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US Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions

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Abbreviations

ACR	American Carbon Registry
C	carbon
CO_2e	carbon dioxide equivalent
CAR	Climate Action Reserve
CGE	computable general equilibrium
FASOM-GHG	Forest and Agricultural Sector Optimization Model with Greenhouse Gases
GHG	greenhouse gas
GWP	global warming potential
HWP	harvested wood products
ha	hectares
IFM	improved forest management
NDC	Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
LCA	life-cycle analysis
LULUCF	land use, land use change, and forestry
Mt	million metric tons
$MtCO_2e$	million metric tons of carbon dioxide equivalent
PE	partial equilibrium
REDD+	Reduced emissions from deforestation and degradation
SOC	soil organic carbon
t	metric ton
tCO_2e	metric ton of carbon dioxide equivalent
Tg	teragram
VCS	Verified Carbon Standard

Abstract

Countries globally are committing to achieve future greenhouse gas emissions reductions to address our changing climate, as outlined in the Paris Agreement from the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties. These commitments, called nationally determined contributions (NDCs), are based on projected anthropogenic greenhouse gas (GHG) emissions levels across all sectors of the economy, including land use, land use change, and forestry (LULUCF) activities. Projecting LULUCF emissions is uniquely challenging, and the uncertainty of future LULUCF emissions could require additional mitigation efforts in the land use sectors to reduce the risk of NDC noncompliance. The objectives of this paper are to provide critical information on what forest sector mitigation activities are currently underway in the United States on private lands, review recent literature estimates of the mitigation potential from these activities (and associated economic costs), identify gaps in the literature where additional analytical work is needed, and provide recommendations for targeted mitigation strategies should US emissions approach or exceed targeted post-2020 NDC levels.

Introduction

Globally, countries are committing to achieve future greenhouse gas emissions reductions to address our changing climate, as outlined in the Paris Agreement from the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties. These commitments, called “nationally determined contributions” (NDCs), are based on projected anthropogenic greenhouse gas (GHG) emissions levels across all sectors of the economy and reflect expected mitigation actions and outcomes. The United States pledged to an economy-wide target of reducing its GHG emissions by 26 to 28 percent below its 2005 level in 2025. However, whether and how the United States will achieve these reduction targets is uncertain. In the United States’ 2016 Second Biennial Report (BR2) to the UNFCCC, both the high- and low-sequestration baseline projection estimates fall short of that mark amounting to a shortfall of between 615 and 1,037 million metric tons of carbon dioxide equivalent ($MtCO_2e$) (see Table 1). Although the BR2 sets out some additional measures that could be implemented to reach the national NDC targets, more research would help us understand how specific sectors and activities within those sectors might contribute to these overall economy-wide GHG reduction goals.

Historic values and baseline projection estimates in the BR2 include emissions as well as sequestration from land use, land use change, and forestry (LULUCF), which when considered together, reflect a substantial net carbon sink (nearly -900 $MtCO_2e$ in 2013; State Department, 2016). An expanding body of literature exists on the potential for land-use sector mitigation through incentive mechanisms such as offsets, including a small but growing literature base on voluntary and compliance forest carbon markets. Although BR2 did not include potential additional actions in the LULUCF sectors, the United States may consider economy-wide approaches to addressing climate change, including actions in the LULUCF sectors, which could play a key part in the US strategy to achieve its NDC goals.

Although achieving emissions reductions from LULUCF activities has potential, projecting land-use–sector emissions is uniquely challenging. Not only do such projections involve uncertainty in future economic conditions, policy, and technological advancement—challenges that all sectors face—but these projections also require capturing complex carbon dynamics of terrestrial ecosystems and the diverse markets that rely on those ecosystem services. Therefore, as future projections in the LULUCF sector play an integral role in establishing GHG-emissions–reduction targets, they also play an important role in determining whether or not such goals are ultimately achieved. For example, if we base GHG-emissions–reduction goals on projections that reflect relatively high sequestration from LULUCF activities, but over time fluxes from the sector start to follow the low-sequestration path instead, then the LULUCF and/or other sectors need to implement additional mitigation actions to reduce emissions or increase sequestration to improve the emissions trajectory. The opposite is also true: if we establish GHG goals using low-sequestration LULUCF-sector estimates, and the sector instead realizes high-sequestration levels, this

Table 1. Economy-wide US emission projections and estimated shortfall from NDC target (in $MtCO_2e$)

	Baseline US emissions (2005)	High-sequestration projection (2025)	Low-sequestration projection (2025)
2016 Second Biennial Report	6,438	5,379	5,672
	US emissions target (2025)	**High-sequestration projection shortfall (2005)**	**Low-sequestration projection shortfall (2005)**
NDC 26% reduction target	4,764	615	908
NDC 28% reduction target	4,635	744	1,037

Note: NDC = nationally determined contributions; $MtCO_2e$ = metric tons of carbon dioxide equivalent.

results in additional insurance against lower-than-expected mitigation levels from other sectors.

Considering the potential for LULUCF activities to contribute to overall emissions reductions goals and the inherent uncertainty in baseline LULUCF emissions trajectories, the objectives of this study are to:

- provide critical information on what forest sector mitigation activities are currently under way in the United States on private lands,
- review recent literature estimates of the mitigation potential from these activities (and associated economic costs),
- identify gaps in the literature where additional analytical work is needed, and
- provide recommendations for targeted mitigation strategies if US emissions levels approach or exceed post-2020 NDC levels.

To achieve these objectives, we first provide an overview of the various LULUCF-sector GHG-offset programs and protocols in the United States and the volume of projects that were implementing mitigation activities under these programs and protocols at the time this paper was developed. We then summarize mitigation-potential estimates of these activities from previous academic literature and publicly available reports. Our discussion focuses primarily on the mitigation potential of traditional forest practices (e.g., afforestation and improved forest management) identified in the program and protocol overview, because to date, these practices have been used more commonly in the United States. We also discuss some other activities that have not traditionally been used to mitigate GHG emissions in the United States but that may also play important roles in meeting emissions reduction targets; these include avoided forest conversion, increased use of wood products for building and other materials, increased soil carbon sequestration, and urban forestry. Both traditional and nontraditional mitigation activities provide varying degrees of sequestration potential in the United States. In this paper, we do not address agriculture-sector mitigation sources, fossil fuel emissions displacement from forest-derived bioenergy production, or mitigation activities or programs specifically on public lands. Furthermore, we focus on domestic (i.e., US) mitigation activities only.

Overview of the US Forest Sector and Mitigation Projects

Forests and the forest sector are increasingly being recognized as an important resource to address climate change through their ability to sequester and store carbon. Today, there are approximately 305 million ha of US forestland, most of which is privately owned in the conterminous United States (US Forest Service, 2010). Covering approximately one-third of the total US land area, the proportion of forested land has not changed substantially since the beginning of the 20th century. Before then, the United States historically experienced high rates of deforestation. Initially, forestland was cleared primarily for agriculture and pasture land, but today, deforestation occurs in large part to convert land to urban and developed uses (US Forest Service, 2010). Between 1992 and 1997, more than 0.4 million ha were converted annually, with over one-half to urban and developed uses (Alig, Latta, Adams, & McCarl, 2010). Net forestland area, however, has increased by approximately 0.6 million ha annually, as forestland that was previously converted for agricultural use is reforested (US Department of State, 2016).

Forestry and land uses in the United States currently serve as a carbon sink, representing nearly 90 percent of the total domestic carbon dioxide (CO_2) removals in 2013 and offsetting approximately 13 percent[1] of total (i.e., gross) greenhouse gas emissions annually. This net sink estimate is largely the result of net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood products (US EPA, 2015).[2] Nonetheless, because it is uncertain whether future LULUCF and forest sector

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[1] The most recently published US GHG Inventory at the time of writing, US EPA (2015) reported that LULUCF activities sequestered 881.7 Mt of CO_2e in 2013.

[2] Includes vegetation, soils, and harvested wood. The remaining CO_2 removals occurred in urban trees, soil carbon stock changes, and landfilled yard trimmings and food scraps.

market patterns will follow historic trends, evaluation of different activities that can help maintain and enhance US carbon sequestration can serve as a foundation for future decisions about how to ensure that the United States meets its emissions-reduction targets.

A variety of mitigation activities in the forestry sector could be key in achieving GHG reduction by increasing carbon sequestration and storage. For example, reforestation, afforestation, improved forest management (IFM) practices, avoided conversion of existing forestland to other land uses, and forest soil carbon sequestration have the opportunity to improve the carbon sequestration capacity of land, as forested lands offer high carbon storage potential when compared to other land uses. Afforestation and reforestation are, broadly, the conversion of nonforested lands to forested lands, with the difference being the length of time the land was without forest (IPCC, 2000). More specifically, reforestation refers to the reestablishment of forest cover after a forest harvest, and the optimization models discussed below consider reforestation to be a forest-management activity (US EPA, 2005). Afforestation, in contrast, refers to the establishment of forest by converting land from a previous land-use type, typically agriculture, to forest. Improved forest management strategies include extending timber harvest rotations, avoiding deforestation of forested lands, preserving existing forests, and increasing forest management intensity (US EPA, 2005). We treat avoided conversion projects separately in this manuscript, because these projects are considered independent of IFM. However, some of the economic models included in this assessment (including FASOM-GHG) include avoided conversion as a specific IFM strategy.

Other activities, such as fuel treatments, urban forestry, and the increased use of harvested wood products, have also been considered as ways to increase GHG mitigation. Forest fuel treatments, important to maintain healthy forest ecosystems and reduce the risk of catastrophic wildfires, include activities that reduce forest density through prescribed forest fires and mechanical thinning (Stephens et al., 2012). Urban forestry projects include efforts to plant trees along city streets, in parks, and in other public and private urban areas, as well as maintaining them, because they offer carbon storage (Nowak, Greenfield, Hoehn, & Lapoint, 2013) and other benefits such as wind breaks. Using harvested wood products (HWP) as a substitute for other more energy-intensive building materials such as steel or concrete also helps to store carbon sequestered during tree growth for long periods of time.

Notably, spatial and temporal variations occur among these mitigation activities, which can influence planning and implementation of mitigation efforts, specifically in terms of deciding which activity would be best suited at what location. Regions with substantial forest resources or relatively low–opportunity-cost agricultural land (such as the Pacific Northwest and Southeast US) have pursued and will likely continue to pursue mitigation efforts.

To place the reported estimates of total mitigation potential into context, we need to understand (1) the extent to which US offsets or other mitigation programs or protocols reflect these different mitigation activities and (2) the volume of such projects currently being implemented domestically. We reviewed the three main registries that cover forest-carbon offsets in the United States: American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verified Carbon Standard (VCS). At the time of writing, there were 181 total forestry projects that represent more than 5.4 million acres of land. Table 2 captures a breakdown of these projects by the type of activity, number of currently listed projects, and acres enrolled.

As Table 2 shows, improved forest management has been responsible for the vast majority of the total acreage for forest carbon offset activities to date. As discussed later in this paper, this finding supports the notion that landowners have been less likely to adopt new activities that change land use (e.g., afforestation, reforestation), or that have higher opportunity costs associated with them (e.g., avoided conversion). In the context of offset protocols, improved forest management activities include increasing the rotation age, increasing the productivity of forests through thinning diseased and suppressed trees, decreasing competition by removing brush and short-lived trees, increasing stock levels in understocked areas, and maintaining stocks at high levels.

Table 2 also includes the total emissions-reduction credits that have been issued thus far for mitigation activity. To date, the credits these protocols have issued represent more than 32 $MtCO_2e$ sequestered through forest-mitigation activities. This figure only includes issued credits and therefore does not represent the total emissions reductions anticipated to occur through these activities. According to projects listed under the VCS registry, IFM activities are anticipated to reduce approximately 50 tCO_2e per acre over the lifetime of the project.[3] Avoided conversion projects, although fewer in number, are anticipated to sequester 140 tCO_2e per acre, and afforestation and reforestation activities over 190 tCO_2e per acre. Table 3 reflects the average annual and cumulative emissions reductions per acre estimated for the various mitigation activities for the entire crediting period.

Table 2. Projects and registered emissions reduction credits in the United States under three carbon registries (ACR, CAR, and VCS) at the beginning of 2016

Mitigation activity	Protocol in place?	Currently listed projects[a]	Acres enrolled	Total emissions-reduction credits issued thus far[b]
Afforestation	✔	4	7,069	1,090,057
Reforestation	✔	13	56,563	14,934
Improved forest management[c]	✔	151	5,161,963	29,934,825
Avoided conversion	✔	13	201,366	1,478.098
Urban forestry	✔	0	0	
Forest soil carbon		—	—	
Totals		**181**	**5,426,961**	**32,517,914**

Notes: ACR = American Carbon Registry; CAR = Climate Action Reserve; VCS = Verified Carbon Standard.

[a] Projects that are listed may not yet be registered, and therefore no credits have been issued. Registering and issuing credits requires verification by an independent, accredited verification body. Some projects have been removed to avoid double-counting. For more information on the current listing of forest carbon projects, please visit websites for the various carbon registries.

[b] Includes project and buffer emissions reductions (buffer withholdings for non-permanence risk is typically 10 percent of total emissions reductions). One emissions reduction credit is equal to one metric ton of CO_2e sequestered.

[c] Includes two conservation-based forest management projects (9,306 acres) established under older versions of the CAR Forest Protocol, prior to Version 3.3 (current version), which no longer lists conservation-based forest management as a project type.

Table 3. Estimated emissions reductions per acre of listed projects under the VCS registry at the beginning of 2016

	Average emissions reductions per acre (tCO_2e)		Crediting period (years)
	Annual	Total for entire crediting period	
IFM	1.4	58.3	42
Avoided conversion	4.9	138.1	30
Afforestation	3.4	191.2	55
Reforestation	3.2	193.4	60

Notes: IFM = improved forest management; tCO_2e = metric ton of carbon dioxide equivalent; VCS = Verified Carbon Standard.

Estimated emissions reductions per acre were calculated by dividing the estimated annual and total emissions reductions of the project by the number of acres, as reported in the project descriptions. These averages account for three IFM projects, one avoided conversion project, three afforestation projects, and one reforestation project. Emissions reductions vary by project based on size, geographic location, crediting years, and so forth, and therefore may not accurately represent the average emissions reductions across all mitigation activities.

According to Forest Trends surveys and analysis, cumulative global forestry offset transaction volumes, including from both mandatory and voluntary markets, were less than 180 $MtCO_2e$ in 2013 (Goldstein & Gonzalez, 2014).[4] To put it in perspective, this amount of mitigation is equivalent to less than 2.7 percent of total anthropogenic GHG emissions in the United States for 2013. Project developers reported that in 2013, 30 million ha were under improved forest management, 1.6 million ha were afforested/reforested, and 20 million ha were covered under avoided deforestation projects (Goldstein and Gonzalez, 2014).

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[3] The number of crediting years varies, but on average, IFM projects are credited for 42 years, avoided conversion for 30 years, and afforestation/reforestation projects for 55 to 60 years.

Estimates of US Forest Sector GHG Mitigation

A growing pool of literature has attempted to quantify the carbon-sequestration–potential of forestry-based mitigation activities in the United States. There are a number of policy instruments that could incentivize activities that increase the carbon-sequestration–capacity of forests, including regulatory policies (e.g., command-and-control type), financial mechanisms (e.g., US Department of Agriculture [USDA] Environmental Quality Incentives Program and Reducing Emissions from Deforestation and Forest Degradation [REDD+]), and other market-based instruments which place a "price" on carbon. Carbon pricing can be established using a number of different mechanisms such as a carbon tax, a cap-and-trade program, or voluntary offset programs that pay land managers for activities that increase terrestrial carbon uptake (or reduce net emissions). These mechanisms can give landowners incentives to make decisions that account for this price of carbon by making land-use decisions to maximize the value of forest outputs that include both timber products as well as the carbon sequestration services of the forest. For instance, as carbon takes on more value relative to forest products, (i.e., increases in price), forest owners may elect to extend timber rotation age (an IFM practice), allowing forests to sequester additional carbon prior to harvesting (van Kooten, Binkley, & Delacourt, 1995). Higher carbon prices could also incentivize landowners to revert marginal agricultural lands or pasture to forests to generate carbon offsets, thus providing more carbon sequestration on the landscape.

Afforestation and Improved Forest Management for Carbon Sequestration

Through a variety of techniques including bottom-up engineering methods, econometric analysis, and optimization models that simulate land-use decisions (e.g., whether to convert agricultural land to forestland), estimating the GHG mitigation potential of forest activities is possible under a variety of carbon pricing scenarios over time. This section offers a review of the recent literature that has attempted to quantify the carbon sequestration or emissions reduction potential from afforestation and IFM activities in the United States. Overall, the studies we survey examined scenarios with carbon prices ranging from \$1 to \$100 per tCO_2e and found that at higher prices, as much as 1 $GtCO_2e$ could be sequestered.

US EPA (2005) produced a seminal report in that provided a comprehensive assessment of the mitigation potential of the private forest and agriculture sectors under a variety of carbon price scenarios. By employing a dynamic optimization, partial equilibrium model (i.e., Forest and Agricultural Sector Optimization Model with Greenhouse Gases, or FASOM-GHG), the report estimated the annualized mitigation potential under a range of price scenarios from \$1 to \$50 per tCO_2e for afforestation and IFM.[5] This report followed on from a USDA study (Lewandrowski et al., 2004), which estimated the mitigation potential of the agriculture sector, including the afforestation of cropland and pasture, over a 15-year time horizon using a US Agriculture Sector Model (USMP). Prices in this analysis ranged from \$3 to \$34, per tCO_2e with a mitigation potential of 31 to 488 $MtCO_2e$. These estimates are generally lower than the range generated by FASOM-GHG in the EPA study for afforestation (for instance, the EPA report estimates that under a \$30 price scenario, 806 $MtCO_2e$ would be sequestered after 15 years) due to differences in model assumptions, methodology, geographic scale, and mitigation activities covered.

Building on these reports, a number of additional studies have further evaluated the mitigation potential of IFM and afforestation activities, which we will discuss and compare in the following section.

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[4] In 2013, global forest carbon markets transacted 32.7 $MtCO_2e$ as reported by 136 forest carbon offsets project developers and retailers, up from 28 $MtCO_2e$ in 2012. The cumulative mitigation volume accrues transactions from pre-2005 (estimated at 4 $MtCO_2e$ cumulatively transacted) to 2013.

[5] In this study, and others covered here (e.g. Lubowski, Plantinga, & Stavins, 2006), avoided conversion/deforestation is considered to be an IFM activity; we therefore include it in the sequestration estimates for IFM.

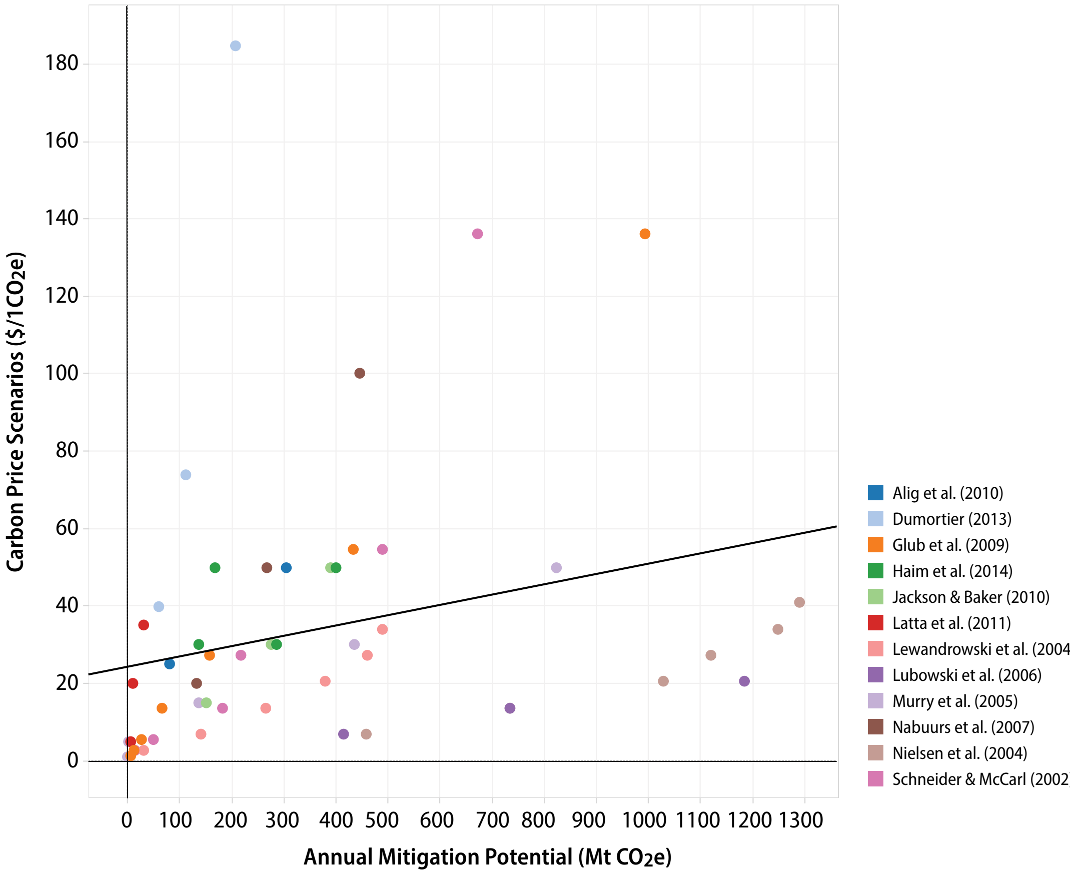
Afforestation Estimates

The technical mitigation potential (i.e., not accounting for the economic opportunity costs) of afforestation is substantial. Potter et al. (2007) use satellite imagery and an ecosystem carbon model to estimate the technical mitigation potential of afforesting marginal agricultural lands. The study shows that converting up to 20 percent of existing cropland and rangeland in the United States to forests can mitigate approximately 20 percent of US emissions from fossil fuel combustion, although Potter et al. (2007) do not consider economic costs or market consequences of land conversion that could lower the feasibility and therefore the extent of this mitigation potential.

Many studies have estimated the economic costs of carbon sequestration through afforestation by accounting for the opportunity costs of conversion (Figure 1 contains relevant studies). These cost estimates can then be used to project the different levels of sequestration activities that would occur through various price incentives. These studies have generated a wide range of sequestration estimates based on various assumptions, such as the amount of land available for conversion and the opportunity costs of land conversion. In addition, studies annualize sequestration estimates across varying time horizons, so we consider these differing input assumptions when comparing studies.

Figure 1 depicts the range in estimates for mitigation potential reported in the studies included in this synthesis. In this analysis, we have included only studies that have attempted to estimate the GHG mitigation potential for afforestation activities across a range of price incentives. A great deal of variability in projected mitigation potential exists across studies, and this variability widens at higher carbon prices.

Figure 1. Past estimates of the carbon sequestration potential in the US through afforestation at various carbon price scenarios



Sources: Alig, Latta, Adams & McCarl (2010); Dumortier (2013); Golub, Hertle, Lee, Rose, & Sohngen (2009); Haim, White, & Alig (2014); Haim, White, & Alig (2015); Jackson & Baker (2010); Latta, Adams, Alig, & White (2011); Lewandrowski et al. (2004); Lubowski, Plantinga, & Stavins (2006); Murray et al. (2005); Nabuurs et al. (2007); Nielsen, Plantinga, & Alig (2014); Schneider & McCarl (2002).

Differences in mitigation potential are primarily attributed to differences in underlying methodologies and model assumptions employed by the studies. Studies that employ an econometric approach to quantify carbon sequestration potential through afforestation typically estimate higher levels than studies that employ sector-optimization models that account for the interaction between agriculture and forestry activities (e.g., FASOM-GHG). This outcome occurs partly because optimization models account for the endogenous price effects between agricultural goods and forest products and explicitly account for land-resource competition between the sectors. For instance, removing agricultural land from production for afforestation could result in higher prices for agricultural goods, thus increasing economic rents from agricultural production. As a result, incentivizing the conversion of additional agricultural land to forest would then require higher carbon prices. Sector-optimization models that capture these interactions can therefore lead to lower carbon-sequestration estimates than studies that employ econometric approaches.

Nielsen et al. (2014) use econometric techniques to derive marginal cost curves for afforestation at the county level and then multiply these costs by the amount of land potentially available for afforestation. The results indicate that at a carbon price of \$14 per tCO_2e, converting nearly 100 million hectares of cropland, pasture, and rangeland to forests annually could result in sequestering more than 700 $MtCO_2e$. At \$27 per tCO_2e, afforesting nearly 160 million hectares could result in sequestering more than 1,100 $MtCO_2e$ annually. One important difference between the estimates in this study and other afforestation estimates is that Nielsen et al. include rangeland, which accounts for roughly one-half of the afforestation estimates at low price points and one-third at higher price points. Lubowski et al. (2006) apply comparable econometric methods and find similar estimates at lower carbon prices but divergence at higher carbon prices (for instance, Lubowski et al.'s estimates at the \$27 per tCO_2e are nearly double the estimates from Nielsen et al.).

Sector-optimization modeling techniques have produced more conservative estimates of the sequestration potential through afforestation for the reasons we have discussed. Jackson and Baker (2010) use FASOM-GHG, which had been updated since Murray et al. (2005) to include a broader range of land-use categories to depict competition between privately owned cropland, forest, pasture, conservation lands, and development (Baker et al., 2010), to estimate that approximately 3.4 million, 8.7 million, and 15.8 million hectares would be converted from cropland to forestry by 2030 under carbon price scenarios of \$15, \$30, and \$50 per tCO_2e respectively, sequestering up to 390 $MtCO_2e$ annually.

Alig et al. (2010) built policy scenarios based on carbon pricing, development rates (land loss to urbanization), and land use changes between forestry and agriculture to simulate the potential impacts of policy instruments by employing FASOM-GHG. Results concluded that under \$50 CO_2e prices, forest area would increase by 25 percent in 2050, with nearly 30 million hectares afforested compared to the base case. The authors estimate that afforestation at \$25 per tCO_2e could result in sequestering 81 $MtCO_2e$, and afforestation at \$50 per ton could result in sequestering up to 304 $MtCO_2e$ could be sequestered.

Few studies have attempted to quantify forest sector mitigation potential through computable general equilibrium (CGE) modeling frameworks. Such models typically lack sufficient forest sector detail or forest-management options to effectively evaluate incentives targeted at afforestation or IFM projects. Golub et al. (2009) link the Global Trade Analysis Project (GTAP) with a dynamic, partial equilibrium model of the global forest sector (the Global Timber Model, or GTM). This study analyzed the role of global land-management alternatives in determining potential GHG mitigation by land-based activities in agriculture and forestry. The study estimated that a lower carbon price (less than \$10) would have an annual mitigation potential of about 6 to 25 $MtCO_2e$ from afforestation, while the highest carbon price (\$136) could abate as much as 993 $MtCO_2e$ (Table 4).

Table 4. Range in reported mitigation potential from afforestation by CO_2e price and empirical methodology

Carbon price range ($/$tCO_2e$)	Approximate mitigation potential range ($MtCO_2e$ annually)		
	Partial equilibrium	Econometric	General equilibrium
Less than $10	0–140	414–459	6–25
Between $10 and $25	81–378	734–1,185	65
Between $25 and $49	60–488	1,119–1,290	158
Between $50 and $99	168–823	—	434
$100 or greater	208–823	—	993

Notes: CO_2e = carbon dioxide equivalent;
$MtCO_2e$ = million metric tons of carbon dioxide equivalent;
tCO_2e = metric ton of carbon dioxide equivalent.

Sources:

Partial Equilibrium: Alig, Latta, Adams & McCarl (2010); Dumortier (2013); Haim, White, & Alig (2014); Haim, White, & Alig (2015); Jackson & Baker (2010); Lewandrowski et al. (2004); US EPA (2005); Nabuurs et al. (2007); Schneider & McCarl (2002).

Econometric: Lubowski, Plantinga, & Stavins (2006); Nielsen, Plantinga, & Alig (2014).

General Equilibrium: Golub, Hertle, Lee, Rose, & Sohngen (2009).

The CGE study that we include in our analysis produced the most pessimistic mitigation estimates at lower CO_2 prices. CGEs reflect the full macroeconomic impact of moving land out of alternative uses and into forestry for carbon sequestration, including household welfare impacts of higher agricultural commodity prices. As a consequence, afforestation carries a fairly high opportunity cost. Note, however, that at high CO_2e prices, Golub et al. (2009) report higher mitigation potential than the PEs, for both IFM and afforestation.

Improved Forest Management Estimates

There are fewer studies focused on estimating the carbon-sequestration potential of IFM activities than those on afforestation activities. This is perhaps partly due to the challenges that arise when estimating a baseline for measurement, because information on current management practices on private land is not typically publicly available. In addition, management practices and costs can vary based on a number of variables including time, location, and intensity level, further complicating estimations of mitigation potential at the national scale. A number of studies, however, attempt to quantify the impacts of a carbon price on changes in management practices on private timber lands. Figure 2 presents results from these studies that apply a carbon-price incentive to estimate the mitigation potential from IFM activities. Overall, the literature indicates that mitigation potential is smaller for IFM activities than for afforestation. As with afforestation, the range in projected mitigation potential expands with the CO_2e price, and differences in modeling methodologies also have a big impact on reported mitigation outcomes.[6]

A number of studies that estimate the mitigation potential of afforestation also consider IFM practices. Jackson and Baker (2010), for instance, estimate that at lower carbon prices (i.e., $25 per tCO_2e), the mitigation potential through IFM is comparable to afforestation (approximately 150 $MtCO_2e$ sequestered annually). At the $50 per tCO_2e level, however, the sequestration potential of afforestation (390 $MtCO_2e$) exceeds the mitigation potential of IFM activities (315 $MtCO_2e$). In contrast, other studies have found the opposite to be true. Alig et al. (2010), for instance, estimate IFM to have more than double the sequestration potential of afforestation at lower carbon prices (223 $MtCO_2e$ for IFM versus 81 $MtCO_2e$ for afforestation at $25 per tCO_2e) as well as at higher carbon prices (357 $MtCO_2e$ for IFM versus 304 $MtCO_2e$ for afforestation at $50 per tCO_2e).

Golub et al. (2009) find the US mitigation potential to be 0 to 90 $MtCO_2e$ at lower carbon prices of less than $10, while the highest carbon price resulted in mitigating about 1,052 $MtCO_2e$ (Table 5). A typical IFM practice includes increased carbon sequestration from extending the timber rotation age. Studies such as Sohngen and Brown (2008) estimated the marginal costs of sequestering carbon by extending rotations in 12 southern and western states of the United States. Their aggregate estimate accounting for cost of extending the rotations indicated sequestration potentials of 15 to 209 $MtCO_2e$ for carbon prices of

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[6] When discussing mitigation estimates in the literature, activities considered improved forest management may vary by study and model. For instance, studies using the FASOM-GHG model, reforestation, and avoided conversion are all considered IFM activities.

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Figure 2. Past estimates of carbon sequestration potential in the United States through improved forest management

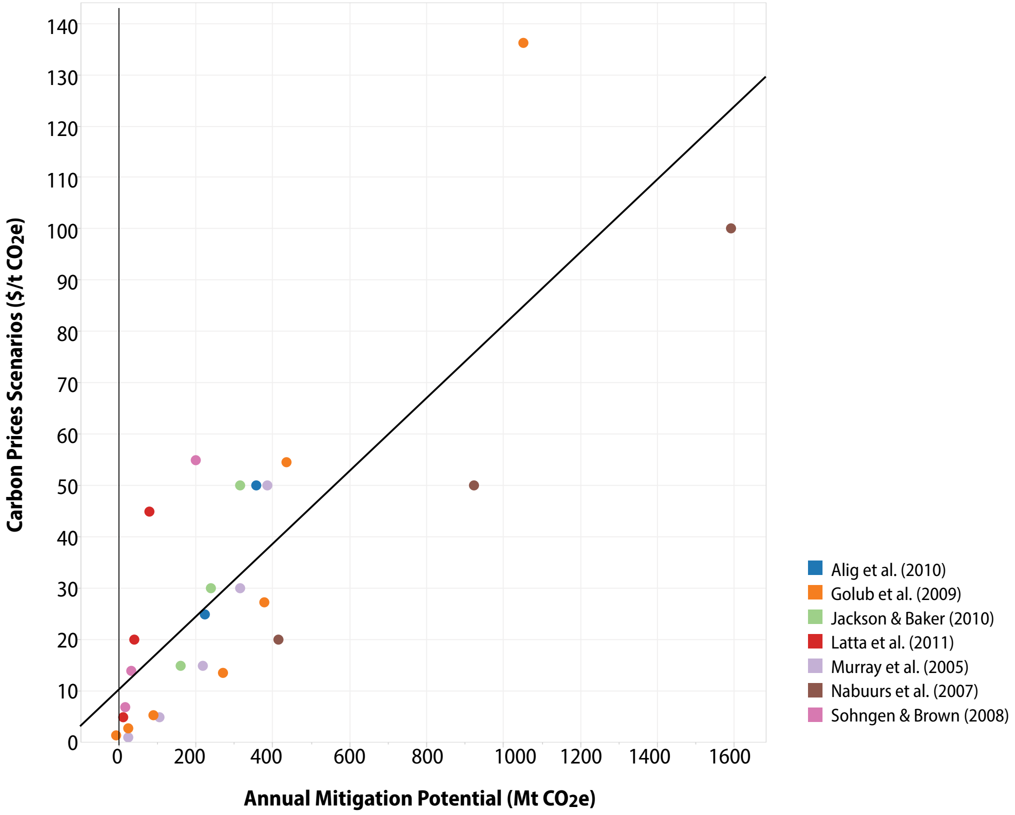

Table 5. Range in reported mitigation potential from IFM by CO$_2$e price and empirical methodology

Carbon price range (\$/tCO$_2$e)	Approximate mitigation potential range (MtCO$_2$e annually)		
	Partial equilibrium	Econometric	General equilibrium
Less than \$10	25–105	9	0–90
Between \$10 and \$25	31–413	19	270
Between \$25 and \$49	223–314	37	377
Between \$50 and \$99	315–922	44	436
\$100 or greater	1,590	47	1,052

Notes: CO$_2$e = carbon dioxide equivalent; IFM = improved forest management; MtCO$_2$e = million metric tons of carbon dioxide equivalent; tCO$_2$e = metric ton of carbon dioxide equivalent.

Sources:

Partial Equilibrium: Alig, Latta, Adams & McCarl (2010); Jackson & Baker (2010); US EPA (2005); Nabuurs et al. (2007); Newell & Stavins (2000), Sohngen & Brown (2008).

Econometric: Newel & Stavins (2000). Based on revealed preference approach covering 36 counties in South-Central region of the United States.

General Equilibrium: Golub, Hertle, Lee, Rose, & Sohngen (2009).

\$7 to \$55 per tCO$_2$e, respectively. A higher carbon price of \$55 per tCO$_2$e could potentially set aside a million ha of softwood forests in the western states. At higher carbon prices, the economic potential of carbon sequestration is relatively higher in the western states. The study also indicated that the set-asides are viable only when carbon prices exceed \$40 per tCO$_2$e.

Another study used a dynamic optimization model of the log market and forest carbon stocks to estimate the potential changes in regional forest carbon sequestration from alternative federal timber harvest scenarios in western Oregon (Im, Adams, & Latta, 2010). The study indicated a carbon price of \$5.1 per tCO$_2$e as sufficient to induce private owners to modify harvests and management activities to levels necessary to maintain the regional flux at its level in the early 2000s.

Again, we find a sizable range in mitigation outcomes by different empirical approaches, with partial-equilibrium optimization models showing the largest range in net mitigation potential estimates. This range is partly due to which modeled activities are included or defined as IFM, because some partial equilibrium models (e.g., FASOM-GHG) classify avoided conversion or reforestation projects as IFM. Thus, if net deforestation or low rates of reforestation after harvest are present in a model's baseline, then reduced emissions from increased reforestation or avoided conversion in the presence of a carbon price incentive would count as an IFM credit.

In summary, the mitigation potential at a single price point varies greatly across studies. Although this is a concern from a policy and planning perspective, studies overwhelmingly indicate that IFM and afforestation activities can provide a meaningful source of mitigation in the United States, especially with a strong price incentive. As discussed, spatial and temporal variations in mitigation potential influence which activity would be best suited at what location. In terms of the temporal element, changes in forest management of existing forestlands will result in the most rapid sequestration response, whereas sequestration through afforestation will rise more gradually as tree stands age (Adams, Alig, Latta, & White, 2011).

Mitigation Potential from Nontraditional Forestry Activities in the United States

There are a number of additional mitigation options that are less commonly applied in the United States and for which estimates of technical or economic mitigation potential domestically are currently limited. The following sections introduce several of these options, briefly summarize recent literature, and discuss how these activities differ from more traditionally used forestry-based mitigation activities (i.e., IFM and afforestation projects) and why such projects may require novel policy levers or programs to effectively incentivize participation in the United States. The nontraditional forestry mitigation activities covered in this section include the avoided conversion of forestland, fuel treatments, harvested wood products, increased soil carbon sequestration, and urban forestry.

Avoided Conversion of Forestland

Avoiding the conversion of forestland to non-forestland use is usually a strategy that tropical and developing countries rather than temperate and industrialized countries such as the United States promote. In recent US history, deforestation has been driven by residential development, a trend that is expected to continue (Wear & Coulston, 2015). Conversely, agricultural expansion is the primary driver of land use change in developing countries. Recent modeling studies focused on the US timber and primary forest product markets estimate costs anywhere from \$45/tCO_2e to \$101/tCO_2e per year for hypothetical US carbon offset programs that pay forest-owners to forego timber sales on part of their land (Latta et al., 2011; Nepal et al., 2013). After a review of the literature, to our knowledge there are no studies that focus on direct assessments of avoided forest conversion in the United States, such as payments to avoided forest conversion to urban development. The absence of such studies is likely because of the paucity of such domestic evaluation projects; such projects are often economically infeasible due partly to high opportunity costs of foregoing future timber harvests or near-term development. As the three main carbon offset registries (ACR, CAR and VCS; see Table 1) report, only 13 avoided conversion projects have been registered to date, representing only 4 percent of the 5.5 million acres enrolled in forest carbon offset activities. Nonetheless, urban encroachment and development are expected to be an increasingly significant cause of land-use change domestically. Alig and Plantinga (2004) projected that 100,000 km^2 of forested land will be converted to developed uses between 1997 and 2030, whereas Nowak and Walton (2005) projected that urbanization will subsume 118,300 km^2 (an area the size of Pennsylvania) by 2050.

Lubowski, Plantinga, and Stavins (2008) modeled factors driving land-use change in the United States between 1982 and 1997. Although this time period saw an increase in forest area as land converted from other uses, they found that once urban development becomes feasible, returns "are so much greater than returns to other land uses that observed changes in non-urban returns are of insufficient magnitude to make a significant difference" (p. 546). Lubowski et al. (2008) further suggest that to reduce the urbanization of land, policy instruments such as outright purchases and the acquisition of development rights may be necessary. The use of these instruments would be a significant departure from an environmental market or price incentive approach that directly incentivizes land managers to change practices and would likely result in high mitigation costs given the typically high real-estate value of forestland on the urban/rural interface.

Fuel Treatments

"Fuel treatments" refer to forest-management practices that reduce forest density using prescribed fires or mechanical thinning for a variety of reasons, including to help reduce the risk of severe wildfire disturbance if wildfires occur. Also, thinning of diseased, misshapen, and suppressed trees is also considered an improved forest management activity because this practice increases the productivity and, in some cases, the associated carbon sequestration capacity (e.g., via improved growth in the remaining trees) of forests. For the purposes of this section, however, we are only referring to thinning or fuel treatments to reduce the potential severity and extent of wildfire disturbances. For more than a century, fire suppression practices in the western US have changed forest composition and made them more susceptible to severe burning. These practices, combined with the increased temperatures attributed to climate change are expected to make fires seasons longer and more severe in the future (Hurteau, Bradford, Fule, Taylor, & Martin, 2014).

Fuel treatments can enhance resilience against catastrophic wildfire disturbances, but there is a debate over its potential to enhance forest carbon sequestration. Wildfires typically consume a relatively small amount of total live and dead forest biomass (less than 20 percent), and as fire-killed materials decompose and release carbon, some of that carbon is sequestered back into the terrestrial system via post-fire regeneration (Deal, Raymond, Peterson, & Glick, 2009). At long temporal scales (>40 years) the net release of carbon from any fire-disturbed ecosystem, even those with fuel treatments, may be zero as long as the forest regenerates and reaches the pre-fire age and density (Deal et al., 2009).

Empirical evidence and modeling efforts show that fuel treatments are more likely to incur carbon benefits in forests with low-severity, high-frequency fire regimes such as those in the dry temperate forests of the Southwest than in forests with high-severity, low-frequency fire regimes such as those in the wet temperate forests of the Pacific Northwest (Hurteau & North, 2009; Mitchell, Harmon, & O'Connell, 2009). However, the types of fuel treatments and management practices that achieve reduced fire risk are well known and practiced in the US, but those used to achieve reduced fire risk and measurable carbon mitigation outcomes across different landscapes are not well known or easily quantified. For example, the total carbon emitted in only a few treatments may offset the carbon emissions avoided from fire-severity reduction from limited fire events. Campbell and Ager (2013) conducted a sensitivity analysis to simulate long-term, landscape-wide carbon stocks under a wide range of treatment efficacy, treatment lifespan, fire impacts, forest recovery rates, forest decay rates, and the longevity of wood products. Results indicate an insensitivity of long-term carbon stocks to both management and biological variables. A 1,600 percent change in either fuel treatment application rate or efficacy in arresting fire spread resulted in only a 10 percent change in total system carbon. None of the fuel treatment simulation scenarios resulted in increased forest-system carbon.

One of the reasons for the uncertainty is that much of the research on the forest carbon impacts of fuel treatments have focused on individual forest stands; this approach is inherently limiting because of the spatiotemporal complexity of fire regimes and the random nature of fire events (Loehman, Reinhardt, & Riley, 2014). This uncertainty has led some authors to suggest that future research should focus more on whether or not fuel treatments can achieve carbon mitigation rather than on how (Campbell, Harmos, & Mitchell, 2012; Mitchell et al., 2009).

Despite this uncertainty in long-term carbon mitigation potential, more than a century of fire exclusion has increased the susceptibility of some forests to wildfire, and fuel treatments can be a useful management tool to reduce the intensity of fires, increase understory species diversity, nutrient cycling, and improve resilience to climate change including drought tolerance (Deal et al., 2009; Hurteau et al., 2014).

Increased Wood Product Use for Increased Carbon Sequestration

Harvested wood products (HWP) represent the portion of carbon from trees that is stored in wood products post-harvest. Once stored in wood products during use (including longer term storage from the use of timber in buildings) or in solid waste disposal sites after use, carbon will ultimately be emitted over time as CO_2 via either decay or combustion (US EPA, 2015). HWPs contributed to carbon storage levels ranging from 110-160 $MtCO_2e$ per year, accounting for 17 to 25 percent of total carbon sequestration in US forests in 2005 (Skog, 2008). Many entities recognize the current role that HWP plays in storing carbon. For example, the IPCC recognizes the wood products carbon pool and offers countries the ability to account for carbon stored in HWP in national greenhouse gas inventories (IPCC, 2006). According to the US GHG Inventory (US EPA, 2015), 19 Mt of carbon (71 $MtCO_2e$) was stored in HWP in 2013 (with the US HWP stock estimated at 2,520 Mt of carbon or 9,240 $MtCO_2e$), with most of that being carbon stored in HWP in solid waste disposals sites.[7,8] Although different quantification methods do exist for HWP-related carbon fluxes and storage (Eggleston, Buendia, Miwa, Ngara, & Tanbe, 2006; USDA 2014), most current offset programs in the United States do not include HWP as an approved offset type. According to Ashton, Tyrell, Spalding, and Gentry (2012), this is largely due to concerns over the ability to track carbon storage effectively, "given the uncertainties associated with their end use once they leave the forest" (p. 344). HWP carbon stock estimates are, however, included in some offset project protocols as part of forest carbon baseline calculation for registered project types. The HWP carbon stock estimation used by USDA (2014)[9] is part of the CAR Forest Protocol calculations for establishing baselines for registered offsets projects.[10] The Regional Greenhouse Gas Initiative's US Forest Projects Offset Protocol also includes HWP calculations as part of their forest carbon offset projects baseline construction.

With appropriate policy incentives and market mechanisms, the potential exists to create significant additional carbon storage in the forestry sector by increasing the amount of HWPs used. For example, as part of its strategy to address climate change, the USDA is working to promote the use of HWPs via a set of voluntary programs and initiatives spanning its programs (USDA, 2015). Also, the extent that increased HWPs can serve as a mitigation activity may be augmented when these products are used in lieu of energy-intensive materials (e.g., metals, concrete, and plastic) if substitution effects are included in the associated carbon accounting.

Encouraging the replacement of nonwood building materials with wood products would likely require different incentive mechanisms than traditional offsets in the land-use sectors. This is partly because efforts to reduce the emissions intensity of a supply chain in an energy-intensive industry by using wood products has not been considered in US voluntary GHG-offset programs to date. Nonetheless, policies that explicitly or implicitly price GHG emissions with a tax or cap-and-trade regime, respectively, provide a price incentive to reduce fossil-fuel–related GHG emissions and energy intensity in production processes. In residential or commercial construction, a GHG price incentive could result in using less GHG-intensive building materials and more HWP.

There are wood substitutes for many nonwood products essential to residential and commercial construction. For example, steel studs can be replaced by wood studs, steel joists can be replaced by wood joists, concrete walls can be replaced by wood panels,

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[7] The US GHG Inventory estimates of the HWP contribution to US carbon storage are based on methods in Skog (2008), which are based on IPCC (2006) guidance for estimating HWP carbon.

[8] This discussion focuses on HWP in use and does not cover HWP in solid waste disposal sites.

[9] Based on Skog (2008).

[10] Climate Action Reserve Forest Project Protocol, Version 3.3

and concrete slab floors can be replaced by hard wood floors (Malmsheimer et al., 2011). Previous studies have quantified the potential net emissions reduction of HWP relative to their nonwood counterparts. Lippke and Edmonds (2010) find that wooden wall studs can reduce net emissions approximately 2 Kg CO_2e per Kg of wood fiber used, or approximately 10 Kg CO_2e per Kg of wood fiber used for floor joists (among other examples). Sathre and O'Connor (2010) conducted a meta-analysis of 21 different international studies to estimate the average substitution rates for the use of HWP in place of nonwood materials. Results of this meta-analysis found that on average, the substitution effect leads to approximately 3.9 tCO_2e emission reductions per ton of dry wood used compared to the alternatives (e.g., steel, concrete, stone). Finally, increased demand for HWP to replace traditional building materials could result in developing new markets for unique wood products such as structural insulated panels and cross-laminated timbers (Giesekam, Barret, Taylor, & Owen, 2014) that offer improved structural performance relative to traditional timber products while maintaining long-term carbon storage potential.

In the absence of a mitigation price incentive, there are other policy levers that can increase the market for wood-based building materials. For example, building codes and procurement policies which encourage or require the comparison of GHG emissions from material choices could have significant mitigation potential (Malmsheimer et al., 2011). Examples of codes adopted in the United States to encourage the use of bio-based materials include the International Green Construction Code (IgCC),[11] ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 189.1,[12] and the California Green Building Standards Code (CALGreen).[13] In Canada, British Columbia's Wood First Act requires wood to be considered before other building materials in all new publicly funded buildings (British Columbia, 2009).

In summary, although increased HWP use is not a traditional offset activity like some of the other mitigation options addressed in this assessment, it offers a potentially large carbon storage opportunity as long as policies and market mechanisms to encourage it are also implemented. Programs and policies that incentivize the replacement of energy-intensive building materials with bio-based materials with lower relative-emissions intensity may also offer additional GHG mitigation benefits. However, if such efforts significantly increase the demand for woody biomass, programs and policies may need to consider the resulting forest industry market and related emissions effects on the terrestrial landscape from increased forest harvests and ensuing planting decisions. Such incentives could counteract efforts to increase terrestrial carbon sequestration in the forestry system (via increased harvesting) and/or reinforce such efforts (via increased planting and/or implementation of management regimes that foster higher yield and sequestration levels). To evaluate policy alternatives that could result in this latter outcome, we need additional empirical work.

Increased Forest-Soil Sequestration

According to the US GHG Inventory (US EPA, 2015), US forest soils store vast quantities of carbon. As of 2013, the domestic forest soils stock was 17,038 Mt of carbon (62,529 $MtCO_2e$), including the 21 Mt of carbon (78 $MtCO_2e$) net flux added that year. Creating additional soil carbon sequestration in forested soils offers significant potential, particularly in afforestation of agricultural lands and management of forest plantations. However, the uncertainty around these values is large because of the complex interaction between climate, soils, tree species and management, and chemical composition of the litter (Lal, 2005). Kimble, Heath, Birdsey, and Lal (2003) estimate the potential for forest soils to sequester carbon resulting from various management activities of US forestlands. The management activities they evaluated included (1) regeneration and fertilization; (2) land-use change activities such as afforestation and reduced deforestation; and (3) agroforestry,

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[11] Florida requires compliance with the IgCC in the construction of state-owned buildings, while Maryland, Rhode Island, Phoenix, and Scottsdale have endorsed it on a voluntary basis.

[12] Washington, DC, has adopted this standard as part of its city building code.

[13] CALGreen awards voluntary credits for the use of bio-based materials.

including activities such as alleycropping, silvopasture, and urban forests. They estimated an average countrywide sequestration potential of 207 $MtCO_2e$/year; 96 $MtCO_2e$/year; and 82 $MtCO_2e$/year, respectively, with a total soil carbon sequestration potential for US forest soils of 389 $MtCO_2e$/year, but with a wide range (179 to 682 Mt CO_2e/year). Their analysis, which focused solely on soil carbon-sequestration potential, did not include the carbon sequestered in tree biomass or forest-floor pools; nor did it include the N_2O emissions associated with fertilization. A meta-analysis of 39 papers from 1957 to 2010 found that when industrialized and wildland areas were afforested they showed categorical and significant increases in soil organic carbon after 15 and 30 years of afforestation, respectively (Nave et al., 2012). Although these soil carbon sequestration estimates represent soil on a range of different forest types, there are certain forests with unique soil carbon dynamics or management needs, such as boreal forests and wetland forests, that represent a relatively small percentage of US forestland but contain a very high amount of organic matter. Kimble et al. (2003) suggest that the mitigation strategy for these forests should be retaining carbon by protecting existing forests or restoring what has been lost due to land-use change.

Therefore, largely because of the uncertainty and variance attributed to forest-soil carbon estimates, most current offset programs in the United States do not include forest-soil carbon storage as an independent type of approved offset. Nonetheless, as with HWP, forest-soil carbon estimates are currently included in some forest carbon offset protocol baseline calculations (Climate Action Reserve, 2012). As scientific methods and certainty improve and as carbon policies and markets evolve, forest-soil carbon storage may play a larger role as a mitigation option in the future.

Mitigation through Urban Forestry

GHG mitigation potential of urban forestry practices has received scarce attention in the literature, likely because the potential scale of such efforts is small in comparison to other traditional forestry mitigation sources such as IFM or afforestation. Nowak et al. (2013) estimated total urban forest carbon storage in the United States to be 2,350 $MtCO_2e$ (circa 2005), with an annual net sequestration rate of approximately 70 $MtCO_2e$, or roughly 3.2 percent of the US forest carbon flux. US EPA (2015) estimated the annual net sequestration rate of urban forests to be 90 $MtCO_2e$ in 2013. Although trees and isolated forests in US urban areas represent a significant carbon stock, increasing carbon storage is unlikely without a major effort to change current practices. Furthermore, Nowak and Greenfield (2012) note that tree cover in urban areas is currently on the decline, so this flux could diminish over time without policy intervention.

Currently, various registries have forest carbon-offset protocols for urban forestry projects, but no projects listed on any of the reviewed registries are urban forest projects. For example, CAR's Urban Forest Project Protocol is now available as two project-specific protocols: Urban Tree Planting and Urban Forest Management. The protocols provide guidance on calculating and verifying GHG reductions from tree planting, maintenance, and/or improved management activities aimed at permanently increasing carbon storage through trees. However, to date, no urban forest projects are registered.

Two other management practices that could increase urban forest carbon stocks in the short term are limiting mowing (which can remove saplings or limit forest understory growth) and improving physical growing conditions through increased water availability (Nowak & Greenfield, 2012; Nowak et al., 2013). Increasing water availability likely requires additional investment in irrigation systems, and there could be a high opportunity cost of using additional water supplies to irrigate trees in urban areas, especially in the Western United States where water availability is currently limited.

Given that urban forest systems are often managed by public entities, mitigation strategies would likely occur as a result of local policy or management decisions, thus falling outside of a traditional offset market. However, it may be possible for urban forestry projects to be cost-effective in a carbon market (McHale, McPherson, & Burke, 2007), but only at a very high mitigation cost (>$100/tCO$_2$e). To improve the cost effectiveness of urban tree planting, we would also need to consider stacking of different benefits, such as the potential energy savings provided by increased shading. Escobedo, Kroeger, and Wagner (2011) present a framework for helping decision makers consider urban forest management goals such as carbon sequestration in the broader social and economic context, including other factors such as urban sustainability goals. Thus, urban forestry is not likely to be a pure GHG mitigation strategy by itself anytime soon, but mitigation could be a co-benefit of broader policy efforts to improve the urban environment, reduce urban energy consumption, and increase green space generally.

Discussion

The literature is unequivocal that forests and forestry practices can provide mitigation benefits through activities that maintain and/or increase the terrestrial or wood-product carbon-stock and carbon-sequestration rates. However, forest practices as mitigation options entail several concerns and limitations that merit evaluation when prioritizing near- and long-term terrestrial mitigation strategies. These include potential economic costs, environmental impacts, fulfillment risks (e.g., whether anticipated offsets are realized), and policy or administrative hurdles. These limitations may vary in different countries; this discussion focuses on limitations specific to the United States. The following section introduces a set of basic qualitative criteria for comparing mitigation activities to help identify these issues and to serve as a tool that can help inform prioritization of activities per different policy and GHG objectives. Applying a simple framework like this can help decision makers consider the benefits and trade-offs associated with near- and long-term mitigation strategies for US forestry.

Elements to Consider for Prioritizing Mitigation Efforts

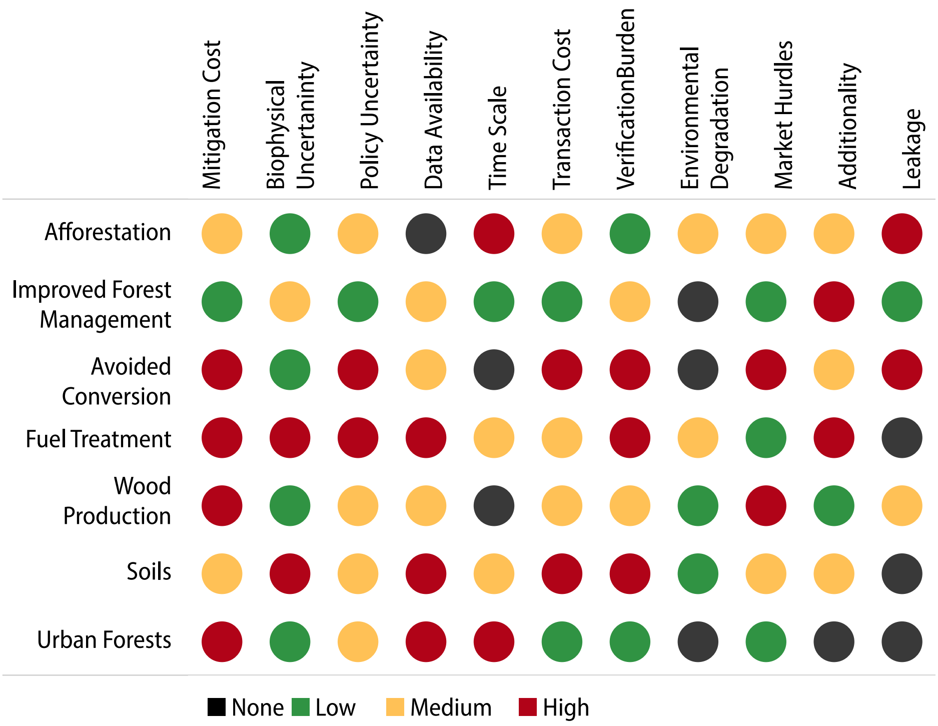
This section presents and then discusses the specific criteria representing areas of potential risk or relative beneficial outcomes associated with the various mitigation activities covered under this review that can be used for the qualitative assessment and ranking of the different options. These criteria are:

- Mitigation costs
- Biophysical uncertainty
- Policy uncertainty
- Data availability
- Time scale
- Transaction costs
- Verification burden
- Environmental degradation
- Market hurdles
- Additionality
- Leakage

Table 6 links the various mitigation activities with the criteria, which were selected to represent relative risk or potential for a “negative” outcome. The classifications range from none-to-low, medium, to high, based on the relative risk of the activity. For example, if an activity is highly likely to induce leakage (thereby shifting a portion of the offset emissions to a different region), we would assign it a “high” relative risk. In terms of mitigation costs, we would assign a low-cost mitigation strategy a “low” classification, for example. This qualitative tool offers a simplified means to generally identify and compare the different risks and other important aspects of the different mitigation activities.

Mitigation costs refers to the total potential cost of an activity on a $/tCO$_2$e basis. This metric excludes transaction costs but includes the economic opportunity costs of forgoing some other land use or production activity to pursue mitigation. For afforestation, this category would include the land use change or site preparation costs needed to plant new forest stands on existing agricultural lands. It would also account for the long-term value of the agricultural production the landowner would forgo by switching to forestry. In the absence of transaction or market hurdle costs, then, the total GHG payments over the lifetime of the project would need to be at least as high as the costs of establishing the forest stand and the forgone agricultural profits over the same time span. For forest management and afforestation projects, these costs are fairly well known and documented in the literature (Galik, Cooley, & Baker, 2012) and are relatively low. For urban forestry and wood products, these costs are unknown, although they would likely involve some infrastructure investment costs. Avoided forest

Table 6. Criteria weighting for mitigation activity risk factor attributes



	Mitigation Cost	Biophysical Uncertaininty	Policy Uncertainty	Data Availability	Time Scale	Transaction Cost	VerificationBurden	Environmental Degradation	Market Hurdles	Additionality	Leakage
Afforestation	🟡	🟢	🟡	⚫	🔴	🟡	🟢	🟡	🟡	🟡	🔴
Improved Forest Management	🟢	🟡	🟢	🟡	🟢	🟢	🟡	⚫	🟢	🔴	🟢
Avoided Conversion	🔴	🟢	🔴	🟡	⚫	🔴	🔴	⚫	🔴	🟡	🔴
Fuel Treatment	🔴	🔴	🔴	🔴	🟡	🟡	🔴	🟡	🟢	🔴	⚫
Wood Production	🔴	🟢	🟡	🟡	⚫	🟡	🟡	🟢	🔴	🟢	🟡
Soils	🟡	🔴	🟡	🔴	🟡	🔴	🔴	🟢	🟡	🟡	⚫
Urban Forests	🔴	🟢	🟡	🔴	🔴	🟢	🟢	⚫	🟢	⚫	⚫

⬛ None 🟩 Low 🟨 Medium 🟥 High

conversion costs could be prohibitively high in the US context. Because the mitigation costs of avoided conversion typically involves capturing the costs of avoided residential development (and not agricultural conversion), the opportunity costs per unit area would reflect the real estate value of the land. Thus, per ton CO_2 mitigation costs for US avoided conversion projects could be higher than expected CO_2 prices under most current GHG offset programs.

Biophysical uncertainty recognizes limits identified in the current scientific literature on estimating existing carbon stocks or fluxes, or the potential GHG benefits of specific mitigation activities (e.g., as the literature maintains, the mitigation potential from fuel treatments is highly uncertain). As more data become available, there may continue to be biophysical uncertainty when assessing the carbon sequestration impacts of a practice or policy (e.g., it may be biophysically uncertain whether afforestation increases soil carbon throughout the whole soil profile compared to previous land uses). Biophysical uncertainty may also relate to how difficult it is to measure carbon outcomes. Measuring carbon in woody biomass (aboveground carbon or in HWPs) is easier to account for than overall long term net carbon effects from, for example, forest thinning and controlled burns.

Policy uncertainty reflects the degree to which policy efforts to incentivize mitigation could come to fruition. The degree of this uncertainty may depend on whether there is a precedent for the policy. For example, there is a precedent for GHG markets and both regional and international experience in establishing them. Therefore, because the United States currently has regional GHG trading markets that effectively incentivize forest offsets in the West and Northeast, a national cap-and-trade scheme could adequately incentivize forest offsets across the United States, and there is a relatively high level of certainty that it could work effectively. (Note that crafting a national GHG market would need to acknowledge and ideally include provisions to address any international leakage effects resulting from the national system. We discuss leakage later in this section.) Here we do not try to weigh issues related to political economy across different policy options, although we recognize that political factors may play a big role in determining the success of a policy (e.g., interest groups representing energy intensive industries such those that compete with wood products might lobby against a policy that mandated consideration of alternative building materials).

Data availability is related to biophysical and policy uncertainty but reflects a case in which there is insufficient literature to determine the techno-economic mitigation potential of an activity. An example would be soils, where information on current soil carbon stocks is lacking, and the impact that different forest management regimes can have on the overall soil carbon flux. Such information is needed to provide guidance on potential policy interventions to increase forest soil carbon sequestration. HWP mitigation is another example—although the literature discusses the potential of HWP to supply net mitigation benefits, we know of no empirical studies that attempt to quantify the mitigation potential of specific policy instruments to incentivize HWP use over functionally equivalent products with higher overall GHG emissions.

Time scale recognizes the concept that a mitigation source may not provide immediate or near-term mitigation benefits, although it may yield long-term benefits (therefore, as applied here, this ranking presupposes that near-term mitigation is more desirable than long-term mitigation). Avoided conversion and increased HWP use provide instantaneous or near-term mitigation benefits—thus, in the ranking scheme presented here, these activities receive a score of "none," or no concern, because these activities do not need time for physical carbon stocks to grow or regrow. Forest management, urban forestry, and afforestation all require longer time periods to realize mitigation benefits. Afforestation, in particular, rates low in this time scale evaluation. Although afforestation has substantial mitigation potential overall, realizing these benefits would take years, even decades in some contexts. In the context of achieving its NDCs goals by 2025, for example, the US might have an interest in prioritizing incentives for near-term land-based mitigation to help meet emissions-reduction targets; afforestation efforts using slow-growing tree species (versus other options or faster growing trees) might not be a first-choice option.

Transaction costs and verification burden are closely linked and important to consider. Verification burden represents the difficulty (in terms of cost) in verifying that an actual mitigation activity has been implemented. The verification burden is essentially zero for wood products and urban forestry because quantifying the extent of these sources is easily done by accounting for the amount of new wood products in use or visually verifying projects in urban areas (as they tend to be smaller, easier to access, etc.). For more traditional offsets, there tend to be higher opportunity costs of (1) verifying that the mitigation activity is being implemented through visual confirmation and written documentation, and (2) evaluating whether net carbon accumulation is occurring through field sampling or biophysical modeling. Verification burden is expected to be highest for soil sequestration activities largely because of the variation of soil types and potential sampling methods needed to test soil organic carbon levels. Transaction costs refer to other cost elements that create a wedge between the GHG price incentive determined by the market and the net mitigation incentive received by suppliers (Galik, Cooley, & Baker, 2012). Transaction cost components potentially include offset aggregation fees, certification fees, and other monitoring, verification and reporting costs. Literature on transaction costs and environmental markets is growing, and there is some evidence that transaction costs decline over time as a market matures. Most of the mitigation sources identified in this paper have relatively new (or nonexistent) markets, so we expect relatively high transaction costs for those mitigation activities. For IFM, for example, we expect lower transaction costs given that there has been previous research and that markets have been in existence for several years.

Environmental degradation refers to the potential risk that an activity results in an adverse environmental outcome. For example, increased HWP use could result in higher-than-anticipated harvest levels and a net loss of forest ecosystems in the short term; however, in the long term, this mitigation approach could also spur increased carbon levels if afforestation occurs to help meet increased wood demand. Afforestation, however, could also potentially result in negative environmental outcomes. Incentives to plant trees for carbon sequestration could result in monoculture plantation stands designed to sequester as much carbon as possible as quickly as possible. While this would produce a carbon benefit, the biodiversity benefits of monoculture stands are low relative to naturally generated diverse forest ecosystems. Furthermore, afforestation can alter hydrologic flows, resulting in reduced water available for alternative uses (Jackson et al., 2005). If afforestation occurs on degraded agricultural lands with high levels of observed input use, then afforestation can lead to reduced land degradation overall.

Market hurdles reflect unknown risks regarding whether a mitigation activity will or will not reach its techno-economic potential based on targeted program participants' willingness to voluntarily participate in the mitigation program. For example, land managers could strongly prefer managing their land a certain way, so mitigation incentives that require a change in management or a complete change in land use to realize would have to be high enough to cover the individual's willingness to accept compensation for the change. Also, some markets and related supply chains are entrenched due to long term contracts and other market arrangements that make some market infrastructures relatively inflexible, especially for new actors and new technologies. Substituting wood products for fossil fuel-derived materials, for example, may face substantial market hurdles because of entrance barriers and established market and business practices.

Additionality is another key concept in the terrestrial GHG mitigation literature—for an activity to provide true GHG benefits, it should be additional to the baseline, or in other words, business as usual. For an afforestation project, for example, additionality implies that a land use transition to forested land would not have occurred under business as usual practices without a mitigation incentive. Verifying additionality for land-based activities can be difficult, because it can be challenging to estimate the actual GHG benefits. For example, if a mitigation incentive is put into place and causes mitigation activity to commence, one must estimate the GHG benefit of the mitigation activity versus what would have likely happened in terms of activities and related GHG profile under the previous land use practice (Baker, Latane, Proville, & Cajka, 2015). Mitigation incentives can require offset protocols with specific criteria or means of identifying what is considered additional and how this can be verified on the ground. Current offset protocols often include built-in thresholds or criteria for determining whether an activity is additional to the baseline, but risk remains that nonadditional projects could still enter the market. (The avoided grassland conversion protocol in the American Carbon Registry [2013] is an example of an offset protocol with specific additionality criteria). In regions with relatively low afforestation rates or forest management, estimating additionality is fairly straightforward. However, in regions like the Pacific Northwest, where privately owned forest resources have been managed with rotational considerations for decades, demonstrating additionality for an "extended rotation" IFM project, for example, could be difficult.

Finally, **leakage** in this context occurs when a mitigation activity unintentionally shifts emissions outside of the target project boundary rather than providing overall emissions mitigation. Considering this effect is particularly important in a forestry context, because forest conservation/avoided conversation or afforestation practices can shift management, harvests and/or other land use practices to different regions, potentially displacing other activities and/or land uses, and the resulting emissions can reduce the net mitigation benefit provided by the original activity (Murray, McCarl, & Lee, 2004). This assessment categorizes leakage risk as medium for IFM based on previous literature, and high for wood products mitigation because this would imply a timber market re-allocation. Following similar logic, leakage is likely high for avoided conversion projects, especially locally, because restricted residential development in a particular area could simply shift development to a different part of the community, state, or country. Depending on the size of the program and the activities that are displaced, afforestation projects could induce agricultural expansion elsewhere (Baker et al., 2010), and therefore can be, in some instances, quite substantial. Leakage is likely low or nonexistent for urban forestry and soil sequestration projects because these activities are not typically explicitly tied to land use changes or market output.

Implications

When considering these various criteria, there is no simple choice of a targeted mitigation strategy for the US forest sector. Ultimately, if we cannot pursue all options simultaneously and must prioritize funds and other resources, the preferred mitigation activity in LULUCF sectors would depend on cost, ease of implementation, and most important, policy goals (e.g., maximizing mitigation efforts over the next 10 years; targeting incentives for mitigation activities by landowner type and/or region over the longer term). This review shows that the potential for mitigation from the US forest sector is substantial, but varying levels of mitigation may occur over different time periods and pose a range of trade-offs and costs, some of which could be quite high. To illustrate this last point, we use the trend lines generated from the meta-analysis studies estimating the mitigation potential of IFM and afforestation activities (refer to Figures 1 and 2), to estimate the total mitigation potential. We use illustrative mitigation prices of \$25 and \$40 per tCO_2e to show hypothetical long-term mitigation potential from US forests (IFM and afforestation only). At \$40/tCO_2e, this projection increases to more than 1,000 $MtCO_2e$ (Table 7). Thus forestry mitigation potential is substantial, but not without a meaningful price incentive.

However, these results should be evaluated with appropriate context—most models provide long term mitigation potential on an annual basis (which is reported in Figures 1 and 2). Realized mitigation potential would likely be far less in the near term because it takes time for environmental markets to mature and for land use and management changes to result in meaningful additional carbon sequestration.

Given existing markets for IFM and afforestation, efforts to continue increasing mitigation supply from these sources are likely to and should continue. Over time and as markets mature, transaction costs and market hurdle costs should decline, encouraging additional participation. For the other forestry mitigation strategies discussed in this report, our review recognizes the need for further research that compares policy options and quantifies the expected mitigation potential from these policies. Avoided conversion poses a relatively high risk, largely due to mitigation, transaction and verification costs, and other hurdles, but this option also could provide a large source of near term mitigation as emissions reductions (via avoided emissions) are essentially instantaneous. However, more analytical work is needed to evaluate the potential of this option because there are currently few studies that have focused on avoided conversion in a developed country context.

Table 7. Hypothetical long-term mitigation potential for improved forest management (IFM) and afforestation (AFF) activities ($MtCO_2e$)

CO_2 price (\$/tCO_2e)	Mean mitigation potential IFM	Mean mitigation potential AFF	Mean total IFM and AFF mitigation potential
25	207.0	16.7	223.8
40	418.1	588.4	1006.6

As mentioned previously, the choice of which mitigation practice or suite of practices to use will ultimately depend on policy goals (e.g., the expected timing and magnitude of expected GHG outcomes, GHG benefits only or co-benefits also), costs, and likely other considerations. Each mitigation activity brings a unique set of opportunities as well as complicating factors and risks that could inhibit mitigation outcomes.

Conclusions

Identifying and evaluating the potential benefits and risks associated with different mitigation opportunities is essential as the United States seeks to fulfill a multitude of federal, state, and local actions on GHG emissions, including efforts to meet its national GHG emissions reduction target of 26 to 28 percent below 2005 levels. To further advance technical discourse on this important topic, this paper assesses current domestic forest sector GHG mitigation project activities and synthesizes mitigation potential estimates from economic studies using mitigation price incentives with a number of economic modeling techniques. Results indicate that with mitigation pricing or other policy actions there is significant potential to reduce or avoid GHG emissions through targeted US forest sector activities, but there are a number of potential risks, challenges, and trade-offs to consider. This paper also provides a simple matrix and various evaluation criteria to help assess these considerations in relation to each other. The results from the market and economic literature review in conjunction with the application of the simple evaluation matrix yielded the following key conclusions.

First, US voluntary market data and economic literature estimates to date indicate that strong mitigation price incentives are necessary to encourage private landowner participation in voluntary offset programs, as prices would need to be sufficiently high to cover any forgone economic opportunities (e.g., timber prices forgone from an avoided conversion project) and any hurdle costs that limit landowner participation. However, market mechanism such as offset pricing will not generally work for activities that fall within the public domain such as urban forestry, so alternative financing options or policies may be required.

Second, important aspects such as the costs, biophysical and policy uncertainties, environmental and social implications, and timing and scale of mitigation results from different forest sector activities and related trade-offs must be considered when evaluating and prioritizing mitigation program goals. Policy or program goals may affect what considerations are given more weight when prioritizing mitigation options. For example, if the goal is solely to achieve as much near-term GHG mitigation as possible at the lowest cost possible, some forest sector mitigation strategies may achieve this (e.g., IFM). However, other activities might not be viewed as providing large-scale mitigation benefits for a decade or more (e.g., afforestation), and other activities that can provide near-term benefits may be more costly or challenging to implement (e.g., avoided conversion), relative to additional mitigation or energy efficiency efforts in other sectors. However, if priority is given to near-term GHG mitigation projects that also yield important environmental and social benefits in addition to GHG beneficial outcomes (e.g., keeping forested lands forested via avoided conversation or increased income in rural areas via afforestation incentives for marginal lands), then these mitigation activities may instead be prioritized as they can achieve GHG as well as other goals.

Last, the different potential outcomes and challenges related to choosing different forest sector mitigation options provide substantial justification for (1) early action and planning to establish clear goals regarding the role of forests in the US GHG emissions reductions strategy, and (2) a concerted research agenda that targets the further development of data and tools to better equip planners and policymakers for forest sector opportunities.

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