Forest Carbon Assessment for the Custer Gallatin National Forest in Region 1

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1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services provided by forests and grasslands. Through the process of photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it in forest biomass (plant stems, branches, foliage, roots) and much of this organic material is eventually stored in forest soils. This uptake and storage of carbon from the atmosphere helps modulate greenhouse gas (GHG) concentrations in the atmosphere. Estimates of net annual storage of carbon indicate that forests in the United States (U.S.) constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan 2011). Forests in the U.S. remove the equivalent of about 12 percent of annual U.S. fossil fuel emissions or about 206 teragrams of carbon after accounting for natural emissions, such as wildfire and decomposition (U.S. Department of Agriculture 2016a, Hayes et al. 2018).

The Intergovernmental Panel on Climate Change (IPCC) has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (Intergovernment Panel on Climate Change 2014). From 2000 to 2009, forestry and other land uses contributed just 12 percent of human-caused global CO_2 emissions.[1] The forestry sector contribution to GHG emissions has declined over the last decade (Intergovernment Panel on Climate Change 2014, Smith et al. 2014)(FAOSTAT, 2013). Globally, the largest source of GHG emissions in the forestry sector is deforestation (Pan et al. 2011, Houghton et al. 2012, Intergovernment Panel on Climate Change 2014) defined as the removal of all trees to convert forested land to other land uses that either do not support trees or allow trees to regrow for an indefinite period (Intergovernment Panel on Climate Change (IPCC) 2000). However, the U.S. is experiencing a net increase in forestland in recent decades because of the reversion of agricultural lands back to forest and regrowth of cut forests (Birdsey et al. 2006), a trend expected to continue for at least another decade (Wear et al. 2013, U.S. Department of Agriculture 2016a).

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools, which also release carbon dioxide through

[1] Fluxes from forestry and other land use (FOLU) activities are dominated by CO_2 emissions. Non-CO_2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate.

decomposition or combustion (fires). Management activities include timber harvests, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Carbon can then be stored in commodities (e.g., paper, lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinning, harvests, and fuel reduction treatments, forests will thin naturally from mortality-inducing disturbances or aging, resulting in dead trees decaying and emitting carbon to the atmosphere.

Following natural disturbances or harvests, forests regrow, resulting in the uptake and storage of carbon from the atmosphere. Over the long term, forests regrow and often accumulate the same amount of carbon that was emitted from disturbance or mortality (McKinley et al. 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients, such as nitrogen, can also influence forest growth and carbon dynamics (Caspersen et al. 2000, Pan et al. 2009).

Box 1. Description of the primary forest carbon models used to conduct this carbon assessment

Carbon Calculation Tool (CCT)

Estimates annual carbon stocks and stock change from 1990 to 2013 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2011 had not occurred.

Integrated Terrestrial Ecosystem Carbon (InTEC) model

A process-based model that integrates FIA data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric CO_2. InTEC estimates the relative effects of aging, disturbance, regrowth, and other factors including climate, CO_2 fertilization, and nitrogen deposition on carbon accumulation from 1950 to 2011. Carbon stock and stock change estimates reported by InTEC are likely to differ from those reported by CCT because of the different data inputs and modeling processes.

In this section, we provide an assessment of the amount of carbon stored on Custer Gallatin National Forest (NF) and how disturbances, management, and environmental factors have influenced carbon storage overtime. This assessment primarily used two recent U.S. Forest Service reports: the Baseline Report (U.S. Department of Agriculture 2015) and Disturbance Report (Birdsey *et al.,* In press). Both reports relied on Forest Inventory and Analysis (FIA) and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). The Baseline Report applies the Carbon Calculation Tool (CCT) (Smith et al. 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the national forest from 1990 to 2013. The Baseline Report also provides information on carbon storage in harvested wood products (HWP) for each Forest Service region. The Disturbance Report provides a national forest-scale evaluation of the influences of disturbances and management activities, using the Forest Carbon Management Framework (ForCaMF) (Healey et al. 2014, Raymond et al. 2015, Healey et al. 2016). This report also contains estimates of the long-term relative effects of disturbance and non-disturbance factors on carbon stock change and accumulation, using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen et al. 2000, Zhang et al. 2012). See Box 1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act (RPA) assessment (U.S. Department of Agriculture 2016b) and regional climate vulnerability assessments (Halofsky et al. 2018a) are used to help infer future forest carbon dynamics. Collectively, these reports incorporate advances in data and analytical methods, representing the best available science to provide comprehensive assessments of NFS carbon trends.

1.1 Background

The Custer Gallatin National Forest (CGNF) consists of several geographically isolated land units extending from the Montana-Idaho border into South Dakota. Inside the administrative boundary are more than 3.4 million acres. More than 3 million of these acres are National Forest System lands including approximately 2.5 million acres of forestland. The CGNF is made up of a distinct series of island mountain ranges, as well as portions of landscapes located in the Greater Yellowstone Ecosystem. The present national forest includes lands that at one time or another were in 16 forest reserves and six national forests, which over the years had many different names. Since 2014, the Custer National Forest and Gallatin National Forests have been managed together as the Custer Gallatin. However, the data in this report is summarized separately for each Forest due to the organization of available data. Douglas-fir, spruce-fir and lodgepole pine forest types are the most abundant across the CGNF.

The carbon legacy of these and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. Wildfire is the most influential disturbance on the CGNF, as lightning storms are common. Fire on the landscape is considered a natural process and many fires on the Custer Gallatin are started by lightning. However, humans have also been a source of fire on the landscape for centuries, and intentional or not, have influenced vegetation successional dynamics. Fire is not a simple process and many factors influence its character, including fuel loadings, climatic and weather conditions, topography, vegetation structure and composition, and elevation. of fuels in some areas contributed to an increase in the acreages burned. Historically, large fires have occurred across the Custer Gallatin National Forest, as shown by fire history studies (Barrett et al. 1997), recent data (1940 to present), and anecdotal evidence (pre-1940). The Custer Gallatin Assessment Fire and Fuels Report contains additional information on fire history.

Insect and diseases also historically played an important role in shaping vegetation. Climate and weather play a major role in controlling insects, as does availability and quality of food and breeding habitat. Historically, insect populations would periodically build to high levels under favorable climatic and host conditions; cool climate conditions were not conducive to outbreaks.

Human activities associated with settlement, such as mining, logging, and grazing began in the mid to late 1800's in most areas. Much of the accessible material was used for rail ties or cordwood, and extensive mining resulted in an ongoing demand for timber. To a lesser extent, modern vegetation management (since 1940) has influenced composition and structure on a relatively small proportion of the CGNF.

Box 2. Carbon Units. The following table provides a crosswalk among various metric measurements units used in the assessment of carbon stocks and emissions.

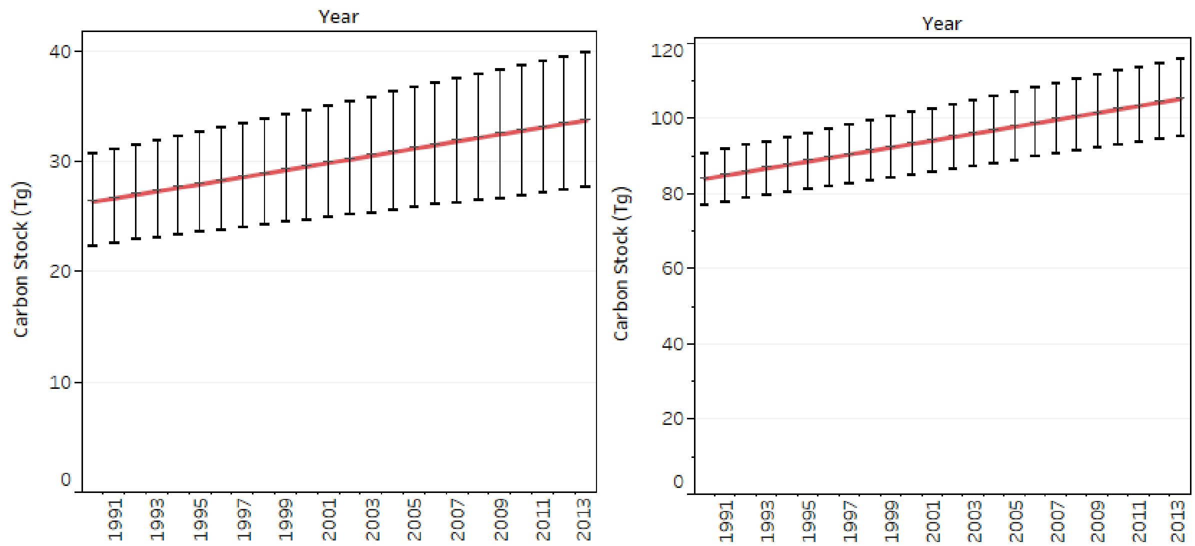
Tonnes				Grams		
Multiple	Name	Symbol		Multiple	Name	Symbol
				10^0	Gram	G
				10^3	kilogram	Kg
10^0	tonne	t		10^6	Megagram	Mg
10^3	kilotonne	Kt		10^9	Gigagram	Gg
10^6	Megatonne	Mt		10^{12}	Teragram	Tg
10^9	Gigatonne	Gt		10^{15}	Petagram	Pg
10^{12}	Teratonne	Tt		10^{18}	Exagrame	Eg
10^{15}	Petatonne	Pt		10^{21}	Zettagram	Zg
10^{18}	Exatonne	Et		10^{24}	yottagram	Yg

1 hectare (ha) = 0.01 km^2 = 2.471 acres = 0.00386 mi^2
1 Mg carbon = 1 tonne carbon = 1.1023 short tons (U.S.) carbon
1 General Sherman Sequoia tree = 1,200 Mg (tonnes) carbon
1 Mg carbon mass = 1 tonne carbon mass = 3.67 tonnes CO_2 mass
A typical passenger vehicle emits about 4.6 tonnes CO_2 a year

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

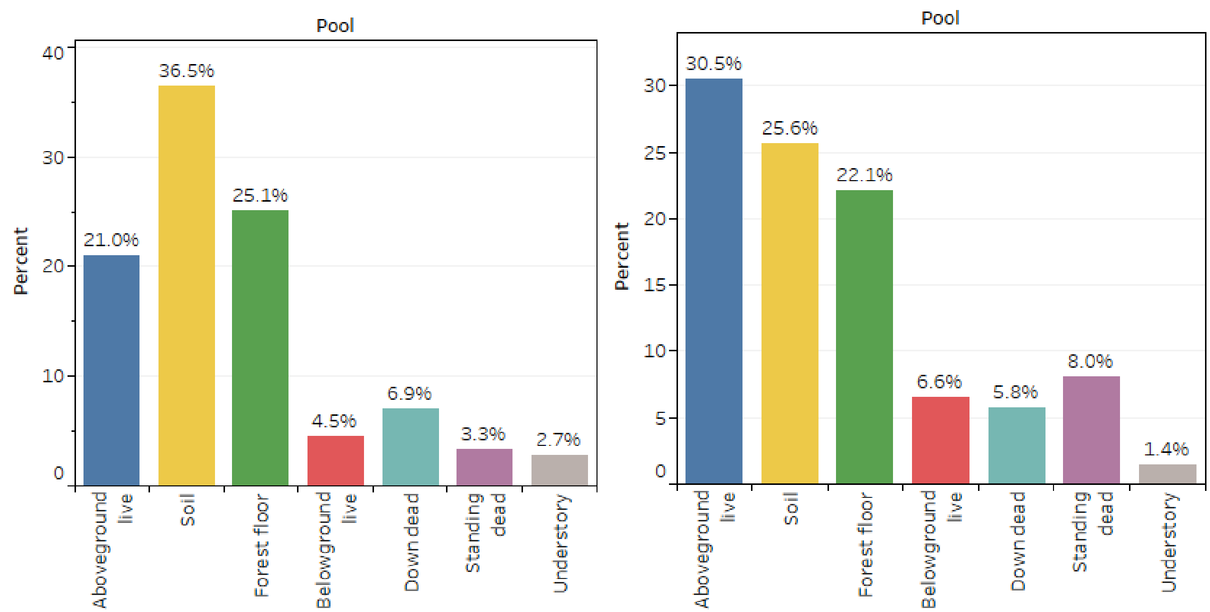
According to results of the Baseline Report (U.S. Department of Agriculture 2015), carbon stocks in the Custer NF increased from 26.3±4.2 teragrams of carbon (Tg C) in 1990 to 33.7±6.1 Tg C in 2013, a 22 percent increase in carbon stocks over this period (Fig. 1). On the Galltin NF, carbon stocks increased from 83.9±6.9 Tg C in 1990 to 105.1±10.2 Tg C in 2013, a 20 percent increase. For context, the total 105.1 Tg C is equivalent to emissions from approximately 84 million passenger vehicles in a year. Despite some uncertainty in annual carbon stock estimates, reflected by the 95 percent confidence intervals, there is a high degree of certainty that carbon stocks on the CG NF have been stable or increased from 1990 to 2013 (Fig. 1).



Custer National Forest ***Gallatin National Forest***

Figure 1. *Total forest carbon stocks (Tg) from 1990 to 2013 for the CGNF, bounded by 95 percent confidence intervals. Estimated using the CCT model.*

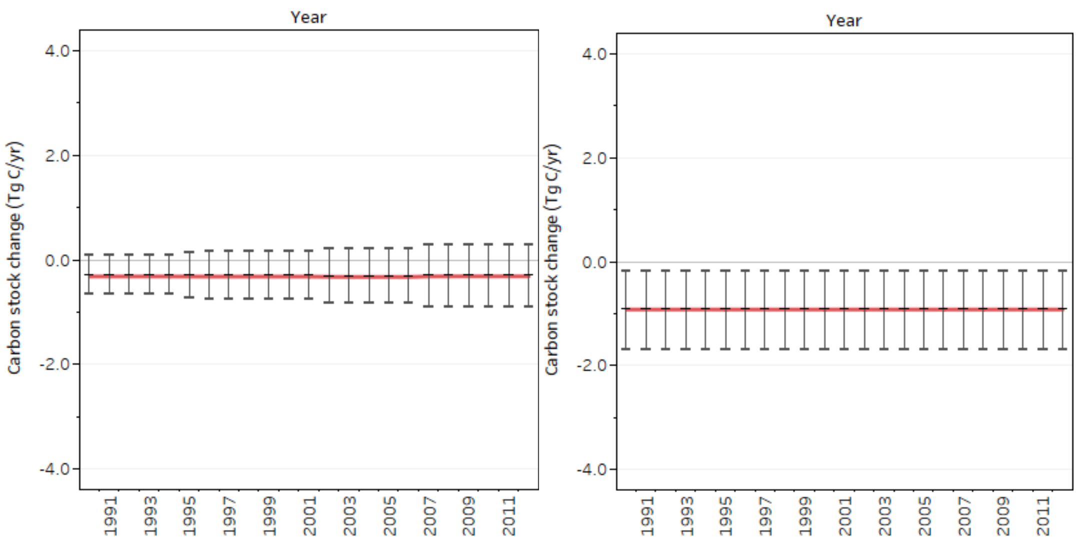
On the Custer and Gallatin National Forests, about 21 and 30 percent (respectively) of forest carbon stocks are stored in the aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig.2). Soil carbon contained in organic material to a depth of one meter (excluding roots) contains another 37 and 26 percent respectively of the forest carbon stocks. Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke et al. 2017).



Custer National Forest ***Gallatin National Forest***

Figure 2. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for the CGNF.*

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source in a given year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink: the forest is absorbing more carbon from the atmosphere (through growth) than it emits (via decomposition, removal, and combustion). A positive value indicates a source: the forest is emitting more carbon than it takes up.



Custer National Forest ***Gallatin National Forest***

Figure 3. *Carbon stock change (Tg/yr) from 1990 to 2012 for CG National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Annual carbon stock changes in the Custer NF were -0.32 ± 0.40Tg C per year (loss) in 1990 and -0.32 ± 0.60Tg C per year (loss) 2012; on the Gallatin NF, the annual carbon stock changes were -0.92±0. 9 Tg C per year (loss) in both 1990 and 2012 (Fig. 3). For the Custer, the uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Fig. 3). However, the trend of decreasing carbon stocks from 1990 to 2013 (Fig. 1) over the 23-year period suggests that the CGNF is a modest carbon sink.

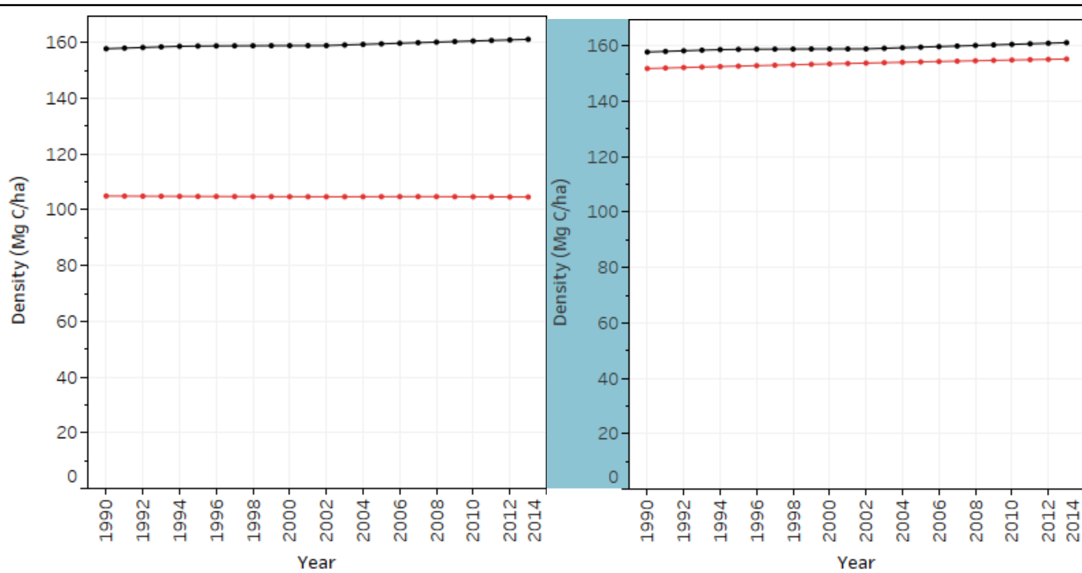
Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area in the Custer NF has increased from 250,781 ha in 1990 to 322,253 ha in 2013, a net change of 71,472 ha.[2] On the Gallatin NF, the forested area has increased from 552,522 ha in

[2] Forested area used in the CCT model may differ from more recent FIA estimates, as well as from the forested areas used in the other modeling tools.

1990 to 677,034 ha in 2013, a net change of 124,512 ha[2]. Part of the apparent increase in forested area is likely due to a change in FIA sampling design (see below for more detail). When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon sink. Conversely, when forestland area decreases, the total stocks typically decrease, indicating a carbon source. The CCT model used inventory data from two different databases. This may have led to inaccurate estimates of changes in forested area, potentially altering the conclusion regarding whether or not forest carbon stocks are increasing or decreasing, and therefore, whether the NF is a carbon source or sink (W. et al. 2011).

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. In the Custer NF, carbon density stayed at around 105 Megagrams of carbon (Mg C) from 1990 to 2103. The Gallatin NF carbon density increased from about 152 and 155 Mg C per ha (Fig. 4). This suggests that total carbon stocks may have indeed increased.

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Most NFs in the Region 1 have experienced increasing stable carbon densities from 1990 to 2013. Carbon density in the CGNF has been steady or slightly increasing (Fig.4). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. These differences may also be affected by disturbance and management regimes (see Section 3.0).



Custer National Forest ***Gallatin National Forest***

***Figure 4**. Carbon stock density (Megagrams per hectare) in the Custer Gallatin NF (red lines) and the average carbon stock density for all forests in the Region 1 (black line) from 1990 to 2013. Estimated using CCT.*

2.2 Uncertainty associated with baseline forest carbon estimates

All results reported in this assessment are estimates that are contingent on models, data inputs, assumptions, and uncertainties. Baseline estimates of total carbon stocks and carbon stock change include 95 percent confidence intervals derived using Monte Carlo simulations[3] and shown by the error bars (Figs. 1, 3). These confidence intervals indicate that 19 times out of 20, the carbon stock or stock change for any given year will fall within error bounds. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infer if or how carbon stocks are changing.

The baseline estimates that rely on FIA data include uncertainty associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). As mentioned in Section 2.1, one such model error has resulted from a change in FIA sampling design, which led to an apparent change in forested area. Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the CG NF have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artefact of altered inventory design and protocols (Woodall et al. 2013).

The inventory design changed from a periodic inventory, in which all plots were sampled in a single year to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (Woodall et al. 2011). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which inventory plots are measured. FIA plots are resampled about every 10 years in the western U.S., and a full cycle is completed when every plot is measured at least once. However, sampling is designed such that partial inventory cycles provide usable, unbiased samples annually but with higher errors. These baseline estimates may lack some temporal sensitivity, because plots are not resampled every year, and recent disturbances may not be incorporated in the estimates if the disturbed plots have not yet been sampled. For example, if a plot was measured in 2009 but was clear-cut in 2010, that harvest would not be detected in that plot until it was resampled in 2019. Therefore, effects of the harvest would show up in FIA/CCT estimates only gradually as affected plots are re-visited and the differences in carbon stocks are interpolated between survey years (Woodall et al. 2013). In the interim, re-growth and other disturbances may mute

[3] A Monte Carlo simulation performs an error analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty (e.g., data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

the responsiveness of CCT to disturbance effects on carbon stocks. Although CCT is linked to a designed sample that allows straightforward error analysis, it is best suited for detecting broader and long-term trends, rather than annual stock changes due to individual disturbance events.

In contrast, the Disturbance Report (Section 3.0) integrates high-resolution, remotely-sensed disturbance data to capture effects of each disturbance event the year it occurred. This report identifies mechanisms that alter carbon stocks and provides information on finer temporal scales. Consequently, discrepancies in results may occur between the Baseline Report and the Disturbance Report (Dugan et al. 2017).

2.3 Carbon in Harvested Wood Products

Although harvest transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, it can be stored in wood products for a variable duration depending on the commodity produced. Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect (Gustavsson et al. 2006, Lippke et al. 2011) Lippke et al., 2014). Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the affected area regrows.

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report was conducted by incorporating data on harvests on national forests documented in cut-and-sold reports within a production accounting system (Smith et al. 2006, Loeffler et al. 2014). This approach tracks the entire cycle of carbon, from harvest to timber products to primary wood products to disposal. As more commodities are produced and remain in use, the amount of carbon stored in products increases. As more products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

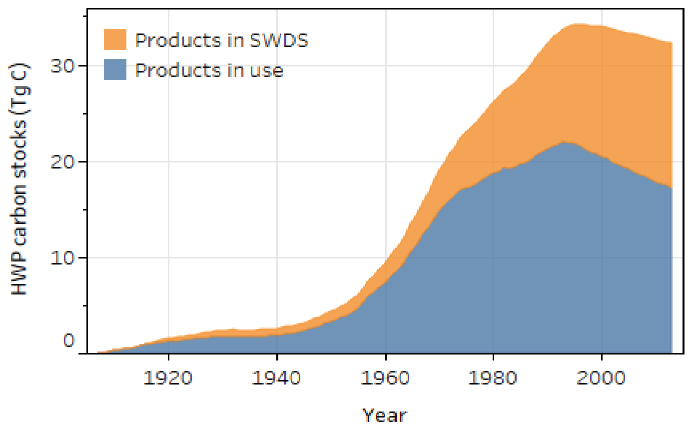


Figure 5. *Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in Region 1. Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

In national forests in the Northern Region (Region 1), harvest levels remained low until the 1940s when they began to rise, which caused an increase in carbon storage in HWP (Fig. 5). Timber harvesting and subsequent carbon storage increased rapidly in the 1960s and 1970s. Storage in products and landfills peaked at about 34 Tg C in 1995. However, because of a significant decline in timber harvesting in the late 1990s and early 2000s (to 1950s levels) carbon accumulation in products in use began to decrease. In the Northern Region, the contribution of national forest timber harvests to the HWP carbon pool is less than the decay of retired products, causing a net decrease in product-sector carbon stocks. In 2013, the carbon stored in HWP was equivalent to approximately 2.2 percent of total forest carbon storage associated with national forests in the Northern Region.

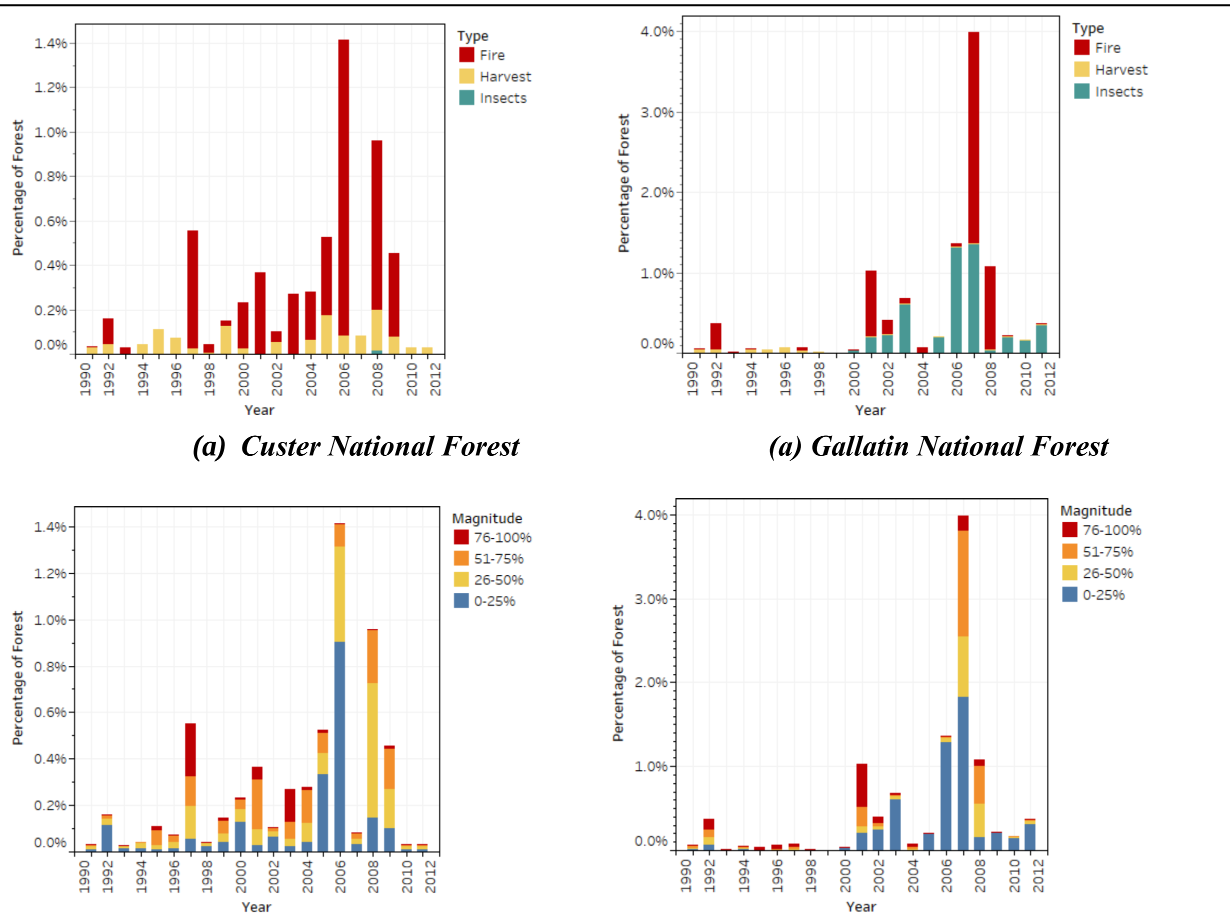
2.4 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of historic harvests to modern national forest boundaries; factors used to convert the volume harvested to biomass; the proportion of harvested wood used for different commodities (e.g., paper products, saw logs); product decay rates; and the lack of distinction between methane and CO_2 emissions from landfills. The approach also does not consider the substitution of wood products for emission-intensive materials or the substitution of bioenergy for fossil fuel energy, which can be significant (Gustavsson et al. 2006). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Loeffler et al. 2014).

3.0 Factors Influencing Forest Carbon

3.1 Effects of Disturbance

The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually-verified, annual disturbance data from Landsat satellite imagery (Healey et al. 2018). The Landsat imagery was used to detect land cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting disturbance maps indicate that wildfire and insects have been the dominant disturbance types detected on the CGNF from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 6a). However, according to the satellite imagery, these disturbance agents affected a relatively small area of the forest during this time. In most years, wildfire affected less than 1 percent of the total forested area of either forest in any single year from 1990 to 2011. However in 2006, approximately 1.3 percent of the Custer NF burned, while in 2007 about 2.5 percent of the Gallatin NF experienced fire. On the Custer NF, wildfire in total affected less than 5 percent (approximately 13,250 ha) of the forested area during this period. Wildfire affected approximately 5.3 percent of the Gallatin NF from 1990 to 2011 (approximately 32,000 ha); and insects affected just under 5 percent (28,000 ha). Harvest also occurred on both forests but impacted less than 1 percent of either forest. Disturbance resulted in a range of canopy cover loss depending on disturbance type and year (Fig. 6b).



(a) Custer National Forest ***(a) Gallatin National Forest***

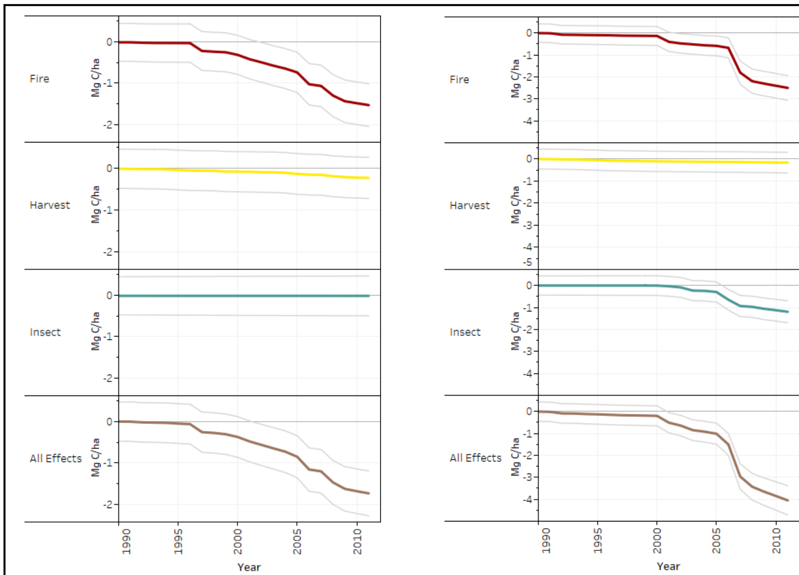
(b) Custer National Forest ***(b) Gallatin National Forest***

Figure 6. *Percentage of forest disturbed from 1990 to 2011 in CG National Forest by (a) disturbance type including fire, harvests, insects, and abiotic (wind), and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery.*

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 6, along with FIA data in the Forest Vegetation

Simulator (FVS) (Crookston and Dixon 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond et al. 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each national forest if the disturbances and harvests during 1990-2011 had not occurred. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey et al. 2014).

Wildfire on the CGNF was the primary disturbance influencing carbon stocks from 1990 to 2011 (Fig. 7). Wildfire accounted for nearly 88 percent of the total non-soil carbon lost from the forest due to disturbances on the Custer NF, and 61 percent on the Gallatin NF. Losses from insects and harvest made up the remainder of the total non-soil carbon loss (U.S. Department of Agriculture 2015). The ForCaMF model indicates that, by 2011, the Custer NF contained 1.5 Mg C per ha less non-soil carbon (i.e., vegetation and associated pools) due to wildfire since 1990, as compared to a hypothetical undisturbed scenario (Fig. 7). As a result, non-soil carbon stocks in the Custer NF would have been approximately 2.3 percent higher in 2011 if wildfire had not occurred since 1990 (Fig. 8). Similarly, the data indicate that, by 2011, the Gallatin NF contained 2.5Mg C per ha less non-soil carbon due to wildfire since 1990, indicating that carbon stocks would have been approximately 2 percent higher in 2011 if wildfires had not occurred during this time. For both portions of the Forest, insects and harvest resulted in less than 0.5 Mg/ha less non-soil carbon each, with percent losses less than 0.5 percent.



Custer National Forest ***Gallatin National Forest***

Figure 7. *Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in CG National Forests. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.*

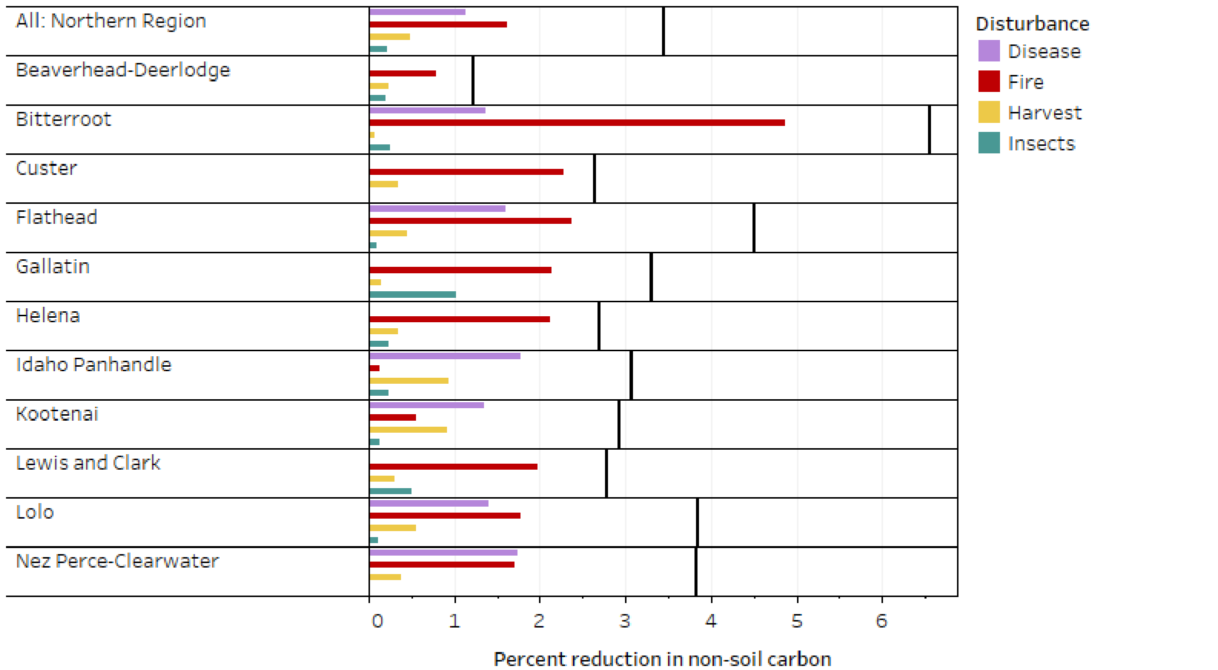


Figure 8. *The degrees to which 2011 carbon storage on each national forest in the Region 1 was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The black line indicates the effect of all disturbances types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT.*

Across all national forests in Region 1 wildfire has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 1.62 percent lower by 2011 (Fig. 8). Considering all national forests in the Region 1, by 2011, disease accounted for the loss of 1.13 percent of non-soil carbon stocks, harvest 0.48 percent, and insects 0.22 percent. There were no non-soil carbon stock reductions caused by abiotic factors such as wind and ice storms.

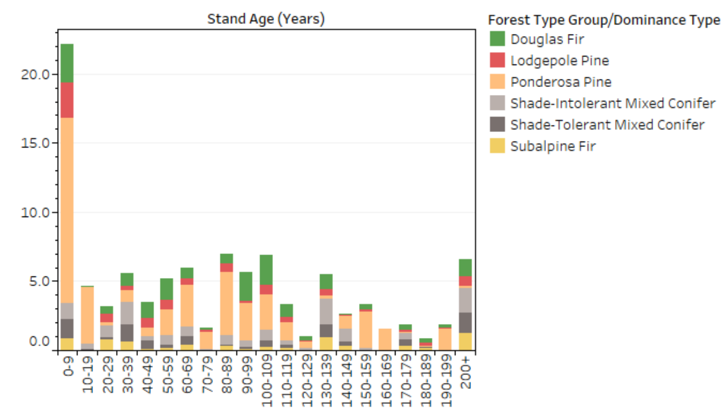
The ForCaMF analysis was conducted over a relatively short time. After a forest is harvested, it will eventually regrow and recover the carbon removed from the ecosystem in the harvest. However, several decades may be needed to recover the carbon removed depending on the type of the harvest (e.g., clear-cut versus partial cut), as well as the conditions prior the harvest (e.g., forest type and amount of carbon) (Wear et al. 2013). The ForCaMF model also does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Lippke et al. 2011, McKinley et al. 2011, Skog et al. 2014, Dugan et al. 2018). Therefore, the IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (Intergovernment Panel on Climate Change (IPCC) 2000).

ForCaMF helps to identify the biggest local influences on continued carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. The purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors.

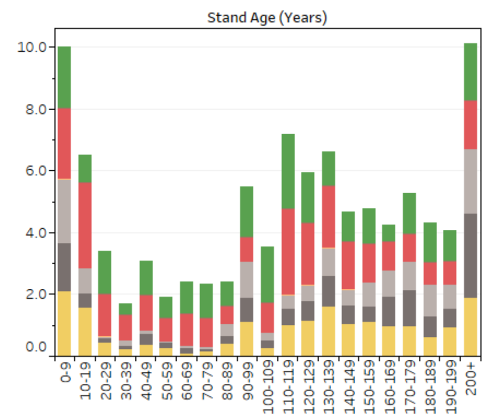
3.2 Effects of Forest Aging

InTEC models the collective effects of forest disturbances and management, aging, mortality, and subsequent regrowth on carbon stocks from 1950 to 2011. The model uses inventory-derived maps of stand age, Landsat-derived disturbance maps (Fig. 6), and equations describing the relationship between net primary productivity (NPP) and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan 2011). In the model, when a forested stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration.

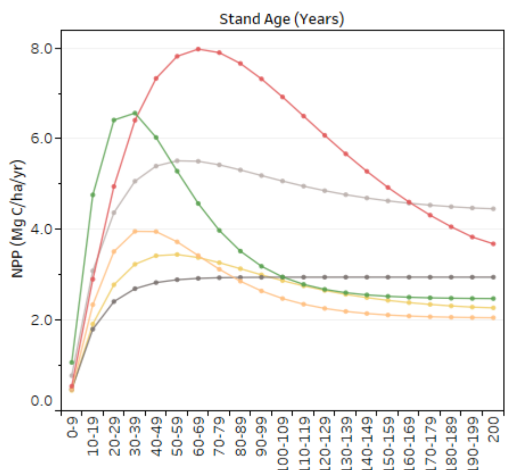
Stand-age distribution for the CGNF derived from 2011 forest inventory data indicates elevated stand establishment around 1880-1930 (Fig. 9a) in both Forests. This period of elevated stand regeneration came after large wildfires in the late 1800s and early 1900s, as well as harvest activities associated with railroad and mining developments, followed by moist climate conditions conducive to forest establishment. Both portions of the CGNF have also experienced a pulse in stand establishment following wildfires in the early 2000’s. Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer and Euskirchen 2004), as indicated by the in NPP-age curves (Fig. 9b), derived in part from FIA data.



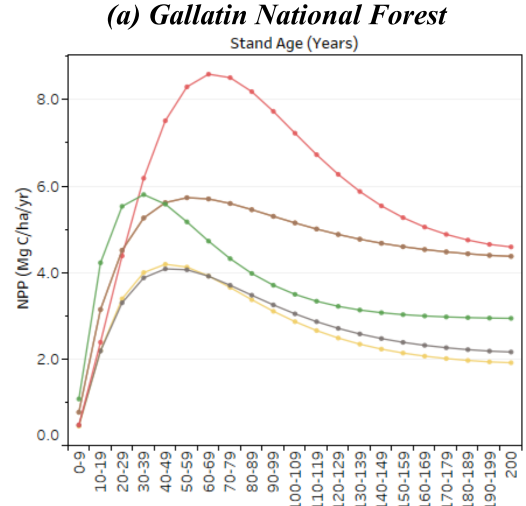
(a) Custer National Forest



(a) Gallatin National Forest



(b) Custer National Forest

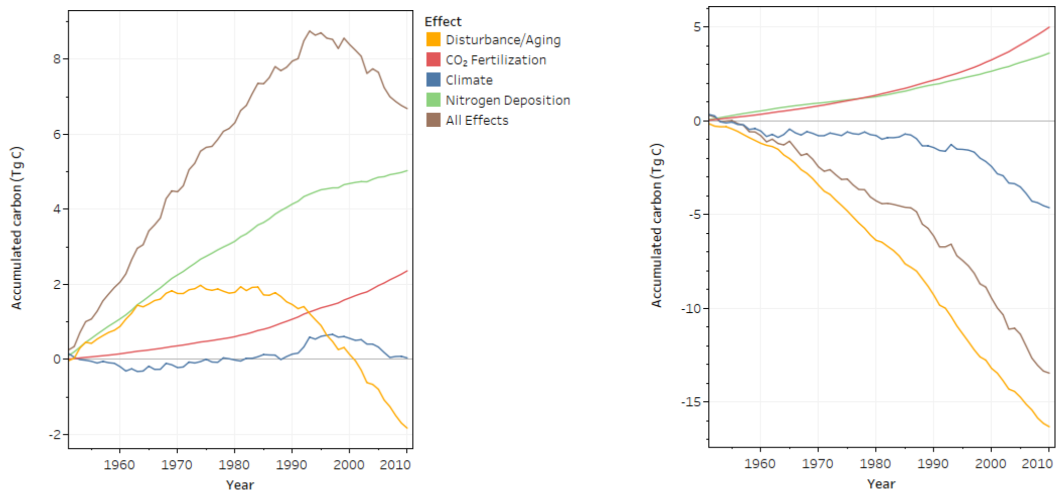


(b) Gallatin National Forest

Figure 9. *(a) Stand age distribution in 2011 and (b) net primary productivity-stand age curves by forest type group in the Custer Gallatin National Forest. Derived from forest inventory data.*

3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO_2 concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year, but overall, climate since 1950 has had a negative effect on carbon stocks in the CGNF relative to other factors (Fig. 10). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju et al. 2007, Melillo et al. 2017), but warming temperatures can also reduce soil moisture through increased evapotranspiration, causing lower forest growth (Xu et al. 2013).



Custer National Forest ***Gallatin National Forest***

Figure 10. *Accumulated carbon in the Custer Gallatin National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in black line) for1950–2011, excluding carbon accumulated pre-1950 Estimated using the InTEC model.*

In addition to climate, the availability of CO_2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen et al. 2000, Pan et al. 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused a significant increase in both CO_2 and nitrogen emissions (Chen et al. 2000, Zhang et al. 2012)(Keeling *et al.*, 2009). According to the InTEC model, higher CO_2 has consistently had a positive effect on carbon stocks in the CGNF, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 10). However, a precise quantification of the magnitude of this CO_2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones et al. 2014, Zhang et al. 2015). Long-term studies examining increased atmospheric CO_2 show that forests initially respond with higher productivity and growth, but the effect is greatly diminished or lost within 5 years in most forests (Zhu et al. 2016). There has been considerable debate regarding the effects of elevated CO_2 on forest growth and biomass accumulation, thus warranting additional study (Korner et al. 2005, Norby et al. 2010, Zhu et al. 2016).

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the CGNF (Fig. 10). Like CO_2, the actual magnitude of this effect remains uncertain. Overall, the InTEC model suggests that CO_2 and nitrogen fertilization only partially offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate.

3.4 Uncertainty associated with disturbance effects and environmental factors

As with the baseline estimates, there is also uncertainty associated with estimates of the relative effects of disturbances, aging, and environmental factors on forest carbon trends. For example, omission, commission, and attribution errors may exist in the remotely-sensed disturbance maps used in the ForCaMF and InTEC models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond et al. 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey et al. 2014).

Uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC because of significant computational requirements. However, process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle et al. 2005). InTEC is highly calibrated to FIA data and remotely-sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel et al. 2015), as well as calibration with observational datasets (Zhang et al. 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Fig. 10, "All effects"). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., national forest scale) are likely to be considerably higher.

Results from the ForCaMF and InTEC models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Zhang et al. 2012). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas ForCaMF and InTEC involve additional data inputs and modeling complexity beyond summarizing ground data.

3.5 Carbon on non-forest lands

The Custer Gallatin NF (Forest) contains approximately 170,000 hectares of non-forest lands. Grasslands, shrublands, and riparian and wetland areas cover most of these lands, accounting for approximately 14 percent of the total area on the Forest. The vast majority of the carbon in these non-forest systems, such as grasslands and shrublands, is stored belowground in soil and plant roots (McKinley and Blair 2008, Janowiak et al. 2017). By contrast, forests typically store roughly one-half of the total carbon belowground (Domke et al. 2017). Soils generally provide a stable ecosystem carbon pool relative to other ecosystem carbon pools.

Many grasslands are highly dependent on frequent fire and grazing, which temporarily remove above ground vegetation. For example, fire suppression and overgrazing is implicated in allowing many grasslands to convert to shrublands with dense woody vegetation by altering wildfire regimes (Van Auken 2009). Replacement of grasslands with woody plants generally tends to increase total ecosystem carbon storage, but can alter ecosystem function and structure (McKinley and Blair 2008, Van Auken 2009). Conversely, invasive species, such as *Bromus tectorum*, can reduce carbon in shrublands by propagating more intense fire that cause mortality of co-occurring woody species (Bradley et al. 2006, Koteen et al. 2011). The Forest supports relatively low amounts of invasive annual species, such as *Bromus,* compared with other areas in the western United States.

The greatest lasting influence in non-forest ecosystem carbon stocks is land-use and land-cover change. For example, it is generally assumed that federal grassland areas have negligible changes in carbon due to limited land use and management change (U.S. Environmental Protection Agency 2019). Because soil carbon in grasslands is generally stable, substantial changes are typically a result of dramatic changes in land use or vegetation cover that persist indefinitely. The majority of grasslands in Great Plains have been converted to agricultural use since European settlement, which has led to substantial losses of soil carbon. Like forests, managing the health of grasslands and other non-forest ecosystems and avoiding land use and land cover change are key concerns for maintaining carbon stocks. Land use change generally does not occur on the Forest, although there is increasing development on private lands in the region.

Grazing has long played an important role in plant composition and nutrient cycling in many non-forest ecosystems in the Great Plains (Knapp et al. 1999). Large grazing ungulates, including domesticated livestock and bison, produce a variety of greenhouse gas (GHG) emissions. Livestock and wild ruminates produce methane from enteric fermentation, resulting from their digestive process. Nitrous oxide can be produced as a byproduct from soil microbial processes that chemically transform nitrogen in animal waste. The (U.S. Environmental Protection Agency 2019) estimates that about 47 percent of the total GHG emissions in the agricultural sector are attributed to livestock. In turn, the agricultural sector contributes to about 9 percent of total GHG emissions in the United States. The USDA's National Agricultural Statistics Service estimated in January 2019 that the United States had about 94.8 million cattle. By comparison, the Forest maintains fewer than 30,000 cows, pairs, and yearlings. However, many of these animals are not typically present on the Forest year round.

4.0 Future Carbon Conditions

4.1 Prospective Forest Aging Effects

The retrospective analyses presented in the previous sections can provide an important basis for understanding how various factors may influence carbon storage in the future. For instance, 47 and 68 percent of the Custer and Gallatin NFs, respectively, are middle-aged and older (greater than 80 years), although there is also a strong representation of stands less than 20 years old due to recent wildfires (Fig. 9a). There is also a pulse of stands over 200 years old on the Gallatin NF. If the Forests continue on this aging trajectory, the pulse of middle-aged stands will reach a slower growth stage in coming years and decades (Fig. 9b), potentially causing the rate carbon accumulation to decline and the Forests may eventually transition to a steady state in the future. However, the pulse of young stands will also be moving into a maximum productivity stage, which may offset the declines in the middle-aged stands to a degree. In the middle aged stands, although yield curves indicate that biomass carbon stocks may be approaching maximum levels (Fig. 9b), ecosystem carbon stocks can continue to increase for many decades as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert et al. 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities and particularly disturbances could affect future stand age and forest growth rates (Davis et al. 2009, Keyser and Zarnoch 2012).

For RPA's Rocky Mountain Region (equivalent to a combination of the Forest Service's Northern, Rocky Mountain, Intermountain West, and Southwest Region boundaries, but includes all land ownerships), projections indicate that the rate of carbon sequestration will decline fairly rapidly in the 2020s mostly due to the loss of forestland (land-use transfer), causing the region's forests to shift to a carbon source. The net sequestration rate is also projected to decline slightly further resulting in a shift to a carbon source (Fig. 11).

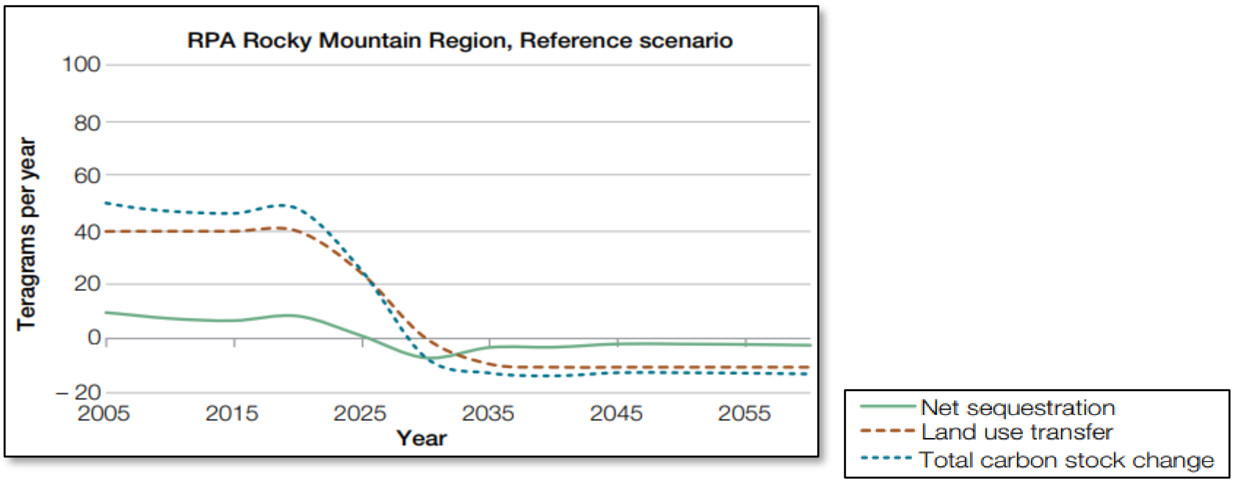


Figure 11. *Projections of forest carbon stock changes in the North Region (equivalent to a combination of the Forest Service's Northern, Rocky Mountain, Intermountain West, and Southwest Region boundaries, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is*

At the global and national scales, changes in land use—especially the conversion of forests to non-forest land (deforestation)—have a substantial effect on carbon stocks (Pan et al. 2011, Houghton et al. 2012). Converting forest land to a non-forest use removes a large amount of carbon from the forest and inhibits future carbon sequestration. National forests tend to experience low rates of land-use change, and thus, forest land area is not expected to change substantially within the CGNF in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2030 followed by a slight increase that stabilizes just below zero.

4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major driver of historic and current forest carbon sequestration that is occurring at the CGNF and elsewhere in across the region. Climate change introduces additional uncertainty about how forests—and forest carbon sequestration and storage—may change in the future. Climate change causes many direct alterations of the local environment, such as changes in temperature and precipitation, and it has indirect effects on a wide range of ecosystem processes (Vose et al. 2012). Further, disturbance rates are projected to increase with climate change (Vose et al. 2018), making it challenging to use past trends to project the effects of disturbance and aging on forest carbon dynamics.

A climate change vulnerability assessment of the Northern Rocky Mountains (Halofsky et al. in press), which encompasses the CGNF indicates that average warming across the five Northern Region Adaptation Partnership (NRAP) subregions is projected to be about 4 to 5 °F by 2050, depending on greenhouse gas emissions. Precipitation may increase slightly in the winter, although the magnitude is uncertain. Climatic extremes will probably be more common, driving biophysical changes in terrestrial and aquatic ecosystems. Droughts of increasing frequency and magnitude are expected, promoting an increase in wildfire, insect outbreaks, and non-native species. These periodic disturbances will rapidly alter productivity and structure of vegetation, potentially altering the distribution and abundance of dominant plant species and animal habitat. Increasing air temperature, through its influence on soil moisture, will cause gradual changes in the abundance and distribution of tree, shrub, and grass species, with more drought tolerant species becoming more competitive. Natural disturbance will be the primary facilitator of vegetation change, and future forest landscapes may be dominated by younger age classes and smaller trees. As wildfires and insect outbreaks become more common, the supply of timber and other forest products could become less reliable. A longer growing season will increase productivity of rangeland types. Carbon sequestration may decline if disturbances increase as expected.

Elevated temperatures may increase soil respiration and reduce soil moisture through increased evapotranspiration, which would negatively affect growth rates and carbon accumulation (Ju et al. 2007, Melillo et al. 2017). Modeled results of recent climate effects using the InTEC model indicate that years with elevated temperatures have generally had a negative effect on carbon uptake in the CGNF (Fig. 10).

Longer, warmer growing seasons may increase growth rates; however, greater soil water deficits and increased evapotranspiration in the summer may offset this and increase plant stress. Growing sites on the CGNF are generally moisture-limited. Therefore, warm/dry climatic periods generally result in slower growth. Competition-based mortality also increases during dry periods, and stress can lead to higher mortality rates indirectly through susceptibility to insects or disease. Increasing soil water deficits can cause eventual shifts in species presence across the landscape as they become less able to regenerate or survive. Species located on sites at the margin of their optimal range would be most vulnerable. On the CGNF, the species expected to be most vulnerable to climate change on the CGNFs include aspen, limber pine, cottonwood, and ponderosa pine (Halofsky et al. 2018b). Changes in climate are expected to drive many other changes in forests through the next century, including changes in forest establishment and composition (Janowiak et al. 2018). Climate-driven failures in species establishment further reduce the ability of forests to recover carbon lost after mortality-inducing events or harvests. Although future climate conditions also allow for other future-adapted species to increase, there is greater uncertainty about how well these species will be able to take advantage of new niches that may become available (Duveneck et al. 2017, Iverson et al. 2017).

Halofsky et al (2018) also suggest a longer growing season is expected to increase net primary productivity of many rangeland types, especially those dominated by grasses, although responses will depend on local climate and soil conditions. Elevated atmospheric carbon dioxide may increase water use efficiency and productivity of some species. In many cases, increasing wildfire frequency and extent will be particularly damaging for big sagebrush and other shrub species that are readily killed by fire. The widespread occurrence of cheatgrass and other non-natives facilitates frequent fire through annual fuel accumulation. In montane grasslands, wildfire may kill Douglas-fir and other species that have recently established in rangelands through fire exclusion. Shrub species that sprout following fire may be quite resilient to increased disturbance, but may be outcompeted by more drought tolerant species over time.

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (Intergovernment Panel on Climate Change 2014). Several models, including the InTEC model (Figure 10), project greater increases in forest productivity when the CO_2 fertilization effect is included in modeling (Aber et al. 1995, Ollinger et al. 2008, Pan et al. 2009, Zhang et al. 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is transient and can be limited by the availability of nitrogen and other nutrients (Norby et al. 2010). Productivity increases under elevated CO_2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond to novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. As climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO_2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions.

5.0 Summary

The CGNF may be functioning as a slight carbon sink. This determination is also unclear because the modeling and uncertainty analyses were split based on the historical Custer and Gallatin National Forests, which are now combined. Forest carbon stocks increased by about 28 percent between 1990 and 2013 on the Custer NF, and by about 25 percent on the Gallatin NF. There is little change observed in the carbon density data. The impacts on carbon stocks have primarily been caused by growth and disturbances and have been positively impacted by nitrogen deposition and carbon dioxide fertilization. According to satellite imagery, wildfire has been the most prevalent disturbance detected on the Forest since 1990. These fire disturbances were variable in terms of severity. Forest carbon losses associated with wildfire have nevertheless been small compared to the total amount of carbon stored in the Forest, resulting in a loss of approximately 2 percent of non-soil carbon from 1990 to 2011 on the Custer and Gallatin NFs respectively. Carbon storage in HWPs sourced from national forests increased since the early 1900s. Recent declines in timber harvesting have slowed the rate of carbon accumulation in the product sector.

The biggest influence on current carbon dynamics on the CGNF is the legacy of large wildfires and some timber harvesting for the railroad and mining industries during the 19th century, followed by a period of forest recovery beginning in the early to mid-20th century. Over half of the stands on the CGNF are now middle to older aged, although there is also a pulse of young stands that established after fires since 2000. The rate of carbon uptake and sequestration generally decline as forests age. Accordingly, projections from the RPA assessment indicate a potential age-related decline in forest carbon stocks in the Region 1 (all land ownerships) beginning in the 2020s.

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, have also influenced carbon accumulation on the CGNF. Climate conditions along with disturbance and aging have had a negative impact on carbon accumulation since the 1950s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

The effects of future climate conditions are complex and remain uncertain. However, under changing climate and environmental conditions, forests of the CGNF may be increasingly vulnerable to a variety of stressors. These potentially negative effects might be balanced somewhat by the positive effects of longer growing season, greater precipitation, and elevated atmospheric CO_2 concentrations. However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the CGNF.

Forested area on the CGNF will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. The CGNF will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

6.0 References

Not in EN:

Birdsey, R, A.J. Dugan, S. Healey, K. Dante-Wood, F. Zhang, J. Chen, A. Hernandez, C. Raymond, J. McCarter. *In press*. Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of United States National Forests. Fort Collins, Colorado: Gen. Tech. Report RM-xxx.

FAOSTAT (2013) Food and agriculture organization of the United Nations. *Statistical database*.

Gustavsson, L., Madlener, R., Hoen, H. F., Jungmeier, G., Karjalainen, T., Klöhn, S., . . . Spelter, H. (2006) The role of wood material for greenhouse gas mitigation. *Mitigation and Adaptation Strategies for Global Change,* **11**, 1097-1127.

Keeling, R., Piper, S., Bollenbacher, A. & Walker, S. (2009) Atmospheric CO2 records from sites in the SIO air sampling network, in Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center. In: *Carbon Dioxide Research Group Scripps Institution of Oceanography (SIO), University of California, La Jolla. California USA. URL: http://cdiac. ornl. gov/ftp/trends/co2/maunaloa. co2*. Oak Ridge Natl. Lab., U.S. Dep. of Energy, Oak Ridge, TN.

He, L., Chen, J.M., Pan, Y., Birdsey, R. & Kattge, J. (2012) Relationships between net primary productivity and forest stand age in U.S. forests. *Global Biogeochemical Cycles*, **26** (GB3009). doi:10.1029/2010GB003942.

Aber, J. D., S. V. Ollinger, C. A. Federer, P. B. Reich, M. L. Goulden, D. W. Kicklighter, J. M. Melillo, and R. G. J. Lathrop. 1995. Predicting the effects of climate change on water yield and forest production in the northeastern United States. Climate Research 5:207-222.

Barrett, S. W., S. F. Arno, and J. P. Menakis. 1997. Fire episodes in the inland northwest (1540-1940) based on fire history data. Report General Technical Report-INT-GTR-370.

Birdsey, R., K. Pregitzer, and A. Lucier. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality 35:1461-1469.

Bradley, B. A., R. A. Houghton, J. F. Mustard, and S. P. Hamburg. 2006. Invasive grass reduces aboveground carbon stocks in shrublands of the Western US. Global Change Biology 12:1815-1822.

Caspersen, J. P., S. W. Pacala, J. C. Jenkins, G. C. Hurtt, P. R. Moorcroft, and R. A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. Forests. Science 290:1148-1151.

Chen, W., J. Chen, and J. Cihlar. 2000. An integrated terrestrial ecosystem carbon-budget model based on changes in disturbance, climate, and atmospheric chemistry. Ecological Modelling 135:55-79.

Crookston, N. L., and G. E. Dixon. 2005. The forest vegetation simulator: A review of its structure, content, and applications. Computers and Electronics in Agriculture 49:60-80.

Davis, S. C., A. E. Hessl, C. J. Scott, M. B. Adams, and R. B. Thomas. 2009. Forest carbon sequestration changes in response to timber harvest. Forest Ecology and Management 258:2101-2109.

Domke, G. M., C. H. Perry, B. F. Walters, L. E. Nave, C. W. Woodall, and C. W. Swanston. 2017. Toward inventory- based estimates of soil organic carbon in forests of the United States. Ecological Applications 27:1223–1235.

Dugan, A. J., R. Birdsey, S. P. Healey, Y. Pan, F. Zhang, G. Mo, J. Chen, C. W. Woodall, A. J. Hernandez, K. McCullough, J. B. McCarter, C. L. Raymond, and K. Dante-Wood. 2017. Forest sector carbon analyses support land management planning and projects: assessing the influence of anthropogenic and natural factors. Climatic Change 144:207-220.

Dugan, A. J., R. Birdsey, V. S. Mascorro, M. Magnan, C. E. Smyth, M. Olguin, and W. A. Kurz. 2018. A systems approach to assess climate change mitigation options in landscapes of the United States forest sector. Carbon Balance and Management 13:13.

Duveneck, M. J., J. R. Thompson, E. J. Gustafson, Y. Liang, and A. M. G. de Bruijn. 2017. Recovery dynamics and climate change effects to future New England forests. Landscape Ecology 32:1385-1397.

Gustavsson, L., R. Madlener, H. F. Hoen, G. Jungmeier, T. Karjalainen, S. KlÖhn, K. Mahapatra, J. Pohjola, B. Solberg, and H. Spelter. 2006. The role of wood material for greenhouse gas mitigation. Mitigation and Adaptation Strategies for Global Change 11:1097-1127.

Halofsky, J. E., S. A. Andrews-Key, J. E. Edwards, M. H. Johnston, H. W. Nelson, D. L. Peterson, K. M. Schmitt, C. W. Swanston, and T. B. Williamson. 2018a. Adapting forest management to climate change: The state of science and applications in Canada and the United States. Forest Ecology and Management 421:84-97.

Halofsky, J. E., D. L. Peterson, S. K. Dante-Wood, L. Hoang, J. J. Ho, and L. A. Joyce. 2018b. Climate change vulnerability and adaptation in the northern Rocky Mountains: Part 1. Gen. Tech. Rep. RMRSGTR-374, Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Halofsky, J. E., D. L. Peterson, S. K. Dante-Wood, L. Hoang, J. J. Ho, and L. A. Joyce, editors, editors. in press. Climate change vulnerability and adaptation in the northern Rocky Mountains. 1 edition. Volume RMRS-GTR-xxx.USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Hayes, D. J., R. Vargas, S. Alin, R. T. Conant, L. R. Hutyra, A. R. Jacobson, W. A. Kurz, S. Liu, A. D. McGuire, B. Poulter, and C. W. Woodall. 2018. Chapter 2: The North American carbon budget. Pages 71-108 *in* N. Cavallaro, G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, andZ. Zhu, editors. Second state of the carbon cycle report (SOCCR2): A sustained assessment report. U.S. Global Change Research Program, Washington, DC.

Healey, S. P., W. B. Cohen, Z. Yang, C. Kenneth Brewer, E. B. Brooks, N. Gorelick, A. J. Hernandez, C. Huang, M. Joseph Hughes, R. E. Kennedy, T. R. Loveland, G. G. Moisen, T. A. Schroeder, S. V. Stehman, J. E. Vogelmann, C. E. Woodcock, L. Yang, and Z. Zhu. 2018. Mapping forest change using stacked generalization: An ensemble approach. Remote Sensing of Environment 204:717-728.

Healey, S. P., C. L. Raymond, I. B. Lockman, A. J. Hernandez, C. Garrard, and C. Q. Huang. 2016. Root disease can rival fire and harvest in reducing forest carbon storage. Ecosphere 7.

Healey, S. P., S. P. Urbanski, P. L. Patterson, and C. Garrard. 2014. A framework for simulating map error in ecosystem models. Remote Sensing of Environment 150:207-217.

Houghton, R. A., J. I. House, J. Pongratz, G. R. van der Werf, R. S. DeFries, M. C. Hansen, C. Le Quéré, and N. Ramankutty. 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9:5125-5142.

Intergovernment Panel on Climate Change. 2014. Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Intergovernment Panel on Climate Change (IPCC). 2000. Special report on land use, land use change and forestry, summary for policy makers. Intergovernmental Panel on Climate Change, Geneva, CH.

Iverson, L. R., F. R. Thompson, S. Matthews, M. Peters, A. Prasad, W. D. Dijak, J. Fraser, W. J. Wang, B. Hanberry, H. He, M. Janowiak, P. Butler, L. Brandt, and C. Swanston. 2017. Multi-model comparison on the effects of climate change on tree species in the eastern U.S.: results from an enhanced niche model and process-based ecosystem and landscape models. Landscape Ecology 32:1327-1346.

Janowiak, M., W. J. Connelly, K. Dante-Wood, G. M. Domke, C. Giardina, Z. Kayler, K. Marcinkowski, T. Ontl, C. Rodriguez-Franco, C. Swanston, C. W. Woodall, and M. Buford. 2017. Considering forest and grassland carbon in land management. General Technical Report WO-95, U.S. Department of Agriculture, Forest Service, Washington, DC.

Janowiak, M. K., A. W. D'Amato, C. W. Swanston, L. Iverson, F. R. I. Thompson, W. D. Dijak, S. Matthews, M. P. Peters, A. Prasad, J. B. Fraser, L. A. Brandt, P. Butler-Leopold, S. D. Handler, P. D. Shannon, D. Burbank, J. Campbell, C. Cogbill, M. J. Duveneck, M. R. Emery, N. Fisichelli, J. Foster, J. Hushaw, L. Kenefic, A. Mahaffey, T. L. Morelli, N. J. Reo, P. G. Schaberg, K. R. Simmons, A. Weiskittel, S. Wilmot, D. Hollinger, E. Lane, L. Rustad, and P. H. Templer. 2018. New England and northern New York forest ecosystem vulnerability assessment and synthesis: A report from the New England climate change response framework project. General Technical Report NRS-173, U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Jones, A. G., J. Scullion, N. Ostle, P. E. Levy, and D. Gwynn-Jones. 2014. Completing the FACE of elevated CO2 research. Environment International 73:252-258.

Ju, W. M., J. M. Chen, D. Harvey, and S. Wang. 2007. Future carbon balance of China's forests under climate change and increasing CO2. Journal of Environmental Management 85:538-562.
Keyser, T. L., and S. J. Zarnoch. 2012. Thinning, age, and site quality influence live tree carbon stocks in upland hardwood forests of the southern Appalachians. Forest Science 58:407-418.
Knapp, A. K., J. M. Blair, J. M. Briggs, S. L. Collins, D. C. Hartnett, L. C. Johnson, and E. G. Towne. 1999. The keystone role of bison in North American tallgrass prairie. BioScience 49:39-50.
Korner, C., R. Asshoff, O. Bignucolo, S. Hattenschwiler, S. G. Keel, S. Pelaez-Riedl, S. Pepin, R. T. W. Siegwolf, and G. Zotz. 2005. Carbon flux and growth in mature deciduous forest trees exposed to elevated CO2. Science 309:1360-1362.
Koteen, L. E., D. D. Baldocchi, and J. Harte. 2011. Invasion of non-native grasses causes a drop in soil carbon storage in California grasslands. Environmental Research Letters 6.
Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, and R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management 2:303-333.
Loeffler, D., N. Anderson, K. Stockman, K. Skog, S. Healey, J. G. Jones, J. Morrison, and J. Young. 2014. Estimates of carbon stored in harvested wood products from United States Forest Service Eastern Region, 1911-2012. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, Missoula, MT.
Luyssaert, S., E. D. Schulze, A. Borner, A. Knohl, D. Hessenmoller, B. E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature 455:213-215.
McKinley, D. C., and J. M. Blair. 2008. Woody plant encroachment by Juniperus virginiana in a mesic native grassland promotes rapid carbon and nitrogen accrual. Ecosystems 11:454-468.
McKinley, D. C., M. G. Ryan, R. A. Birdsey, C. P. Giardina, M. E. Harmon, L. S. Heath, R. A. Houghton, R. B. Jackson, J. F. Morrison, B. C. Murray, D. E. Pataki, and K. E. Skog. 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications 21:1902-1924.
Melillo, J. M., S. D. Frey, K. M. DeAngelis, W. J. Werner, M. J. Bernard, F. P. Bowles, G. Pold, M. A. Knorr, and A. S. Grandy. 2017. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science 358:101–105.
Norby, R. J., J. M. Warren, C. M. Iversen, B. E. Medlyn, and R. E. McMurtie. 2010. CO2 enhancement of forest productivity constrained by limited nitrogen availability. Proceedings of the National Academy of Sciences 107:19368-19373.
Ollinger, S. V., C. L. Goodale, K. Hayhoe, and J. P. Jenkins. 2008. Potential effects of climate change and rising CO2 on ecosystem processes in northeastern U.S. forests. Mitigation and Adaptation Strategies for Global Change 13:467-485.
Pan, Y. 2011. A large and persistent carbon sink in the world's forests. Pages 988-993 *in* Science.

Pan, Y., R. Birdsey, J. Hom, and K. McCullough. 2009. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. Forest Ecology and Management 259:151-164.
Pan, Y., J. M. Chen, R. Birdsey, K. McCullough, L. He, and F. Deng. 2011. Age structure and disturbance legacy of North American forests. Biogeosciences 8:715-732.
Pregitzer, K. S., and E. S. Euskirchen. 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology 10:2052–2077.
Raymond, C. L., S. Healey, A. Peduzzi, and P. Patterson. 2015. Representative regional models of post-disturbance forest carbon accumulation: Integrating inventory data and a growth and yield model. Forest Ecology and Management 336:21-34.
Schimel, D., B. B. Stephens, and J. B. Fisher. 2015. Effect of increasing CO2 on the terrestrial carbon cycle. Proceedings of the National Academy of Sciences 112:436-441.
Skog, K. E., D. C. McKinley, R. A. Birdsey, S. J. Hines, C. W. Woodall, E. D. Reinhardt, and J. M. Vose. 2014. Chapter 7: Managing carbon. Pages 151-182 *in* D. L. Peterson, J. M. Vose, andT. Patel-Weynand, editors. Climate change and United States forests, Advances in Global Change Research 57.
Smith, J. E., L. S. Heath, and M. C. Nichols. 2007. U.S. forest carbon calculation tool: Forest-land carbon stocks and net annual stock change. General Technical Report NRS-13, U.S. Department of Agriculture, Forest Service, Newtown Square, PA.
Smith, J. E., L. S. Heath, K. E. Skog, and R. A. Birdsey. 2006. Methods for calculation forest ecosystem and harvested carbon with standard estimates for forest types of the United States. General Technical Report NE-343, U.S. Department of Agriculture, Forest Service, Newtown Square, PA.
Smith, P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. R. Abad, A. Romanovskaya, F. Sperling, F. N. Tubiello, and S. Bolwig. 2014. Agriculture, forestry and other land use (AFOLU). Pages 811-922 *in* Climate change 2014: Mitigation of climate change, contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
U.S. Department of Agriculture. 2016a. U.S. agriculture and forestry greenhouse gas inventory 1990-2013. Technical Bulletin 1943, U.S. Department of Agriculture, Office of the Chief Economist, Climate Change Program Office.
U.S. Department of Agriculture, Forest Service. 2015. Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System units: Northern Region
(Two baselines: 1990-2013, 2005-2013).
_____. 2016b. Future of America's forests and rangelands: Update to the Forest Service 2010 resources planning act assessment. General Technical Report WO-94, U.S. Department of Agriculture, Forest Service, Research and Development, Washington, DC.

U.S. Environmental Protection Agency. 2019. Inventory of U.S. greenhouse gas emissions and sinks 1990-2017. EPA 430-R-19-001, U.S. Environmental Protection Agency, Washington, DC.
Van Auken, O. W. 2009. Causes and consequences of woody plant encroachment into western North American grasslands. Journal of Environmental Management 90:2931-2942.
Vose, J. M., D. L. Peterson, G. M. Domke, C. J. Fettig, L. A. Joyce, R. E. Keane, C. H. Luce, J. P. Prestemon, L. E. Band, J. S. Clark, N. E. Cooley, A. D'Amato, and J. E. Halofsky. 2018. Chapter 6: Forests. Pages 232-267 *in* D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, andB. C. Stewart, editors. Impacts, risks, and adaptation in the United States: Fourth national climate assessment, volume II. U.S. Global Change Research Program, Washington, DC.
Vose, J. M., D. L. Peterson, and T. Patel-Weynand. 2012. Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the U.S. forest sector. Report PNW-GTR-870.
W., W. C., L. S. Heath, G. M. Domke, and M. C. Nichols. 2011. Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. Forest inventory, 2010. General Technical Report NRS-88, U.S. Department of Agriculture, Forest Service, Newtown Square, PA.
Wear, D. N., R. Huggett, R. Li, B. Perryman, and S. Liu. 2013. Forecasts of forest conditions in U.S. regions under future scenarios: A technical document supporting the Forest Service 2010 RPA assessment. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.
Woodall, C., J. Smith, and M. Nichols. 2013. Data sources and estimation/modeling procedures for National Forest System carbon stocks and stock change estimates derived from the US National Greenhouse Gas Inventory.
Woodall, C. W., R. J. Piva, W. G. Luppold, K. E. Skog, and P. J. Ince. 2011. An assessment of the downturn in the forest products sector in the northern region of the United States. Forest Products Journal 61:604-613.
Xu, W., W. Yuan, W. Dong, J. Xia, D. Liu, and Y. Chen. 2013. A meta-analysis of the response of soil moisture to experimental warming. Environmental Research Letters 8:1-8.
Zaehle, S., S. Sitch, B. Smith, and F. Hatterman. 2005. Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. Global Biogeochemical Cycles 19.
Zhang, F., J. M. Chen, Y. Pan, R. A. Birdsey, S. Shen, W. Ju, and A. J. Dugan. 2015. Impacts of inadequate historical disturbance data in the early twentieth century on modeling recent carbon dynamics (1951-2010) in conterminous U.S. forests. Journal of Geophysical Research: Biogeosciences 120:549-569.
Zhang, F. M., J. M. Chen, Y. D. Pan, R. A. Birdsey, S. H. Shen, W. M. Ju, and L. M. He. 2012. Attributing carbon changes in conterminous U.S. forests to disturbance and non-disturbance factors from 1901 to 2010. Journal of Geophysical Research-Biogeosciences 117.
Zhu, Z., S. Piao, R. Myneni, M. Huang, Z. Zeng, J. Canadell, P. Ciais, S. Sitch, P. Friedlingstein, A. Arneth, C. Cao, L. Cheng, E. Kato, C. Koven, Y. Li, X. Lian, Y.

Liu, R. Liu, J. Mao, and N. Zeng. 2016. Greening of the Earth and its drivers. Nature Climate Change 6.