RESEARCH ARTICLE

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policy

Potential for Additional Carbon Sequestration through Regeneration of Nonstocked Forest Land in the United States

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An analysis of 2014 forest inventory data for the contiguous United States shows nearly 8 million ha of forestland that are currently defined as nonstocked after recent natural and human disturbances. It is estimated that forest regeneration on these lands could result in an additional terrestrial sequestration of 48.9 million metric tons of CO_2 equivalent (CO_2e) annually. Analysis across a range of seven site productivity classes indicates that approximately 58% of the total area is productive timberland, defined as capable of producing merchantable volume of $\geq$1.4 m^3/ha/year. It is estimated that regeneration of just the productive timberland portion of the total could produce an additional 44.4 million metric tons of CO_2e annually in carbon sequestration. On National Forest System lands, more than 50% of the total potential carbon sequestration benefit from regenerating nonstocked lands could be achieved by reforesting just the top 30% of these lands in the moderate-to-high site productivity classes. On private lands, more than 70% of the total potential carbon benefit can be achieved by regenerating the most productive 30%.

Keywords: forest regeneration, reforestation, forest carbon, climate change mitigation, climate policy

Forests in the United States absorb more than 700 million metric tons[1] of CO_2 equivalent per year (Smith and Heath 2004, US Environmental Protection Agency [USEPA] 2014). Forests represent 90% of the country's terrestrial carbon sink and currently offset 14–16% of total US carbon emissions. A 2010 assessment of US forest resources projected that this forest carbon sink could decline significantly and that as soon as 2030 US forests overall could become a net *source* of greenhouse gas emissions (US Department of Agriculture [USDA] Forest Service 2012). There are several factors underlying this projected decline, including a continuation of deforestation due to conversion to development and other nonforestland uses, the increasing demand for wood biomass for biofuels and electric power generation, and the increasing average age of US forests (Wear and Greis 2013, Woodall et al. 2015b). Subsequent developments may moderate these projections, particularly in regard to potential increases in timber harvest for wood bioenergy (Abt et al. 2014, Wear and Coulston 2015, Woodall et al. 2015a) and changes in the pattern of disturbances, given the influence of a changing climate.

Nonetheless, a significant decline in the forest carbon sink could make it more challenging to meet the recent US commitment to a net reduction in greenhouse gas emissions by 26–28% from 2005 levels by 2025 (United Nations Framework Convention on Climate Change 2015). Recognizing this, the United States has reiterated its commitment to supporting forest-sector initiatives to mitigate greenhouse gas emissions, at home as well as abroad (US Department of State 2015). Among the USDA's "building blocks" for mitigating climate change is a commitment to reforest an additional 12,500 ha annually on the National Forests (USDA 2014). In 2011, the United States made a commitment to restore 15 million ha of deforested or degraded forest by 2020 in response to the Bonn Challenge, a global initiative to restore 150 million ha by 2020 (International Union for the Conservation of Nature 2011).

Recent policy studies on options to increase net carbon sequestration by terrestrial carbon sinks have focused heavily on the agricultural sector (USEPA 2005, 2014) but have also identified a range of opportunities in the forest sector for expanding the capacity of the US forest carbon sink, increasing the rate of atmospheric carbon removal and

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decreasing carbon emissions from forest management activities. Broad categories of forestry activities that can contribute to increasing carbon stocks or reducing emissions (Peterson et al. 2014) include the following:

Reduce deforestation and increase afforestation: Reduce deforestation from conversion to development or other nonforestland uses; promptly reforest after timber harvest or fire; and increase afforestation of marginal crop and pasture land.

Manage forests to 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.

Substitute wood biomass for fossil fuels and energy-intensive materials: Increase the efficient and sustainable use of wood biomass in place of fossil fuels in energy production; and increase carbon storage in long-lived wood products, especially in applications in which wood can be substituted for materials that are more fossil fuel-intensive in manufacture and production.

Tradeoffs among Forest-Sector Options for Greenhouse Gas Reduction

Each of these categories of forestry activities has a significant potential for contributing to additional net reductions in carbon emissions (Malmsheimer et al. 2008, Council on Environmental Quality 2014), but most of them also have environmental, economic, or social tradeoffs that must be carefully considered during policy decision-making and through monitoring during application (USEPA 1995, USEPA 2005, McGlynn et al. 2016). For example, the ability to reduce deforestation may be restricted by land-use policies, population growth, and the high potential for simple displacement of forest loss from one location to another ("leakage") (Murray et al. 2004). Opportunities for afforestation of marginal crop and pasture land are significant (US Department of Energy 2016) but may be limited by competition with agriculture and potential impacts on agricultural commodity prices (USEPA 2014).

Increases in the use of wood biomass for energy may be limited by its high cost relative to that of other forms of energy and by public concerns over possible impacts on wildlife habitat, water resources, or biodiversity (Sample et al. 2010, Evans et al. 2012, Kittler 2013). The substitution of wood biomass for fossil fuels, especially in electric power production, may be limited by continuing differences of view on the appropriate methodology to account for biogenic carbon emissions, and the net effect of this substitution on atmospheric concentrations of greenhouse gasses over time (Searchinger et al. 2009, USEPA 2012, 2014, Miner et al. 2014).

One forestry activity in which the tradeoffs seem to be minimal is the regeneration of forests that have been affected by natural disturbances such as fires, drought, insect infestations, or disease or by human disturbances such as timber harvesting. In terms of the potential for additional carbon sequestration, how much forestland in the United States is in need of regeneration? What are the productive capacity and thus the carbon sequestration potential of these lands, and how might this be influenced by geography, climate, and other physical factors? Who owns these nonstocked forestlands, and how does this influence the choice of policy tools available to address needs for forest restoration and regeneration?

Methods

Extent of Nonstocked Productive Forestland

Analysis of recent forest inventory data compiled by the US Forest Service shows a total of 7,956,032 ha of "nonstocked" forestland in the contiguous United States in 2014, the latest year for which complete data are available for most states.[2] The database description and user guide for USDA Forest Service Forest Inventory and Analysis (FIA) defines nonstocked forestland as "land that currently has less than 10% stocking but formerly met the definition of forestland" (USDA Forest Service 2014a).

The FIA data for the area of nonstocked forestland was sorted by several inventory codes: state (STATECD), ownership (OWNGRPCD), source of disturbance (DSTRB1 and DSTRB2), recent treatment (TRTCD1 and TRTCD2), and site productivity class (SITECLCD). Ownership categories were National Forest, other federal, state, and private. State-level data were grouped into regions consistent with those in the national forest and rangeland resource assessment prepared every 10 years by the USDA Forest Service (2014b) (Figure 1). Natural disturbance codes included insect damage to trees including seedlings and saplings, disease damage to trees including seedlings and saplings, fire including crown and ground fires, domestic animal/livestock grazing, and drought. Treatment code included timber harvest that has occurred since the last measurement or within the last 5 years for new plots. The area affected by the treatment must be at least 0.4 ha in size.

Potential for Growth and Carbon Sequestration

Site productivity codes are distributed across seven classes, the first six of which are defined as productive timberland with a growth potential ranging from ≥1.4 to 15.8+ m^3/ha/year in merchantable volume (Table 1). Class 7 is defined as marginal or unproductive timberland capable of growing <1.4 m^3/ha/year in merchantable volume. The potential for merchantable wood

Management and Policy Implications

As the nation's largest carbon sink, forests will play an essential role in achieving national policy goals for net reductions in CO_2, and regeneration of currently nonstocked forestland is a key component in this strategy. Timely forest regeneration after both past and future timber harvest or natural disturbance is key to sustaining an array of goods and services from forest ecosystems, including but not limited to carbon. This has been recognized in federal policy through numerous financial incentive programs and tax policies to support reforestation on private lands and mechanisms such as the Knutson-Vandenberg Act and the Reforestation Trust Fund to support reforestation on public lands. Regenerating the most productive 30% (by site productivity class) could achieve 70% of the total potential carbon benefit on private lands and 50% of that on National Forests. Detailed analysis of the type of reforestation investments needed and a reevaluation of existing policies promoting forest regeneration on public and private lands are needed to direct reforestation assistance to the most productive opportunities and to provide forest managers with the resources and tools necessary to make sound public investments in the future of the nation's forests and environment.

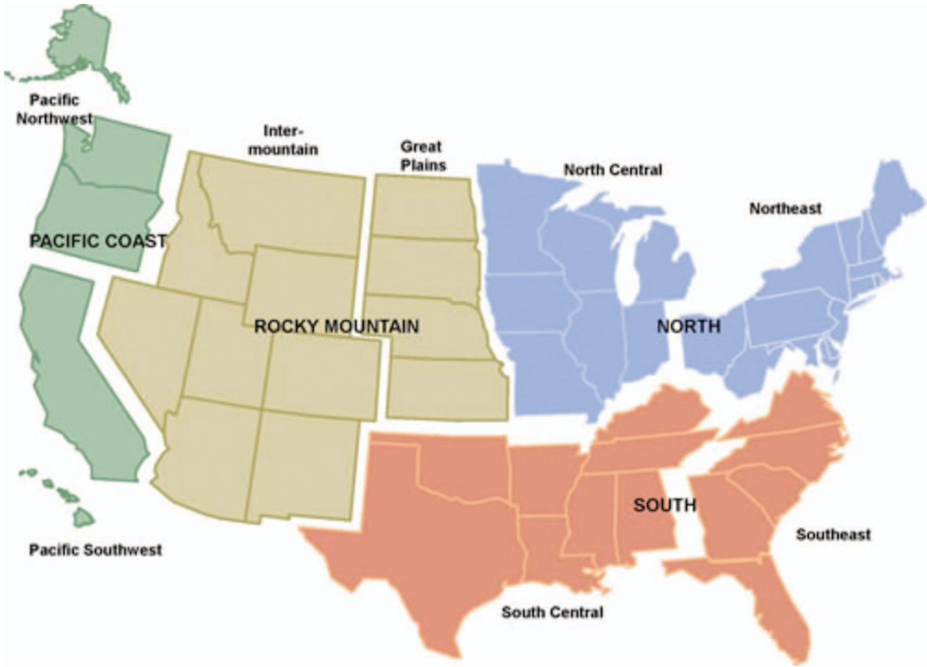

Figure 1. Forest regions of the United States (USDA Forest Service 2014a).

Table 1. Volume growth and carbon sequestration potential, site productivity class.

Site productivity class	Volume growth		
	cu ft/ac/yr	cu m/ha/yr	Mg CO_2e/ha/yr
Productive forest land			
1	225+	16.4+	35.5+
2	165–224	12.1–16.3	26.2–35.3
3	120–164	8.8–12.0	19.1–26.0
4	85–119	6.2–8.7	13.4–18.9
5	50–84	3.7–6.1	8.0–13.2
6	20–49	1.5–3.6	3.3–7.8
Nonproductive forest land:			
7	0–19	0–1.4	0–3.0

production was calculated by applying site productivity (m^3/ha/year) to the number of hectares in each productivity class. The potential growth of merchantable volume on lands in site productivity class 1 may be underestimated because the data for this class are coded simply as 15.8+ m^3/ha/year, and the actual growth potential may be significantly higher in some areas.

Total volume growth was calculated on the basis of ratios of total biomass volume to merchantable volume developed by Cost et al. (1990) and later refined by Birdsey (1992) and Smith et al. (2002) to account for belowground biomass as well as aboveground biomass (tops and limbs) in addition to the merchantable bole. The ratios of total biomass volume to merchantable volume developed by Birdsey (1992) account for carbon content differences between hardwoods and softwoods (Lamlom and Savidge 2003) and variations in species composition among the major forest regions of the United States. Estimates of total volume are derived from weighted averages of the proportion of hardwoods and softwoods in each region, based on the net volume of hardwood and softwood timber in each region as reported in Oswalt et al. (2014).

Carbon sequestration and offset potential were estimated based on an average biomass content of 0.6 metric ton/m^3, half of which (0.3 metric ton/m^3) is carbon (Food and Agriculture Organization of the United Nations 2000). Carbon offset potential is calculated at 1 metric ton C = 3.67 metric ton CO_2e, or 1.1 metric ton CO_2e/m^3 of wood. For each region and site productivity class, the annual sequestration potential is the product of the total volume growth potential (m^3/year) times the carbon offset potential of 1.1 metric ton CO_2e/m^3.

Results

Ownership of Nonstocked Forestland

Of the total of 7,956,032 ha of nonstocked forestland in the contiguous United States in 2014, more than half is in private ownership (Table 2), and nearly half of this is located in the South Central region. Roughly 28% of nonstocked forestland is on the National Forests. The largest area of nonstocked forestland on public lands is in the Rocky Mountain region, which contains 71% of the total nonstocked forest on National Forest System lands, 42% of the nonstocked state forestlands, and 83% of the nonstocked forest on lands managed by other federal agencies such as the Bureau of Land Management, National Park Service, US Fish and Wildlife Service, and the Department of Defense. A large majority (88%) of the nonstocked forestlands in the four eastern regions is on private lands, reflecting the predominance of private forest ownership generally in the East, but in the West the nonstocked forestland is distributed broadly across the four ownership categories. National Forests constitute the largest area of nonstocked forestland (54%) in the combined Pacific Southwest and Pacific Northwest regions.

Disturbance Source

Fire is the single largest primary source of forest disturbance in every region except the Northeast and North Central. It is associated with more of the nonstocked forest area than all other sources of natural and human disturbance combined, not just in the Rocky Mountain region but in the Pacific Southwest and Pacific Northwest regions as well. Nationally, fire is responsible for 62% of the area of nonstocked forest (Figure 2). Timber harvest areas that remain unregenerated account for only 4% of the nonstocked forestland. Disease and insect infestations account for a total of about 8%, reflecting the extensive forest mortality in the interior West caused by the mountain pine beetle (*Dendroctonus ponderosae*) and western pine beetle (*Dendroctonus brevicomis*). Livestock grazing (11%) and drought (3%) are also listed as major disturbance factors. Although these may not have constituted the disturbance that originally resulted in the loss of forest cover, they may play a significant role in delaying or preventing regeneration. Livestock grazing is a leading disturbance factor on nonstocked forestland in the South Central region on lands in pri-

Table 2. Nonstocked forest land in the contiguous United States, by ownership.

Region	National Forest	Other federal	State	Private	Total
	(ha)				
Northeast	192	5,485	33,685	195,432	234,794
North Central	15,746	13,886	73,252	203,219	306,103
Southeast	11,015	40,784	64,758	436,575	553,132
South Central	3,232	42,837	70,278	1,879,582	1,995,929
Rocky Mountain	1,574,054	955,195	219,129	982,421	3,730,799
Pacific Southwest	237,050	37,214	3,347	82,507	360,118
Pacific Northwest	375,651	45,100	53,838	300,569	775,158
Total (%)	2,216,942 (28)	1,140,499 (14)	518,286 (7)	4,080,305 (51)	7,956,032

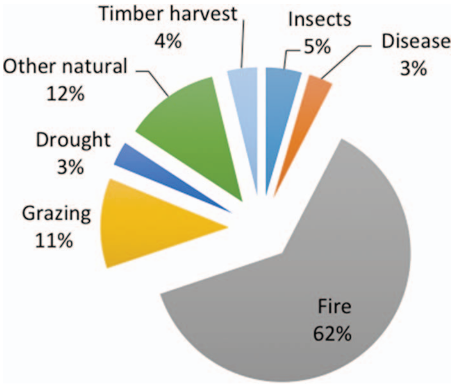

Figure 2. Nonstocked forestland in the United States, by disturbance source, 2014.

vate ownership and in the Rocky Mountain region on both private and public lands.

Potential Productivity and Carbon Sequestration Capacity

The site productivity classification of these lands was examined as an indicator of their potential for forest regeneration. Nonstocked forestlands are distributed unevenly across a wide range of site productivity classes, regions, and ownership categories, complicating the process of setting priorities and achieving easily measureable results. More than 42% of the nonstocked forest area, or 3.4 million ha, is in the lowest site productivity class (Table 3), below the definition for productive timberland (USDA Forest Service 2014c). More than 35% of these lands (1.2 million ha) is in National Forests and other federal lands in the western regions, but more than 58% of these low-productivity forests (2 million ha) is on private lands, 76% of which are in the South Central region.

The remaining 4.6 million ha of currently nonstocked forestland is categorized as productive timberland, distributed across site productivity classes ranging from 1.4 to more than 15.8 m^3/ha/year. The most productive of these forests are concentrated in the Southeast and South Central regions and are primarily in private ownership (Table 3). Although less than 2% of the land in the highest site productivity classes is on public (federal and state) forestland, 84% of the nonstocked area on the National Forests is classified as productive timberland.

It is estimated that regeneration of the 4.6 million ha of nonstocked productive timberland has the capacity to produce a total volume of 40.4 million m^3 of wood annually. This estimate may be less than what is actually possible, since the growth rate in the highest site productivity class is recorded in the FIA data as $\geq$15.8 m^3/ha/year and some forestlands in this class may have significantly higher productivity. The long-term potential for additional carbon sequestration is estimated at 44.4 million metric tons annually (Table 4). This rate of carbon sequestration would develop gradually over the period of time required to regenerate the area of nonstocked productive timberland and for regenerated forests to reach their full potential rate of annual growth (Smith et al. 2006).

Discussion

Private Forestlands

More than half of the total potential for additional carbon sequestration through forest regeneration is on currently nonstocked forestland in private ownership (4.1 million ha). For just the 2.1 million ha of this total that is productive timberland ($\geq$1.4 m^3/ha/year), growth potential is estimated at 20.3 million m^3/year, with an estimated potential additional carbon sequestration of 22.4 million metric tons per year (Mg CO_2e $year^{-1}$) (Table 4). Published FIA data for private forestlands do not distinguish between those of small woodland owners and those managed by large commercial forestry enterprises. There could be significant differences in how quickly private lands in different categories are reforested after harvest or disturbance.

In instances after a fire, insect infestation, disease, or timber removal, expected returns to private forest owners from future wood production alone may not be sufficient to finance the up-front expenses of site preparation and planting (de Steiguer 1984, Hyberg and Holthausen 1989, Beach et al. 2005). Opportunities to augment these returns with income from carbon offsets are presently limited, and owners of small forest tracts typically find that transaction costs (carbon inventory, modeling, and verification) outweigh potential financial returns from carbon offsets (Fletcher et al. 2009, Markowski-Lindsay et al. 2011, Thompson and Hansen 2013).

Rules governing existing markets for carbon offsets may require long-term or perpetual transfers of development rights that many private land owners are unwilling to make (Markowski-Lindsay et al. 2011, Miller et al. 2012). Considering the limited market for forest carbon offsets and tradeoffs with nonforestland uses, there may be little economic incentive for private land owners to make costly investments in reforestation unless there are policy interventions to stimulate the development of a broader carbon market or provide direct financial incentives for regeneration of nonstocked forestland (Nordhaus 2002, USEPA 2005, DeBerry 2009, Hamilton et al. 2010, Kossoy and Guigon 2012).

The extent to which private sector entities undertake mitigation activities is highly sensitive to carbon market prices and/or subsidies (USEPA 2005). Using a combination of models including the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG), the Timber Assessment Market Model (TAMM), and the North American Pulp and Paper model (NAPAP), the USEPA estimated a private sector supply response to carbon prices ranging

Table 3. Nonstocked forest land, by ownership, region, and site productivity class.

Region	Site productivity class								Productive forest land only (1–6)
	1	2	3	4	5	6	7	Total	
	(ha)								
National Forests									
Northeast					192			192	192
North Central			3,269		451	12,026		15,746	15,746
Southeast					5,957	4,803	255	11,015	10,760
South Central		604			992	581	1,055	3,232	2,177
Rocky Mountain			8,714	46,639	247,222	981,097	290,383	1,574,054	1,283,672
Pacific Southwest		5,648	17,266	50,750	60,492	63,008	39,887	237,050	197,164
Pacific Northwest		8,566	64,749	26,452	119,090	130,116	26,677	375,651	348,974
Total (%), National Forests	0	14,819	93,998	123,842	434,397	1,191,630	358,256	2,216,942	1,858,685
	(0.0)	(0.7)	(4.2)	(5.6)	(19.6)	(53.8)	(16.2)	(100.0)	(83.8)
Other federal									
Northeast						5,485		5,485	5,485
North Central				1,110	5,177	5,975	1,624	13,886	12,262
Southeast					32,467	6,514	1,803	40,784	38,981
South Central				2,895	12,808	2,425	24,709	42,837	18,128
Rocky Mountain				3,976	8,662	182,162	760,395	955,195	194,800
Pacific Southwest			2,189		1,957	4,908	28,159	37,214	9,055
Pacific Northwest			6,069	1,117		7,519	30,395	45,100	14,705
Total (%), Other federal	0	0	8,259	9,097	61,072	214,987	847,085	1,140,500	293,415
	(0.0)	(0.0)	(0.7)	(0.8)	(5.4)	(18.9)	(74.3)	(100.0)	(25.7)
State									
Northeast				1,058	12,720	15,818	4,089	33,685	29,596
North Central			2,538	11,198	23,630	31,621	4,265	73,252	68,987
Southeast				8,806	31,773	18,869	5,310	64,758	59,448
South Central				4,427	11,619	2,305	51,927	70,278	18,351
Rocky Mountain				7,603	9,739	65,079	136,708	219,129	82,421
Pacific Southwest			2,343				1,003	3,347	2,343
Pacific Northwest	3,853	8,200	13,017		15,343	11,224	2,200	53,838	51,638
Total (%), State	3,853	8,200	17,899	33,092	104,824	144,916	205,502	518,286	312,784
	(0.7)	(1.6)	(3.5)	(6.4)	(20.2)	(28.0)	(39.7)	(100.0)	(60.3)
Private									
Northeast			8,856	29,214	34,575	111,905	10,881	195,432	184,551
North Central		1,902	6,153	37,644	86,355	67,277	3,889	203,219	199,330
Southeast		9,269	38,153	100,498	180,813	100,418	7,423	436,575	429,152
South Central		13,434	51,974	110,615	152,790	59,623	1,491,146	1,879,582	388,435
Rocky Mountain		3,166	8,332	21,623	70,499	449,859	428,942	982,421	553,480
Pacific Southwest	2,613	298	13,252	17,673	23,265	14,770	10,637	82,507	71,871
Pacific Northwest	18,174	56,442	70,361	23,314	72,010	46,341	13,928	300,569	286,641
Total (%), Private	20,787	84,510	197,080	340,583	620,307	850,193	1,966,845	4,080,305	2,113,460
	(0.5)	(2.1)	(4.8)	(8.3)	(15.2)	(20.8)	(48.2)	(100.0)	(51.8)
Summary—All lands									
Northeast			8,856	30,273	47,488	133,208	14,970	234,794	219,824
North Central		1,902	11,959	49,952	115,613	116,899	9,778	306,103	296,326
Southeast		9,269	38,153	109,304	251,011	130,604	14,791	553,132	538,341
South Central		14,038	51,974	117,937	178,209	64,933	1,568,838	1,995,929	427,091
Rocky Mountain		3,166	17,046	79,841	336,122	1,678,197	1,616,427	3,730,799	2,114,372
Pacific Southwest	2,613	5,946	35,051	68,423	85,715	82,685	79,686	360,118	280,433
Pacific Northwest	22,027	73,209	154,196	50,884	206,443	195,200	73,199	775,158	701,959
Total (%), All lands	24,640	107,529	317,235	506,613	1,220,600	2,401,727	3,377,688	7,956,032	4,578,344
	(0.3)	(1.4)	(4.0)	(6.4)	(15.3)	(30.2)	(42.5)	(100.0)	(57.5)

from \$1 to \$50 per metric ton CO_2e. At \$5 per metric ton CO_2e (constant price over the period 2010–2110), private investment in reforestation is projected to result in 2.3 million Mg CO_2e year^{-1} in additional carbon removal. At a carbon price of \$50 per metric ton CO_2e, carbon removal resulting from private investments in forestation are projected to be 823.2 million Mg CO_2e year^{-1} (USEPA 2005). Forestland owners who are anticipating a higher price on carbon in the future may actually delay any such investments to optimize their returns from carbon payments (USEPA 2005).

EPA has estimated the current "social cost of carbon" at \$36–42 per metric ton CO_2e year^{-1} to analyze the carbon dioxide impacts of various regulations and projected that this cost will rise significantly during the period 2020–2050 (USEPA 2015). Similarly, a number of national and multinational corporations now factor potential future prices for carbon into their capital investment decisions in anticipation of future government policy interventions such as a carbon tax or cap-and-trade program (USEPA 2015). If market prices or subsidies for carbon sequestration were to accurately reflect the USEPA's estimated current social cost of carbon, the 22.4 million Mg CO_2e year^{-1} in potential additional carbon sequestration from the regeneration of commercially productive private forestland would be valued at \$806–941 million per

Table 4. Carbon sequestration potential, total volume, by ownership, region, and site productivity class.

Region	Site productivity class 1	2	3	4	5	6	7	Total	Productive timberland only (1–6)
	(Mg CO_2e/yr)								
National Forests									
Northeast					2,136			2,136	2,136
North Central			87,015		5,667	78,913		171,595	171,595
Southeast					61,561	25,926	394	87,880	87,487
South Central		7,577			4,298	1,314	682	13,872	13,190
Rocky Mountain			231,304	889,264	3,096,277	6,418,871	542,812	11,178,529	10,635,717
Pacific Southwest		148,861	333,096	703,263	550,623	299,601	54,189	2,089,633	2,035,445
Pacific Northwest		220,402	1,219,380	357,836	1,058,202	603,970	35,379	3,495,169	3,459,790
Total (%), National Forests	0 (0.0)	376,840 (2.2)	1,870,795 (11.0)	1,950,363 (11.4)	4,778,765 (28.0)	7,428,595 (43.6)	633,456 (3.7)	17,038,814 (100.0)	16,405,358 (96.3)
Other federal									
Northeast						33,188		33,188	33,188
North Central				22,143	67,853	40,911	3,177	134,083	130,907
Southeast					350,078	36,691	2,901	389,670	386,769
South Central				19,918	57,887	5,724	16,668	100,196	83,528
Rocky Mountain				79,092	113,197	1,243,563	1,483,137	2,918,990	1,435,853
Pacific Southwest			44,067		18,591	24,351	39,918	126,927	87,009
Pacific Northwest			119,266	15,762		36,417	42,061	213,505	171,444
Total (%), Other federal	0 (0.0)	0 (0.0)	163,333 (4.2)	136,915 (3.5)	607,606 (15.5)	1,420,844 (36.3)	1,587,861 (40.5)	3,916,559 (100.0)	2,328,698 (59.5)
State									
Northeast				18,659	147,344	95,718	7,069	268,789	261,720
North Central			70,495	223,440	309,702	216,494	8,343	828,474	820,132
Southeast				144,547	342,596	106,283	8,546	601,972	593,426
South Central				30,461	52,510	5,443	35,027	123,441	88,414
Rocky Mountain				151,255	127,272	444,274	266,647	989,447	722,800
Pacific Southwest			47,173				1,422	48,595	47,173
Pacific Northwest	119,976	220,152	255,795		142,254	54,362	3,044	795,585	792,541
Total (%), State	119,976 (3.3)	220,152 (6.0)	373,464 (10.2)	568,361 (15.5)	1,121,678 (30.7)	922,573 (25.2)	330,098 (9.0)	3,656,303 (100.0)	3,326,205 (91.0)
Private									
Northeast			217,409	515,194	400,510	677,160	18,813	1,829,085	1,810,272
North Central		72,164	170,914	751,109	1,131,788	460,616	7,607	2,594,198	2,586,591
Southeast		289,384	871,902	1,649,704	1,949,626	565,624	11,946	5,338,186	5,326,240
South Central		175,802	497,835	761,076	690,531	140,764	1,005,852	3,271,860	2,266,008
Rocky Mountain		119,805	230,770	430,194	921,298	3,071,046	836,643	5,609,756	4,773,114
Pacific Southwest	83,344	8,183	266,748	255,541	220,969	73,281	15,078	923,144	908,066
Pacific Northwest	565,857	1,515,254	1,382,604	329,083	667,647	224,447	19,274	4,704,165	4,684,892
Total (%), Private	649,201 (2.7)	2,180,592 (9.0)	3,638,182 (15.0)	4,691,901 (19.3)	5,982,369 (24.6)	5,212,938 (21.5)	1,915,212 (7.9)	24,270,395 (100.0)	22,355,183 (92.1)
All lands									
Northeast			217,409	533,852	549,990	806,066	25,882	2,133,199	2,107,317
North Central		72,164	328,424	996,692	1,515,011	796,933	19,127	3,728,351	3,709,224
Southeast		289,384	871,902	1,794,251	2,703,861	734,523	23,787	6,417,708	6,393,922
South Central		183,379	497,835	811,455	805,225	153,246	1,058,228	3,509,368	2,451,140
Rocky Mountain		119,805	462,074	1,549,806	4,258,044	11,177,755	3,129,238	20,696,721	17,567,483
Pacific Southwest	83,344	157,044	691,084	958,804	790,184	397,233	110,607	3,188,299	3,077,693
Pacific Northwest	685,833	1,955,807	2,977,045	702,681	1,868,104	919,196	99,758	9,208,424	9,108,666
Total (%), All lands	769,177 (1.6)	2,777,584 (5.7)	6,045,774 (12.4)	7,347,540 (15.0)	12,490,418 (25.6)	14,984,951 (30.7)	4,466,626 (9.1)	48,882,071 (100.0)	44,415,444 (90.9)

year. A regional analysis of forest regeneration opportunities and costs, in the context of site productivity classifications, could help more directly identify reforestation projects that would produce a net positive economic return.

Public Forestlands

Actions to increase carbon sequestration by publicly owned forests (115 million ha, or 37% of total US forestland) are less driven by markets than by historical legislative mandates and by perceived environmental, economic, and sociopolitical tradeoffs (USEPA 2005). Federal and state forestland management agencies face additional challenges to integrate carbon management, for which there is seldom any statutory authority, into their existing multiple-use forest resource management plans that must be responsive to existing legislative mandates and trust responsibilities. Employment of an imputed price for carbon, similar to the approach used by private sector corporations to avoid investment in carbon-intensive infrastructure that could become a "stranded asset" in the future, would be one way to factor carbon sequestration into land and resource management planning models that are designed to optimize net public benefits.

Forest carbon management is one of several mechanisms by which today's public lands managers can continue to achieve existing statutory mandates to ensure the sustainability and resilience of public forests (Dilling et al. 2013). The regeneration of existing burned-over or cut-over lands under the stewardship of federal and state natural resource agencies has long been central to the mission of conserving and sustainably managing the public's forests (P.L. 93−378 1974, Adams 1993, USDA Forest Service 1993, Souder and Fairfax 1996). Among the public forestlands, the National Forest System has the largest area of currently nonstocked forestland, 2.2 million ha with a carbon sequestration potential of 17.0 million Mg CO_2e year^{-1}, or 16.4 million Mg CO_2e year^{-1} if one is considering only the lands classified as having site productivity ≥1.4 m^3/ha/year.

The US Congress has enacted policies to ensure that "all forested lands in the National Forest System be maintained in appropriate forest cover with species of trees, degree of stocking, rate of growth, and conditions of stand designed to secure the maximum benefits of multiple use sustain yield management in accordance with land management plans" (P.L. 93-378 1974, P.L. 94-588 1976). The Knutson-Vandenberg Act (P.L. 71-319 1930) requires deposits from timber sale receipts to ensure a funding source for reforestation ("KV funds") after timber harvests on National Forests. A growing National Forest reforestation backlog in the 1970s prompted Congress to authorize reforestation expenditures of $200 million annually, in federal fiscal year 1977 "and each fiscal year thereafter" (P.L. 93-378 as amended), to eliminate the reforestation backlog. The intent of this congressional authorization was to "replant and otherwise treat an acreage equal to the acreage to be cut over that year, plus a sufficient portion of the backlog of lands found to be in need of treatment to eliminate the backlog within the eight year period." (P.L. 93-378 as amended). The Forest Service was further required, after this 8-year period, to submit to Congress "an estimate of sums necessary to replant and otherwise treat all lands…so as to prevent the development of a backlog." In 1980, Congress established the Reforestation Trust Fund to provide a reliable source of funding to assist in eliminating the reforestation backlog (P.L. 96-451). The law authorized funding of up to $30 million annually from the Reforestation Trust Fund to the US Forest Service to supplement KV deposits and annual appropriations for reforestation.

Funding for reforestation has not kept up with forest regeneration needs. For at least the past decade, reforestation funding has remained level at roughly $50 million annually. This includes the capped $30 million contribution from the Reforestation Trust Fund, which operationally translates to approximately $24 million annually after allocation of indirect costs (Valerie Hipkins, USDA Forest Service, pers. comm., Sept. 8, 2016). Adjusted for inflation, the $30 million cap on annual expenditures from the Reforestation Trust Fund enacted in 1980 would be equivalent to more than $87 million in 2016 dollars (Bureau of Labor Statistics 2016). Similarly, the $200 million Congressional authorization for reforestation expenditures in fiscal year 1977 "and each fiscal year thereafter" would be equivalent to more than $800 million in 2016 dollars.

A large proportion of the forest regeneration need is a result of the increasing frequency, size, and resulting burned area of wildfires in the United States (Littell et al. 2009), a trend that is expected to continue, especially in the western United States (Running 2006). It is estimated that roughly 80% of the 80,000 ha reforested annually on the National Forest System is regeneration of areas burned in wildfires (Nicole Balloffet, USDA Forest Service, pers. comm., May 18, 2016). With so much of the regeneration need on federal forestlands not resulting from timber harvest (Figure 2), KV deposits from timber sales provide only a small portion of the funding needed to meet these needs.

A well-documented estimate of the funding that would be required to address the current forest regeneration need, in the context of a prioritized strategy spanning at least a decade, would be a valuable first step in securing the resources needed to implement such a strategy. Not all forestlands identified as nonstocked require planting to be regenerated. For example, site preparation to remove invasive plant species or brush that has occupied the site since disturbance may be all that is needed to facilitate natural regeneration in some areas. Other currently nonstocked forestland may eventually regenerate naturally, although the regeneration delay may be lengthy and difficult to predict. To develop a prioritized, well-targeted forest regeneration strategy, further research is needed to differentiate among these lands, determine the type of reforestation investments needed, and identify those opportunities with the greatest positive impact and probability of success. The FIA data alone do not clearly distinguish among those currently nonstocked areas that can be expected to regenerate naturally within an acceptable period of time and those that will require intensive investments in site preparation and planting, perhaps including costly intermediate steps such as the eradication of invasive species that may have occupied the site after disturbance.

Not all of the nonstocked forestland is easily accessible for reforestation actions of any type, especially areas affected by fire and other natural disturbance (USDA Forest Service 2014a), and outside the Northeast and North Central regions fire is the largest single source of disturbance. Larger and more intense fires make natural regeneration more difficult, so the increasing size and severity of fires in recent years may be a factor (Johnstone et al. 2004, Zald et al. 2008).

Some areas of currently nonstocked forestland may be unsuitable for reforestation because climatic and other environmental conditions have changed to the extent that they no longer support forest growth. The effects of climate variability and prolonged drought are becoming a more significant factor in western US forests (Allen and Breshears 1998, Allen et al. 2010, Luce et al. 2016) and increasingly in southern US forests as well (Dale et al. 2001, Wear and Greis 2013). Changes in temperature and precipitation patterns in some regions are resulting in long-term ecological shifts to grasslands or open woodlands in areas that until recently supported forests (Allen et al. 2010), suggesting that reforestation efforts of any type on these lands would be unsuccessful.

Finally, new policy goals emphasizing wildfire risk reduction and improving the resiliency of forests to drought and other climate-related factors could reduce the potential contribution of forest regeneration to carbon sequestration capacity. In fire-prone ecosystems, especially in the western regions of the United States, optimal stand density may be something significantly less than the full stocking that is the basis of growth potential in FIA site productivity classifications. Thinning, partial overstory removal, and other forest management actions aimed to moderate the risk of fire and adverse climate effects may run counter to the protocols required by certain carbon registries (Hurteau et al. 2008). Whether the specific objective is to reduce carbon emissions and other ecosystem impacts from catastrophic wildfires or to increase forest carbon stocks and the capacity for additional carbon sequestration, the common goal is to reduce net carbon emissions. The optimal stocking level for achieving that goal is highly dependent on local conditions and trends and is likely to differ among regions and across large landscapes.

Conclusion

Forests are the largest terrestrial carbon sink in the United States, and opportunities in the forest sector for additional carbon sequestration are among the most significant and cost efficient means to achieve policy goals for net reductions in greenhouse gas emissions. Numerous recent studies and policy reports, including the current national climate action strategy for the United States (Executive Office of the President 2013), have identified forest-sector opportunities to increase carbon removal and mitigate climate change. Subsequent research has estimated the potential carbon benefits associated with each of these actions and also identified possible environmental, economic, and social tradeoffs and potential legal or policy barriers. Regeneration of lands classified as forest (i.e., not marginal agricultural lands and generally lands on which there was standing forest during the previous inventory cycle) may have significant potential for additional carbon sequestration, without the environmental, economic, and political drawbacks that have become associated with other forest-sector mitigation options.

Regeneration of currently nonstocked forestlands presents an opportunity to increase forest carbon sequestration in the contiguous United States by as much as 48.9 million metric tons annually. Prioritizing forest regeneration investments on the basis of site productivity classification and other information developed through existing FIA protocols, in combination with more detailed, site-specific information on the type of reforestation investment needed, can help maximize the benefit from limited funding. On National Forest System lands, more than 50% of the total potential carbon sequestration benefit from regenerating nonstocked lands could be achieved by reforesting just the top 30% of these lands in the moderate-to-high site productivity classes. On private lands, more than 70% of the total potential carbon benefit can be achieved by regenerating the most productive 30%, but until there is a market price on carbon or there are public policy interventions to create subsidies or incentives for reforestation investments in reforestation on private lands will likely remain low.

Decisions to invest in the regeneration of productive forestlands on the National Forests and other federal and state public forestlands might be guided by other considerations such as the estimated social cost of carbon and how forest carbon management can be folded into existing public policy and agency mandates that determine how they conserve and sustainably manage public forestlands. Forest regeneration is a key component of forest restoration and has numerous cobenefits beyond carbon sequestration. Timely regeneration after harvest or natural disturbance can expand other ecosystem goods and services, especially watershed protection, wildlife habitat, wood production, and increased economic opportunity in rural communities, that should also be valued and factored into an analysis of costs and benefits.

Forest regeneration continues to be one in an array of forest sector opportunities to achieve net reductions in US greenhouse gas emissions and is best considered in context with opportunities to reduce deforestation, maintain existing forest carbon stocks, substitute wood biomass for fossil fuel energy where practical, and increase carbon storage in long-lived wood products. A regionally based national technical and economic analysis of these opportunities would help quantify their relative effectiveness. Carbon benefits from forest regeneration start slowly and build over a period of years, whereas minimizing deforestation from conversion to development or other nonforestland use avoids a large and immediate pulse of carbon emissions. Given that loss of forest cover is likely to continue to some extent to accommodate future population growth, state and local governments might consider a "no net loss of forests" policy in which developers' payments into a mitigation bank are used to incentivize the conservation of existing forest and also the restoration of forests on currently nonstocked productive forestland.

Endnotes

1. One metric ton (Mg) of CO_2 contains 0.27 metric tons of carbon; 1 metric ton of carbon is equivalent to 3.67 metric tons of CO_2 (CO_2e). A teragram (Tg) is a million metric tons.
2. The year 2013 was the latest for which forest inventory data were available for Delaware, Kentucky, Louisiana, Tennessee, and Virginia and 2012 for Texas.

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