DISCUSSION PAPER

Forest Carbon Conservation and Management:

Integration with Sustainable Forest Management for Multiple Resource Values and Ecosystem Services

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May 2015

Pinchot Institute for Conservation

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Abstract. Forest carbon management is an important consideration in temperate forests as well as tropical and boreal forest biomes. It is estimated that US forests absorb 10-20 percent of total US carbon dioxide emissions, or more than 200 Tg C yr^{-1}. Recent research suggests that this net carbon sink is likely to decline over the next few decades, and that US forests could become a net carbon source unless decisive action is taken in the near term to alter this trajectory. This paper will summarize ongoing research to determine how carbon management can be made compatible with existing sustainable forest management programs, and how it may be possible to maintain or enhance the forest carbon sink through targeted management policies. Examples are drawn from private forests managed primarily for timber and other economic values, and from public forests in which management for specific forest uses, values, and services are mandated by law or policy.

Cover image: Berry Meadow in the Pioneer Mountains on the Beaverhead-Deerlodge NF. Courtesy USFS/Amy Shovlain CC BY 2.0.

The US forest carbon sink in a global context

The world's forests were accumulating carbon at an average annual rate of 1.2 Pg C yr^{-1} over the period 2000-2007 (Pan et al. 2011), offsetting 10-15% of global carbon dioxide emissions. The carbon sink in forests was not evenly distributed. The largest sinks were in the boreal forests of Russia and the temperate-zone forests of the US, Europe, and China (Table 1). In contrast, tropical forests were a slight source of carbon (0.08 Pg C yr^{-1}): a small sink in Africa was offset by small sources in tropical Asia and Latin America.

Table 1. Net fluxes and gross sinks of carbon for the world's forests (in Pg C yr^{-1} during 2000-2007) (from Pan et al., 2011). Sinks are positive; sources, negative.

Boreal		Net		Gross sinks
	North America	0.01		
	Europe	0.03		
	European Russia	0.20		
	Asian Russia	0.26		
	Sub-total	0.50	Sink	
Temperate				
	United States	0.24		
	Europe	0.24		
	China	0.18		
	Japan & S. Korea	0.06		
	Australia & New Zealand	0.06		
	Sub-total	0.78	Sink	
Non-tropics	Sub-total	1.28	Sink	2.84
Tropics				
	Latin America	-0.09		
	Africa	0.16		
	Asia	-0.14		
	Sub-total	-0.08	Source	2.74
Global	Total	1.20	Sink	5.58

The net sinks and sources of carbon in forests, however, hide a much more dynamic forest landscape. In the tropics, intact (unmanaged) forests are believed to have been a net carbon sink of 1.02 Pg C yr^{-1}, (Pan et al. 2011), although this sink seems to be declining according to recent observations (Brienen et al. 2015). Moreover, the sink in intact tropical forests has been offset by a net source of 1.10 Pg C yr^{-1} from land management (including deforestation, wood harvest, and regrowth following harvests and agricultural fallow). The source of carbon from land management can, in turn, be broken into sources of carbon from decay of wood products and debris and the cultivation of native soils (2.82 Pg C yr^{-1}) and sinks in recovering forests (1.72 Pg C yr^{-1}). Thus, the total carbon sink in tropical forests can be calculated as 2.74 Pg C yr^{-1} (1.02 Pg C yr^{-1} in intact forests and 1.72 Pg C yr^{-1} in recovering managed forests). That gross sink is 34 times the net tropical source of 0.08 Pg C yr^{-1}.

Although the carbon budgets of managed and unmanaged forests are not distinguished outside the tropics, the methods used to determine the budgets enable the effects of management to be separated from natural effects, at least crudely. The estimated net sink in boreal and temperate-zone forests (1.28 Pg C yr^{-1} = 0.50 + 0.78 Pg C yr^{-1}) (Table 1) is based on successive forest inventories involving periodic measurements of large numbers of sample plots. In contrast, the effects of forest management (including conversion of forests to agriculture, wood harvests, and forest recovery) yield a budget for these non-tropical forests that is nearly balanced. The emissions (attributable to decay of wood products, logging debris, and losses of carbon from cultivation of native soils) were 1.52 Pg C yr^{-1}, while the uptake of carbon (in forests regrowing from agricultural abandonment and harvests) was a sink of 1.56 Pg C yr^{-1} (Houghton 2010, 2013).

How is the measured accumulation (1.28 Pg C yr^{-1} outside the tropics) related to the accumulation rate attributed to management (1.56 Pg C yr^{-1})? Does the calculated uptake confirm the measured uptake? No. The uptake attributable to management is largely offset by emissions (from management). The plausible explanation (assuming both inventory and calculated estimates are correct) is that natural processes, unrelated to management, are responsible for the measured uptake, while the net effect of management is nearly zero. Embedded in both management and the effects of natural processes are the effects of natural disturbances, mainly fire, insects, and wind, which cause pulses of emissions followed by gradual recovery of carbon stocks.

If that interpretation holds, the uptake of carbon by the world's forests averaged 5.58 Pg C yr^{-1} (2.74 Pg C yr^{-1} from tropical forests + 1.28 Pg C yr^{-1} +1.56 Pg C yr^{-1} from temperate-zone and boreal forests). Most of that gross uptake was offset by emissions, for a global net uptake of 1.2 Pg C yr^{-1}, but the large sources and sinks making up that net flux suggest that forest management has the potential to offset, for a limited time, a sizeable fraction of the global emissions of carbon from fossil fuels.

History and current status of US forest carbon budget

The dynamics of how forests affect sources and sinks of carbon can be seen in more detail by considering the history of forest use in the United States and how this has influenced carbon stocks over time. The US forest carbon sink (including the harvested wood C pool) has been consistently estimated at about 0.22 Pg C yr^{-1} over the last decade according to the national Forest Inventory and Analysis (FIA) as reported in the US greenhouse gas inventory (US EPA 2014). Over the longer term, US forests have been significantly more dynamic following settlement and clearing of land and forests to support a growing nation, and then massive recovery of C stocks as forests re-grew on abandoned agricultural land and cutover forest land (Figure 1).

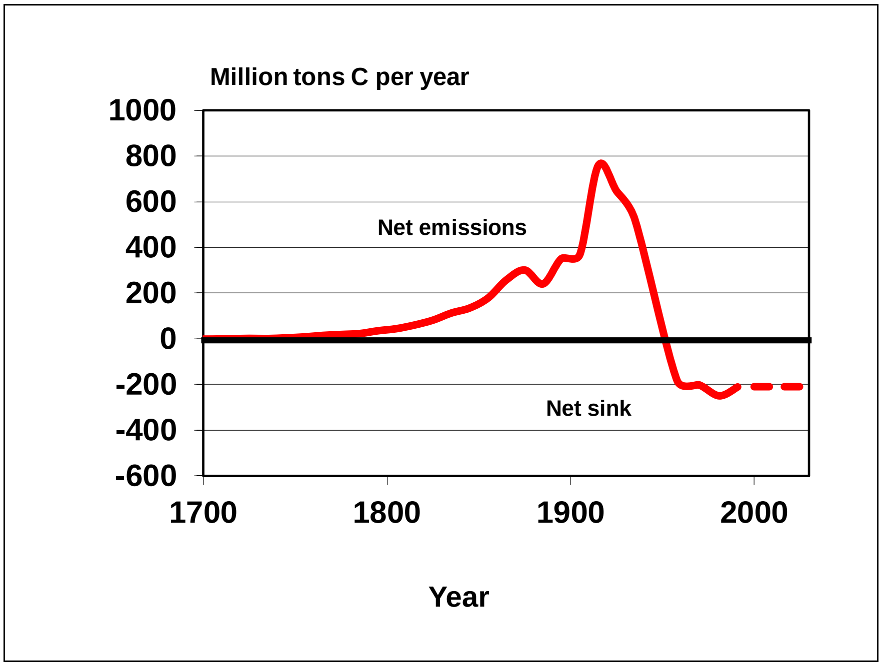

Figure 1. The carbon budget of the US forest sector, 1700-2020 (Birdsey et al. 2006).

It is estimated that US forests overall absorb 216-313 Tg C yr^{-1}, or 10-20 percent of total US emissions of greenhouse gases, making them the country's single most important terrestrial carbon sink (US EPA 2010). However, a 2010 assessment of US forest resources projected that the effectiveness of the US forest carbon sink is declining, and that as soon as 2030 US forests overall may become a net source of greenhouse gas emissions (USDA Forest Service 2012). There are several factors underlying this projected decline, including a continuation of deforestation due to conversion to development and other non-forest land uses, and increasing demand for wood biomass for biofuels and electric power generation (Wear et al. 2013).

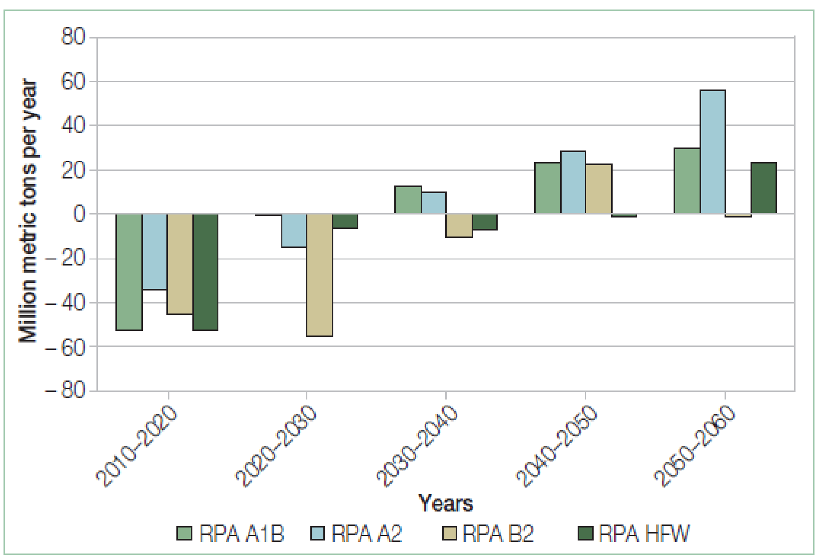

Figure 2. Average annual change in US forest carbon stocks for four scenarios (USDA Forest Service 2012).

Subsequent developments have moderated these projections, particularly in regards to demand for wood bioenergy. Federal legislation in 2007 established a goal of using biofuels to replace 25 percent of petroleum-based fuels by 2025 (EIA 2008). In addition, several states passed laws requiring roughly 25 percent of electric power generation to come from renewable sources by 2025. The combined effect of the Renewable Fuel Standard (RFS) and Renewable Electricity Standards (RES) was estimated to require 1,302 Mg of cellulosic biomass annually (EIA 2007). It was estimated that approximately half of this supply would be provided from agricultural and forestry residues, but that roughly 587 Mg of this would be supplied from harvesting an additional 498 million m^3 of roundwood stock (Perlack et al. 2011, Perlack et al. 2005). Since then, however, difficulties in advanced biofuel technology development, increased supplies of less expensive natural gas, and federal regulations that do not differentiate between biogenic and fossil fuel greenhouse gas emissions from electric power generation have significantly reduced the projected increase in demand for wood biomass for energy production (EIA 2014).

There are continuing uncertainties in other factors that could significantly affect the US forest carbon sink. The increasing average age of US forests may mean reduced growth rates, meaning less CO_2 removed from the atmosphere (Wear et al. 2013). On the other hand, forest growth may continue to respond positively to increasing atmospheric CO_2 concentration (Schimel et al. 2014). Carbon stored in wood products will be strongly influenced by the effect of the overall economy on housing construction, and technological changes in the use of wood in large, multi-story buildings. Perhaps most significantly, the potential for increasing frequency and intensity of natural disturbances, and how this will be influenced by future changes in climate, make it difficult to predict with confidence how the US forest carbon sink will change during the next few decades.

The possibility of a significant reduction in the magnitude of the US forest carbon sink has raised concerns at the national policy level. The next two decades will be a critical period for reducing CO_2 emissions and maintaining atmospheric greenhouse gases below critical levels. A significant reduction in this terrestrial carbon sink could mean additional pressure to reduce emissions from fossil fuels to compensate. In response, the President's Climate Change Action Plan (Executive Office of the President 2013) envisions actions to "preserve the role of forests in mitigating climate change." Decisive actions can be taken in the near-term to minimize the projected reduction of sink strength or increase the sink strength above previous levels. Broad categories of forestry activities that can contribute to increasing carbon stocks or reducing emissions include:

- **Increase forest coverage:** reduce deforestation from conversion to development or other non-forest land uses; promptly reforest after timber harvest or fire; increase afforestation of marginal and pasture land.

- **Increase carbon stocks:** use forest management to maintain or increase carbon storage in live trees, reduce carbon loss from disturbance, and encourage forest regrowth as quickly as possible after harvest and disturbance.

- **Increase the use of wood bioenergy:** increase the efficient and sustainable use of wood biomass in place of fossil fuels in energy production.

Because carbon storage is not often the main goal of land ownership, mitigation is generally considered in the context of multiple goals and objectives. Fortunately, mitigation activities can be consistent with many common landowner objectives such as timber production, provision of wildlife habitat, and watershed protection. At the same time, there may also be tradeoffs. For example, greater amounts of carbon can be stored in trees and long-lived wood products when forests are allowed to mature, but the transition to older forests may reduce early successional habitat for some common wildlife species.

McKinley et al. (2011) summarized current knowledge about forests and carbon storage in the United States and described forest management strategies that can increase forest carbon, prevent its loss, and/or reduce fossil fuel consumption. Each strategy has tradeoffs, risks, and uncertainties which are vital considerations for any effort to promote forest carbon storage, especially with the uncertainty of forest growth and disturbance under future climate. The effectiveness of each strategy depends on many factors including time horizon of analysis, geographic location, forest type, and specific practices applied. Key factors determining rates of sequestration are the biological potential of the land to absorb more CO_2, the economic potential as determined by the future price of CO_2 in the market, and the policies implemented at national, regional, state, and local levels. Estimates from literature summarized by McKinley et al. (2011) about the potential mitigation effects of forestry activities are shown in Table 2, along with some commentary about the range of estimates and their uncertainties.

Uncertainties about the future effects of climate change on forests and carbon stocks are seldom explicitly included in policy assessments and monitoring, even though the effects could be significantly positive or negative. This is partly due to the requirements of accounting and reporting systems that are focused on the direct impacts of management exclusive of indirect and natural effects, and partly because effective analysis tools that can integrate the effects of these multiple factors are not widely deployed. Nonetheless, it is clear that the future success of climate change mitigation in the forestry sector will be significantly affected by climate change, increasing atmospheric CO_2 concentration, and other atmospheric changes such as N deposition (Zhang et al. 2012).

Table 2. Potential mitigation effects of forestry activities, US forest sector (adapted from McKinley et al. 2011).

Category of forestry activity	**Estimate (Tg C yr^{-1})**	**Uncertainties**
Reduce deforestation	0-45	Ability to reduce deforestation is restricted by land-use policies and high potential for “leakage.”
Afforestation	37-225	Highly dependent on price of C. Marginal areas may not regenerate or growth rates could be slow because of climate change.
Improved forest management[1]	29-105	Highly dependent on price of C. Growth rates may vary from those predicted, and species composition may shift because of climate change.
Biomass energy	0-190	Highly dependent on price of energy and transportation costs. Accounting issues are largely unresolved and may inhibit potential.
TOTAL	66-565	

[1] Estimates do not account for the effects of substituting wood products for other materials.

The policy context for forest carbon management in the US

The US forestry community, both private and public, is responding to the need and opportunity for enhancing the role of forests in climate change mitigation, albeit for different motivating reasons. Managers of public forests are finding ways to reduce net carbon emissions as a matter of policy, recognizing that there are broad and long-term public benefits associated with reducing greenhouse gases and mitigating the damaging effects of climate change. Managers of private forests are responding to opportunities for additional income by monetizing their increase in forest carbon stocks through purchases in emerging carbon markets.

Following the UN Framework Convention on Climate Change (UNFCCC) in 1992, there was a surge of research interest in forest carbon management, and in particular on protocols for estimating and verifying carbon gains as a basis for offsets that could be sold under expected carbon cap-and-trade programs. The US was a signatory to the 1997 Kyoto Protocol, which set legally-binding national targets for greenhouse gas emissions reductions (7 percent below 1990 emissions levels for the US), but by the time the protocol was ratified in 2005 the US had withdrawn from participation. There were several unsuccessful attempts at national legislation to establish emissions reduction targets to be accomplished through cap-and-trade programs or a carbon tax.

In the absence of federal policy, several states and groups of states established their own greenhouse gas emissions targets. Most of these relied upon voluntary emissions reductions, with carbon offsets trading at prices significantly below those in compliance-driven markets in countries that were party to the Kyoto Protocol. The Verified Carbon Standard (VCS) (2013) is a third-party project standard that projects can use to quantify greenhouse gas emissions and issue credits in voluntary markets. The VCS provides both protocol standards and a registry system for generating and tracking carbon offsets. The VCS has established methodologies for a variety of agriculture, forestry, and land use-related projects involving improved forest management and avoided conversion. The Climate Action Reserve (CAR) (2013) is a voluntary standard that evolved from the California Climate Action Registry (CCAR). The CAR project protocols are intended for national use, but are not accepted by all registries (e.g. VCS). CAR also provides its own registry system for carbon offset credits that are generated by projects. Forest-related projects may include reforestation, improved forest management, and avoided conversion.

California was the first state to enact a mandatory cap-and-trade program and, in the process, establish a compliance market and a stable price for carbon. The Global Warming Solutions Act of 2006 (Assembly Bill 32) required California to reduce its GHG emissions to 1990 levels by 2020, a reduction of approximately 15 percent below emissions expected under a “business as usual” scenario. Regulated GHG emitters are allowed to satisfy a portion of their reduction compliance targets through offsets approved by the California Air Resources Board (CARB), creating a “compliance market” in which carbon offsets are purchased from projects throughout the US and in several partner countries (California Environmental Protection Agency 2013). The ARB has specified four offset protocols, of which forestry is one, that can be used to generate compliance offset credits. This “Compliance Offset Protocol” allows for forestry projects based on reforestation, improved forest management, and avoided conversion.

Forest carbon management on public lands is driven by policy directives rather than market incentives. Under the National Environmental Policy Act, federal agencies must consider the impacts on carbon sequestration and greenhouse gas emissions in land management decisions. Federal regulations pursuant to the National Forest Management Act include a provision to identify and evaluate existing information relevant to a baseline assessment of carbon stocks for the forest management unit (Federal Register 2012). These regulations prompted the US Forest Service to develop a Climate Change Roadmap, which includes the Performance Scorecard (US Forest Service 2013), comprised of 10 elements designed to gauge performance in a wide variety of climate change activities.

The intention is that the Forest Service will actively demonstrate sustainable forest stewardship under a changing climate, as well as provide technical assistance to state and private forestry. Scorecard element 9 assesses whether national forests have: (1) developed a baseline assessment of C stocks, and (2) assessed the influence of disturbance and management activities on C stocks. This scorecard element reflects the fact that both forest management and natural factors can influence CO_2 removal rates or emissions from forests. Other scorecard elements address climate education, public and private partnership, vulnerability assessment, and adaptation. An underlying theme in these elements is the understanding that healthy forests are actively sequestering and storing carbon, regardless of intentional objectives of carbon storage and emissions mitigation.

Most recently, the President's Climate Change Action Plan (Executive Office of the President 2013) and the President's Priority Agenda "Enhancing the Climate Resilience of America's Natural Resources" (Council on Climate Preparedness 2014) outline increasingly aggressive mitigation actions for both public and private forests as part of a comprehensive strategy for mitigating climate change.

Compatibility of forest carbon management with other sustainable forest management objectives

Although both the compliance market and the voluntary market for carbon have increased in recent years, only a small fraction of US forest land is currently managed with an explicit goal of maintaining or enhancing carbon stocks. There are 251 million hectares of forests in the conterminous United States, containing an estimated 41,000 Tg C (McKinley et al. 2011, Smith and Heath 2004). Roughly 63 percent of this carbon stock (25,800 Tg C) is in the eastern US, mostly in private ownership (Smith and Heath 2004, Smith et al. 2009). About 40 percent of the country's total forest carbon stock (19,000 Tg C) is in public forests, primarily in the western US (Smith and Heath 2004).

For the most part, these lands are currently being managed for other objectives. Private forest lands are managed for a variety of commercial and investment purposes. About 85 percent of the private forest land is in relatively small holdings, often owned by individual families for whom producing timber for wood products is not a primary management objective (Butler 2008). Only about 15 percent of private lands (9 percent of total US forest land) are in large holdings managed primarily for wood products and investment (Smith et al. 2009). Public forest lands, about 78 percent of which are federal, are managed for an array of environmental, economic, and social values, determined largely through federal, state, and tribal laws and public policies. Maintaining forest carbon stocks is only recently a consideration in the management of these lands. In many instances, it is still unclear whether forest carbon management is compatible with existing, carefully balanced public forest management objectives. A technical support system will be needed to provide land managers with the knowledge and tools necessary to make competent decisions about how to managed specific forest systems to reduce greenhouse gases (Birdsey et al 2006).

With a demonstrated ability to absorb 10-20 percent of total US carbon emissions (US EPA 2010), forests will play a critically important role in achieving ambitious national policy goals for reducing net greenhouse gas emissions. Whether the US can maintain or enhance its forest carbon sink depends on the collective actions of literally millions of individual forest owners and land managers. This will depend in turn on finding ways to integrate forest carbon management into existing sustainable forest management plans on both public and private lands, with proven effective carbon management practices that are compatible with the production of an array of other forest values and services.

Generalized prescriptions for increasing carbon stocks and flows have focused primarily on extending rotation age and using some type of variable-retention harvesting that retains a significant portion of a forest's above-ground carbon on-site at all times (Harmon and Marks 2002). Research results have challenged common intuitions about how forest practices influence carbon stocks. For example:

- Replacing older forests with young, fast growing forests is not necessarily optimal; older forests are often more effective at sequestering and storing carbon (Harmon, Ferrell, Franklin 1990).

- Although wildfires can emit large amounts of carbon over short periods, often only 20-25% of forest carbon is released, with remaining carbon in forms that persist for a relatively long time; prescribed broadcast burning of understory and thinned materials to reduce fire risk can itself be a significant source of carbon emissions (Mitchell et al. 2009).

- Timber harvest has greater impact on carbon emissions than most other forms of disturbance; harvest typically captures 20-33% of above-ground carbon in forest products and releases the rest (Birdsey et al.1996, Skog and Nicholson 1998, Harmon et al. 1996). The carbon sequestered in forest products is gradually released, with a half-life ranging from 80 years for a single-family house built after 1920 to less than three years for paper and paperboard products (Skog 2008, US EPA 2014). It is important to consider the carbon release for timber harvesting in comparison to the carbon emissions that would have occurred had concrete or steel been used in construction rather than wood products.

Forest carbon offsets and alternative silvicultural systems

In this section we show two examples of forest management strategies that include producing carbon offsets among the management goals. We focus on the carbon accounting in response to alternative management practices that could be applied in northern US forests, taking account of ecosystem dynamics and carbon in harvested wood products, and considering uncertainties related to social, economic, and environmental factors.

Forest management practices can be designed to manipulate carbon stocks and rates of carbon uptake by forest systems. The impact of a selected management practice will depend on the type of the management practices (e.g., thinning, prescribed burning), how the practice transfers carbon between the different carbon pools, the time period between disturbances or management practices, and the area of forests under management. Accounting methods are also important, such as: the starting point, the time period of the analysis, which changes in carbon pools are estimated, whether the substitution of wood for other materials is counted, and whether indirect effects such as leakage are included in the analysis. Integration of the potential effects of climate change on disturbance and species composition may reveal additional opportunities and risks. Here we focus on accounting for changes in carbon stocks on the land plus the fate of carbon in harvested wood products, but acknowledge that this is a limited but commonly applied analysis. We also comment on uncertainties from socio-economic factors and climate change.

Nunery and Keeton (2010) looked at the effects of both harvesting intensity and postharvest retention on forest carbon storage in stands of northern hardwood-conifer forests of the Northeast United States. They found a clear gradient of increasing carbon sequestration (total carbon stocks) as forest management intensity ranged from high (clearcut) to low (individual tree selection or no management) (Figure 3). The no-management scenario had significantly higher mean carbon stocks than all other scenarios. Among active management scenarios, individual tree selection with high structural retention sequestered the greatest amount of carbon. Postharvest structural retention significantly affected carbon sequestration, but longer rotations still resulted in the largest carbon stocks. The importance of carbon retained in harvested wood products (HWP) is evident in Figure 3, where all of the management scenarios increase over time as the stock in HWP builds up, despite variability in the ecosystem C stocks on decadal time scales. If this analysis were continued beyond the 150 years, eventually the results of management would intersect the "no management" scenario. If the substitution effect using wood instead of other materials were counted, the management and no management curves would intersect much sooner.

This simulation of carbon stock changes in northeastern forests under several different silvicultural alternatives over a period of 160 years following harvest suggests that there are high-retention strategies—using even-aged as well as individual tree selection silvicultural systems—that can provide regular periodic timber income to forest owners while continuing to increase forest carbon stocks over the entire period. The decline in the last decades of the "no management" scenario suggests carbon saturation and the effects of mortality and natural disturbance. The risks of this approach may become higher over time with the effects of continuing climate change, which for this region include a greater frequency of severe storms. Recent hurricanes and other severe storms have been responsible for significant forest damage. This has resulted in substantial short-term carbon emissions, the conversion of densely-stocked older forests with young growth that sequesters carbon more slowly, and additional impacts on wildlife habitat, endangered species, water quality, and wood production.

In another study of northern forests using a different modeling approach that included climate change projections, Duveneck et al. (2014) compared business-as-usual management with scenarios of expanding forest reserves and modified silviculture specifically designed to assist forests with adaptation. This was a landscape-scale study in an ecotone region where forests are expected to be highly sensitive to effects of climate change. The accounting only included above-ground biomass in the ecosystem and harvested carbon (but not including the fate of C in HWP after harvest). For each climate scenario and both study locations, modified silviculture resulted in increased biomass compared with the business-as-usual baseline (Figure 4). Expanding forest reserves had only a small effect on biomass although the effects on resistance of individual species to climate change were significant.

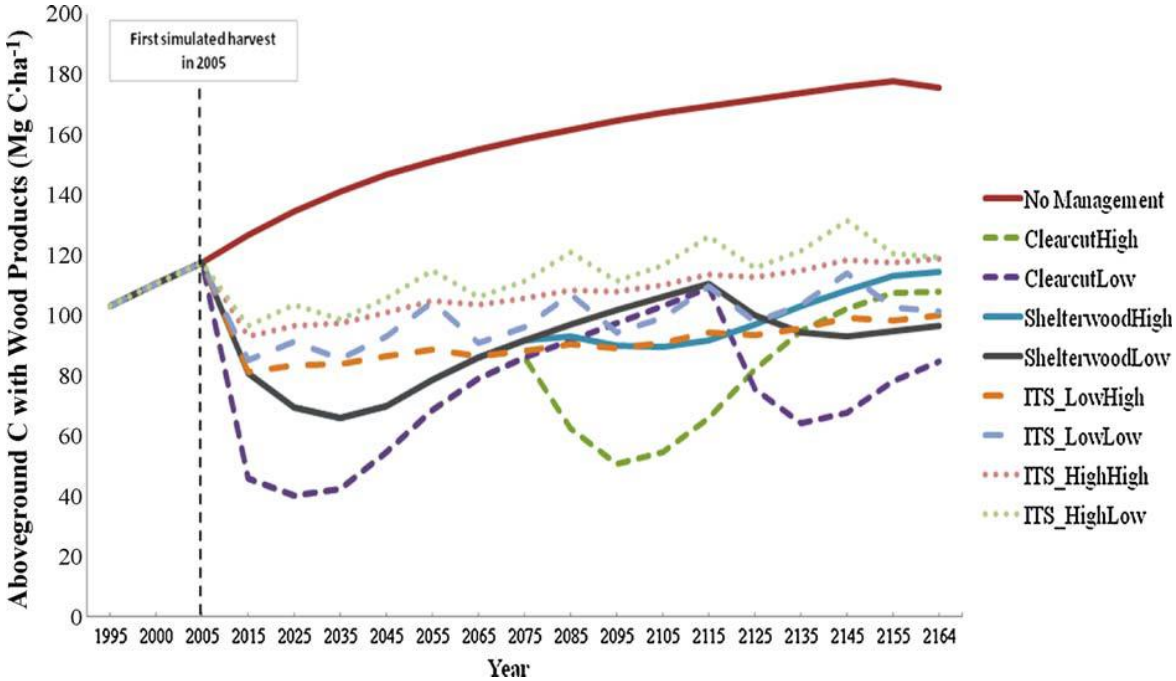

Figure 3. Simulated carbon stocks for nine different management scenarios (from Nunery and Keeton, 2010).

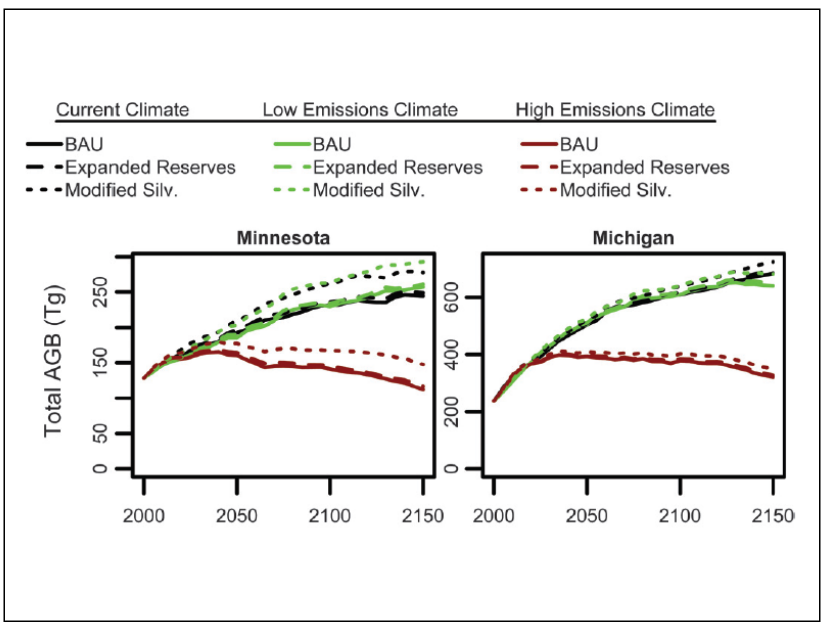

Figure 4. Above-ground biomass for three management scenarios and three climate scenarios (from Duvenek et al. 2014).

In another study that also examined the effect of climate change, modified silviculture to facilitate adaptation resulted in increased biomass compared with the business-as-usual baseline (Figure 4).

Some important principles emerge from these case studies:

- Accounting for harvested wood products, including substitution of wood for other materials, is important for obtaining a comprehensive comparison among scenarios.
- When using an unmanaged forest as a baseline and then imposing management treatments, it takes decades to recover the carbon lost from harvest even when accounting for C in HWP.
- When using a managed forest as a baseline, there are obvious and significant differences among silvicultural practices.
- Climate change has a very significant potential to affect the "no management" baseline scenario and this effect may be greater than the comparable effect on a managed forest.
- There are situations where managing for both mitigation and adaptation may have positive effects to support both objectives.

Thus, if the goal is to maintain the US forest carbon sink, and to manage US forest carbon stocks sustainably for the indefinite future, then there may be silvicultural options—some of them incorporating regular periodic timber harvests—that are superior to a no-management strategy or to existing management strategies. For a country as large and diverse as the United States, specific management practices will need to be tailored carefully to landscape-scale and stand-level conditions, and fit into the management goals of private landowners and public land management agencies.

Factoring forest carbon management into multi-resource land management planning

Integrating forest carbon management into local forest management planning and decision making must account for conditions and circumstances that vary widely within and among the major forest regions of the US, however. Further, effective forest carbon management strategies must be developed at appropriate spatial and temporal scales (Harmon 2001), often necessitating a high level of cooperation and information sharing among the managers of many individual parcels of neighboring public and private land, each of which are managed for a different mix of resource values and owner objectives.

The Pacific Northwest has the highest forest carbon density of any region of the US (Smith and Heath 2004). This is likely to increase under the terms of the Northwest Forest Plan, enacted in 1992 to restore critical habitat for the northern spotted owl (*Strix occidentalis*), marbled murrelet (*Brachyramphus marmoratus*), coho salmon (*Oncorhynchus kisutch*) and other species dependent upon late-successional forest habitat in this region (Thomas et al. 2006). In addition to protecting much of the remaining old growth forest, the plan designated large areas of younger forest as "late-successional reserve" or "riparian reserve" that would be left largely unmanaged to become old growth in the future (Thomas et al. 2005). Although forest carbon management was not an objective at the time the plan was developed, it is a strategy that is almost ideal for increasing carbon stocks in this highly productive region. An unintended consequence of this strategy, however, is an increasing scarcity of habitat for animal and plant species requiring early seral-stage habitat (Spies et al. 2007, Burnett et al. 2007). In such circumstances, the blanket application of a carbon-maximizing forest management prescription across a large regional landscape could result in unacceptable losses of biodiversity.

In other areas of the western US, fire suppression has altered the fire intervals in many forests, resulting in forest density (and carbon stocks) that are far higher than in the past (Houghton et al. 2000). But this also has resulted in a greater number frequency, and size of stand-replacing crown fires (Westerling 2006) that can release a large proportion of a forest's above-ground carbon in a very short time, as well as cause severe damage to watersheds, wildlife and fish habitat, and local threatened or endangered species.

Forests in the US South have the highest carbon stocks of any region and are a significant carbon sink due to their high growth rate and the proportion of that growth that is captured in wood products (Johnson et al. 2001). Intensive forest management practices that include fertilization, irrigation, and tree breeding can grow wood (and store carbon) at up to four times the rate of naturally regenerated forests (Fox 2007). However, an accurate accounting of the overall effect on carbon emissions must consider both the on-site and off-site emissions from nitrogen fertilizers, as well as the carbon release from frequently harvested wood that does not find its way into wood products or biomass energy. Conversion of native hardwood forests or forested wetlands to intensively managed plantations, though positive from a carbon sequestration perspective, can have significant detrimental effects on wildlife habitat, native species diversity, and streamflow.

There are somewhat lower aboveground C stocks in the US upper Midwest and Northeast, but these areas often contain very high carbon density in soils (Johnson and Kern 2003). This presents some reason for caution, but also opportunity. Although most soils are robust to modern best management practices, the high-carbon forested peatlands of the upper Midwest and the spodic soils of the northeast are more vulnerable to near-term losses and were likely heavily impacted by logging, fires, and conversion to hardwoods near the early 1900s (Pielke, 1981; Barrett and Schaetzl, 1998). This provides opportunity, however, in that natural and intentional restoration of coniferous forests that foster spodic soils in the northeast may lead to significant sequestration of soil carbon in coming decades (Nave et al. 2010, Nauman et al. 2015).

Case examples

Commercial private forests

Commercial timberlands in the US have largely been divested by integrated forest products companies to timberland investment organizations (TIMOs) and real estate investment trusts (REITs) that manage forests for explicit financial objectives. Many of these organizations have undertaken “carbon projects” to optimize income to investors based on continued commercial wood production plus an additional income stream from carbon offset purchases.

For example, one of these organizations, The Forestland Group (TFG), has completed several large carbon projects certified under the California Air Resource Board compliance market, and successfully integrated them with prior existing management objectives for wood production and investment returns. Carbon projects in northern hardwoods/mixed conifer forests in Michigan (90,550 ha), New Hampshire (57,480 ha), and New York (40,551 ha) have generated US$27.4 million in carbon offset revenue for TFG. Carbon projects in southern Appalachian hardwood forests in Virginia (3,343 ha) and North Carolina (1,074 ha) have generated an additional estimated US$1.2 million (Finite Carbon 2015). At a carbon price US$9 per Mg C under the California Climate Action Reserve program, these projects have produced additional carbon revenue averaging approximately US$145 per hectare. TFG was able to develop projects that fully align forest carbon management with its overall sustainable forest management strategy, and optimize the return on investment.

Forest carbon is a new asset class for commercial forestry operations and the value of carbon is now comparable with conventional wood products (Finite Carbon 2015). The ability to monetize carbon allows landowners to diversify forest management returns and reduce financial and climate risks, while also achieving a range of environmental, economic, and social objectives in the context of certified sustainable forest management programs.

Family woodlands

More than half of US forest carbon stocks are in relatively small private holdings, typically owned by individual families (Smith et al. 2009), so these forests will play a critically important role in maintaining the US forest carbon sink. Accomplishing this on family woodlands will be especially challenging. Owing to the relatively small tract sizes, carbon projects of sufficient size often must be developed across aggregates of a dozen or more individually-owned tracts, making the development and implementation of long-term forest management plans far more complex than in the case of a single corporate forest landowner. Higher transaction costs for inventory, management planning, verification, and risk management all become more costly, and can quickly erode net returns to landowners, especially at current low carbon prices. Integrating forest carbon management with other existing forest management objectives is more complex as well, given that these objectives are almost as diverse as the 16 million individual family entities who own these lands (Butler 2008).

Many of these family forestry operations are financially marginal, making them particularly vulnerable to conversion for development or other non-forest land uses (Mater et al. 2005). Numerous federal and state policies and technical assistance programs are aimed at improving economic returns to family woodland owners (USDA Forest Service 2013), thus reducing the rate of deforestation and conversion. In addition, programs to facilitate the sale or donation of development rights to private organizations and local governments through conservation easements have put more than 8.7 million hectares of private forest land into permanent protection (National Conservation Easement Database 2014). Yet the gross forest loss on private lands nationwide is still estimated at more than 1,000 ha per day (Stein et al. 2005). The highest rates of forest loss are in the US South and the Pacific Northwest, where forest carbon stocks and future sequestration potential tend to be the highest in the US. Improving forest management practices to increase rates of carbon storage is important, but for this category of forest lands in the US the higher priority is finding additional means to reduce deforestation through conversion and forest loss.

Research on the demographics of family woodland ownership in the US has identified contributing factors that suggest the need for innovative policy responses. The average age of family woodland owners in the US is nearly 70 years (Butler 2008), suggesting that a large segment of these forest lands will be transferred during the next three decades, when it will be particularly important to minimize carbon emissions from deforestation and maintain a net forest carbon sink.

Rising health care expenses incurred by family woodland owners has emerged as an important factor in forest loss, as aging landowners are forced to liquidate land assets in order to cover substantial costs for medical treatment and long-term care (Mater et al. 2005). A pilot program currently being tested in the Pacific Northwest facilitates direct carbon offset purchases by healthcare companies, with payments made to family woodland owners in the form of credits or discounts that can be applied to healthcare expenses. These credits can also be used to pay healthcare insurance policy premiums, deductibles, and co-payments on policies obtained from state exchanges established under the federal Affordable Care Act (Internal Revenue Service 2010, Tozzi 2013). The credits available to each family are determined on the basis of (1) a conservation easement or long-term contractual commitment to maintain forest land use (i.e., not converting to development or other non-forest land use), and (2) adherence to a forest management plan designed to sustainably maintain or enhance carbon stocks, and subject to periodic independent verification.

Public forest lands

Public lands constitute 25 percent of US forests by area, and contain roughly 42 percent of total US forest carbon stocks as of the mid-2000's (Heath et al. 2011). Lands managed by the US Forest Service have the highest average carbon density of all ownerships groups, about 192 Mg C ha^{-1} compared with the national average of 162 Mg C ha^{-1}. On average, carbon stocks on public forest lands have increased by about 90 Tg C yr^{-1} in the 2000's although much of this increase is attributed to an increase in land classified as forest (Heath et al. 2011). However, many of these forests, especially federal forests in the western US, have experienced an increasing size, frequency, and intensity of wildfires (Westerling et al. 2006) and large-scale forest mortality from insect infestations. Where they have occurred, these large-scale disturbance events have significantly reduced forest carbon stocks and flows. Carbon emissions from single large wildfire events, such as the 2002 Biscuit Fire in western Oregon, have been estimated at 3.5-4.5 Tg C over a matter of a few days (Campbell et al. 2007). In addition to the initial pulse of emissions during such an event, subsequent emissions of methane, which is 20 times more potent than carbon dioxide as a greenhouse gas (NASA 2012), can continue for several years as killed trees and other vegetation decompose. As a result, certain areas of public forest land have declined in their ability to serve as net carbon sinks.

Carbon accumulation in many public forests is further slowed by low stocking levels due to reliance on natural regeneration or backlogs in planting. Regeneration failures on areas of federal forest land following timber harvesting or disturbance now account for nearly 400,000 hectares of formerly forested land now in scrub (USDA Forest Service 2009). Much of this deforested area is likely to remain in this condition due to the high cost of reclaiming and reforesting areas of relatively low site productivity, many of them in remote areas with steep slopes and other conditions that make them difficult in which to operate. These represent lost opportunities in long-term carbon sequestration even as they reflect the practical realities of public land management. Changing climate conditions, such as the continuing warming and drying trend in much of the western US, are also contributing to what may be a long-term shift in many areas from a forest biome to an open woodland or savanna biome (Allen et al. 2002, Breshears et al. 2005, Hicke et al. 2012). Even in resilient forests the effect of major disturbance events on forest carbon stocks is still significant when mid- or late-successional forests with high carbon densities are replaced by young trees, which may require hundreds of years to reach similar carbon densities (Harmon et al. 1990)

On public forest lands where increasing future carbon stocks is technically possible, there are additional challenges to integrating this objective into the existing management objectives mandated by law, policy, or court order. On federal forest lands, laws such as the Multiple-Use Sustained-Yield Act, National Forest Management Act, and the Endangered Species Act (USDA Forest Service 1993) already require forest planners and decision makers to balance public needs for wood, wildlife, water, range, outdoor recreation, wilderness, and critical habitat for endangered species (Federal Register 2012). Managing for older forests with few openings created by timber harvesting may severely limit habitat for bird species requiring early seral stage habitat, or ungulates that rely on forest openings for browse and breeding habitat. Forests with high stocking levels and closed canopies reduce snow accumulation, resulting in decreased late-season water flows for agriculture, industry, and municipal uses. Heavily-stocked forests can pose higher risks for large uncontrollable wildfires that have major impacts on drinking water supplies and endanger lives and property in adjacent communities.

Optimizing forest carbon management in the context of multiple resource objectives

Optimization modeling may hold significant potential for identifying opportunities to significantly increase forest carbon stocks while minimizing tradeoffs to other objectives in a multi-resource forest management context. However, the maximization of carbon stocks may not be compatible with current objectives of national forest management. For example, the need to reduce wildfire risk on the eastern slopes of the Cascade Mountains may require removing down wood material, the pool where carbon sequestration rates were recently described as increasing (Gray and Whittier 2014).

Linear-programming and goal-programming optimization models were used extensively in the first cycle of land and resource management planning pursuant to National Forest Management Act. Early versions were designed to maximize timber yield subject to constraints aimed at protecting water quality, wildlife and fish habitat, and other forest values. Later versions were designed around a primary goal (objective function) of maximizing net public value, using market values for commodities such as wood, and assigning imputed values for unpriced benefits such as water and wildlife.

Developing optimization models in which maximizing carbon stocks is the objective function, subject to constraints to limit any diminishment of other forest resource uses and values, could help identify unexpected opportunities to enhance forest carbon stocks with a minimum of tradeoffs to other environmental, economic, and social values.

At the forest-level, accommodating a forest carbon stock objective or constraints into mathematical programming methods is no more laborious than accommodating timber volume or wood flow objectives or constraints. Of course, this assumes that the coefficients describing carbon stocks in trees (similar to volume) are adequately developed.

Recent work involving multi-objective optimization methods like linear and mixed-integer programming illustrated how the selection of forest management regimes at the stand-level could be used to maximize two objectives (economic and either carbon stock (Trivino et al. *in press*) or wildlife (Mönkkönen et al. 2014)) over a long (50 year) time horizon. This process involved fixing the value of one objective and subsequently optimizing the other to create production possibility curves that allow the examination of trade-offs amongst the objectives. However, no other forest-level or operational constraints were assumed in these models.

Heuristics have also been used to examine the trade-offs between policies that maximize wood production and policies that maximize carbon stocks. In British Columbia, Man et al. (2013) developed 100-year projections of timber harvests and carbon stocks for two forests in order to examine the impact of desired wood production levels on carbon stocks (or vice-versa). Stand-level simulations of forest management regimes have also provided insight into the potential trade-offs among seemingly diverse objectives, such as carbon stocks and timber yields (Briceño-Elizondo et al. 2006).

Even the most detailed and sophisticated optimization models are only approximations of the way real ecosystems and economies function. So although they cannot in themselves identify the best course of action, they can help narrow in on solutions to be worked out through collaborative social and policy processes.

Optimization models are often used to develop forest plans, yet the results should only be viewed as a guide to forest management activities during the near-term of the plan. Models are reduced to equations and relationships that represent a tractable, or solvable system. A large number of real-life events are not included in forest plans due to the difficulties in estimating their timing, placement, or value (e.g., hurricanes, fires, changes in timber markets). Further, a large number of resources are often not valued in forest plans simply due to the lack of functional relationships (e.g., science) associating management activities and impacts on these resources.

Conclusion

Maintaining the forest carbon sink is an essential component in the US climate change mitigation strategy. Accomplishing this will require integrating forest carbon management into existing sustainable forest management programs on commercial timberlands, family woodlands, and public forests, while minimizing tradeoffs to other forest management objectives. Policies supporting forest planning focused at large spatial and temporal scales will help to ensure that carbon stocks are stable or increasing over time, and that environmental, economic, and social values associated with early seral-stage conditions are not inadvertently diminished by a focus on maximizing carbon stocks.

As the nation's largest terrestrial carbon sink, forests will play a major role in achieving the goals in the national Climate Action Plan for net reductions of greenhouse gas emissions in the coming decades. US forests currently absorb 14-19% of *total* US carbon emissions annually, so any significant decline in this carbon sink will greatly complicate efforts to achieve these national targets through other mechanisms. Public policies that establish market prices for carbon, such as California's Climate Action Reserve, have already resulted in substantially slowing the loss of forest to developed land uses, and demonstrated the potential value of enacting similar policies in other states and at the national level.

Forest management policies and planning models designed to maintain existing carbon stocks and maximize capacity for future sequestration—subject to existing laws regarding wildlife habitat, water resources, and other forest ecosystem values—can help identify underutilized opportunities to increase forest carbon stocks without significant diminishment of other forest values, products, or services. Demonstrating approaches to forest carbon integration that increase net return on investment on commercial and other private forest lands, or enhance the net public benefits provided from public forests, are likely to accelerate the adoption and large-scale implementation of these approaches, and contribute significantly to the achievement of GHG emissions reduction targets at the national scale.

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