Appendix 2: Carbon Assessment

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1. Preparers

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2. 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 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 et al. 2011a). 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. Environmental Protection Agency 2012),(Hayes et al. 2018).

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 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).

The Intergovernmental Panel on Climate Change has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (Intergovernmental 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 greenhouse gas emissions has declined over the last decade (Tubiello et al. 2013),(Intergovernmental Panel on Climate Change 2014);(Smith et al. 2014). Globally, the largest source of greenhouse gas emissions in the forestry sector is deforestation (Pan et al. 2011a), (Houghton et al. 2012); (Intergovernmental 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 (Intergovernmental Panel on Climate Change 2000). However, the United States 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 2006), a trend expected to continue for at least another decade (Wear et al. 2013, U.S. Department of Agriculture 2016).

In this section, we provide an assessment of the amount of carbon stored on the Lolo National Forest 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. 2019). Both reports relied on Forest Inventory and Analysis and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System. The Baseline Report applies the Carbon Calculation Tool (Smith et al. 2007), which summarizes available Forest Inventory and Analysis data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the

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[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.

national forest from 1990 to 2013. The Baseline Report also provides information on carbon storage in harvested wood products 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 (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 model (Chen et al. 2000, Zhang et al. 2012). See Table A2.1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act assessment (U.S. Department of Agriculture 2016) and regional climate vulnerability assessments (Halofsky et al. 2018a;b) 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 National Forest System carbon trends.

Table A2.1—Description of the primary forest carbon models used to conduct this carbon assessment

Carbon Tool	Description
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 survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.
Forest Carbon Management Framework (ForCaMF)	Integrates Forest Inventory and Analysis 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 Forest Inventory and Analysis data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric CO2. InTEC estimates the relative effects of aging, disturbance, regrowth, and other factors including climate, CO2 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.

2.1 Background

The Lolo National Forest, located in the Rocky Mountains of western Montana, covers approximately 2.1 million acres of forestland. Douglas-fir and Lodgepole pine forest types are the most abundant across the Forest according to Forest Inventory and Analysis data. he carbon legacy of Lolo and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. For early settlers, the welfare of their community was dependent upon timber supply, regulation of stream flow for irrigation, and use of the land for cattle range. Mining began in the 1860s, peaked in the 1880s, and fluctuated over the following century with the extraction of gold, silver, lead, zinc and copper. Most of the logging in the region was for firewood and timber for miners and homesteaders. As the need for sustainable forest management became evident, the U.S. government began purchasing large areas of these overharvested and often submarginal lands in the United States in the early and mid-20th century to be established as national forests.

3. Baseline Carbon Stocks and Flux

3.1 Forest Carbon Stocks and Stock Change

According to results of the Baseline Report (USDA Forest Service, 2015), carbon stocks in the Lolo National Forest increased from 124.8±9.2 teragrams of carbon (Tg C) in 1990 to 135.6±12.6 Tg C in 2013, a 9 percent increase in carbon stocks over this period (Figure A2.1; Table A2.1). For context, 135.6 Tg C is equivalent to the emissions from approximately 108 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 Lolo National Forest have remained stable or slightly increased from 1990 to 2013 (Figure A2.1).

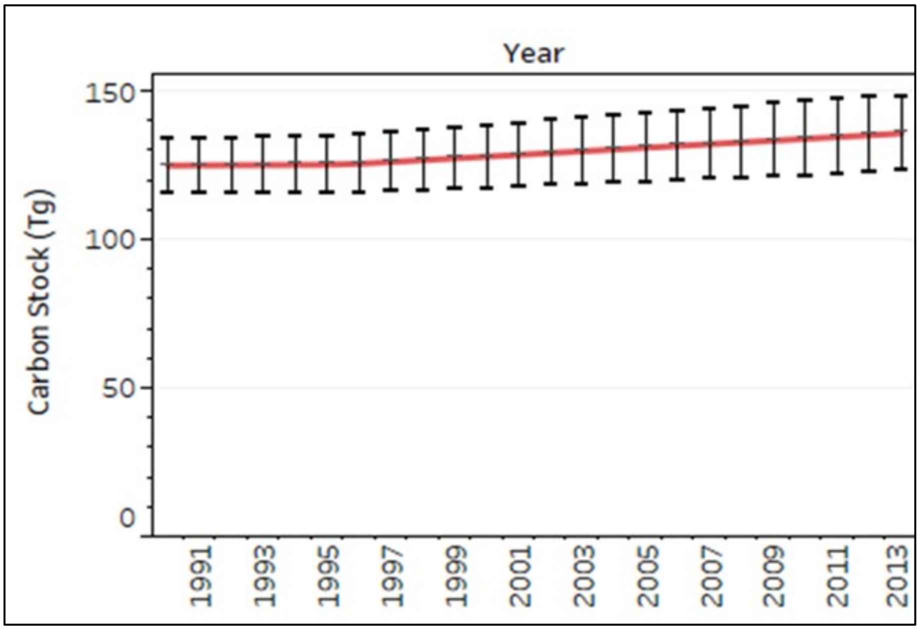

Figure A2.1—Total forest carbon stocks (Tg) from 1990 to 2013 for the Lolo National Forest, bounded by 95 percent confidence intervals. Estimated using the Carbon Calculation Tool

About 47.3 percent of forest carbon stocks in the Lolo National Forest are stored in the soil carbon contained in organic material to a depth of one meter (excluding roots) and the forest floor. Up to half the total site carbon in our northern forests is attributed to ground residue and within mineral soils.

Mycorrhizae perform a vital function by forming a forest network that enhances nutrient and water for vegetation in exchange for carbon. Forest ecosystems have unique conditions where carbon materials congregate along the topsoil as the forest floor and woody residual material. Mycorrhizae concentrate in this upper mulch layer facilitating decomposition as well as effectively extending plants rooting network. For carbon, the fungus network is key to decomposing animal and plant detritus into metabolites. Not all detritus is decomposed; roughly a third of the material persists in our northern forests annually on a much slower timeline for decomposition (DeLuca et al. 2019). The soil organic matter which includes this persistent carbon accentuates forest nutrient and water capacity. This carbon rich soil organic matter may persist as long as 6,000 years as humus (ibid). The aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Figure A2.2) is the second largest carbon pool, storing another 32 percent of the forest carbon stocks.

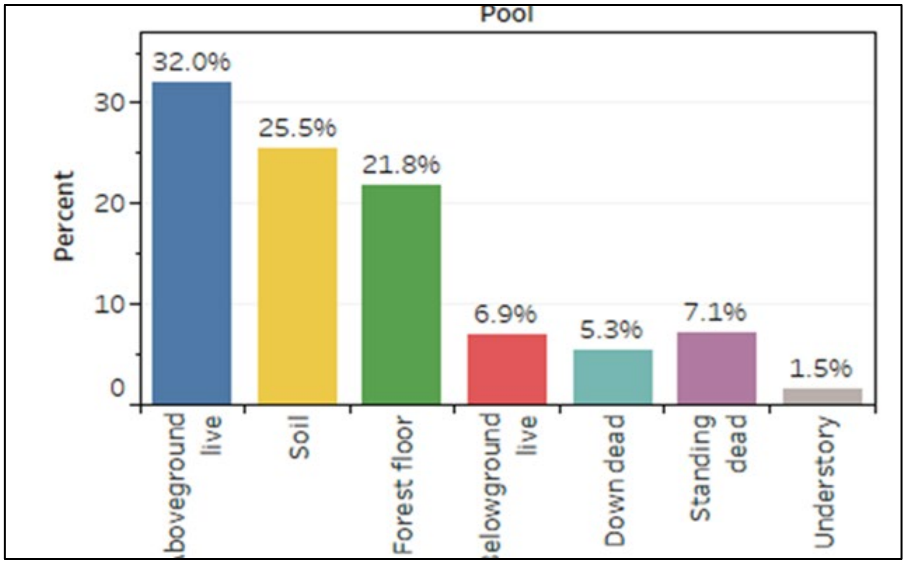

Figure A2.2—Percentage of carbon stocks in 2013 in each of the forest carbon pools, for Lolo National Forest. Estimated using the Carbon Calculation Tool

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.

Annual carbon stock changes in the Lolo National Forest were -0.1 ± 0.6 Tg C per year (gain) in 1990 and -0.6 ± 1.2 Tg C per year in 2012 (gain) (Figure A2.3). 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) (Figure A2.3). However, the trend of increasing carbon stocks from 1990 to 2013 (Figure A2.1) over the 23-year period suggests that carbon stocks in the Lolo National Forest have remained stable; the Forest may also be a modest carbon sink.

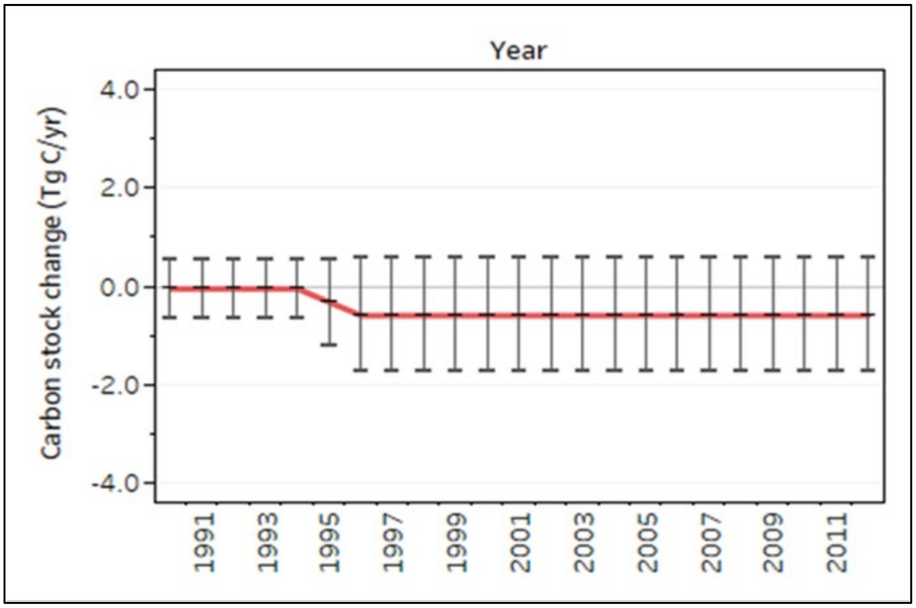

Figure A2.3—Carbon stock change (Tg/yr) from 1990 to 2012 for Lolo National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the Carbon Calculation Tool

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on Forest Inventory and Analysis data, which may indicate changes in the total forested area from one year to the next. According to the Forest Inventory and Analysis data used to develop these baseline estimates, the forested area in Lolo NF has increased from 2,032,237 acres in 1990 to 2,140,580 acres in 2013, a net change of 108,343 acres[2]. When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon sink. 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 forest carbon stocks are increasing or decreasing, and therefore, whether the national forest is a carbon source or sink (Woodall 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 Lolo National Forest, carbon density increased from about 151.8 Megagrams of carbon (Mg C) per ha in 1990 to 156.6 Mg C per ha in 2013 (Figure A2.4). This increase in carbon density suggests that total carbon stocks may have indeed increased.

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[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.

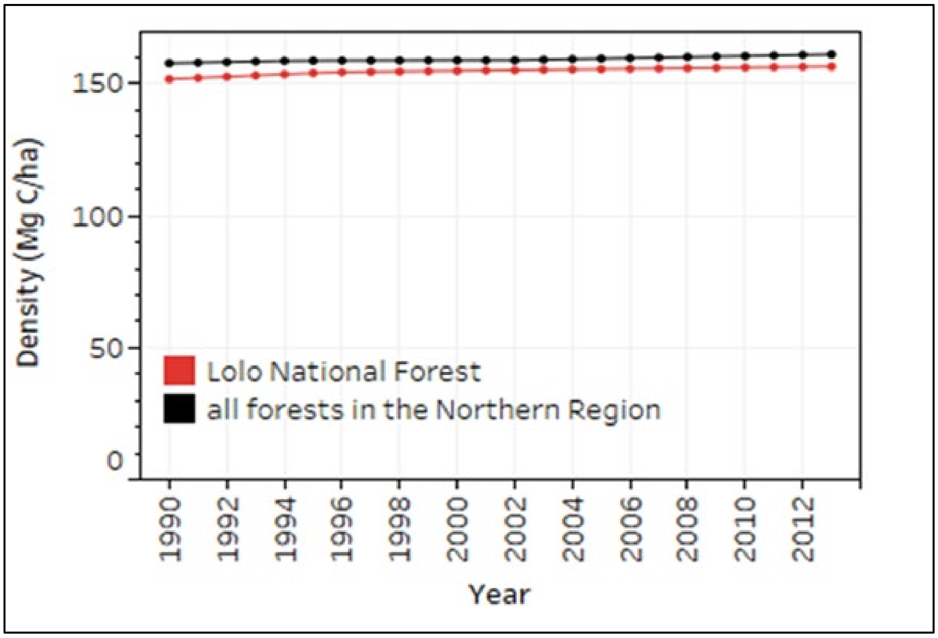

Figure A2.4—Average carbon stock density (Megagrams per hectare) on the Lolo National Forest and for all forests in the Northern Region from 1990 to 2013. Estimated using Carbon Calculation Tool

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Similar to the Lolo National Forest, most national forests in the Northern Region have experienced increasing carbon densities from 1990 to 2013. Carbon density in the Lolo National Forest has been similar to but slightly lower than the average for all national forest units in the Northern Region (Figure A2.4). 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.

3.2 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 (Figure A2.1, Figure A2.3). 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 Forest Inventory and Analysis 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 3.2, one such model error has resulted from a change in Forest Inventory and Analysis 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, in the case of the Lolo National Forest, the change in forested

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[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.

area is also likely a result of land exchange. From 2005 to 2020, the Lolo National Forest acquired about 149,000 acres through various land exchanges, primarily old industrial timber lands that were heavily logged prior to conversion.

The change in forested area incorporated in CCT could also be 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 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. Forest Inventory and Analysis plots are resampled about every 10 years in the Western United States, 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. 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 4) 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).

The stocking potential for forests varies and land management activities have major implications for land management and carbon storage. There is a need to better compare the stocking and carbon potential of the Lolo National Forest with current carbon sequestration levels, balancing this potential in ways that maintain healthy levels of forest disturbance.

3.3 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). 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 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, Stockmann 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.

In national forests in the Northern Region, harvest levels remained low until the 1940s when they began to rise, which caused an increase in carbon storage in harvested wood products (Figure A2.5). 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 harvested wood products 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 harvested wood products was equivalent to approximately 2.2 percent of total forest carbon storage associated with national forests in the Northern Region.

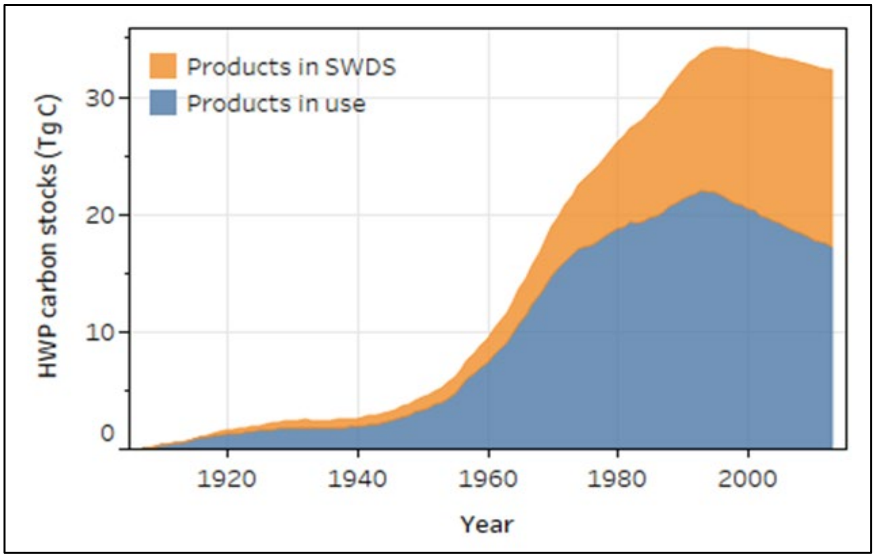

Figure A2.5—Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the Northern Region. Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach

3.4 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 harvested wood products 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 (Stockmann et al. 2014).

4. Factors Influencing Forest Carbon

4.1 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 has been the dominant disturbance type detected on the Lolo National Forest from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Figure A2.6). However, according to the satellite imagery, fire affected a relatively small area of the forest during this time. In most years, fire affected less than 0.2 percent of the total forested area of the Lolo National Forest in any single year from 1990 to 2011, with the exceptions of 2000, 2004, 2007 and 2008. In total, roughly 5.1 percent (approximately 104,540 ac) of the average forested area (2,053,448 ac) was disturbed by fire from 1991 to 2012.

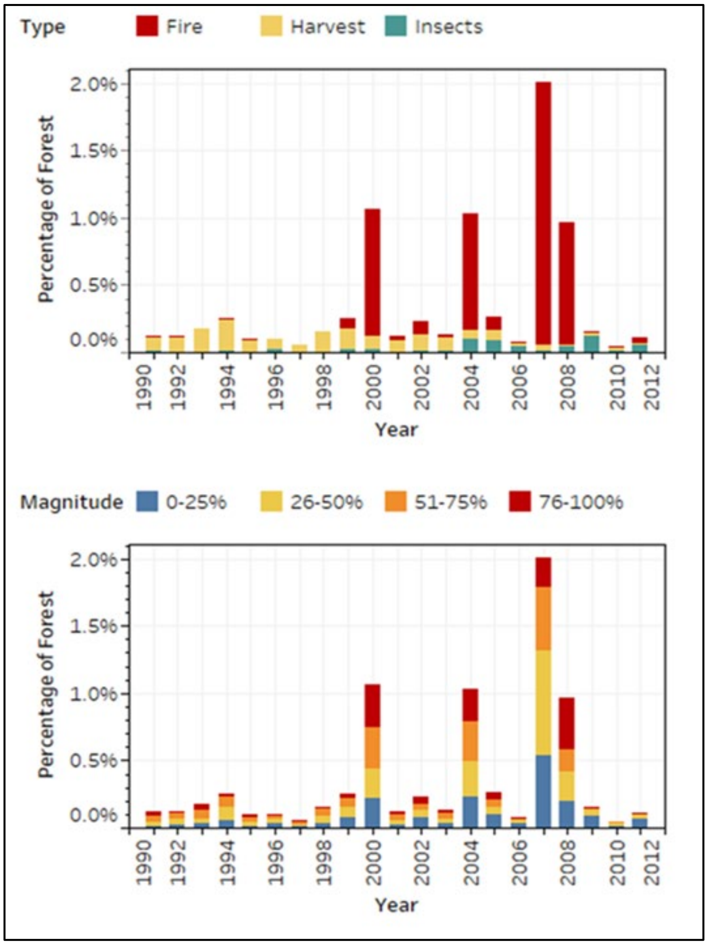

Figure A2.6—Percentage of forest disturbed from 1990 to 2011 in Lolo National Forest by (a) disturbance type including fire, harvests, and insects, and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery

In addition, timber harvest also affected a relatively small area of the forest during this time. In most years, timber harvest affected less than 0.3 percent of the total forested area of the Lolo National Forest in any single year from 1990 to 2011, and in total less than 2 percent (approximately 38,146 ac) of the average forested area during this period (2,053,448 ac). The percentage of the forest harvested annually has also decreased slightly over this 21-year period (Figure A2.6). The total amount of disturbed forest from all factors during this period was 7.5 percent, a total of 154,613 acres disturbed. Although disturbances varied in type and scale, they generally removed less than 75 percent of canopy cover (magnitude) on the forest (Figure A2.6). In total, only 1.5 percent of the forest had a disturbance that resulted in a canopy loss of greater than 75 percent from 1990 to 2012.

The Forest Carbon Management Framework incorporates Landsat disturbance maps summarized in Figure A2.6, along with Forest Inventory and Analysis data in the Forest Vegetation Simulator (Crookston and Dixon 2005). The Forest Vegetation Simulator 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 Forest Carbon Management Framework 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. Forest Carbon Management Framework simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like the Carbon Calculation Tool, Forest Carbon Management Framework results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey et al. 2014).

Fire on the Lolo National Forest was the primary disturbance influencing carbon stocks from 1990 to 2011 (Figure A2.7). The Forest Carbon Management Framework model indicates that, by 2011, the Lolo National Forest contained 2.1 Mg C per hectare less non-soil carbon (i.e., vegetation and associated pools) due to fire since 1990, as compared to a hypothetical undisturbed scenario (Figure A2.7). As a result, non-soil carbon stocks in the Lolo National Forest would have been approximately 1.8 percent higher in 2011 in the absence of fire since 1990 (Figure A2.8). Root disease also had an influence on carbon stocks from 1990 to 2011 (Figure A2.7). For context, root diseases are known to suppress forest regeneration and reduce growth rates (Healey et al. 2016). By 2011, the Lolo National Forest contained 1.6 Mg C per hectare less non-soil carbon (i.e., vegetation and associated pools) due to root disease since 1990, as compared to a hypothetical undisturbed scenario (Figure A2.7). As a result, non-soil carbon stocks in the Lolo National Forest would have been approximately 1.4 percent higher in 2011 if root disease had not occurred since 1990 (Figure A2.8).

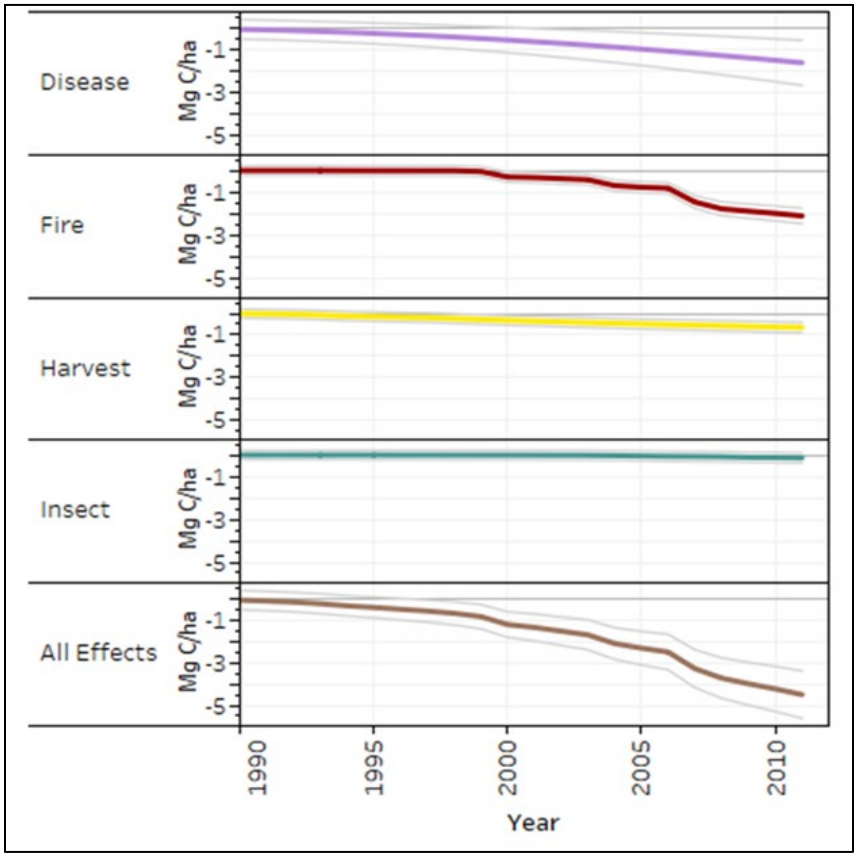

Figure A2.7—Lost potential storage of carbon (Megagrams/ha) as a result of disturbance for the period 1990-2011 in Lolo National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model

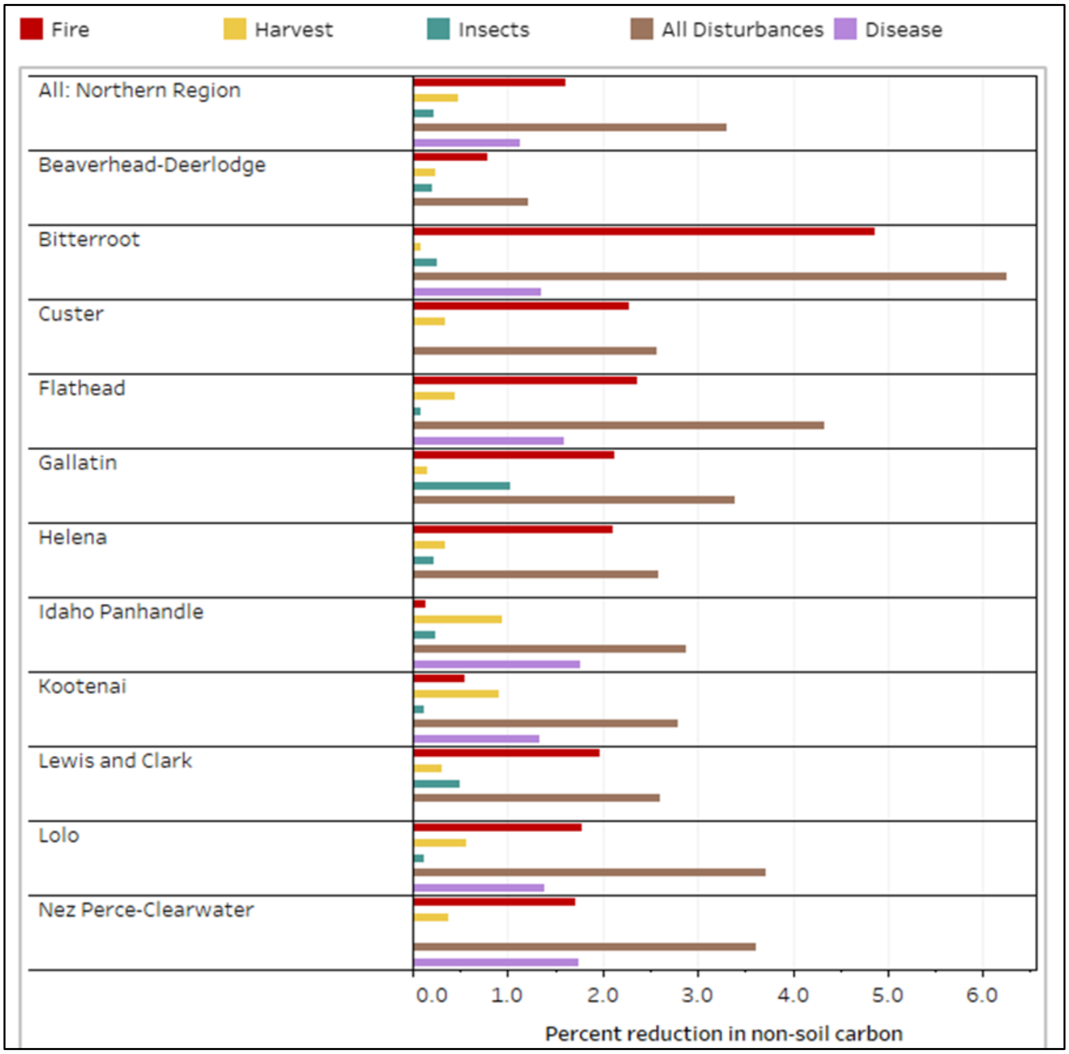

Figure A2.8—The degrees to which 2011 carbon storage on each national forest in the Northern Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The brown line indicates the effect of all disturbances types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT

Across all national forests in the Northern Region, fire has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 1.6 percent lower by 2011 (Figure A2.8). Considering all national forests in the Northern Region, by 2011, fire accounted for the loss of 1.6 percent of non-soil carbon stocks, disease 1.1 percent, harvest 0.5 percent, and insects 0.2 percent.

The Forest Carbon Management Framework 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) (Raymond et al. 2015). The Forest Carbon Management Framework 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 greenhouse gases 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 Intergovernmental Panel on Climate change recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (Intergovernmental Panel on Climate Change 2000).

Forest Carbon Management Framework 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 Integrated Terrestrial Ecosystem Carbon model was to reconcile recent disturbance impacts with these other factors.

4.2 Effects of Forest Aging

Integrated Terrestrial Ecosystem Carbon 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 (Figure A2.6), and equations describing the relationship between net primary productivity and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan et al. 2011b). 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 Lolo National Forest derived from 2011 Forest Inventory and Analysis data indicates elevated stand establishment around 1900–1930 (Figure A2.9a). This period of elevated stand regeneration came after decades of intensive logging and large wildfires in the late 1800s and early 1900s, including the fires of 1910. 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, He et al. 2012), as indicated by the in net primary productivity-age curves (Figure A2.9b), derived in part from Forest Inventory and Analysis data.

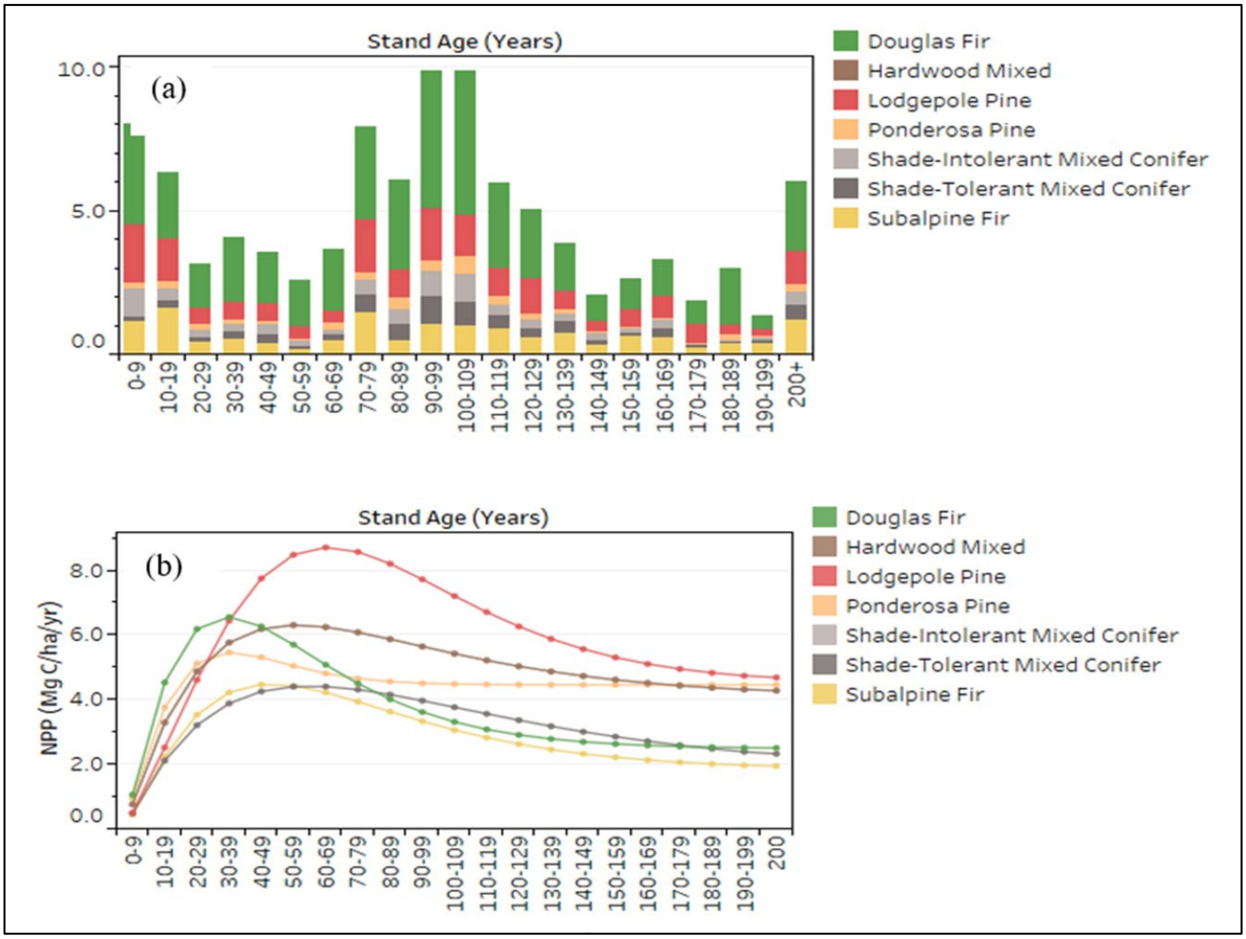

Figure A2.9—(a) Stand age distribution in 2011by percentage of forested area by dominance type on the Lolo National Forest. Derived from forest inventory data. (b) Net primary productivity-stand age curves (in megagrams of carbon per ha per year) by dominance type on the Lolo National Forest. Derived from forest inventory data

Integrated Terrestrial Ecosystem Carbon model results show that Lolo National Forest was accumulating carbon steadily at the start of the analysis in the 1950s through about 1970 (Figure A2.10) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Figure A2.9b). As stand establishment declined and more stands reached slower growth stages around the 1980s, accumulation stabilized. Since roughly the mid-1990s, the rate of carbon accumulation declined (negative slope) as more stands reached maturity and peaked in productivity (Figure A2.10).

(b)

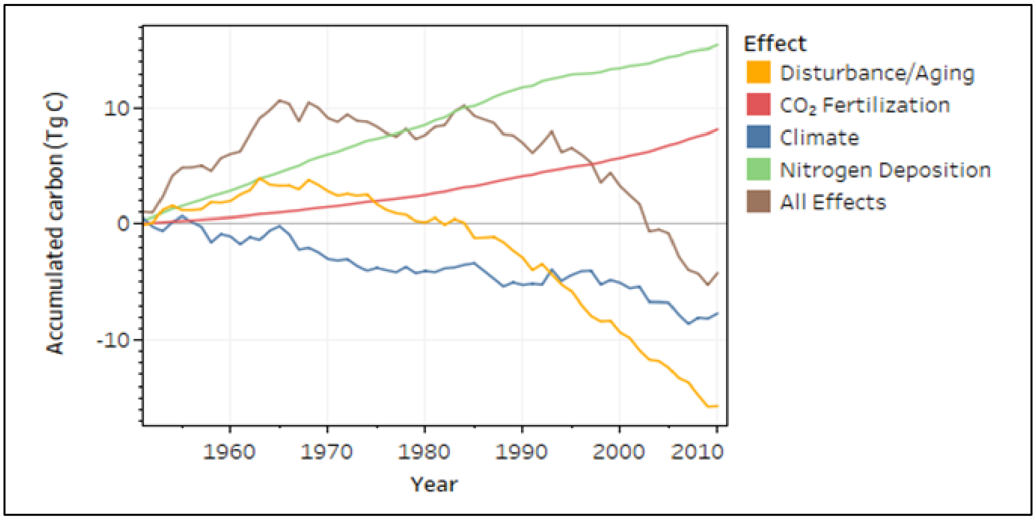

Figure A2.10—Accumulated carbon (in teragrams) on the Lolo National Forest due to disturbance/aging, climate, nitrogen deposition, CO2 fertilization, and all factors combined (shown in brown line) for1950–2010, excluding carbon accumulated pre-1950. Estimated using the InTEC model

4.3 Effects of Climate and Environment

The Integrated Terrestrial Ecosystem Carbon 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 small negative effect on carbon stocks in the Lolo (Figure A2.10). 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).

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). According to the Integrated Terrestrial Ecosystem Carbon model, higher CO_2 has consistently had a positive effect on carbon stocks on the Lolo National Forest, tracking an increase in atmospheric CO_2 concentrations worldwide (Figure A2.10). 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). 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 Lolo National Forest (Figure A2.10). Like CO_2, the actual magnitude of this effect remains uncertain. Overall, the Integrated Terrestrial Ecosystem Carbon model suggests that CO_2 fertilization and nitrogen deposition partially offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate.

4.4 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 Forest Carbon Management Framework and Integrated Terrestrial Ecosystem Carbon models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. Forest Carbon Management Framework results may also incorporate errors from the inventory data and the Forest Vegetation Simulator-derived carbon accumulation functions (Raymond et al. 2015). To quantify uncertainties, the Forest Carbon Management Framework 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 Integrated Terrestrial Ecosystem Carbon model 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). The Integrated Terrestrial Ecosystem Carbon model is highly calibrated to Forest Inventory and Analysis data and remotely sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the Integrated Terrestrial Ecosystem Carbon estimates. National-scale sensitivity analyses of Integrated Terrestrial Ecosystem Carbon 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., Figure A2.10, "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 Forest Carbon Management Framework and Integrated Terrestrial Ecosystem Carbon models may differ substantially from baseline estimates (Carbon Calculation Tool), given the application of different datasets, modeling approaches, and parameters (Zhang et al. 2012, Dugan et al. 2017). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas Forest Carbon Management Framework and Integrated Terrestrial Ecosystem Carbon models involve additional data inputs and modeling complexity beyond summarizing ground data.

5. Carbon on non-forest lands

The Western and Central Subregions (which include the Lolo National Forest), contains 2,779,985 acres of non-forest lands (Reeves et al. 2018). 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 (Knapp et al. 1998). 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 *et al.*, 2008 (McKinley and Blair 2008). 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 Lolo National 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. Most 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.

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 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 Environmental Protection Agency (2019) estimates that about 47 percent of the total greenhouse gas emissions in the agricultural sector are attributed to livestock. In turn, the agricultural sector contributes to about 9 percent of total greenhouse gas 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 (National Agricultural Statistics Service 2019).

6. Future Carbon Conditions

6.1 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, forest stands on the Lolo National Forest are mostly middle-aged and older (greater than 70 years) with approximately 30% of the stands less than 70 years old, and about 20% greater than 150 years of age (Figure A2.9). If the Forest continues this aging trajectory, more stands will reach a slower growth stage in coming years and decades (Figure A2.9), potentially causing the rate carbon accumulates to decline and the Forest may eventually transition to a steady state in the future. Although yield curves indicate that biomass carbon stocks may be approaching maximum levels (Figure A2.9), 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 or disturbances could affect future stand age and forest growth rates (Williams et al. 2012).

The Resources Planning Act assessment provides regional projections of forest carbon trends across forestland ownerships in the United States based on a new approach that uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (Woodall et al. 2015, U.S. Department of Agriculture 2016). The Resources Planning Act reference scenario assumes forest area in the U.S. will continue to expand at current rates until 2022, when it will begin to decline due to land use change. However, national forests tend to have higher carbon densities than private lands and may have land management objectives and practices that differ from those on other lands.

For Resources Planning Act'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, which shows the effects of aging, disturbance, and mortality, also indicates a small projected decline, further resulting in a shift to a carbon source (Figure A2.11). 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. 2011a, 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 Lolo National Forest in the future, though planned land acquisitions will continue to occur. Therefore, on National Forest System lands, the projected carbon trends may closely resemble the "net sequestration" trend in Figure A2.11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline through 2035 in the rate of net carbon sequestration then stabilizes through 2060.

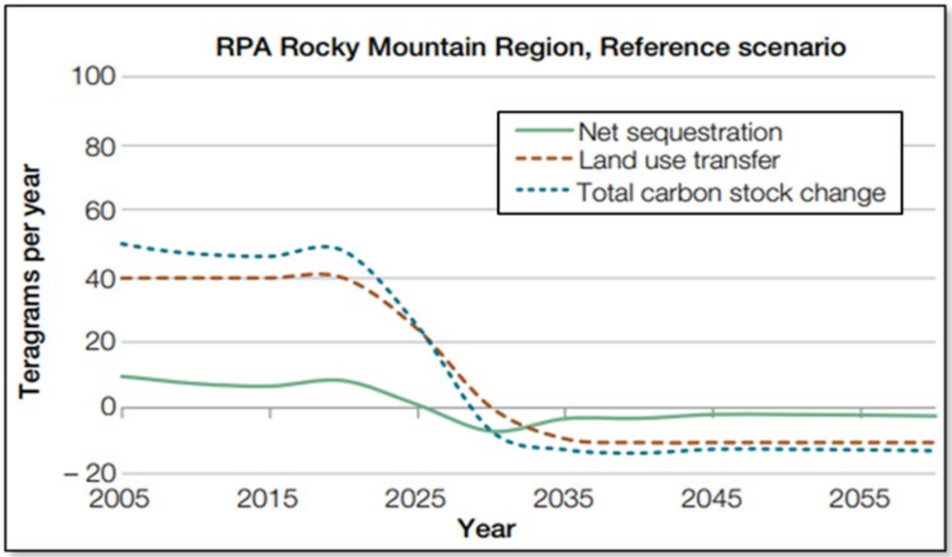

Figure A2.11—Projections of forest carbon stock changes in the North Region (equivalent to the boundaries of Northern Region but includes all land tenures) for the Resources Planning Act reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change

6.2 Prospective Climate and Environmental Effects

The description of forest carbon stocks and fluxes above highlights the role of disturbances, management, and environmental factors in influencing carbon dynamics on the Lolo National Forest and elsewhere across the region. However, climate change introduces additional uncertainty about how vegetation—and vegetation carbon uptake and storage—may change in the future. Climate change causes direct alterations of the local environment, including temperature and precipitation, and indirectly affects a wide range of ecosystem processes (Vose et al. 2012), including vegetation growth, regeneration, and mortality. Because disturbance regimes are projected to increase with climate change (Vose et al. 2018), understanding past trends is not sufficient to fully understand vegetation carbon dynamics in the future.

A climate change vulnerability assessment for the Forest Service Northern Rockies Region (Halofsky et al. 2018a), including the Lolo National Forest, indicates that temperature is projected to increase throughout the 21st century. By the 2040s, mean annual monthly temperatures are projected to increase in the Northern Rockies region. In the Western and Central Subregions (which include the Lolo National Forest), maximum annual temperature is projected to increase by 5–11 degrees Fahrenheit by 2100, and minimum annual temperature is projected to increase by 5–12 degrees Fahrenheit by 2100. Minimum and maximum temperatures are projected to increase in all seasons. The frequency of summer days with extreme heat is likely to increase (Halofsky et al. 2018a).

Higher temperatures will increase the length of the growing season. A longer growing season may enhance vegetation growth and carbon sequestration, particularly where water supply is adequate and temperatures are not excessive (e.g., at higher elevations) (Vose et al. 2018). However, elevated temperatures may also increase evapotranspiration, resulting in increased soil respiration and reduced soil moisture. Thus, higher temperatures may negatively affect growth rates and carbon accumulation (Melillo et al. 2017), particularly in water-limited vegetation at lower elevations. Modeled results of recent climate effects using the Integrated Terrestrial Ecosystem Carbon model indicate that years with elevated temperatures have generally had a negative effect on carbon uptake in the Lolo National Forest (Figure A2.10).

In the Northern Rockies Region, projections for precipitation suggest a very slight increase in the future. However, projections for precipitation are much more uncertain than those for temperature. Many global climate models project decreases in summer precipitation in the region (Easterling et al. 2017). Precipitation extremes (i.e., high precipitation days and consecutive dry days) are projected to increase in frequency and intensity across the United States (ibid). Snowfall is projected to decrease in the Northern Rockies region, particularly in relatively warm locations (i.e., mid- to low-elevation locations) (Klos et al. 2014, Luce et al. 2014).

The combination of higher temperature, lower snowpack, and more consecutive dry days related to climate change will likely lead to lower soil moisture and greater drought stress (Wehner et al. 2017). These effects will be more pronounced at middle and lower elevations in the Northern Rockies Region. Drought stress may negatively affect plant productivity and carbon uptake and storage and increase effects of other stressors. For example, drought-stressed vegetation is more susceptible to insect outbreaks (Logan and Powell 2009), which can significantly reduce carbon uptake (Kurz et al. 2008). Drought is also associated with increased wildfire area burned in the Western United States (McKenzie and Littell 2017). The area burned by wildfires (McKenzie et al. 2004, Kitzberger et al. 2017) and the potential for very large fires (>12,000 acres) (Barbero et al. 2015) are projected to increase in the Northern Rockies Region in a warming climate. These disturbances may decrease forest carbon stocks in the future.

Climate change and associated stressors are likely to lead to changes in the distribution and abundance of vegetation, particularly by the end of the 21st century. For example, lower-elevation species, such as Douglas-fir, may increase in abundance at the lower end of the subalpine zone with warming temperatures and lower snowpack in the Northern Rockies Region (Keane et al. 2018). More drought- and fire-tolerant species, such as ponderosa pine and western larch will likely increase in abundance. Species that are less tolerant of drought and fire, such as grand fir and Engelmann spruce, will likely decrease in abundance. These changes in species and abundance can also influence carbon storage.

Vegetation shifts are most likely to occur after disturbance. For example, drought stress may preclude the establishment of tree species after high-severity disturbance, allowing dominance by non-forest vegetation (e.g., grasses and shrubs) (Keane et al. 2018). Establishment of non-native and invasive species, such as cheatgrass, may also increase after disturbance (Hellmann et al. 2008). Invasive species establishment can shift the dominance of vegetation (e.g., from perennial shrubs to annual grasses) and alter the fire regime by changing fuels (Balch et al. 2013). These and other vegetation type shifts could alter the long-term carbon storage in some ecosystems.

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (Intergovernmental Panel on Climate Change 2014). Several models, including the Integrated Terrestrial Ecosystem Carbon model (Figure A2.10), project future increases in forest productivity when the CO_2 fertilization effect is included in modeling (Zhang et al. 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is likely to be transient and can be limited by the availability of nitrogen and other nutrients (Norby et al. 2010). Thus, increases in plant productivity 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 under novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. For example, 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 vegetation type. Some factors may enhance vegetation growth and carbon uptake, whereas others may hinder the ability of vegetation to store carbon.

6.3 Summary

Forests on the Lolo National Forest are likely maintaining stable carbon stocks and may be a modest carbon sink. Forest carbon stocks increased by about 9 percent between 1990 and 2013, and negative impacts on carbon stocks caused by disturbances and environmental conditions have been modest and exceeded by forest growth. According to satellite imagery, fire has been the most prevalent disturbance detected on the Forest since 1990. Additionally, timber harvests that occurred during this period have been relatively small and low intensity. Forest carbon losses associated with harvests have been small compared to the total amount of carbon stored in the Forest, resulting in a loss of about 0.6 percent of non-soil carbon from 1990 to 2011. These estimates represent an upper bound because they do not account for continued storage of harvested carbon in wood products or the effect of substitution. Carbon storage in harvested wood products 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 Lolo National Forest is the legacy of intensive timber harvesting and land clearing for agriculture during the 19th century, followed by a period of forest recovery and more sustainable forest management beginning in the early to mid-20th century, which continues to promote a carbon sink today (Birdsey et al. 2006). However, stands on the Lolo National Forest are now mostly middle to older aged. The rate of carbon uptake and sequestration generally decline as forests age. Accordingly, projections from the Resources Planning Act assessment indicate a potential age-related decline in forest carbon stocks in the Northern Region (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 Lolo National Forest. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in the 2000s. 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 Lolo National Forest 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 Lolo National Forest.

Forested area on the Lolo National Forest will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. Across the broader region, land conversion for development on private ownerships is a concern (Wear et al. 2013) and this activity can cause substantial carbon losses (Tubiello et al. 2013, U.S. Department of Agriculture 2016). The Lolo National Forest will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

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