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Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands

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Abstract

Scientists and policy makers have long recognized the role that forests can play in countering the atmospheric buildup of carbon dioxide (CO_2), a greenhouse gas (GHG). In the United States, terrestrial carbon sequestration in private and public forests offsets approximately 11% of all GHG emissions from all sectors of the economy on an annual basis. Although much of the attention on forest carbon sequestration strategy in the United States has been on the role of private lands, public forests in the United States represent approximately 20% of the U.S. timberland area and also hold a significantly large share (30%) of the U.S. timber volume. With such a large standing timber inventory, these forested lands have considerable impact on the U.S. forest carbon balance. To help decision makers understand the carbon implications of potential changes in public timberland management, we compared a baseline timber harvest scenario with two alternative harvest scenarios and estimated annual carbon stock changes associated with each. Our analysis found that a ''no timber harvest'' scenario eliminating harvests on public lands would result in an annual increase of 17–29 million metric tonnes of carbon (MMTC) per year between 2010 and 2050—as much as a 43% increase over current sequestration levels on public timberlands and would offset up to 1.5% of total U.S. GHG emissions. In contrast, moving to a more intense harvesting policy similar to that which prevailed in the 1980s may result in annual carbon losses of 27–35 MMTC per year between 2010 and 2050. These losses would represent a significant decline (50–80%) in anticipated carbon sequestration associated with the existing timber harvest policies. If carbon sequestration were valued in the marketplace as part of a GHG offset program, the economic value of sequestered carbon on public lands could be substantial relative to timber harvest revenues.
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1. Introduction

Forest ecosystems play an important role in the global carbon cycle, absorbing large amounts of atmospheric carbon dioxide (CO_2) through photosynthesis and emission of CO_2 to the atmosphere through respiration, decomposition, and disturbances such as timber harvesting, fire, pest infestations, and land use change. Globally, terrestrial ecosystems are a net carbon sink[1] because removals and storage of CO_2 from the atmosphere (about 2300 million metric tonnes of carbon [MMTC] per year) exceed emissions (1600 MMTC per year) (IPCC, 2000). Most of the terrestrial sink is in forests. The global carbon balance masks some regional disparities; for instance, tropical forests are a source of emissions as deforestation outpaces regrowth, while the reverse is true currently in temperate forests, which are a net sink. The latest data for the United States indicate that land use, land use change, and forestry (predominately forest) comprises a net carbon sink of over 210 MMTC per year, offsetting about 11% of the country's GHG emissions (U.S. EPA, 2006).[2]

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[1] A carbon pool is a net sink if, over a certain time interval, more carbon is flowing into the pool than is flowing out of the pool. Conversely, a carbon pool can be a net source of CO_2 emissions if less carbon is flowing into the pool than is flowing out of the pool.

[2] Note that EPA data are reported in teragrams (million metric tonnes) of CO_2 equivalent (Tg CO_2). One ton of carbon equals 3.667 tons of CO_2.

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Expanding the area of land in forest cover, avoiding deforestation, and managing existing forests to store carbon in ecosystem stocks for longer periods by increasing the length of time between harvests can increase the net size of the carbon sink or, in some cases, turn a source into a sink. This has been recognized in the global and domestic policy arenas as a mix of mandatory and voluntary initiatives have sprung forth in the last decade that incentivize expansion of carbon sinks as a climate mitigation strategy. In the United States, much of the emphasis has been on incentives to expand carbon sinks on private lands (U.S. EPA, 2005; Lewandrowski et al., 2004; Richards and Stokes, 2004; McCarl and Schneider, 2001; Adams et al., 1999; Stavins, 1999; Plantinga et al., 1999). The more limited work regarding estimates of public lands' contribution to the U.S. carbon sink pertains to the projection of the status quo or business-as-usual case or BAU (Turner et al., 1995; Smith and Heath, 2004) or to regional contributions (e.g., Alig et al., 2006). Yet public timberlands constitute a sizable share of the U.S. forest resource in terms of both land area and timber volume (see Section 2) and thereby provide a potentially important resource to manage for climate change mitigation.

This paper departs from the literature by examining public timberlands' forest carbon sequestration potential at a national scale, not only under BAU conditions, but also under changes in forest management. The change in public forest management addressed in this paper is the level of allowable timber harvests, with two alternative scenarios to BAU defining the range of options from no timber harvest (elimination of all timber harvests on public timberlands) to a return to the historically high harvest period of the 1980s. Public land managers could consider other forms of forest management, such as modified rotations and intensive management of inputs, but those remain outside the scope of this paper.

The next section of the paper provides a brief overview of the public forestland resources in the United States, followed by a description of the data and methods used in the analysis and presentation of results for public timberlands. The paper ends with policy conclusions that can be drawn from the study and suggestions for future work.

2. Public timberland in the United States

The contiguous 48 (C48) states have approximately 228 million acres of public forests. Approximately 80% of this land, or 182 million acres, is in federal ownership (W.B. Smith et al., 2004; J. Smith et al., 2004). States, counties, and municipalities own the remaining 46 million acres; approximately 61% (138 million acres) of the public forestland is classified as *timberland* because it meets site productivity criteria and is not withdrawn from timber utilization by statute or administrative regulation.[3] Public timberland in the C48 states is concentrated in the West (west of the 100th meridian), which holds about 80% of U.S. public forestland. The top six states in order of public timberland area are Oregon, Idaho, Montana, California, and Colorado/Washington (tie).

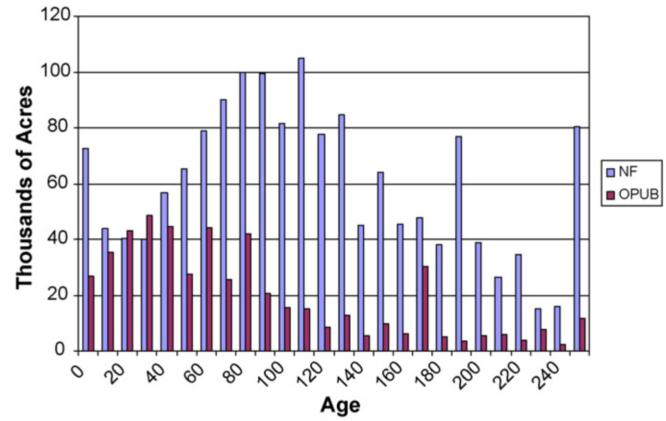

Fig. 1. Distribution of national forests and other public lands acres by age class: 2000.

Although the public owns a significant share of U.S. timber resources, they contribute a much smaller fraction of total U.S. timber removals. Public timberlands held 41% of growing stock inventory in 2001. The largest concentration of public timberlands is on National Forest (NF) lands, which alone held 30% of U.S. timber growing stock in 2001 (W.B. Smith et al., 2004; J. Smith et al., 2004). However, public timberlands produced only 8% of the U.S. timber removals in 2001, with NF lands providing just 2% of U.S. timber removals in 2001. Public policy makers have reduced timber harvests in favor of other nontimber outputs (e.g., wildlife, recreation, watershed protection, scenic amenities) since the late 1980s (Wear and Murray, 2004). Note that annual mortality is larger in volume than growing stock removals on both NF and other public (OPUB) timberlands, while net growth volume is at least two times the amount of mortality volume for those ownerships, leading to a net accumulation of growing stock and carbon. For example, in the case of NF timberlands, many acres are in young age classes with relatively rapid growth. However, public timberlands hold a relatively large share of the nation's older timber on timberland, especially on NFs, as shown in Fig. 1.

3. Analysis scenarios

Current management of U.S. public forestlands centers on a mix of environmental and socioeconomic objectives. For example, the Northwest Forest Plan (NWFP) covers almost 25 million acres and addresses northern spotted owl population and habitat, marbled murrelet population and habitat, late successional old-growth habitat, watershed conditions, and socioeconomic characteristics. Monitoring efforts are also underway to evaluate the success of the NWFP in achieving its objectives based on new scientific knowledge on key topics that include old-growth forest habitat, watersheds, and rural economies. Currently, carbon sequestration is more a by-product

[3] Timberland is defined as forestland that can produce 20 ft^3 of industrial wood per acre per year in naturally regenerated stands and that is not withdrawn from timber utilization by statute or administrative regulation (W.B. Smith et al., 2004; J. Smith et al., 2004).

than a primary management objective of the plan, but that could change with the renewed interest in climate change mitigation at the federal level in the United States (Paltsev et al., 2007).

For this analysis, we characterize a baseline (referred to as the BAU timber harvest scenario) and compare and contrast annual carbon stock changes associated with two alternative timber harvest scenarios. The baseline scenario for public timberlands identified by Mills and Zhou (2003) was derived from the USDA Forest Service's (USFS's) Washington office and represents expectations at that time based on guidelines of USFS policy. Timber harvests are drawn from a characterization that we call a ''removals scenario'' after Mills and Zhou (2003) and were allocated according to the number of acres in each age class (see below). Regeneration volumes were based on ATLAS model (Mills and Kincaid, 1992) projections of forest inventory (see below for details).

The first alternative scenario, ''no harvest,'' eliminates timber harvest completely and thereby reflects nontimber forest management objectives in the extreme. NF timber stands are assumed to grow without any timber harvest-related disturbances for the next 100 years. Mills and Zhou (2003) assumed that other naturally occurring disturbances such as fire, insects and diseases, and other natural mortality would remove timber volume and require the natural regeneration of an additional 140,000 acres annually. This acreage number came from the average rate of acres disturbed in the 10 years preceding the publication of ''Projecting National Forest Inventories for the 2000 Resources Planning Act (RPA) Timber Assessment'' by the USDA Forest Service (Mills and Zhou, 2003). The disturbed acres were taken from the two dominant forest types, those occupying the largest acreage. Within the two dominant forest types, disturbed acreage was removed from every age class above the minimum harvest age for the ATLAS model.

The second alternative, ''high-harvest/pre-1989'' scenario, follows timber harvest levels as depicted in the 1989 USFS's Timber Assessment (USDA Forest Service, 1990), the most recent period of timber harvesting on public timberlands that is above historical averages. These timber harvest levels, as reported in the 1989 RPA Assessment, for NFs came from the forest plans in effect or drafted in 1987 in response to the National Forest Management Act of 1976. NFs at that time provided about two-thirds of timber harvests from public timberlands, and NF timber harvest was assumed to increase by about 400 million ft^3, from 2.3 billion in 1986 to 2.7 billion by 2040. The 1986–2040 projected harvest levels took into consideration the anticipated impacts at that time of the Threatened and Endangered Species Act of 1973. The scenarios are intended to convey differences in forest carbon and carbon that is disposed of off-site – in products, landfills, and energy use – under different timber harvest assumptions.

As shown in Fig. 2, the BAU timber harvests per decade from public timberlands in 2010 range from 15 to 20 billion ft^3 during the period of the analysis. Approximately two-thirds of the harvests come from other public timberlands (see Fig. 2a and b), a reverse of the relative contributions of the two major sources of public timber harvest in 1986. In contrast, the pre-1989 scenario harvests per decade are significantly higher and

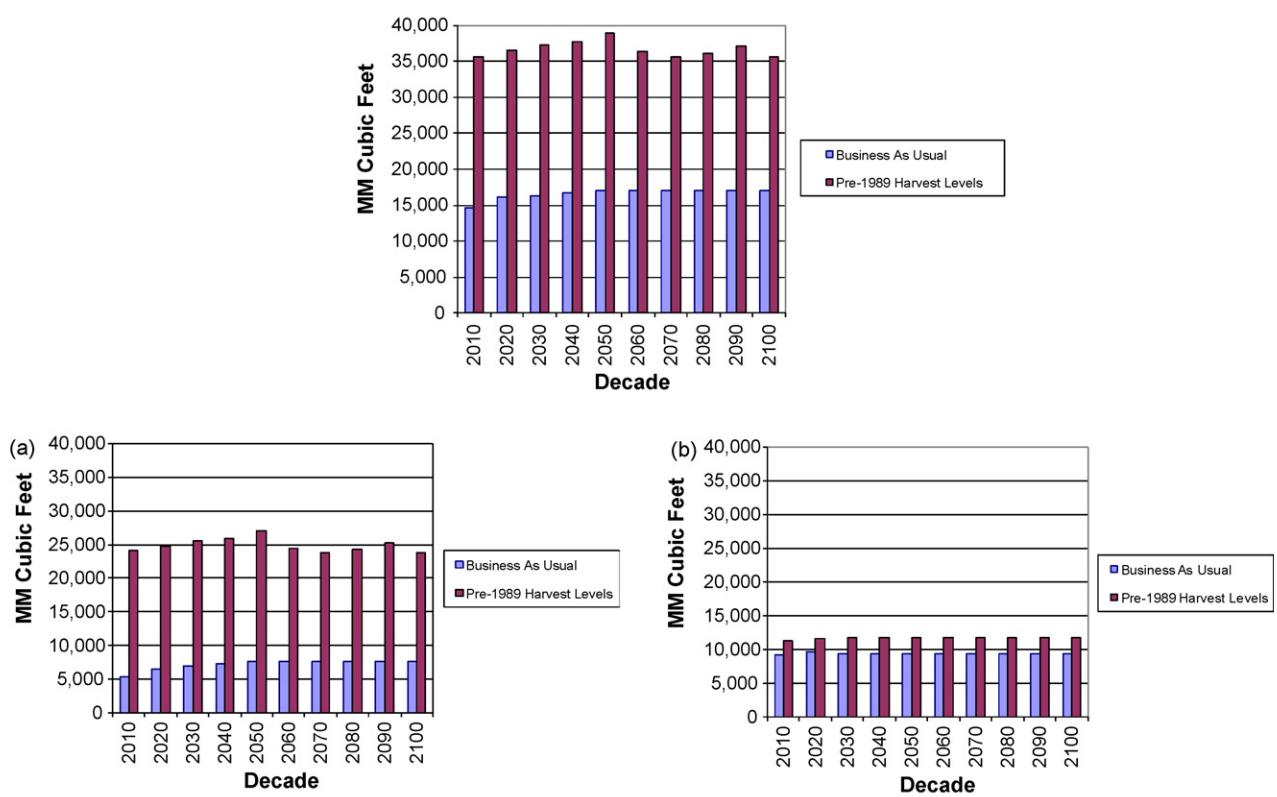

Fig. 2. Total public timberland harvests by decade and scenario 2010–2100. This includes harvests from (a) National forests and (b) other public lands.

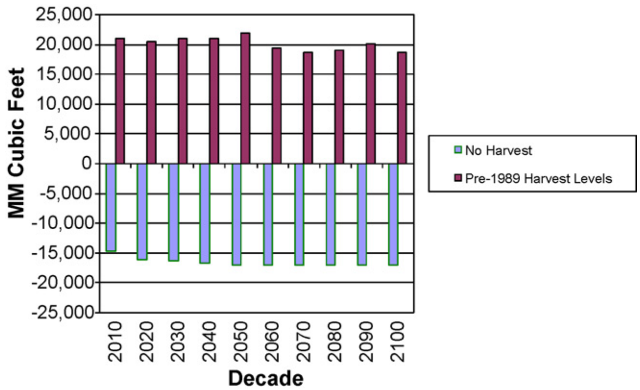

Fig. 3. National forests and other public lands: changes from BAU harvest volume by scenario.

range from 35 to 40 billion ft^3. Timber harvests in these scenarios increasingly rely on NF lands, with approximately two-thirds of the decades' total harvests coming from NFs.

As shown in Fig. 3, the no-harvest scenario reduces public timber harvests by approximately 15 billion ft^3 per decade. Presumably, this scenario will increase carbon stocks by avoiding carbon losses associated with converting standing forests into wood products. In contrast, the pre-1989 scenario increases baseline public timber harvest levels by approximately 20 billion ft^3 per decade. As a result, carbon losses will increase as more timber is removed. Our analysis is designed to estimate, compare, and contrast annual carbon stock changes associated with the two radically different timber harvest scenarios.

4. Data and methods

Simulating public forest management requires data specific to public timberlands on a range of variables, including land class, timberland area, forest type, timber yields for specified land management trajectories, growing stock or biomass volume by age class, site productivity, and regeneration yields. These data also need to be linked to data or models that quantify the relationship between these variables and carbon storage.

4.1. Timberland inventory

Public timberland data were obtained from ATLAS modeling used in the 2000 RPA Timber Assessment. We assembled the inventory data, along with existing and regenerated timberland yield projections for NF aggregates, using strata identical to those used in the private timberland tables in the Forest and Agricultural Sector Optimization Model-Greenhouse Gases, or FASOMGHG (McCarl et al., 2005; Adams et al., 1996). Data for projections came from USFS Forest Inventory Analysis (FIA) permanent sample plots. Collected data for NF and OPUB timberlands were stratified by region, ownership, forest type, and age class (Mills and Zhou, 2003). Assembling inventory data included identifying public timberland area and growing stock volumes by age, land class, region, forest type, site class, and broad management intensity class. Timber growth and yield relations were developed from a broad cross section of field plots. In ATLAS, timber management intensity classes correspond to a specific regime of silvicultural treatments to represent a regional average response for a particular forest type. The management intensity classes are initially populated with a timberland inventory derived from forest survey plots. Empirically derived parameters dictate forest stand development in terms of net growing stock volume as the ATLAS model simulates growth, timber harvesting, and regeneration. The ATLAS modeling approach has been applied in regional and national timber resource assessments, for modeling of changes on both private and public timberland.

Mills and Zhou (2003) provided public timberland data, based on USFS Forest Inventory and Analysis (FIA) plots. We used 5-year age classes to represent public timberlands, up to ages of 250+ in all regions except the South, where the oldest age class was 90+ for the generally younger forests held there. Some Northeast and South Central plots did not have age class data assigned by the FIA units; for these plots age was assigned using a method that considers volume and stocking.

Age class is one of the parameters used to calibrate the yield functions that determine volume; another parameter is region. Nine timber supply regions were designated to categorize the United States described in Mills and Zhou (2003). These regional designations help organize forest area into areas of similar growth characteristics, making the model more accurate than if only one yield function were used for the entire United States.

Across all regions, forestland was aggregated into softwood and hardwood forest-type groups. In the Pacific, Rocky Mountain, Lake States, and Corn Belt regions, all land with trees over 250 years old was aggregated into the age cohort of >250. In the Southern regions, land with trees 90 years or older was aggregated into the uppermost age cohort of >90. In the Southeast and South Central regions, ATLAS was unable to project yields of older stands for the entire 100-year time horizon. In the older stands, the total volume within the strata was used to extrapolate yield curves throughout the projection period. Based on data limitations, each stand in the inventory was assigned a medium site class. Public timberland only occurred on the FORONLY (''forest only'') land class, areas not suitable or not available for conversion to crop or pasture. Because of this limitation, no conversion is allowed to agriculture on public land, which, regardless of whether it is biophysically feasible to do so, is not likely to occur for legal and political reasons.

Timber management intensity on NF timberland consists of three categories: a low intensity of even-age management, uneven-age management, and reserved (Mills and Zhou, 2003). Other public timberlands only had the low intensity of timber management. With a low intensity of timber management, no significant intermediate stand treatments are assumed to occur between stand establishment and final harvest.

Timber stands are final harvested over a range of stand ages. The uneven-age regime allows partial cutting (Mills and Zhou, 2003), where a treatment removes a portion of timber volume to reflect a stand subject to multiple entries. Timberland in a reserved class is not available for timber harvest, but growth of the reserved stands is projected forward in time. The number of acres assigned to these regimes was derived from a survey of NF regional silviculturists (Mills and Zhou, 2003). The majority of the NF acres are assigned to either the partial cutting or reserved classes.

Timber yield estimation for regenerated stands was based on the ATLAS model approach. ATLAS calculates regeneration failures by region and used lagged yields to reflect failed cases. ATLAS has acres remain in the youngest timber age class for an extra 5 years for the South or 10 years elsewhere. Lacking data on pre- and postdisturbance forest types, all regenerated stands returned to the same forest type from which they originated in the same proportions of hardwood and softwood as they had before disturbance.

Assumptions concerning future harvest patterns and land base changes included that the public timberland area does not change over the planning horizon. All clear-cut harvested acres are regenerated as a single stratum with the other harvested acres in that same period and region. Harvests are distributed according to area in each age class; no age class or management intensity is excluded from harvest except for reserved acres.

4.2. Carbon projection methods

Our analysis calculates the stocks and flows (fluxes) of carbon on public timberlands in the United States, including NF and OPUB lands. These estimates are based on USFS projections of future timberland inventories and timber harvest levels, forest carbon accounting equations of the USFS FORCARB2 model (see below), and wood product accounting methods based on the previous work of Smith et al. (2006). As shown in Fig. 4, the carbon accounting framework separates forest carbon calculations into two parts: the accumulation of forest ecosystem carbon as forested stands mature before harvest and the disposition of carbon into various destination pools after the point of harvest. We discuss each component below.

4.2.1. Forest ecosystem carbon accumulation before harvest

On-site carbon accounting closely mirrors the FORCARB2 system used by the USFS in their aggregate assessments of

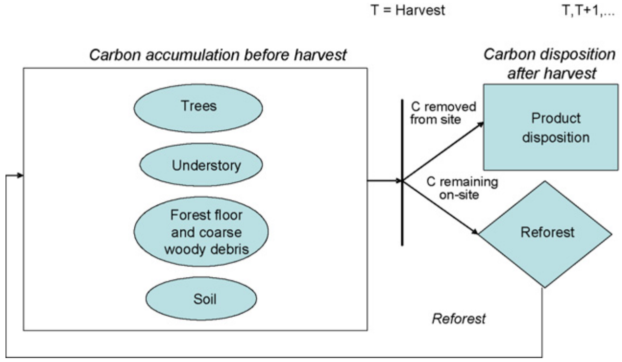

Fig. 4. Carbon accounting framework.

forest carbon sequestration. Using this framework, carbon accumulates in four pools and we describe each below:

- trees
- understory
- forest floor and coarse woody debris
- soil

4.2.1.1. Trees. In FORCARB2, tree carbon is a function of two factors: merchantable timber volume and parameters of a forest volume-to-biomass model developed by USFS researchers (Smith et al., 2003). Merchantable volume, by age, on each representative stand is obtained from the timber growth and yields tables in the ATLAS model described above. Tree carbon includes live and standing dead tree carbon and is calculated using the parameters of the forest volume-to-biomass model equations for live and dead tree mass densities (above and below ground) in Smith et al. (2003).[4] Birdsey's (1992) assumption that mass of wood is approximately 50% carbon is used to derive the associated quantity of carbon:

$$C^{\mathrm{R}} = \left(\frac{D^{\mathrm{L}} + D^{\mathrm{D}}}{U^{\mathrm{B}}}\right) \times 0.5, \tag{1}$$

where live and dead tree biomass are computed as

$$D^{\mathrm{L}} = F^{\mathrm{w}} \times (G^{\mathrm{vbw}} + (1 - \exp^{(-V^{\mathrm{T}}/H^{\mathrm{vbw}})})) \tag{2}$$

$$D^{\mathrm{D}} = D^{\mathrm{L}} \times A^{\mathrm{vbw}} \times \exp^{(-(V^{\mathrm{T}}/B^{\mathrm{w}})^{C^{\mathrm{vbw}}})}. \tag{3}$$

The variables in these equations are reported in Table 1.

4.2.1.2. Understory. Understory vegetation is the smallest component of total carbon stock and includes all live vegetation except trees larger than seedlings. In this analysis, understory carbon is a fixed fraction of live tree carbon based on published ratios reported by the U.S. EPA (2003). Weighted ratios for regions/forest types are created using forestland area data reported by the USDA Forest Service (Miles, 2003).

$$C^{\mathrm{U}} = \frac{D^{\mathrm{L}}}{U^{\mathrm{B}}} \times 0.5 \times R^{\mathrm{Uw}} \tag{3}$$

The variables in this equation are defined in Table 2. The weighted parameters used are reported in Table 3.

4.2.1.3. Forest floor and coarse woody debris. Forest floor carbon constitutes the third largest carbon storage pool, but this pool is much smaller than tree or soil carbon pools. Smith and Heath (2002) developed a model for estimating forest floor carbon mass, which forms the basis for the forest floor carbon estimates used here. Their model's definition of forest floor excludes coarse woody debris (CWD) materials (i.e., pieces of dead wood that are not attached to trees). CWD includes large woody material fallen or cut and left from live and standing

[4] The parameters used are weighted for the economic model's (McCarl et al., 2005) region/forest-type designations. Forestland area data reported in the RPA Assessment (Miles, 2003) are used to calculate the appropriate weights.

Table 1
Tree carbon variables and parameters

Symbol	Description	Source
D^{L} (Mg C/ha)	Live tree mass density (above and below ground)	See Eq. (2)
D^{D} (Mg C/ha)	Dead tree mass density (above and below ground)	See Eq. (3)
C^{R} (Mg C/acre)	Total tree carbon	See Eq. (1)
V^{T} (m^3/ha)	Total timber volume	–
F^{vbw}, G^{vbw}, H^{vbw}	Weighted live tree density parameters from volume-to-biomass equations	Smith et al. (2003) Table 3 weighted by forestland area data from RPA (Miles, 2003) Tables 5 and 6
A^{vbw}, B^{vbw}, C^{vbw}	Weighted dead tree mass density parameters from volume-to-biomass equations	Smith et al. (2003) Table 4 weighted by forestland area data from RPA (Miles, 2003) Tables 5 and 6
U^{B} (1 hectare (ha) = 2.471 acres)	Units conversion factor	–

Mg C = megagram ("metric" tonne) of carbon equivalent m^3 = cubic meters of timber volume.

dead trees with a diameter of at least 7.5 cm (W.B. Smith et al., 2004; J. Smith et al., 2004). CWD accumulates over the life of a forested stand. At the time of harvest, a relatively large component of CWD may be left on site, which decays over time as the next rotation of trees grows. To account for effects of growth, mortality, disturbance, and decay of carbon in this material, we assumed CWD is a fixed fraction of tree carbon. Published ratios of CWD carbon to live tree carbon reported by the U.S. EPA (2003) were weighted for regions/ forest types using forestland area data reported by the USDA Forest Service (Miles, 2003). This formulation of the CWD model clearly has limitations because CWD dynamics depend on the time since harvest and the amount of dead wood left after the disturbance. Although we view the results of the simulations using the current CWD model as fairly robust, given the relatively small factor that CWD plays in stand dynamics over time, the CWD model likely underestimates CWD stocks. Future CWD modeling work could adopt methods similar to recently published work (Smith et al., 2006).

The model for net accumulation of forest floor carbon is a continuous and increasing function of age. The rate of accumulation eventually approaches zero (i.e., a steady-state level of forest carbon):

$$C^{FFA} = \left(\frac{A^{ffw} \times \text{age}}{B^{ffw} + \text{age}}\right) / U^{B} \quad (4)$$

The variables in this equation are defined in Table 4.

Forest floor carbon mass following clear-cutting is assumed to begin at the level of carbon for a mature forest, and decay is described using an exponential function of time and average mature forest floor carbon mass:

$$C^{FFR} = (C^{ffw} \times \exp^{-(\text{age}/D^{ffw})}) / U^{B} \quad (5)$$

The variables in this equation are defined in Table 5.

For CWD, we report the weighted parameters used in Table 6.

4.2.1.4. Soil. Although the soil carbon pool is the second largest carbon storage pool in aggregate in the United States (Birdsey and Heath, 1995), Heath et al. (2002) note that little change in soil carbon occurs if forests are regenerated after harvest. This analysis assumed that all public timberland harvested returns to forest after harvest (i.e., no land is deforested), as is consistent with a mandate to manage and protect public forests. As a result, we assumed soil carbon on public timberland remains at a steady-state value (i.e., there is no change in soil carbon stock in the analysis) for the entire period of analysis.

4.2.2. Carbon disposition after harvest

At the time of harvest, some timber is removed from the site and used to make pulpwood-based products such as paper and sawlog-based products such as lumber, veneer, and

Table 2
Understory carbon variables and parameters

Symbol	Description	Source
C^{U} (Mg/acre)	Total understory carbon	See Eq. (3)
D^{L} (Mg/ha)	Live tree mass density (above and below ground)	See Eq. (2)
U^{B} (1 hectare (ha) = 2.471 acres)	Units conversion factor	–
R^{Uw} (%)	Weighted ratio of understory carbon to live tree carbon	U.S. EPA (2003) Table O-2 weighted by forestland area data from RPA (Miles, 2003) Tables 5 and 6

Table 3
Weighted ratio of understory to live tree carbon (%)

Region	Softwood	Hardwood	Planted pine	Natural pine	Oak pine	Douglas fir	Bottomland hardwood	Upland hardwood	Other softwoods
Northeast	2.6	2.2	NA	NA	NA	NA	NA	NA	NA
Lake states	2.1	2.4	NA	NA	NA	NA	NA	NA	NA
Corn Belt	2.1	2.4	NA	NA	NA	NA	NA	NA	NA
Southeast	NA	NA	6.8	6.8	4.4	NA	2.2	4.4	NA
South central	NA	NA	5.9	5.9	4.4	NA	2.2	3.7	NA
Rocky mountain	5.7	9.2	NA	NA	NA	NA	NA	NA	NA
Pacific northwest west	2.0	4.5	NA	NA	NA	2.0	NA	NA	3.2
Pacific northwest east	3.0	4.5	NA	NA	NA	NA	NA	NA	NA
Pacific southwest	5.0	2.9	NA	NA	NA	NA	NA	NA	NA

Source: Author calculations using U.S. EPA (2003) and forestland area data from RPA (Miles, 2003).

Table 4
Forest floor carbon variables and parameters: net accumulation

Symbol	Description	Source
C^{FFA} (Mg/acre)	Total forest floor carbon net accumulation	See Eq. (4)
Age (years)	Age of stand	–
A^{ffw}, B^{ffw}	Weighted forest floor carbon model coefficients	Smith and Heath (2002) Table 4 weighted by forestland area data from RPA (Miles, 2003) Tables 5 and 6
U^{B} (1 hectare (ha) = 2.471 acres)	Units conversion factor	–

Table 5
Forest floor carbon variables and parameters: decay of forest floor carbon mass existing prior to clear-cut

Symbol	Description	Source
C^{FFR} (Mg/acre)	Total forest floor carbon, residual	See Eq. (5)
Age (years)	Age of stand	–
C^{ffw}, D^{ffw}	Weighted forest floor carbon mass coefficients	Smith and Heath (2002) Table 4 weighted by forestland area data from RPA (Miles, 2003) Tables 5 and 6
U^{B} (1 hectare (ha) = 2.471 acres)	Units conversion factor	

panels. These products are then used to produce goods and services such as furniture, housing, and printed materials that are put into use for some period of time. The ultimate disposition over time of harvested carbon removed from the site depends on the products produced, their end uses, and the period of time elapsed since they were harvested and turned into product. Carbon in logging residue left on site is tracked separately in the forest floor carbon pool described above.

The wood product carbon accounting method used here is based on early versions of recent product accounting work (Smith et al., 2006). The modified approach uses calculation methods that are distinguished by the starting point of the harvest input (e.g., roundwood harvests or primary products produced). Because future NF and OPUB timberland inventories and timber harvest levels are expressed in terms of roundwood harvested rather than primary products produced, we used the roundwood harvests approach to track the fate of product carbon in the following pools:[5]

- products in use (sink),
- landfills (sink),
- energy (source or sink), and
- emissions (source).

Note, our primary analysis treats wood products allocated to the energy pool as a source of GHG emissions. However, we have also included calculations that treat energy uses as a sink

[5] In contrast, the FASOMGHG economic model (McCarl et al., 2005), which incorporates the carbon accounting methods described herein and applies them to estimate forest carbon sequestration at the national and regional levels in the United States, includes production technologies that convert roundwood harvests into primary products. Therefore, FASOMGHG's product accounting system uses the alternative starting point for product carbon calculations (i.e., quantities of primary products produced).

Table 6
Weighted ratio of coarse woody debris (CWD) to live tree carbon (%)

Region	Softwood	Hardwood	Planted pine	Natural pine	Oak pine	Douglas fir	Bottomland hardwood	Upland hardwood	Other softwoods
Northeast	12.3	11.2	NA	NA	NA	NA	NA	NA	NA
Lake states	14.1	10.8	NA	NA	NA	NA	NA	NA	NA
Corn belt	14.1	10.8	NA	NA	NA	NA	NA	NA	NA
Southeast	NA	NA	23.9	23.9	17.3	NA	21.8	24.3	NA
South central	NA	NA	18.6	18.6	17.3	NA	15.7	15	NA
Rocky mountain	12.6	26.7	NA	NA	NA	NA	NA	NA	NA
Pacific northwest west	11.9	3.9	NA	NA	NA	11.9	NA	NA	15.4
Pacific northwest east	14.8	3.9	NA	NA	NA	NA	NA	NA	NA
Pacific southwest	13.0	11.4	NA	NA	NA	NA	NA	NA	NA

Source: Author calculations using U.S. EPA (2003) and forestland area data from RPA (Miles, 2003).

for GHG emissions, assuming that biomass energy sources from the forest sector substitute for fossil fuel energy sources and serve as an offset for those emissions.

To calculate product carbon, we used cubic feet of roundwood harvested, divided into pulpwood or sawtimber products using yield tables, and converted volumes harvested into metric tonnes of carbon using factors reported in earlier versions of Smith et al. (2006). These factors include the average specific gravity, an upward adjustment to account for bark (1.18), and the carbon content of wood (0.5). Next, we allocated the carbon into the wood product pools (see Fig. 5) according to years since harvest and the disposition patterns. Examples of these patterns for the Southeast region are reported in Table 7.[6]

5. Results

Carbon sequestrations for U.S. public timberlands under the three scenarios (BAU, no harvest, and high harvest/pre-1989) are presented in Tables 8–10 respectively. Results are reported separately for all public timberlands and subcomponents (NF and OPUB) and for forest ecosystem carbon and wood product carbon. The projection time period is 10 decades, starting in 2010 and running through 2110. Tables 8–10 report detail for the first 5 decades, but summary totals are provided below for all 10 decades in the projection (Figs. 6–8). All carbon quantities are reported in average annual change in carbon stocks for that period, also known as annual flux.

Under the BAU scenario, public timberlands sequester, on average, 50 MMTC annually during the first 5 decades. This estimate ranges from 65 to 40 MMTC between 2010 and 2050, and decline after that (Fig. 6). The annual carbon flux occurs primarily in the ecosystem carbon pools of public forests prior to harvest (NF and OPUB), and the remainder is associated with postharvest wood and paper product sequestration. The ecosystem fluxes range between 82 and 92% of the total flux depending on decade and whether energy is treated as a credit. NFs account for over 60% of the annual carbon flux for all public timberlands. In 2030, for example, we estimated a total annual forest carbon flux of 33 million metric tonnes for NF timberlands compared with 15 million metric tonnes for OPUB timberlands (see Table 8). As shown in Fig. 7, over 85% of the NF forest carbon flux occurs in the West. The Rocky Mountain region accounts for 41%, followed by the Pacific northwest west (23%) and Pacific southwest (21%).

Table 8 and Fig. 6 display a positive but declining sequestration rate for public timberlands under BAU, with sequestration levels highest in the first decade and falling after that. The magnitudes of stock changes are consistent with the estimates for public forests in Smith and Heath (2004), although they do exhibit slightly different trends. These patterns reflect recent dynamics in the way public lands have been managed. Many of the current forest stands on public timberland today were regenerated after the heavier timber harvest periods of the 1960s–1980s. The net growth in such forest stands eventually slows down considerably as the stands age. Together with the recent slowdown in timber harvest levels, the age distribution of the public timberland stands will

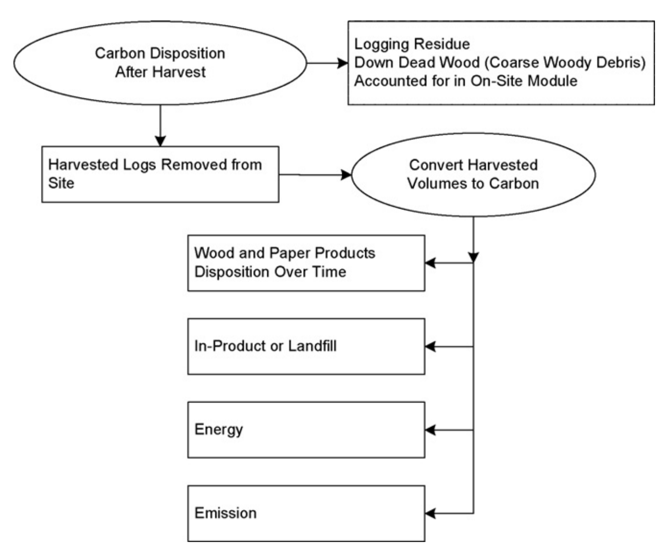

Fig. 5. Wood and paper product carbon disposition.

[6] Data for other regions are available upon request.

Table 7
Example of disposition patterns of harvested wood by region and harvest type, 100-Year period: southeast[a]

Region	Type	Product	Disposition	Years after harvest										
				0	10	20	30	40	50	60	70	80	90	100
Southeast	Softwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Southeast	Softwood	Pulpwood	Landfills	0.00	0.16	0.16	0.16	0.10	0.14	0.14	0.13	0.12	0.11	0.11
Southeast	Softwood	Pulpwood	Energy	0.44	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Southeast	Softwood	Pulpwood	Emissions	0.26	0.32	0.34	0.35	0.41	0.37	0.38	0.39	0.40	0.41	0.41
Southeast	Softwood	Sawtimber	Products	0.47	0.28	0.24	0.21	0.18	0.17	0.15	0.14	0.13	0.13	0.12
Southeast	Softwood	Sawtimber	Landfills	0.00	0.13	0.16	0.17	0.18	0.19	0.19	0.19	0.18	0.18	0.18
Southeast	Softwood	Sawtimber	Energy	0.38	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41
Southeast	Softwood	Sawtimber	Emissions	0.15	0.19	0.20	0.22	0.24	0.24	0.25	0.26	0.28	0.28	0.29
Southeast	Hardwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Southeast	Hardwood	Pulpwood	Landfills	0.00	0.16	0.16	0.15	0.15	0.14	0.13	0.12	0.12	0.11	0.10
Southeast	Hardwood	Pulpwood	Energy	0.39	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Southeast	Hardwood	Pulpwood	Emissions	0.31	0.37	0.38	0.40	0.40	0.42	0.43	0.44	0.44	0.45	0.46
Southeast	Hardwood	Sawtimber	Products	0.27	0.12	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.04
Southeast	Hardwood	Sawtimber	Landfills	0.00	0.11	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12
Southeast	Hardwood	Sawtimber	Energy	0.42	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Southeast	Hardwood	Sawtimber	Emissions	0.31	0.34	0.36	0.35	0.36	0.37	0.38	0.39	0.39	0.39	0.40

[a] These are proportions of the harvested stock allocated to each pool in the years following harvest. Column totals may not sum to one due to independent rounding.

Table 8
Annual stock changes: business-as-usual scenario (MM metric tonnes of carbon, MMTC, unless otherwise specified)

Decade	Forest carbon			Disposition of wood product carbon					Total in wood products		Total carbon stock change	
	Existing	Regenerated	Total in forest	Cumulative harvest volume since 2000 (MM cf)[a]	Decade harvest (MM cf)	Products	Land-fills	Energy	Without energy credit	With energy credit	Without energy credit	With energy credit
All public lands												
2010	55.1	4.5	59.7	28,009	14,695	2.5	2.5	2.5	5.0	7.5	64.6	67.1
2020	45.2	10.1	55.3	44,159	16,150	2.5	2.5	2.5	5.0	7.5	60.3	62.8
2030	34.0	13.5	47.5	60,477	16,318	2.2	2.2	2.2	4.3	6.5	51.9	54.0
2040	20.1	17.5	37.5	77,236	16,759	2.1	2.1	2.1	4.1	6.2	41.7	43.7
2050	15.7	20.4	36.2	94,239	17,003	1.9	1.9	1.9	3.8	5.6	39.9	41.8
National forests												
2010	50.0	1.2	51.2	9,424	5,394	1.2	1.2	1.2	2.5	3.7	53.7	54.9
2020	35.3	2.9	38.2	15,912	6,488	1.4	1.4	1.4	2.7	4.1	40.9	42.3
2030	28.6	4.1	32.8	22,862	6,950	1.3	1.3	1.3	2.6	3.9	35.4	36.6
2040	22.1	5.6	27.6	30,253	7,391	1.3	1.3	1.3	2.5	3.8	30.2	31.4
2050	17.6	7.1	24.7	37,888	7,635	1.2	1.2	1.2	2.4	3.5	27.0	28.2
Other public lands												
2010	5.2	3.3	8.4	18,585	9,301	1.2	1.2	1.2	2.5	3.7	10.9	12.2
2020	9.9	7.2	17.2	28,247	9,662	1.1	1.1	1.1	2.3	3.4	19.4	20.6
2030	5.4	9.4	14.8	37,615	9,368	0.9	0.9	0.9	1.7	2.6	16.5	17.4
2040	−2.0	11.9	9.9	46,983	9,368	0.8	0.8	0.8	1.6	2.4	11.5	12.3
2050	−1.9	13.4	11.5	56,351	9,368	0.7	0.7	0.7	1.4	2.1	12.9	13.6

[a] The cumulative harvest for periods includes all harvests for the previous decades plus the current decade.

shift to older stands in the coming decades and the growth rate will slow.[7]

A comparison of timber harvest scenarios illustrates the carbon storage trade-offs that policy makers face when considering alternative timber harvest levels from public forests. As shown in Fig. 8, moving from the baseline to a no-harvest regime leads to a significant increase in the carbon sequestered on public timberlands. Our estimates suggest an annual increase (above baseline) of 17–29 MMTC per year between 2010 and 2050, approximately a 40–50% increase in carbon storage depending on the decade. Interestingly, this is just below the 55–57% additional carbon sequestration reported by Harmon et al. (1990) when looking at the carbon sequestration potential of maintaining old-growth stands versus converting to

[7] One possible change to this growth projection is the effect of a changing climate. As shown in various studies at different spatial scales (Sohngen and Mendelsohn, 1998; Alig et al., 2002; Abt and Murray, 2001), future changes in climate can affect the growth and species distribution of forests in ways that are either favorable or unfavorable, depending on location.

Table 9
Annual stock changes: no-harvest scenario (MM metric tonnes of carbon, MMTC, unless otherwise specified)

Decade	Forest carbon			Disposition of wood product carbon					Total in wood products		Total carbon stock change	
	Existing	Regenerated	Total in forest	Cumulative harvest volume since 2000 (MM cf)	Decade harvest (MM cf)	Products	Land-fills	Energy	Without energy credit	With energy credit	Without energy credit	With energy credit
All public lands												
2010	93.3	0.0	93.3	0	0	0.0	0.0	0.0	0.0	0.0	93.3	93.3
2020	85.5	0.0	85.5	0	0	0.0	0.0	0.0	0.0	0.0	85.5	85.5
2030	76.1	0.0	76.1	0	0	0.0	0.0	0.0	0.0	0.0	76.1	76.1
2040	61.0	0.0	61.0	0	0	0.0	0.0	0.0	0.0	0.0	61.0	61.0
2050	57.3	0.0	57.3	0	0	0.0	0.0	0.0	0.0	0.0	57.3	57.3
National forests												
2010	64.3	0.0	64.3	0	0	0.0	0.0	0.0	0.0	0.0	64.3	64.3
2020	52.2	0.0	52.2	0	0	0.0	0.0	0.0	0.0	0.0	52.2	52.2
2030	46.8	0.0	46.8	0	0	0.0	0.0	0.0	0.0	0.0	46.8	46.8
2040	41.1	0.0	41.1	0	0	0.0	0.0	0.0	0.0	0.0	41.1	41.1
2050	36.9	0.0	36.9	0	0	0.0	0.0	0.0	0.0	0.0	36.9	36.9
Other public lands												
2010	29.0	0.0	29.0	0	0	0.0	0.0	0.0	0.0	0.0	29.0	29.0
2020	33.3	0.0	33.3	0	0	0.0	0.0	0.0	0.0	0.0	33.3	33.3
2030	29.4	0.0	29.4	0	0	0.0	0.0	0.0	0.0	0.0	29.4	29.4
2040	19.9	0.0	19.9	0	0	0.0	0.0	0.0	0.0	0.0	19.9	19.9
2050	20.4	0.0	20.4	0	0	0.0	0.0	0.0	0.0	0.0	20.4	20.4

sustained harvesting of stands under rotational forestry. Sequestration under the no-harvest scenario in the first 5 decades would offset between 1 and 2% of total CO_2 emissions in the United States at current levels and is equivalent to removing the emissions of about 13–24 million cars per year. Most of the additional sequestration occurs within NFs (see Table 9). This rate of additional carbon sequestration declines over time (Fig. 8).

In contrast with the no-harvest scenario, increasing the baseline harvest levels to pre-1989 levels leads to a significant decrease in the carbon sequestered in public forests. Our estimates suggest losses ranging from 27 to 35 MMTC per year

Table 10
Annual stock changes: pre-1989 harvest levels (MM metric tonnes of carbon, MMTC, unless otherwise specified)

Decade	Forest carbon			Disposition of wood product carbon					Total in wood products		Total carbon stock change	
	Existing	Regenerated	Total in forest	Cumulative harvest volume since 2000 (MM cf)[a]	Decade harvest (MM cf)	Products	Land-fills	Energy	Without energy credit	With energy credit	Without energy credit	With energy credit
All public lands												
2010	5.6	9.1	14.8	69,470	35,630	7.5	7.5	7.5	14.9	22.4	29.7	37.1
2020	−3.1	17.7	14.6	105,975	36,504	6.6	6.6	6.6	13.2	19.8	27.8	34.3
2030	−17.7	25.5	7.8	143,301	37,327	6.0	6.0	6.0	12.0	18.0	19.9	25.9
2040	−29.9	32.2	2.3	181,085	37,784	5.3	5.3	5.3	10.5	15.8	12.9	18.1
2050	−33.1	36.1	3.0	220,015	38,929	5.0	5.0	5.0	10.0	15.0	13.1	18.1
National forests												
2010	2.7	5.8	8.6	47,200	24,220	5.6	5.6	5.6	11.1	16.7	19.7	25.3
2020	−11.0	10.1	−0.8	72,040	24,840	5.0	5.0	5.0	10.1	15.1	9.2	14.3
2030	−19.2	15.4	−3.8	97,562	25,522	4.6	4.6	4.6	9.2	13.8	5.4	10.0
2040	−24.3	19.0	−5.3	123,472	25,910	4.1	4.1	4.1	8.1	12.2	2.9	6.9
2050	−27.3	21.3	−6.0	150,527	27,055	4.0	4.0	4.0	8.0	12.0	1.9	5.9
Other public lands												
2010	2.9	3.3	6.2	22,270	11,410	1.9	1.9	1.9	3.8	5.7	10.0	11.9
2020	7.8	7.6	15.4	33,935	11,664	1.6	1.6	1.6	3.1	4.7	18.5	20.1
2030	1.6	10.1	11.7	45,739	11,804	1.4	1.4	1.4	2.8	4.2	14.5	15.9
2040	−5.6	13.2	7.6	57,613	11,874	1.2	1.2	1.2	2.4	3.6	10.0	11.2
2050	−5.7	14.8	9.1	69,487	11,874	1.0	1.0	1.0	2.0	3.0	11.1	12.1

[a] The cumulative harvest for periods includes all harvest for the previous decades plus the current decade.

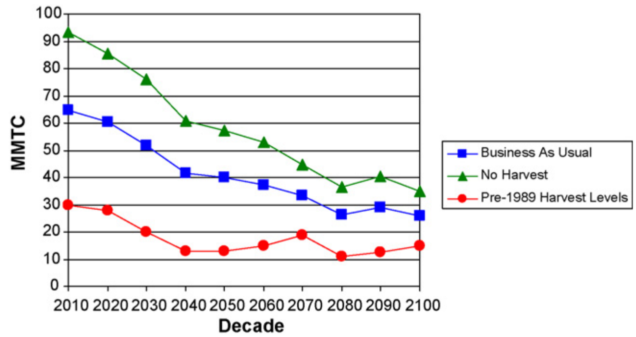

Fig. 6. Annual carbon sequestration in all public lands by scenario.

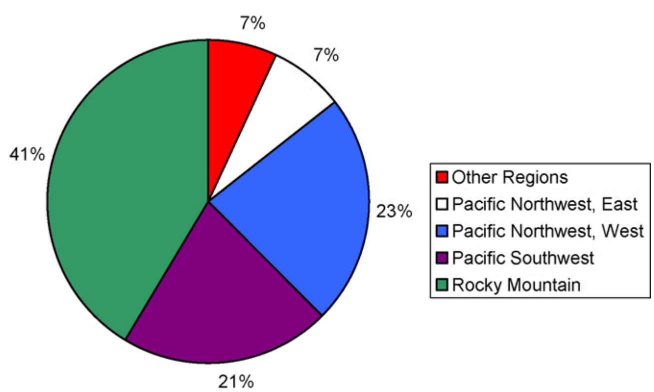

Fig. 7. Distribution of annual NF carbon stock changes by region: BAU scenario (2030).

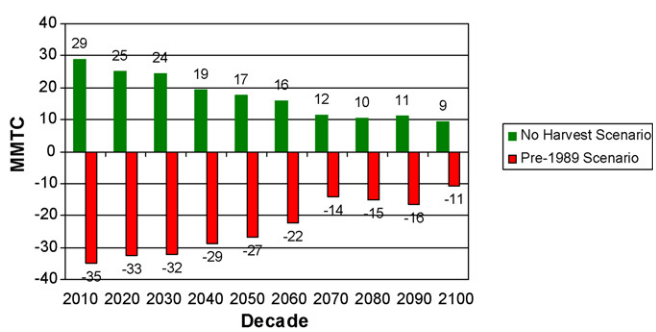

Fig. 8. Comparison of annual carbon stock changes with business-as-usual scenario.

between 2010 and 2050, approximately a 50–80% decline in carbon storage from BAU depending on the decade. This tempers some in the last 5 decades as the regrowth from harvested stands contribute more strongly to the sequestration rate. The vast majority of timber harvests come from NF timberlands: an average of 26 billion ft^3 are harvested per decade in NFs compared with 12 billion ft^3 in OPUB timberlands. As a result, returning to these high timber harvest levels would make NFs a net source of emissions between 2020 and 2050. Although OPUB timberlands continue to be carbon sinks, the annual carbon stock changes in forests are substantially lower than in the BAU case. Carbon losses associated with the more intense harvesting scenario are reduced to some degree through carbon storage in wood and paper products. Our estimates suggest that wood and paper products sequester between 10 and 15 MMTC per year. If we treat energy uses as a sink for GHG emissions, assuming energy use substitutes for other energy sources and serves as an offset for those emissions, our wood and paper product sequestration estimates increase another 5–7 MMTC per year, rising between 15 and 22 MMTC per year total, depending on the decade (see Table 10).

It is instructive to view these results in terms of the potential monetary value of sequestered carbon in the different scenarios. Payments for carbon sequestration can be viewed as part of a potential broader system to offset emissions of CO_2 and other GHGs. CO_2 emission credits are currently being traded for between US$ 15 and 30 per metric tonne (Mg) of CO_2 equivalent on the EU's Emissions Trading System (EU ETS). Translating to units of carbon, this is about US$ 55–110 per Mg C. Although forest carbon sequestration is not currently traded in the EU ETS, this range provides some sense, perhaps an upper range, of its monetary potential if sequestered carbon on public timberlands were included in a trading mechanism.[8] At this price range, the annual value of carbon sequestered on public timberlands under BAU ranges from US$ 2.2 to 7.1 billion, depending on the decade. However, GHG compensation schemes that include forest carbon offsets might not consider BAU sequestration to be creditable, focusing instead on carbon that is additional to BAU (Murray et al., 2007). We can estimate that the additional amount of carbon sequestered under the no-harvest scenario would be between US$ 0.9 and 3.2 billion per year, and foregone carbon revenue would be between US$ 1.5 and 3.9 billion per year under the pre-1989 harvest scenario. By contrast, timber harvest revenues on public lands in 2005 were approximately US$ 800–900 million (Adams, 2006). One should note that these revenue comparisons do not capture all relevant aspects of welfare. A more complete comparison would capture effects on consumer and producer surplus and thereby the net benefits to society of each harvesting plan. That is beyond the scope of this study. The revenue comparisons here, however, do indicate relative trade-offs between timber and carbon revenue that might be expected under different management regimes.

6. Conclusions

For decades, public timberlands have been managed for multiple uses and ecosystem services including timber, range, wildlife habitat, watershed protection, recreation, and visual amenities. More attention in recent years has been placed on establishing and maintaining forest carbon sinks to help regulate atmospheric GHGs and climate, but little empirical work at a national scale has estimated the biophysical potential

[8] Rather than evaluating its revenue potential in a greenhouse gas trading market, another perspective is the social cost of carbon remaining in the atmosphere. This measures the value of climate change damages caused by carbon accumulation in the atmosphere and thus the marginal benefit of carbon removed from the atmosphere. The most recent IPCC assessment report provides a range of values for social cost of carbon at about US$ 43 per tonne C or about US$ 12 per tonne CO_2 (IPCC, 2007).

of modifications in public timberland management to sequester more carbon. This paper addresses that gap by combining data on public timber inventories, timber harvest scenarios, and carbon accounting to quantify the accumulation of carbon on public timberlands and in wood product stocks from harvested timber under three scenarios: BAU, no harvest, and high harvest (equivalent to the 1980s). Findings suggest that under BAU, public timberlands will continue to sequester carbon through the next century, though at a diminishing rate. The BAU accumulation of carbon occurs because of the age class and growth dynamics of the current inventory of public timberland, which has experienced timber harvest levels in the recent past that are substantially lower than the preceding decades. These changes in timber harvest were done for a wide variety of ecological and economic reasons, but a by-product of these efforts was an increase in public timberlands' positive contribution to global climate regulation.

Variations in BAU in either direction – elimination of harvests altogether or a substantial ramp-up in public harvests to levels of 20 years ago – could substantially alter the annual carbon balance of public timberlands, at least 50% in either direction. Each action would have opportunity costs in terms of the economic and ecological value of the corresponding changes in market and nonmarket ecosystem services, but a market for sequestered carbon could alter the balance considerably with public sequestration worth potentially billions of dollars in value per year. Although markets for carbon are in their nascent stages and the level of future carbon prices are highly uncertain, public decision makers should nonetheless consider the economic value of carbon when developing national, regional, and forest-level targets for timber harvests and other public timberland outputs.

This study provides a rough estimate of the potential from a relatively few, though wide-ranging, timber harvest policy alternatives. Forest and carbon management, however, is much more subtle than simply determining how much to harvest. Many forest management decisions from the time of stand establishment through mid-rotation treatments to the timber harvest decision could be affected with carbon sequestration as a more accentuated objective. Of particular interest is the link between carbon management, fire management, and biofuel production, each of which can have a profound impact on the carbon balance, ecological integrity, and economic value of the forest. One research need is a better understanding of how such linkages are affected by the stochastic nature of certain disturbances such as fires. Future research should carefully evaluate these trade-offs and opportunities at regional, landscape, and individual forest scales.

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