relatively light C removal would substantially reduce emissions, (2) fire occurrence is high in the near term (while fuel treatments are still effective), and (3) thinnings can provide wood for energy or long-lived products that yield substitution benefits. If fuel treatments are implemented, it is preferable from a C management standpoint to use removed fuels for energy production or wood products, rather than burning them onsite (Coleman et al. 2010; Jones et al. 2010). Feasibility and energy implications depend in part on hauling distance (Jones et al. 2010). An alternative to hauling biomass to conversion facilities is *in situ* pyrolysis to produce energy-dense liquid fuel and biochar which can remain onsite to enhance soil productivity and sequester C (Coleman et al. 2010). Even if thinning and fuel treatments reduce overall forest C, they may have the benefit of providing small C emissions every few decades, rather than large pulses from wildfire (Restaino and Peterson 2013).

7.5.3 Increasing Forest C Stocks by Increasing Forest Growth

Increasing growth rates in existing or new forests can increase C storage and the supply of forest products or biomass energy. Practices that increase forest growth include fertilization, irrigation, use of fast-growing planting stock, and control of weeds, pathogens, and insects (Albaugh et al. 1998, 2003, 2004; Nilsson and Allen 2003; Borders et al. 2004; Amishev and Fox 2006; Allen 2008). The potential for increasing forest growth differs by site and depends on specific climate, soil, tree species, and management.

Increased yields from these practices can be impressive. In pine forests in the southern United States, tree breeding has improved wood growth by 10–30 % (Fox et al. 2007b) and has increased resistance to insects and other stressors (McKeand et al. 2006). In this region, pine plantations using improved seedlings, control of competing vegetation, and fertilizer grow wood four times faster than naturally regenerated second-growth pine forests without competition control (Carter and Foster 2006). Tree breeding and intensive management also provide an opportunity to plant species and genotypes better adapted to future climates.

Many U.S. forests are N limited and would likely respond to fertilization (Reich et al. 1997). Nitrogen and phosphorus fertilizers have been used in about 6.5 million ha of managed forests in the southern United States to increase wood production (Liski et al. 2001; Seely et al. 2002; Albaugh et al. 2007; Fox et al. 2007a). Fertilization can produce 100 % gains for wood growth (Albaugh et al. 1998, 2004), although the benefits of fertilization for growth and C increase need to be balanced by the high GHG emissions associated with fertilizer production and from eutrophication in aquatic systems (Carpenter et al. 1998) (Table 7.3). Other risks include reduced water yield (faster growth uses more water), which is more pronounced in arid and semiarid forests, and potential loss of biodiversity if faster growth relies on monocultures (limited diversity can make some forests vulnerable to insects and pathogens). Increasing the genetic and species diversity of trees and increasing C stocks could be compatible goals in some areas (Woodall et al. 2011).

Markets for forest products can provide revenue to invest in accelerating forest growth. For example, expectation of revenue from the eventual sale of high value timber products would support investment in treatments or tree planting to increase growth rate. Taxation or other government incentives may also support growth-enhancing management. To the extent that incentives to alter growth alter timber harvest and wood product use, evaluation will require a type B accounting with system boundaries that include the forest sector, services sector, and non-forest land.

7.6 *Ex Situ* Forest C Management

Wood is removed from the forest for a variety of uses, each of which has different effects on C balance. Carbon can be stored in wood products for a variable length of time, oxidized to produce heat or electrical energy, or converted to liquid transportation fuels and chemicals that would otherwise come from fossil fuels (Fig. 7.5). In addition, a substitution effect occurs when wood products are used in place of other products that emit more GHG in manufacturing (Lippke et al. 2011).

Strategies that increase use life, use of wood products in place of higher emitting alternate products, and storage in long-lived wood products can complement strategies aimed at increasing forest C stocks. Risk and uncertainty in attaining benefits need to be considered when comparing strategies for increasing forest C with strategies for attaining wood product C offsets—successful strategies need to ensure energy offsets are attained in an acceptable period of time and that substitution effects are attained.

7.6.1 Carbon in Forest Products

Wood and paper store C when in use and also in landfills (Fig. 7.5). Rates of net C accumulation depend on rates of additions, disposal, combustion, and landfill decay. The half-life for single-family homes made of wood built after 1920 is about 80 years (Skog 2008; USEPA 2008), whereas the half-life of paper and paperboard products is less than 3 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 77 % of the C in solid wood products and 44 % in paper products remain in landfills for decades (Chen et al. 2008; Skog 2008). However, current rates of methane release and capture can eliminate this C storage benefit for some low-lignin paper products (Skog 2008). About 2,500 Tg C was accumulated in wood products and landfills in the United States from 1910 to 2005 (Skog 2008), with about 700 Tg C (in 2001) in single- and multi-family homes. In 2007, net additions to products in use and those in landfills combined were 27 Tg C year^{-1} (USEPA 2009b), with about 19 Tg C year^{-1} from products in use (Skog 2008).

7.6.2 Product Substitution

Net C emissions associated with production and use of forest products is typically much less than with steel and concrete. Use of 1 Mg of C in wood materials in construction in place of steel or concrete can result in 2 Mg less C emissions (Schlamadinger and Marland 1996; Sathre and O'Connor 2008). Using wood from faster-growing forests for substitution can sometimes be more effective in lowering atmospheric CO_2 than storing C in the forest (Marland and Marland 1992; Marland et al. 1997; Baral and Guha 2004) (Fig. 7.5a). On the other hand, harvesting forests with very high C stocks that have accumulated over many decades may result in a large deficit of biological C storage that could take many decades to restore (McKinley et al. 2011) (Fig. 7.5b). Opportunities for substitution are largely in non-residential buildings (McKeever et al. 2006; Upton et al. 2008) because most houses are already built with wood, although some building practices, such as using wood for walls, can create a substitution effect in residential buildings (Lippke and Edmonds 2006). Attaining the substitution effect requires incentives that encourage increased use of wood.

7.6.3 Biomass Energy

Biomass energy could prevent the release of an estimated 130–190 Tg C year^{-1} from fossil fuels (Perlack et al. 2005; Zerbe 2006). Biomass energy comprises 28 % of renewable energy supply and 2 % of total energy use in the United States; the latter amount has the potential to increase to 10 % (Zerbe 2006). Currently, wood is used in the form of chips, pellets, and briquettes to produce heat or combined heat and generation of electricity (Saracoglu and Gunduz 2009). These basic energy carriers can be further transformed into liquid transportation fuels and gases (e.g., methane and hydrogen) (Demirbas 2007; Bessou et al. 2011). Conversion processes for these fuels require further development to improve efficiency and commercial viability. In addition, the potential exists to create high-value chemicals and other bioproducts from wood that would otherwise be made from fossil fuels, resulting in reduced emissions (Hajny 1981; USDOE 2009).

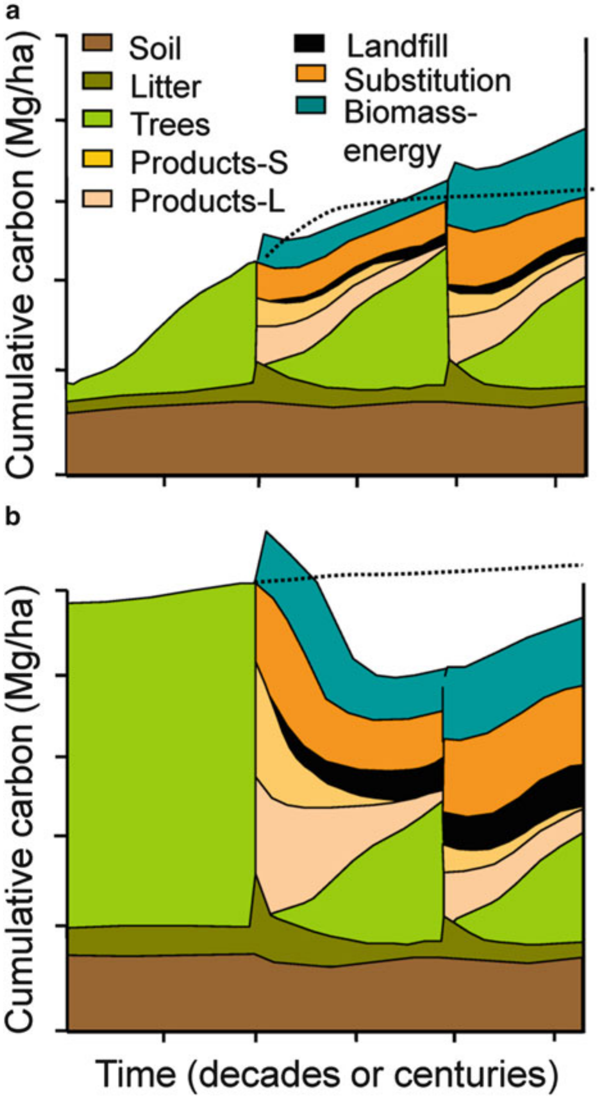

Fig. 7.5 Carbon (C) balance from two hypothetical management projects with different initial ecosystem C stocks and growth rates. Cumulative C stocks in forest, C removed from forest for use in wood projects (long [L]- and short-lived [S]), substitution, and biomass energy are shown on land that (**a**) has been replanted or afforested, or (**b**) has an established forest with high C stocks. The dotted line represents the trajectory of forest C stocks if no harvest occurred. Actual C pathways vary by project. Carbon stocks for trees, litter, and soils are net C stocks only. The scenario is harvested in x-year intervals, which in the United States could be as short as 15 years or longer than 100 years. This diagram assumes that all harvested biomass will be used and does not account for logging emissions. Carbon is sequestered by (1) increasing the average ecosystem C stock (tree biomass) by afforestation, or (2) accounting for C stored in wood products in use and in landfills, as well as preventing the release of fossil fuel C through product substitution or biomass energy. The product-substitution effect is assumed to be 2:1 on average. Biomass is assumed to be

Most biomass for energy is a byproduct of conventional forest product streams, such as milling residues (Gan and Smith 2006a), with some use of trees killed by insects, disease, fire, and wind (Peng et al. 2010; Tumuluru et al. 2010). Most of these residues, mainly sawdust and bark, are already used for direct heating in milling operations or used for other wood products (Ackom et al. 2010; Mälkki and Virtanen 2003; Nilsson et al. 2011); obtaining higher quantities of biomass feedstock would require using other residues. Residues that are generally not used are from logging, hazardous fuel reduction treatments, precommercial thinning, and urban areas (Mälkki and Virtanen 2003; Perlack et al. 2005; Gan and Smith 2006b; Gan 2007; Smeets and Faaij 2007; Ackom et al. 2010; Repo et al. 2011).

If forest harvesting for biomass energy is expanded, roundwood from standing trees will increasingly be used for energy, and short-rotation plantations (e.g., poplars) devoted to biomass feedstock production (Solomon et al. 2007) may become more common (Tuskan 1998; Fantozzi and Buratti 2010). Carbon emissions from increased use of roundwood for energy may be offset over time by a subsequent increase in forest C, which can be done through increased forest growth on land where roundwood is harvested. The amount and speed of the offset are influenced by the time period considered, forest growth rate, initial stand C density, and the efficiency with which wood offsets fossil fuel emissions (Schlamadinger et al. 1995). The offset can also be done through increased landowner investment in forestry, including converting non-forest land to forest, retaining land in forest that would otherwise be converted to non-forest, and planting land in faster growing pulpwood or short-rotation plantations. Forest inventory and C projections indicate that for scenarios with high wood energy use, more land will be retained in forest plantations for the southern United States (USDA FS 2012b). However, landowner investment in revenue for biomass is expected to be low for other parts of the United States.

Reductions in GHG emissions from wood-to-energy pathways depend, in part, on how efficiently wood substitutes for fossil fuels. The energy value of wood (energy content per unit mass) is lower than for fossil fuels (Demirbas 2005; Patzek and Pimentel 2005), and is most pronounced when wood substitutes for fossil fuels with high energy values (e.g., natural gas). The risk of not attaining various levels of offset from use of wood for energy differs, depending on whether biomass is from residues or from roundwood (Schlamadinger et al. 1995; Zanchi et al. 2010). Risks for using residues are small, especially if harvests and supply chains are well managed. Risks associated with using roundwood differ by forest conditions, treatments, and landowner investment in forest management. Large increases in

Fig. 7.5 (continued) a 1:1 substitute for fossil fuels in terms of C, but this is not likely for many wood-to-energy options. This represents a theoretical maximum C benefit for these forest products and management practices. Carbon "debt" is any period of time at which the composition of forest products and remaining forest C stocks after harvest is lower than estimated C stocks under a no-harvest scenario (Adapted from Solomon et al. 2007; Pachauri and Reisinger 2007; McKinley et al. 2011) demand could cause loss of C if natural forest with high C density were converted to plantations with lower C density.

Several studies report that using biomass instead of fossil fuels can significantly reduce net C emissions (Boman and Turnbull 1997; Spath and Mann 2000; Mann and Spath 2001; Cherubini et al. 2009; Jones et al. 2010; Malmsheimer et al. 2011). However, other studies report that the postharvest regrowth period during which forest C is initially low negates the benefits of wood energy in the near term (Schlamadinger et al. 1995; Fargione et al. 2008; Pimentel et al. 2008; Mathews and Tan 2009; Melillo et al. 2009; Searchinger et al. 2009; Cardellichio and Walker 2010; Manomet Center for Conservation Sciences 2010; Bracmort 2011; McKechnie et al. 2011; Melamu and von Blottnitz 2011; Repo et al. 2011). Depending on assumptions about processes included in system boundaries and period of evaluation, studies that used LCAs with biomass pathways and forest C dynamics over time calculated limited or substantial reductions in CO_2 emissions. For some cases and time periods, LCAs with biomass pathways and forest C dynamics indicate biomass emissions can be higher than fossil fuel emissions (Pimentel et al. 2008; Searchinger et al. 2008; Johnson 2009; Manomet Center for Conservation Sciences 2010; McKechnie et al. 2011).

These conflicting conclusions are the result of different assumptions and methods used in the LCAs (Cherubini et al. 2009, 2012; Matthews and Tan 2009). Emerging C accounting methods are increasingly focused on the effect of emissions on the atmosphere and climate over an extended time period, rather than assuming C neutrality (Cherubini et al. 2012). Evaluation frameworks are needed to accurately quantify overall C and climate effects of specific combinations of forest management and wood energy use.

7.7 Mitigation Strategies: Markets, Regulations, Taxes, and Incentives

Forests comprise about a third of the land area in the United States, but fragmentation and conversion of forest to other land uses is increasing, especially in the East (Drummond and Loveland 2010). Various mechanisms exist at national, regional, and local scales that can enhance mitigation efforts while providing incentives to keep forests intact. Markets and incentive programs can potentially play a role in ecosystem-enhancing mitigation on private and non-federal lands, providing a means for landowners to be financially compensated for voluntary activities that improve ecosystem services. Some of these mechanisms, such as C markets, are designed to encourage mitigation, while other mechanisms help maintain or augment C stores as an ancillary benefit.

7.7.1 Markets, Registries, and Protocols for Forest-Based Carbon Projects

Carbon markets are an emissions trading mechanism and are typically designed to create a multi-sector approach that encourages reductions and (often but not always) enhances sequestration of GHG emissions (measured in Mg CO_2 equivalent, or CO_2e) in an economically efficient manner. Registries exist to track and account for C, and protocols outline the specific methodologies that are a prerequisite to creating legitimate C offsets. The United States does not have a national-level regulatory market, but several mandatory regional efforts and voluntary over-the-counter markets provide limited opportunities for mitigation through forest-based C projects. Offsets generated from these projects can compensate for emissions generated elsewhere. Forest C projects generally take the following form:

- Avoided emissions—Avoided deforestation (or avoided conversion): projects that avoid emissions by keeping forests in forest..
- Enhanced sequestration
  - Afforestation/reforestation: projects that reforest areas that are currently non-forest but may have been forested historically.
  - Improved forest management: projects that offer enhanced C mitigation through better or more sustainable management techniques. These projects are compatible with sustainable levels of timber harvest.
  - Urban forestry: projects that plant trees in urban areas. Only sequestered C is eligible (avoided C emissions that result from energy savings are not eligible for credit).

The Regional Greenhouse Gas Initiative (RGGI) is a mandatory multi-state effort in New England and the Mid-Atlantic that allows offset credits to be generated through afforestation projects within RGGI member states. The Climate Action Reserve is a mandatory initiative in California but accepts forest projects from throughout the country. In addition, protocols created by the American Carbon Registry, Verified Carbon Standard provide quality assurance for forest C projects that may be sold on the voluntary market (Kollmuss et al. 2010; Peters-Stanley et al. 2011). In 2009, 5.1 Mg of CO_2e, or 38 % of the global share of forest-based C offsets, was generated in North America (Hamilton et al. 2010). However, factors such as substantial startup and transaction costs and restrictions on the long-term use and stewardship of forest land enrolled in C projects are often barriers to participation by private forest landowners (Diaz et al. 2009).

7.7.2 Tax and Incentive Programs

Tax incentives may be designed to maintain a viable timber industry and achieve open space objectives, but also help maintain or enhance forest C stores. Many

Table 7.4 Programs that influence carbon mitigation

Program	Agency	Land area (10^6 ha)	Purpose
Conservation Reserve Program and Continuous Conservation Reserve Program	Farm Service Agency	∼13	Reduce erosion, increase wildlife habitat, improve water quality, and increase forested acres
Environmental Quality Incentives Program	Natural Resources Conservation Service (NRCS)	∼6.9	Encourages active forest management including timber stand improvement, site preparation for planting, culverts, stream crossings, water bars, planting, prescribed burns, hazard reduction, fire breaks, pasture, fence, grade stabilization, plan preparation
Conservation Stewardship Program	NRCS	Not applicable	Incentives for sustainable forest management and conservation activities
Wildlife Habitat Incentive Program	NRCS	0.26	Provides incentives to develop or improve fish and wildlife habitat, including prairie and savanna restoration, in-stream fish structures, livestock exclusion, and tree planting
Forest Legacy Program	U.S. Forest Service (USFS)	∼0.8	Provides incentives to preserve privately owned working forest land through conservation easements and fee acquisitions
Stewardship Program	USFS	∼14	Encourages private landowners to create and implement forest stewardship plans

states offer reduced taxes on forest land if it is maintained in forest and managed responsibly. For example, private forest landowners enrolled in the Managed Forest Law Program in Wisconsin receive an 80–95 % tax reduction on land that is at least 80 % forested and is managed for sustainable production of timber resources. In the Use Value Appraisal Program in Vermont, C benefits from these programs are evaluated for specific circumstances; younger, fast growing forests have higher rates of C uptake, whereas older stands may have lower C uptake but higher C storage (Harmon 2001; Malmsheimer et al. 2008). Therefore, a no-harvest unmanaged forest may produce more or less C benefit than an actively managed forest, but much depends on current C stocks, likelihood of disturbance, and how harvested timber is used (Ingerson 2007; Nunnery and Keeton 2010). The timeframe of expected C benefits depends on both forest management plans and forest product pathways, both short term and long term (McKinley et al. 2011).

Federal programs administered by the Natural Resources Conservation Service, U.S. Forest Service, and Farm Service Agency (Table 7.4) provide cost-share and rental payment incentives for farm, forest, watershed, and wildlife habitat stewardship. These programs may also enhance C storage, although it is not an explicit goal. The area enrolled in each program fluctuates annually and depends on commodity prices, program funding, and authorization levels. In 2010, 13 million ha of U.S. farmland were enrolled in the Conservation Reserve Program, down from 15 million ha in 2005 (Claassen et al. 2008; USDA Farm Service Agency 2010).

If new policies were to favor land management that reduces atmospheric CO_2, existing programs can be modified to explicitly provide incentives that encourage C mitigation. For example, the overall objective of a program could remain as is (to determine general eligibility), but the financial incentives for enrollment could be related to estimated average C benefit per land unit. Carbon benefit per hectare could be estimated at a county or regional scale based on a combination of factors, including geographic location, land use, species planted, and overall landscape connectivity. This would help to ensure that priority lands for C management receive the highest potential benefits. Alternatively, a specific forest C incentive program could complement current incentive programs by targeting small forest owners and providing financial incentives to retain forest land in forest. Best management practices could be made available (e.g., for artificial regeneration, thinning, and insect control) (Table 7.5), and financial incentives could be based on estimated C benefits (Pinchot Institute for Conservation 2011). These estimated benefits would require only a credible verification of practices rather than annual site monitoring.

7.8 The Role of Public Lands in C Mitigation

Public lands contain about 37 % of the land area of the United States, with federally managed lands occupying 76 % of the total area managed by all public entities. Managing these lands for C benefits would involve multiple jurisdictions, social objectives, and political factors, and would be governed by laws mandating multiple uses of land in the public domain. The Council on Environmental Quality, which is responsible for overseeing environmental policy across the federal government, developed draft guidelines on how federal agencies can improve how they consider the effects of GHG emissions and climate change when evaluating proposals for federal actions under the National Environmental Policy Act (Sutley 2010). Executive Order 13514 (2009) requires agencies to set targets that focus on sustainability, energy efficiency, reduced fossil fuel use, and increased water efficiency. In addition, the order requires agencies to measure, report, and reduce GHG emissions from direct and indirect activities, including federal land management practices. Recent guidance and orders are being considered by land management agencies, but it is unclear how effective they will be in reducing GHGs, given the many other uses of federal lands. Large areas of forest land protected by conservation organizations (e.g., The Nature Conservancy) across the United States are managed for public

Table 7.5 Tools and processes to inform forest management

Organization	Relevant content	Internet site
U.S. Forest Service Forest Inventory and Analysis	Forest statistics by state, including carbon (C) estimates Sample plot and tree data Forest inventory methods and basic definitions	http://fia.fs.fed.us
U.S. Forest Service Forest Health Monitoring	Forest health status Regional data on soils, dead wood stocks Forest health monitoring methods	http://www.fhm.fs.fed.us
U.S. Department of Agriculture Greenhouse Gas (GHG) Inventory	State-by-state forest C estimates	http://www.usda.gov/oce/global_change/gg_inventory.htm
United Nations Framework Convention on Climate Change and Intergovernmental Panel on Climate Change	International guidance on C accounting and estimation	http://unfccc.int http://www.ipcc.ch
Natural Resources Conservation Service	Soil Data Mart—access to a variety of soil data	http://soildatamart.nrcs.usda.gov
U.S. Forest Service, Northern Research Station	Accounting, reporting procedures, and software tools for C estimation	http://www.nrs.fs.fed.us/carbon/tools
U.S. Energy Information Administration, Voluntary GHG Reporting	Methods and information for calculating sequestration and emissions from forestry	http://www.eia.gov/oiaf/1605/gdlinshtml
U.S. Environmental Protection Agency	Methods and estimates for GHG emissions and sequestration	http://www.epa.gov/climatechange/emissions/usinventoryreport.html

benefits, and because they are often not subject to the regulatory issues above, they may be able to contribute to C mitigation more quickly than is possible on other public lands.

References

Ackom, E. K., Mabee, W. E., & Saddler, J. N. (2010). Industrial sustainability of competing wood energy options in Canada. *Applied Biochemistry and Biotechnology, 162*, 2259–2272.

Ager, A. A., Finney, M. A., McMahan, A., & Cathcart, J. (2010). Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. *Natural Hazards and Earth System Sciences, 10*, 2515–2526.

Akbari, H. (2002). Shade trees reduce building energy use and CO_2 emissions from power plants. *Environmental Pollution, 116*, S119–S1260.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., et al. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *Forest Science, 44*, 317–328.

Albaugh, T. J., Allen, H. L., Zutter, B. R., & Quicke, H. E. (2003). Vegetation control and fertilization in midrotation *Pinus taeda* stands in the southeastern United States. *Annals of Forest Science, 60*, 619–624.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., & Johnsen, K. H. (2004). Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *Forest Ecology and Management, 192*, 3–19.

Albaugh, T. J., Allen, H. L., & Fox, T. R. (2007). Historical patterns of forest fertilization in the southeastern United States from 1969 to 2004. *Southern Journal of Applied Forestry, 31*, 129–137.

Alig, R. J., Plantinga, A. J., Ahn, S., & Kline, J. D. (2003). *Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050* (General Technical Report PNW-GTR-587, 92 p). Portland: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Allen, H. L. (2008). Silvicultural treatments to enhance productivity. In J. Evans (Ed.), *The forests handbook: Vol. 2, Applying forest science for sustainable management* (pp. 129–139). Oxford/Malden: Blackwell Science Ltd.

Amishev, D. Y., & Fox, T. R. (2006). The effect of weed control and fertilization on survival and growth of four pine species in the Virginia Piedmont. *Forest Ecology and Management, 236*, 93–101.

Aukland, L., Costa, P. M., & Brown, S. (2003). A conceptual framework and its application for addressing leakage: The case of avoided deforestation. *Climate Policy, 3*, 123–136.

Balboa-Murias, M. A., Rodriguez-Soalleíro, R., Merino, A., & Álvarez-González, J. G. (2006). Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. *Forest Ecology and Management, 237*, 29–38.

Balshi, M. S., McGuire, A. D., Duffy, P., et al. (2009). Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. *Global Change Biology, 15*, 1491–1510.

Baral, A., & Guha, G. S. (2004). Trees for carbon sequestration or fossil fuel substitution: The issue of cost vs. carbon benefit. *Biomass and Bioenergy, 27*, 41–55.

Barlaz, M. A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochemical Cycles, 12*, 373–380.

Battaglia, M. A., Rocca, M. E., Rhoades, C. C., & Ryan, M. G. (2010). Surface fuel loadings within mulching treatments in Colorado coniferous forests. *Forest Ecology and Management, 260*, 1557–1566.

Bessou, C., Ferchaud, F., Gabrielle, B., & Mary, B. (2011). Biofuels, greenhouse gases and climate change. A review. *Agronomy for Sustainable Development, 31*, 1–79.

Birdsey, R. A., Plantinga, A. J., & Health, L. S. (1993). Past and prospective carbon storage in United States forests. *Forest Ecology and Management, 58*, 33–40.

Birdsey, R., Pregitzer, K., & Lucier, A. (2006). Forest carbon management in the United States: 1600–2100. *Journal of Environmental Quality, 35*, 1461–1469.

Boman, U. R., & Turnbull, J. H. (1997). Integrated biomass energy systems and emissions of carbon dioxide. *Biomass and Bioenergy, 13*, 333–343.

Borders, B. E., Will, R. E., Markewitz, D., et al. (2004). Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. *Forest Ecology and Management, 192*, 21–37.

Bracmort, K. (2011). *Is biopower carbon neutral?* (7-5700, 14 p). Washington, DC: Congressional Research Service.

Cardellichio, P., & Walker, T. (2010). Why the Manomet study got the biomass carbon accounting right. *The Forestry Source, 15*, 4.

Carpenter, S. R., Caraco, N. F., Correll, D. L., et al. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications, 8*, 559–568.

Carter, M. C., & Foster, C. D. (2006). Milestones and millstones: A retrospective on 50 years of research to improve productivity in loblolly pine plantations. *Forest Ecology and Management, 227*, 137–144.

Chen, J., Colombo, S. J., Ter-Mikaelian, M. T., & Heath, L. S. (2008). Future carbon storage in harvested wood products from Ontario's Crown forests. *Canadian Journal of Forest Research, 38*, 1947–1958.

Cherubini, F., Bird, N. D., Cowie, A., et al. (2009). Energy- and green-house gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resource Conservation and Recycling, 53*, 434–447.

Cherubini, F., Guest, G., & Stømman, A. H. (2012). Application of probability distributions to the modeling of biogenic CO_2 fluxes in life cycle assessment. *GCB Bioenergy*. doi:10.1111/j.1757-1707.2011.01156.x.

Churkina, G., Brown, D. G., & Keoleian, G. (2010). Carbon stored in human settlements: the conterminous United States. *Global Change Biology, 16*, 135–143.

Claassen, R., Cattaneo, A., & Johansson, R. (2008). Cost-effective design of agri-environmental payment program: U.S. experience in theory and practice. *Ecological Economics, 65*, 737–752.

Coleman, M., Page-Dumroese, D., Archuleta, J., et al. (2010). Can portable pyrolysis units make biomass utilization affordable while using bio-char to enhance soil productivity and sequester carbon. In T. B Jain, R. T Graham, & J. Sandquist, Tech. (Eds.), *Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proceedings RMRS-P-61* (pp. 159–168). Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Demirbas, A. (2005). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Progress in Energy and Combustion Science, 31*, 171–192.

Demirbas, A. (2007). Progress and recent trends in biofuels. *Progress in Energy and Combustion Science, 33*, 1–18.

Depro, B. M., Murray, B. C., Align, R. J., & Shanks, A. (2008). Public land, timber harvests, and climate mitigation: quantifying carbon sequestration potential on U.S. public timberlands. *Forest Ecology and Management, 255*, 1122–1134.

Diaz, S., Hector, A., & Wardle, D. A. (2009). Biodiversity in forest carbon sequestration initiatives: Not just a side benefit. *Current Opinion in Environmental Sustainability, 1*, 55–60.

Donato, D. C., Fontaine, J. B., Campbell, J. L., et al. (2009). Conifer regeneration in stand-replacement portions of a large mixed-severity wildfire in the Klamath-Siskiyou Mountains. *Canadian Journal of Forest Research, 39*, 823–838.

Dore, S., Kolb, T. E., Montes-Helu, M., et al. (2010). Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. *Ecological Applications, 20*, 663–683.

Drummond, M. A., & Loveland, T. R. (2010). Land-use pressure and a transition to forest-cover loss in the eastern United States. *Bioscience, 60*, 286–298.

Exec. Order No. 13,514, 74 Fed. Reg. 194, 52117 (2009, October 8). *Federal leadership in environmental, energy, and economic performance*. http://www.whitehouse.gov/administration/eop/ceq/sustainability. 28 Dec 2011.

Fantozzi, F., & Buratti, C. (2010). Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. *Biomass and Bioenergy, 34*, 1796–1804.

Fargione, J., Hill, J., Tilman, D., et al. (2008). Land clearing and the biofuel carbon debt. *Science, 319*, 1235–1238.

Farley, K. A., Jobbágy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology, 11*, 1565–1576.

Farley, K. A., Piñeiro, G., Palmer, S. M., et al. (2008). Stream acidification and base cation losses with grassland afforestation. *Water Resources Research, 44*, W00A03.

Finkral, A. J., & Evans, A. M. (2008). Effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *Forest Ecology and Management, 255*, 2743–2750.

Food and Agriculture Organization of the United Nations [FAO]. (2007). *State of the world's forests 2007* (144 p). Rome: Food and Agriculture Organization of the United Nations, Communications Division, Electronic Publishing Policy and Support Branch. http://www.fao.org/docrep/009/a0773e/a0773e00.htm. November 2011.

Fox, T. R., Allen, H. L., Albaugh, T. J., et al. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *Southern Journal of Applied Forestry, 31*, 5–11.

Fox, T. R., Jokela, E. J., & Allen, H. L. (2007). The development of pine plantation silviculture in the southern United States. *Journal of Forestry, 105*, 337–347.

Gan, J. (2007). Supply of biomass, bioenergy, and carbon mitigation: Method and application. *Energy Policy, 35*, 6003–6009.

Gan, J., & McCarl, B. A. (2007). Measuring transnational leakage of forest conservation. *Ecological Economics, 64*, 423–432.

Gan, J. B., & Smith, C. T. (2006a). A comparative analysis of woody biomass and coal for electricity generation under various CO_2 emission reductions and taxes. *Biomass and Bioenergy, 30*, 296–303.

Gan, J., & Smith, C. T. (2006b). Availability of logging residues and potential for electricity production and carbon displacement in the USA. *Biomass and Bioenergy, 30*, 1011–1020.

Hajny, G. J. (1981). *Biological utilization of wood production for production of chemicals and foodstuffs* (Research Paper FPL-RP-385, 65 p). Madison: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Hamilton, K., Sjardin, M., Peters-Stanley, M., & Marcello, T. (2010). *Building bridges: State of the voluntary carbon markets 2010: A report by Ecosystem Marketplace and Bloomberg New Energy Finance* (108 p). New York/Washington, DC: Bloomberg New Energy Finance/Ecosystem Marketplace.

Harden, J. W., Trumbore, S. E., Stocks, B. J., et al. (2000). The role of fire in the boreal carbon budget. *Global Change Biology, 6*, 174–184.

Harmon, M. (2001). Carbon sequestration in forests—Addressing the scale question. *Journal of Forestry, 99*, 24–29.

Harmon, M. E., & Marks, B. (2002). Effects of silvicultural practices on carbon stores in Douglas-fir–Western hemlock forests in the Pacific Northwest, U.S.A.: Results from a simulation model. *Canadian Journal of Forest Research, 877*, 863–877.

Harmon, M. E., Harmon, J. M., Ferrell, W. K., & Brooks, D. (1996). Modeling carbon stores in Oregon and Washington forest products: 1900–1992. *Climatic Change, 33*, 521–550.

Harmon, M. E., Moreno, A., & Domingo, J. B. (2009). Effects of partial harvest on the carbon stores in Douglas-fir/western hemlock forests: A simulation study. *Ecosystems, 12*, 777–791.

Houghton, R. A. (2005). Aboveground forest biomass and the global carbon balance. *Global Change Biology, 11*, 945–958.

Hurteau, M. D., Koch, G. W., & Hungate, B. A. (2008). Carbon protection and fire risk reduction: Toward a full accounting of forest carbon offsets. *Frontiers in Ecology and the Environment, 6*, 493–498.

Ingerson, A. (2007). *U.S. forest carbon and climate change: Controversies and win-win policy approaches* (18 p). Washington, DC: The Wilderness Society.

Intergovernmental Panel on Climate Change [IPCC]. (2001). *Climate change 2001: Mitigation. Third assessment report of the Intergovernmental Panel on Climate Change, Working Group III* (753 p). Cambridge: Cambridge University Press.

Jackson, R. B., & Schlesinger, W. H. (2004). Curbing the U.S. carbon deficit. *Proceedings of the National Academy of Sciences, USA, 101*, 15827–15829.

Jackson, R. B., Jobbágy, E. G., Avissar, R., et al. (2005). Trading water for carbon with biological carbon sequestration. *Science, 310*, 1944–1947.

Jackson, R. B., Randerson, J. T., Canadell, J. G., et al. (2008). Protecting climate with forests. *Environmental Research Letters, 3*, 044006.

Jiang, H., Apps, M. J., Peng, C., et al. (2002). Modeling the influence of harvesting on Chinese boreal forest carbon dynamics. *Forest Ecology and Management, 169*, 65–82.

Jobbágy, E. G., & Jackson, R. B. (2004). Groundwater use and salinization with grassland afforestation. *Global Change Biology, 10*, 1299–1312.

Johnson, E. (2009). Good-bye to carbon neutral: Getting biomass footprints right. *Environmental Impact Assessment Review, 29*, 165–168.

Johnson, D. W., & Curtis, P. S. (2001). Effects of forest management on soil C and N storage: Meta analysis. *Forest Ecology and Management, 140*, 227–238.

Jones, G., Loeffler, D., Butler, E., et al. (2010). Emissions, energy return and economics from utilizing forest residues for thermal energy compared to onsite pile burning. In T. B. Jain, R. T. Graham, & J. Sandquist, Tech. (Eds.), *Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate, Proceedings RMRS-P-61* (pp. 145–158). Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kaipainen, T., Liski, J., Pussinen, A., & Karjalainen, T. (2004). Managing carbon sinks by changing rotation length in European forests. *Environmental Science and Policy, 7*, 205–219.

Keyser, T. L., Lentile, L. B., Smith, F. W., & Shepperd, W. D. (2008). Changes in forest structure after a large, mixed-severity wildfire in ponderosa pine forests of the Black Hills, South Dakota, USA. *Forest Science, 54*, 328–338.

Kollmuss, A., Lee, C., & Lazaru, M. (2010). How offset programs assess and approve projects and credits. *Carbon Management, 1*, 119–134.

Lippke, B., & Edmonds, L. (2006). Environmental performance improvement in residential construction: The impact of products, biofuels, and processes. *Forest Products Journal, 56*, 58–63.

Lippke, B., Oneil, E., Harrison, R., et al. (2011). Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. *Carbon Management, 2*, 303–333.

Liski, J., Pussinen, A., Pingoud, K., et al. (2001). Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Research, 31*, 2004–2013.

Magnani, F., Dewar, R. C., & Borghetti, M. (2009). Leakage and spillover effects of forest management on carbon storage: Theoretical insights from a simple model. *Tellus Series B: Chemical and Physical Meteorology, 61*, 385–393.

Mälkki, H., & Virtanen, Y. (2003). Selected emissions and efficiencies of energy systems based on logging and sawmill residues. *Biomass and Bioenergy, 24*, 321–327.

Malmsheimer, R. W., Heffernan, P., Brink, S., et al. (2008). Forest management solutions for mitigating climate change in the United States. *Journal of Forestry, 106*, 115–173.

Malmsheimer, R. W., Bower, J. L., Fried, J. S., et al. (2011). Managing forest because carbon matters: Integrating energy, products, and land management policy. *Journal of Forestry, 109*, S7–S50.

Mann, M. K., & Spath, P. L. (2001). A life-cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Products and Processes, 3*, 81–91.

Manomet Center for Conservation Sciences. (2010). *Massachusetts biomass sustainability and carbon policy study: Report to the Commonwealth of Massachusetts Department of Energy Resources* (Report NCI-201003, 182 p). Brunswick: Manomet Center for Conservation Sciences.

Marland, G., & Marland, S. (1992). Should we store carbon in trees? *Water, Air, and Soil Pollution, 64*, 181–195.

Marland, G., Schlamadinger, B., & Leiby, P. (1997). Forest/biomass based mitigation strategies: Does the timing of carbon reductions matter? *Critical Reviews in Environmental Science and Technology, 27*, S213–S226.

Mathews, J. A., & Tan, H. (2009). Biofuels and indirect land use change effects: The debate continues. *Biofuels, Bioproducts and Biorefining, 3*, 305–317.

McKeand, S. E., Jokela, E. J., Huber, D. A., et al. (2006). Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. *Forest Ecology and Management, 227*, 178–184.

McKechnie, J., Colombo, S., Chen, J., et al. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology, 45*, 789–795.

McKeever, D. B., Adair, C., & O'Connor, J. (2006). *Wood products used in the construction of low-rise nonresidential buildings in the United States, 2003* (68 p). Tacoma: Wood Products Council.

McKenzie, D., Peterson, D. L., & Littell, J. (2009). Global warming and stress complexes in forests of western North America. In A. Bytnerowicz, M. J. Arbaugh, A. R. Riebau, & C. Andersen (Eds.), *Wildland fires and air pollution* (pp. 317–337). The Hague: Elsevier Publishers.

McKinley, D. C., & Blair, J. M. (2008). Woody plant encroachment by *Juniperus virginiana* in a mesic native grassland promotes rapid carbon and nitrogen accrual. *Ecosystems, 11*, 454–468.

McKinley, D. C., Ryan, M. G., Birdsey, R. A., et al. (2011). A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications, 21*, 1902–1924.

Melamu, R., & von Blottnitz, H. (2011). 2nd generation biofuels a sure bet? A life cycle assessment of how things could go wrong. *Journal of Cleaner Production, 19*, 138–144.

Melillo, J. M., Reilly, J. M., Kicklighter, D. W., et al. (2009). Indirect emissions from biofuels: How important? *Science, 326*, 1397–1399.

Meyfroidt, P., Rudel, T. K., & Lambin, E. F. (2010). Forest transitions, trade, and the global displacement of land use. *Proceedings of the National Academy of Sciences, USA, 107*, 20917–20922.

Mitchell, S. R., Harmon, M. E., & O'Connell, K. E. B. (2009). Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. *Ecological Applications, 19*, 643–655.

Murray, B. C., McCarl, B. A., & Lee, H.-C. (2004). Estimating leakage from forest carbon sequestration programs. *Land Economics, 80*, 109–124.

Nave, L. E., Vance, E. D., Swanston, C. W., & Curtis, P. S. (2010). Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management, 259*, 857–866.

Nilsson, U., & Allen, H. L. (2003). Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *Forest Ecology and Management, 175*, 367–377.

Nilsson, D., Bernesson, S., & Hansson, P. A. (2011). Pellet production from agricultural raw materials—A systems study. *Biomass and Bioenergy, 35*, 679–689.

Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*, 381–389.

Nowak, D. J., Kuroda, M., & Crane, D. E. (2004). Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry and Urban Greening, 2*, 139–147.

Nunnery, J. S., & Keeton, W. S. (2010). Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. *Ecological Applications, 259*, 1363–1375.

Pacala, S. W., Hurtt, G. C., Baker, D., et al. (2001). Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science, 292*, 2316–2320.

Pachauri, R. D., & Reisinger, A. (Eds). (2007). *Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change* (104 p). Geneva: Intergovernmental Panel on Climate Change.

Pataki, D. E., Alig, R. J., Fung, A. S., et al. (2006). Urban ecosystems and the North American carbon cycle. *Global Change Biology, 12*, 2092–2102.

Patzek, T. W., & Pimentel, D. (2005). Thermodynamics of energy production from biomass. *Critical Reviews in Plant Sciences, 24*, 327–364.

Peng, J. H., Bi, H. T., Sokhansanj, S., et al. (2010). An economical and market analysis of Canadian wood pellets. *International Journal of Green Energy, 7*, 128–142.

Perlack, R. D., Wright, L. L., Turhollow, A. F., et al. (2005). *Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply* (60 p). Oak Ridge: U.S. Department of Energy, Oak Ridge National Laboratory.

Peterson, D. L., Johnson, M. C., Agee, J. K., et al. (2005). *Forest structure and fire hazard in dry forests of the western United States* (General Technical Report PNW-GTR-628, 30 p). Portland: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Peters-Stanley, M., Hamilton, K., Marcello, T., & Sjardin, M. (2011). *Back to the future: State of the voluntary carbon markets 2011* (78 p). Washington, DC: Ecosystem Marketplace.

Pimentel, D., Marklein, A., Toth, M. A., et al. (2008). Biofuel impacts on world food supply: Use of fossil fuel, land and water resources. *Energies, 1*, 41–78.

Pinchot Institute for Conservation. (2011). *The Pinchot letter*, *16*(1). Available at http://www.pinchot.org/pubs/c34

Reich, P. B., Grigal, D. F., Aber, J. D., & Gower, S. T. (1997). Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology, 78*, 335–347.

Reinhardt, E. D., Keane, R. E., Calkin, D. E., & Cohen, J. D. (2008). Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management, 256*, 1997–2006.

Reinhardt, E. D., Holsinger, L., & Keane, R. (2010). Effects of biomass removal treatments on stand-level fire characteristics in major forest types of the Northern Rocky Mountains. *Western Journal of Applied Forestry, 25*, 34–41.

Repo, A., Tuomi, M., & Liski, J. (2011). Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy, 3*, 107–115.

Restaino, J. C., & Peterson, D. L. (2013). Wildfire and fuel treatment effects on forest carbon dynamic in the western United States. *Forest Ecology and Management, 303*, 46–60.

Saracoglu, N., & Gunduz, G. (2009). Wood pellets—Tomorrow's fuel for Europe. *Energy Sources: Part A: Recovery Utilization and Environmental Effects, 31*, 1708–1718.

Sathre, R., & O'Connor, J. (2008). *A synthesis of research on wood products and greenhouse gas impacts* (Technical Report TR-19). Vancouver: FPInnovations, Forintek Division.

Schlamadinger, B., & Marland, G. (1996). The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy, 10*, 275–300.

Schlamadinger, B., Spitzer, J., Kohlmaier, G. H., & Lüdeke, M. (1995). Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy, 8*, 221–234.

Schönau, A. P. G., & Coetzee, J. (1989). Initial spacing, stand density and thinning in eucalypt plantations. *Forest Ecology and Management, 29*, 245–266.

Schwarze, R., Niles, J. O., & Olander, J. (2002). Understanding and managing leakage in forest-based greenhouse-gas-mitigation projects. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences, 360*, 1685–1703.

Scott, J. H., & Reinhardt, E. D. (2001). *Assessing crown fire potential by linking models of surface and crown fire behavior* (Research Paper RMRS-RP-29, 59 p). Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Searchinger, T., Heimlich, R., Houghton, R. A., et al. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science, 319*, 1238–1240.

Searchinger, T. D., Hamburg, S. P., Melillo, J., et al. (2009). Fixing a critical climate accounting error. *Science, 326*, 527–528.

Seely, B., Welham, C., & Kimmins, H. (2002). Carbon sequestration in a boreal forest ecosystem: Results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management, 169*, 123–135.

Skog, K. E. (2008). Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal, 58*, 56–72.

Smeets, E. M. W., & Faaij, A. P. C. (2007). Bioenergy potentials from forestry in 2050: An assessment of the drivers that determine the potentials. *Climatic Change, 81*, 353–390.

Smithwick, E. A. H., Harmon, M. E., Remillard, S. M., et al. (2002). Potential upper bounds of carbon stores in forests of the Pacific Northwest. *Ecological Applications, 12*, 1303–1317.

Sohngen, B., & Brown, S. (2008). Extending timber rotations: Carbon and cost implications. *Climate Policy, 8*, 435–451.

Sohngen, B., Mendelsohn, R., & Sedjo, R. (1999). Forest management, conservation, and global timber markets. *American Journal of Agricultural Economics, 81*, 1–13.

Sohngen, B., Beach, R. H., & Andrasko, K. (2008). Avoided deforestation as a greenhouse gas mitigation tool: Economic issues. *Journal of Environmental Quality, 37*, 1368–1375.

Solomon, B. D., Barnes, J. R., & Halvorsen, K. E. (2007). Grain and cellulosic ethanol: History, economics, and energy policy. *Biomass and Bioenergy, 31*, 416–425.

Spath, P. L., & Mann, M. K. (2000). *Life cycle assessment of a natural gas combined-cycle power generation system* (NREL/TP-570-27715, 55 p). Golden: National Renewable Energy Laboratory.

Stephens, S. L., Moghaddas, J. J., Hartsough, B. R., et al. (2009). Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Canadian Journal of Forest Research, 39*, 1538–1547.

Sutley, N. H. (2010). *Draft NEPA guidance on consideration of the effects of climate change and greenhouse gas emissions* (12 p). Washington, DC: Council on Environmental Quality. http://ceq.hss.doe.gov/nepa/regs/Consideration_of_Effects_of_GHG_Draft_NEPA_Guidance_FINAL_02182010.pdf

Thornley, J. H. M., & Cannell, M. G. R. (2000). Managing forests for wood yield and carbon storage: A theoretical study. *Tree Physiology, 20*, 477–484.

Tumuluru, J. S., Sokhansanj, S., Lim, C. J., et al. (2010). Quality of wood pellets produced in British Columbia for export. *Applied Engineering in Agriculture, 26*, 1013–1020.

Tuskan, G. A. (1998). Short-rotation woody crop supply systems in the United States: What do we know and what do we need to know? *Biomass and Bioenergy, 14*, 307–315.

U.S. Climate Change Science Program. (2007). *The first state of the carbon cycle report (SOCCR): The North American carbon budget and implications for the global carbon cycle: A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research* (242 p). Asheville: National Oceanic and Atmospheric Administration, National Climatic Data Center.

U.S. Department of Agriculture, Farm Service Agency. (2010). *Conservation reserve program: Annual summary and enrollment statistics*. https://www.fsa.usda.gov/Internet/FSA_File/annual2010summary.pdf

U.S. Department of Agriculture, Forest Service [USDA FS]. (2012a). *Future of America's forest and rangelands: Forest Service 2010 Resources Planning Act assessment* (General Technical Report WO-87, 198 p). Washington, DC: USDA FS.

U.S. Department of Agriculture, Forest Service. [USDA FS]. (2012b). *Southern forest futures project*. http://www.srs.fs.usda.gov/futures. 20 June 2012.

U.S. Department of Energy [USDOE]. (2009). *Annual energy review 2008* (407 p). Washington, DC: Energy Information Administration.

U.S. Environmental Protection Agency [USEPA]. (2005). *Greenhouse gas mitigation potential in U.S. forestry and agriculture* (EPA 430-R-05-006, 157 p). Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

U.S. Environmental Protection Agency [USEPA]. (2008). *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2006* (430-R-08-005). Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

U.S. Environmental Protection Agency [USEPA]. (2009a). *Land use, land use change and forestry. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2007*. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

U.S. Environmental Protection Agency [USEPA]. (2009b). *Waste. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2007*. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

U.S. Environmental Protection Agency [USEPA]. 2010. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008* (EPA 430-R-09-006). Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

U.S. Environmental Protection Agency [USEPA]. (2011). *Draft inventory of U.S. greenhouse gas emissions and sinks: 1990–2009* (EPA 430-R-11-005). Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs. http://epa.gov/climatechange/emissions/usinventoryreport.html. 12 Mar 2011.

United Nations. (1992). *United Nations framework convention on climate change*. FCCC/INFORMAL/84, GE.05-62220 (E) 200705. http://unfccc.int/resource/docs/convkp/conveng.pdf. 20 Sept 2012.

Upton, B., Miner, R., Spinney, M., & Heath, L. S. (2008). The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass and Bioenergy, 32*, 1–10.

Van Auken, O. W. (2000). Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics, 31*, 197–215.

Woodall, C. W., D'Amato, A. W., Bradford, J. B., & Finley, A. O. (2011). Effects of stand and inter-specific stocking on maximizing standing tree carbon stocks in the eastern United States. *Forest Science, 57*, 365–378.

Zanchi, G., Pena, N., & Bird, N. (2010). The upfront carbon debt of bioenergy. Graz: Joanneum Research. http://www.birdlife.org/eu/pdfs/Bioenergy_Joanneum_Research.pdf. 23 Nov 2011.

Zerbe, J. I. (2006). Thermal energy, electricity, and transportation fuels from wood. *Forest Products Journal, 56*, 6–14.