Appendix J. Climate and Carbon, Supplemental Information

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Climate change considerations and assumptions

Climate change is expected to have profound effects on the Earth's ecosystems in the coming decades (Intergovernment Panel on Climate Change (IPCC), 2007). Description and analysis of these effects rely on a broad array of scientific literature and a recent meta-analysis of climate change and potential effects published for the Northern Rockies Adaptation Partnership (Halofsky et al., 2018a, 2018b). These publications, and the references cited therein, represent the current state of the science on climate change in the region and on the HLC NF.

There is little debate that atmospheric carbon dioxide is increasing and that this increase will cause changes in climate but there is a great deal of uncertainty about the magnitude and rate of climate change, especially as projections are made at more local scales or for longer time periods (Halofsky et al., 2018b). Despite the uncertainty in downscaled projections, scientists expect the impacts of climate change on forest vegetation to be primarily driven by vegetation responses to shifts in disturbance regimes, and secondarily, through direct effects of vegetation interactions with climate through shifts in regeneration, growth, and mortality processes at both individual plant and community scales (ibid).

Specific to forested vegetation, the Northern Rockies Adaptation Partnership assessed projected climate change responses for 17 tree species, 5 forest vegetation types, and three resources of concern: landscape heterogeneity, carbon sequestration and timber production. The study rated the vulnerability of these elements to climate change. Vulnerability was determined from a number of factors including stressors, exposure, sensitivity to climate change, impact of that response, and adaptive capacity. Forests at all elevations are projected to have increased outbreaks of forest pest species and more frequent fire.

The table below displays the ranking of climate change vulnerability for the tree species found on the HLC NF (Halofsky et al., 2018b). The HLC NF spans across three of the subregions considered by the Northern Rockies Adaptation Partnership. Most of the Forest is in the East subregion, but areas west of the continental divide (in the Upper Blackfoot and Divide GAs) are in the Central subregion and the Crazies GA lies within the Greater Yellowstone Area subregion. There are some key differences in the vulnerabilities across these subregions; for example, Douglas-fir is more vulnerable in the East and Greater Yellowstone subregions than it is in the Central subregion.

Table 1. Ranking of climate change vulnerability tree species found on the HLC NF. A ranking of "1" indicates the highest vulnerability.

Species	Northern Rockies	Central Subregion (western portions of Upper Blackfoot and Divide GAs)	Greater Yellowstone Area (Crazies GA)	NRAP 2018 – East subregion (all other areas of the HLC NF)
Whitebark pine	2	2	1	1
Western larch	3	3	N/A	N/A
Douglas-fir	5	8	2	2
Engelmann spruce	9	11	4	3
Subalpine fir	10	12	5	4
Lodgepole pine	11	10	6	5
Cottonwood	13	13	3	6
Limber pine	15	15	8	7
Aspen	14	14	7	8

Species	Northern Rockies	Central Subregion (western portions of Upper Blackfoot and Divide GAs)	Greater Yellowstone Area (Crazies GA)	NRAP 2018 – East subregion (all other areas of the HLC NF)
Ponderosa pine -east	17	N/A	9	8
Ponderosa pine - west	16	16	N/A	N/A

Considerable uncertainties underlay projections of vegetation under future climates, including:

- Complex interactions of climate with vegetation and disturbance are difficult to predict in time and space making future projections difficult;
- Abundant scale problems in nature and in the literature that made it difficult to generalize species and ecosystem trends at consistent temporal and spatial scale; and
- Uncertainty in climate projections (22 GCMs, 6 scenarios) made it difficult to project climate change responses at the local level.

The 2020 Forest Plan and EIS incorporate models, plan components, and resource management strategies developed using the latest understanding of climate and potential changes into the future. The climate section of the EIS describes specific future expectations for temperature, precipitation, and potential resource effects based on information found in Halofsky et al. (2018). 2020 Forest Plan direction incorporates strategies to address the uncertainties associated with climate change and its potential impacts to vegetation. While many effects of climate change are anticipated to be gradual, we also recognize the potential for interacting disturbances such as insects, drought and fire to dive systems towards sudden large-scale transformations (Millar & Stephenson, 2015).

As noted by Halofsky et al. (2018), a warming climate will rarely be the direct agent of change for terrestrial vegetation on the HLC NF. Rather, most of the changes will likely result from responses to climate change-induced disturbance or to some combination of other climate-exacerbated stressors. Whether it is invasive species, drought, uncharacteristic wildfires, elevated native insect and disease levels, loss of fire-adapted trees, or unusually high forest densities, the most significant effect of climate change is likely to be further exacerbating these stressors and “stress complexes”. Plan direction, which emphasizes ecological integrity and resilience, will be critical to minimizing the undesirable effects of these increasing and interacting stressors. Nevertheless, managers and the public should expect climate change to drive changes on ecosystem structure, function and composition in the coming decades.

Incorporating climate change in vegetation modeling

It is not possible to model or predict if, when, and where megadisturbances, regeneration failures, or shifts to novel ecosystems may occur on the HLC NF. As noted in the literature, prediction of potential tree mortality, or future forest decline, is currently difficult if not possible given scientific uncertainties and the complex interactions of contributing factors (Allen, Breshears, & McDowell, 2015; Anderegg et al., 2013; Wong & Daniels, 2016).

To the extent feasible, the SIMPPLLE model was calibrated to encompass likely future scenarios. This included applying an increase in expected wildfire acres burned, up to 2x the current levels. Regeneration pathways were calibrated to the best available information on tree species seeding dispersal and establishment mechanisms. Finally, the model was run assuming that all future periods are warm and dry, which affects disturbances and vegetation pathways. The model results did not indicate future forest die-backs or massive regeneration failures. However, the model is limited in its capacity to incorporate all possible scenarios, and is based on known successional pathways which may be altered in the future. The model results are used to compare the differences across alternatives, and are not precise predictions of the future. All alternatives were relatively similar with regards to future vegetation, and therefore the potential risk to and outcomes of large disturbances and regeneration failures (although unquantifiable) would also be similar across alternatives.

Incorporating climate change into plan components

Approaches to address forest and ecosystem management in the face of an uncertain and variable future should be flexible, emphasize ecological processes, and have the capacity to be adaptive to new information as it becomes available (Millar, Stephenson, & Stephens, 2007). Approaches published in the literature include promoting resilience to change, creating resistance to change, and enabling forests to respond to change (Halofsky et al., 2018b, 2018c; Holling, 1973; M. K. Janowiak et al., 2014; Millar et al., 2007).

Resilience is defined as the degree to which forests and ecosystems can recover from one or more disturbances without a major shift in composition or function, and is the most commonly suggested adaptation option discussed in a climate-change context (Millar et al., 2007). Resilient forests accommodate gradual changes related to climate and are able to cope with disturbances. *Resistance* is the ability of the forest or ecosystem to withstand disturbances without significant loss of structure or function, in other words, to remain unchanged. From a management perspective, resistance includes both the degree to which communities are able to resist change, such as from warming climate; and the manipulation of the physical environment to counteract and resist physical or biological change, such as through burning or harvest treatments (Halofsky et al., 2018b). The *response* approach intentionally accommodates change rather than resists it, with a goal of enabling or facilitating forest ecosystems to respond adaptively as environmental changes accrue. Treatments would mimic, assist or enable ongoing natural adaptive processes, anticipating events outside the historical conditions, such as extended fire seasons or increased summer water deficits. Response tactics may include such practices as shifting desired species to new potentially more favorable sites through planting, managing early successional forests to “re-set” normal successional trajectories to create desired future patterns and structures, and promoting connected landscapes (Millar et al., 2007). Integration of various adaptive approaches and management practices is the best strategy (Millar et al., 2007; Spittlehouse & Stewart, 2003).

For the development of the programmatic management direction in the 2020 Forest Plan, all of approaches described above are integrated to one degree or another, though promoting resilience is the primary approach. The resistance approach is integrated, for example with protection of highly valued habitats, species or other resources. Approaches that could be considered response options are promotion of landscape connectivity and treatments in young stands to develop desired future forest patterns and structures. Another key plan component that is critical in the context of future climate change is the establishment of a monitoring plan to inform an adaptive management approach. This enables the intentional use of monitoring to evaluate effectiveness of plan direction and resulting management actions.

To date, there is not broad agreement within the research community about the degree to which forests are vulnerable globally; however, while there is evidence to support perspectives of both relatively lesser and greater vulnerabilities, there are some drivers with high confidence that point toward the perspective of greater vulnerabilities (Allen et al., 2015). The vulnerabilities described by Halofsky and others (2018) are used as the best available information for the HLC NF. Rather than attempting to predict and quantify the unknowable, the 2020 Forest Plan prepares the vegetation on the HLC NF for potential future climate-driven change by focusing on resilience of vegetation and maintenance of the suite of biodiversity currently present, as guided in the framework of law, regulation, and policy. This guides management actions within FS control, as well as FS responses to events that are outside FS control.

The literature indicates that there is risk of elevated tree mortality, and the potential for large disturbances that combined with drought and climate conditions could push some vegetation communities into new or novel states (such as a shift to nonforested plant communities) at some point in the future. This risk is acknowledged at the broad scale, but it is impossible to quantify or predict this spatially or temporally for landscapes on the HLC NF, because a myriad of site-specific factors would influence these events and outcomes. Instead, the plan relies on the best information available to quantify appropriate vegetation conditions, while acknowledging potential risks and alternate scenarios, and providing the framework for monitoring and adaptive management to allow managers to respond to future conditions.

As a cornerstone, the Plan relies on desired condition envelopes that are informed by the natural range of variation (NRV), but also incorporate adjustments that reflect possible future conditions, such as allowing for more nonforested plant communities. Specific best available scientific information (BASI) is cited in cases where the desired condition differs from the modeled NRV (see appendix H of the EIS). Desired conditions are consistent with concepts for increasing forest resiliency, such as promoting fire-resistant species, large trees, and lower stand densities. These conditions are appropriate for the anticipated life of the Plan (15 years), were extensively reviewed by forest specialists, and are consistent with the findings of expert reviews on similar efforts (Hansen et al., 2018; Timberlake, Joyce, Schultz, & Lampman, 2018). Moving towards these desired conditions would help ensure the maintenance of biodiversity, species habitat, and ecosystem services regardless of whether future conditions may change after the planning period. Management actions designed to mitigate the effects of drought are supported by the desired conditions, including the following described by Vose and others (2016):

- Implement structural changes by thinning or density management of planted forests;
- Favor or plant more drought-adapted species; and
- Manage for a diversity of species to reduce vulnerability to drought given uncertainty in future climate.

It is possible that at some point in the future, the desired conditions as currently outlined in the 2020 Forest Plan may no longer be appropriate or achievable (for example, if sites shift to novel ecosystems). It is even possible that large disturbances and site-specific shifts could occur within the planning period. It is not possible to quantify desired conditions that reflect novel ecosystems, because predictions of species shifts in the literature are made at the broad scale using climate envelopes, and do not encompass site-specific conditions that would influence species persistence at the local scale. Further, it is not possible to predict or quantify potential megadisturbances, or broad-scale die-off events, although the risk of such events is noted. If such events do occur, or monitoring shows that species shifts are occurring within the plan period, it would be possible to amend the plan regarding appropriate desired conditions.

Climate adaptation strategies

The Northern Rockies Adaptation Partnership publication (Halofsky et al., 2018b, 2018c) is the main source of information on possible strategies and approaches. Initiated in 2013, this is a science-management partnership consisting of multiple agencies, organizations, and stakeholders who worked together over a period of two years to identify issues relevant to resource management in the Northern Rocky Mountains and to find practical solutions that can make ecosystems adaptable to the effects of a changing climate. Climate adaptations strategies that are supported by plan components in the 2020 Forest Plan include but are not limited to the following. Many of these strategies would also be possible with the no-action alternative.

- Build aquatic ecosystem resilience to changing climate, higher peak flows, and higher variability.
- Respond to climate-induced occurrence of disturbances such as drought and flooding.

- Reduce erosion potential to protect water quality.
- Increase stream flows and moderate changes in instream flows.
- Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.
- Provide opportunities for native fish to move and find suitable stream temperatures.
- Manage nonnative fish populations to eliminate or reduce their impact on native fish.
- Increase resilience to fire-related disturbance.
- Maintain/enhance species and structural diversity at multiple scales; protect forests from severe and uncharacteristic disturbances; and reduce impacts of stressors such as insects and disease and invasive species.
- Maintain/create areas where ecological processes are generally allowed to function with minimal human influence.
- Maintain particular species or community types of concern/high vulnerability.
- Incorporate increased knowledge and new science related to climate change and species responses.

Forest carbon assessment for the HLC NF

Alexa Dugan, Duncan McKinley, and Amanda Milburn – October 2019

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 (CO2) 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 U.S. constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Yude 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 (Hayes et al., 2018; U.S. Enviornmental Protection Agency, 2015).

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 CO2 emissions. Fluxes from forestry and other land use (FOLU) activities are dominated by CO2 emissions. Non-CO2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate. The forestry sector contribution to greenhouse gas emissions has declined over the last decade (FAOSTAT, 2013; (Intergovernment Panel on Climate Change, 2014; P. Smith et al., 2014). Globally, the largest source of these emissions in the forestry sector is deforestation (Houghton et al., 2012; Intergovernment Panel on Climate Change, 2014; Yude Pan, 2011), 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 (Richard Birdsey, Pregitzer, & Lucier, 2006), a trend expected to continue for at least another decade (U.S. Department of Agriculture, 2016; Wear, Huggett, Li, Perryman, & Liu, 2013).

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, harvest, 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 CO2 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; Yude Pan, Birdsey, Hom, & McCullough, 2009).

In this section, we provide an assessment of the amount of carbon stored on the HLC NF and how disturbances, management, and environmental factors have influenced carbon storage overtime. This assessment primarily used two recent USFS reports: the Baseline Report (U.S. Department of Agriculture, 2015) and Disturbance Report (R. Birdsey et al., 2019). 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 NFS lands. The Baseline Report applies the Carbon Calculation Tool (CCT) (J. E. Smith, Heath, & Nichols, 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the NF 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 NF-scale evaluation of the influences of disturbances and management activities, using the Forest Carbon Management Framework (ForCaMF) (S. P. Healey et al., 2016; Sean P. Healey, Urbanski, Patterson, & Garrard, 2014; Raymond, Healey, Peduzzi, & Patterson, 2015). 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 (W. J. Chen, J. Chen, & J. Cihlar, 2000; F. M. Zhang et al., 2012). Additional reports, including the most recent Resource Planning Act assessment (U.S. Department of Agriculture, 2016) and regional climate vulnerability assessments (Halofsky et al., 2018b, 2018c) 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.

Primary forest carbon models and carbon units

The following models were 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 NF 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 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.

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

Table 2. Carbon stock and emission metric measurement units

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 km2 = 2.471 acres = 0.00386 mi2
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 CO2 mass
A typical passenger vehicle emits about 4.6 tonnes CO2 a year

Background

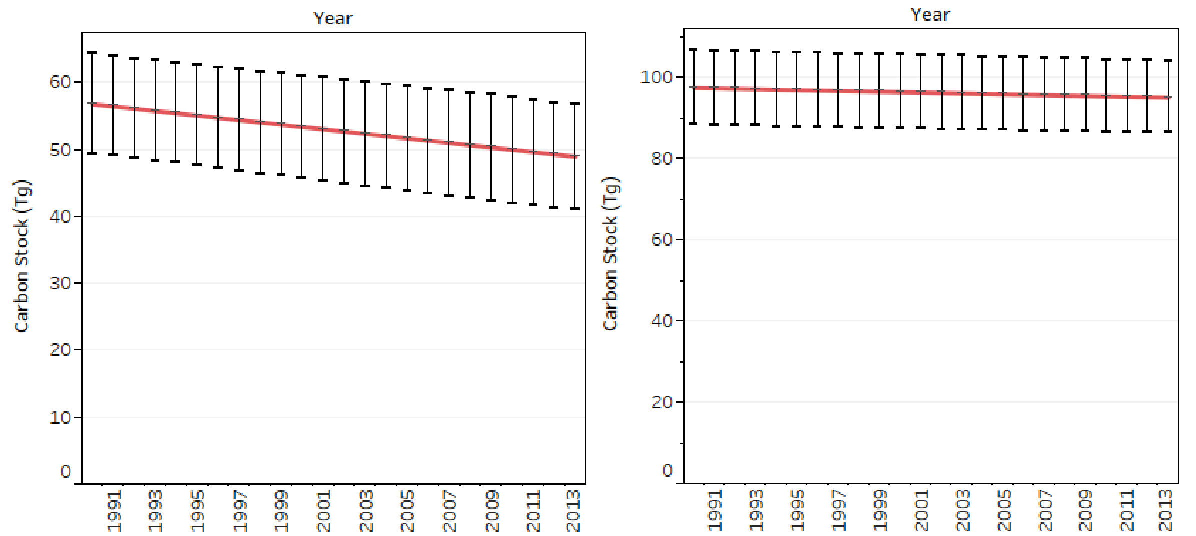
The HLC NF, located in the Rocky Mountains of Montana, covers approximately 1,074,000 ha of forestland. The HLC NF is made up of a distinct series of island mountain ranges, as well as portions of landscapes located along the Continental Divide. For planning purposes, the HLC NF is described in terms of ten “Geographic Areas” (GAs). The Helena and Lewis and Clark NFs were recently combined; however, the data in this report is summarized separately for each Forest due to the organization of available data. Douglas-fir and lodgepole pine forest types are the most abundant across the HLC NF. The carbon legacy of these and other NFs in the region is tied to the history of Euro-American settlement, land management, and disturbances, as described in the NRV report (appendix I).

Baseline carbon stocks and flux

Forest carbon stocks and stock change

According to results of the Baseline Report (U.S. Department of Agriculture, 2015), carbon stocks in the Helena NF decreased from 56.7±7.5 teragrams of carbon (Tg C) in 1990 to 48.9±7.8 Tg C in 2013, a 14 percent decrease in carbon stocks over this period (Figure 1). On the Lewis & Clark NF, carbon stocks decreased from 97.8±9.2 Tg C in 1990 to 94.9±8.9 Tg C in 2013, a 2.44 decrease. For context, the total 143.8 Tg C present on both Forests in 2013 is equivalent to emissions from approximately 115 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 these NF have been stable or decreased from 1990 to 2013 (Figure 1).

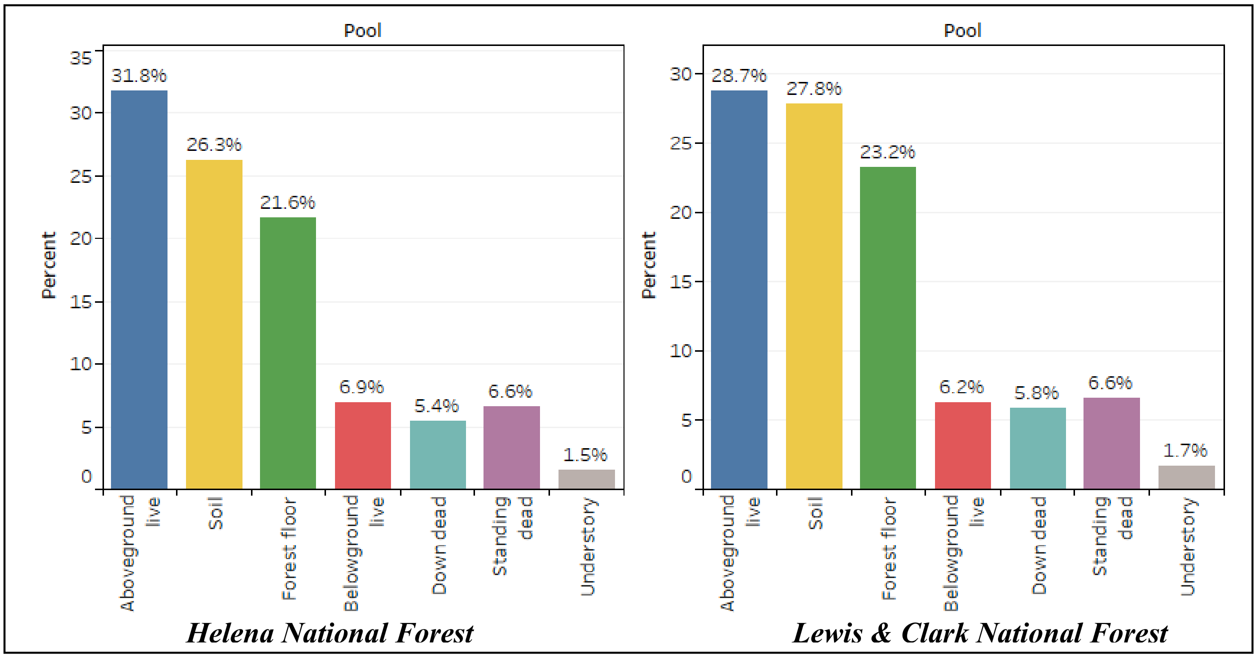
Figure 1. Total forest carbon stocks (Tg) from 1990 to 2013 for the HLC NF, bounded by 95 percent confidence intervals. Estimated using the CCT model.



Helena National Forest *Lewis & Clark National Forest*.

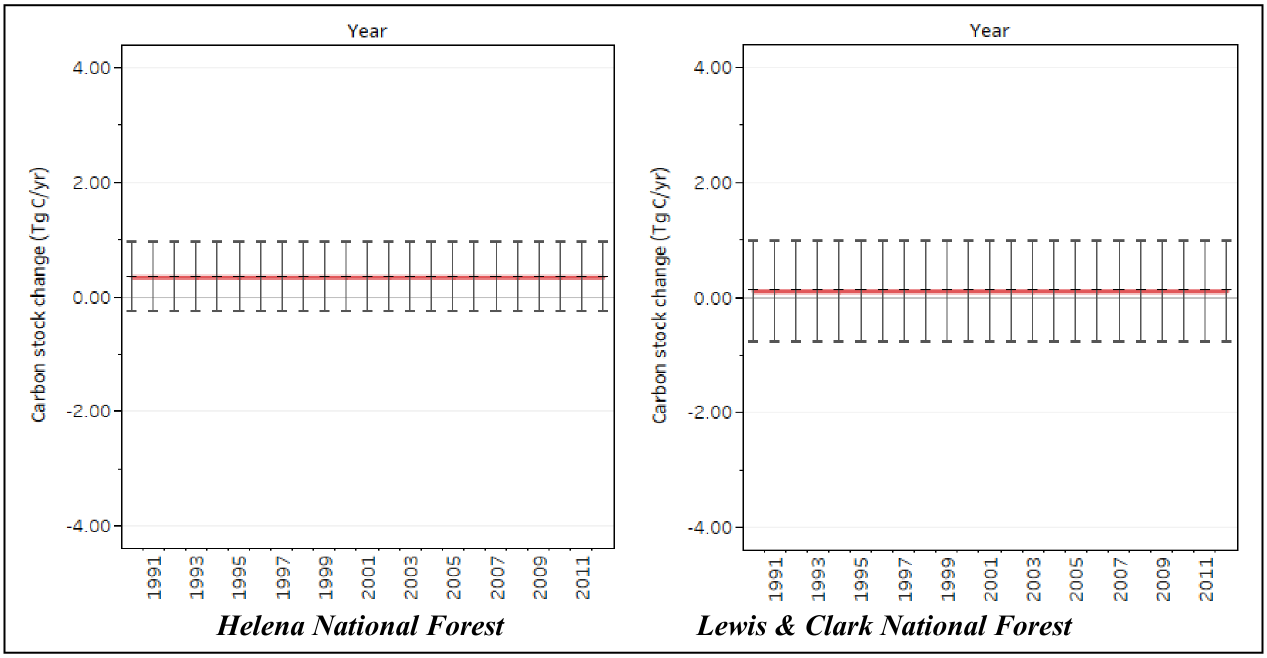
On the Helena and Lewis & Clark NFs, about 32 and 29 percent (respectively) of forest carbon stocks are stored in the aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Figure 2). Soil carbon contained in organic material to a depth of one meter (excluding roots) is the second largest carbon pool, storing another 26 and 28 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 U.S. (Domke et al., 2017).

Figure 2. Percentage of carbon stocks in 2013 in each of the forest carbon pools, for the HLC NF. Estimated using the CCT model



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.

Figure 3, Carbon stock change (Tg/yr) from 1990 to 2012, 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



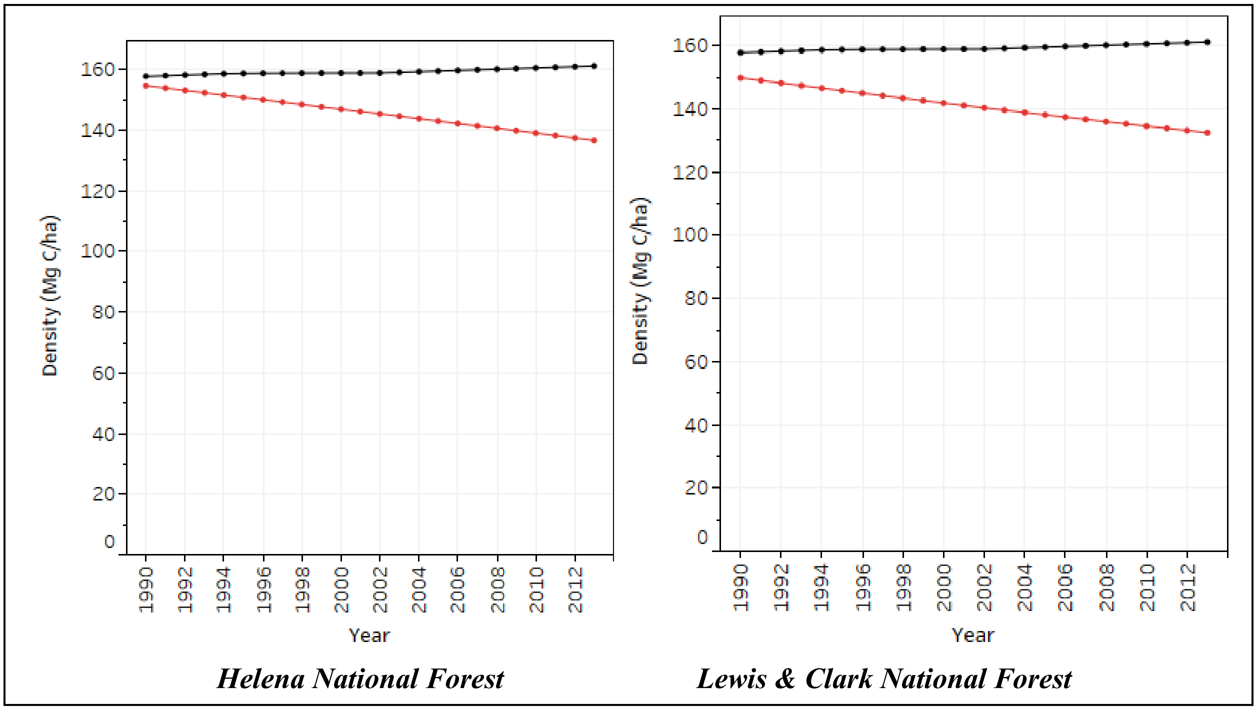
Annual carbon stock changes in the Helena NF were 0.3 ± 0.6 Tg C per year (loss) in both 1990 and 2012; on the Lewis & Clark NF, the annual carbon stock changes were 0.1 ±0.9 Tg C per year (loss) in both 1990 and 2012 (Figure 3). The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Figure 3). However, the trend of decreasing carbon stocks from 1990 to 2013 (Figure 1) over the 23-year period suggests that the HLC NF are stable on the Lewis & Clark NF portion, and a modest carbon source on the Helena NF portion.

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 Lewis & Clark NF has increased from 649,149 ha in 1990 to 716,287 ha in 2013, a net change of 67,138 ha. On the Helena NF, the forested area has decreased slightly from 367,058 ha in 1990 to 357,738 ha in 2013, a net change of -9,320 ha. 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. 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., Heath, Domke, & Nichols, 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 Helena NF and Lewis & Clark NFs, carbon density decreased from about 155 and 150 Megagrams of carbon (Mg C) per ha in 1990 to 137 and 133 Mg C per ha in 2013, respectively (Figure 4). This decrease in carbon density suggests that total carbon stocks may have indeed decreased.

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. In contrast, carbon density in the HLC NF has been declining more than the average for all NF units in the Region 1 (Figure 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.

Figure 4. Carbon stock density (Megagrams per hectare) in the HLC NF (red lines) and the average carbon stock density for all forests in the Recommended Wilderness Analysis Process (black line) from 1990 to 2013. Estimated using CCT.



Helena National Forest *Lewis & Clark National Forest*

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, shown by the error bars (Figure 1, Figure 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. 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 these 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, Smith, & Nichols, 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 (W. 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 clearcut 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 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 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).

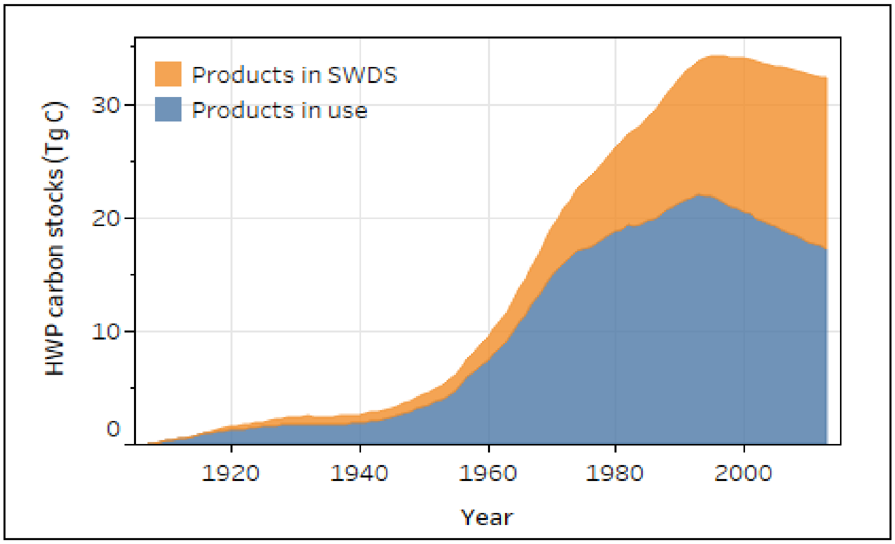
Carbon in harvested wood products

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 (Loeffler et al., 2014; J. E. Smith, Heath, Skog, & Birdsey, 2006). 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 NFs 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 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 product 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 NFs in the Northern Region.

Figure 5. Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in Recommended Wilderness Analysis Process[1]



[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.

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 CO2 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).

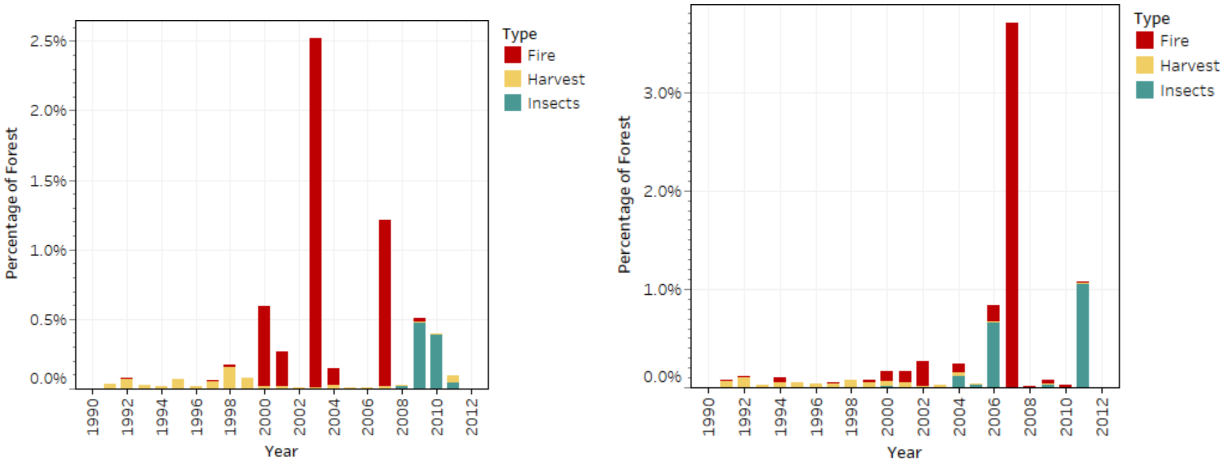
Factors influencing forest carbon

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 (Sean P. 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 HLC NF from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Figure 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 the Helena or Lewis & Clark NFs in any single year from 1990 to 2011. However in 2003, approximately 2.5 percent of the Helena NF burned, while in 2007 about 3.7 percent of the Lewis & Clark NF experienced fire. On the Lewis & Clark NF, wildfire in total affected less than 5 percent (approximately 31,500 ha) of the average forested area during this period (679,799 ha); and insects impacted less than 2 percent (approximately

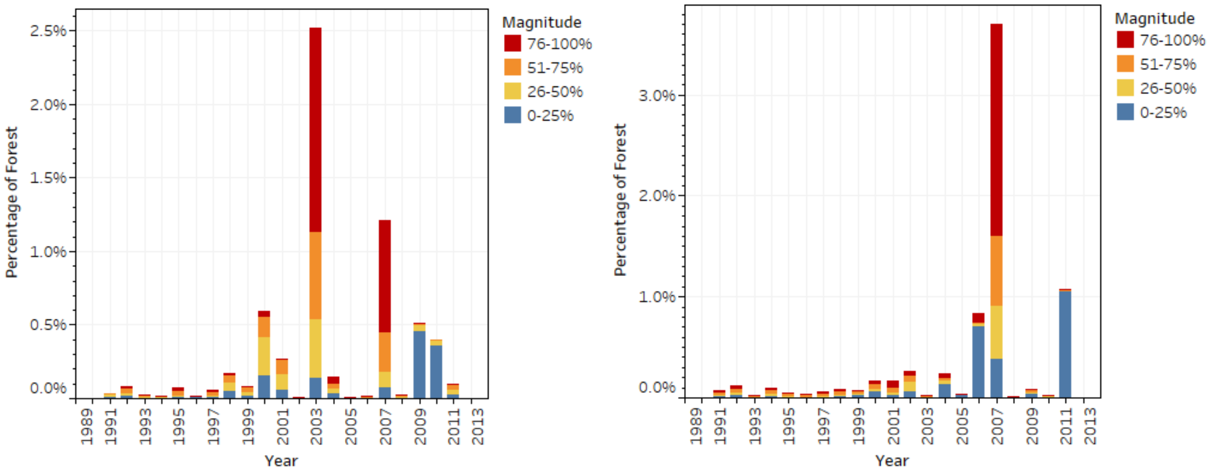
13,200 acres). Wildfire also affected less than 5 percent of the Helena NF from 1990 to 2011, (roughly 17,000 acres of the average forested area of 362,800 ha); and insects affected just under 1 percent, 3,500 acres. Harvest also occurred on both forests but impacted less than 1 percent of either the Lewis & Clark or Helena NFs, 4,495 ha and 3,500 ha respectively. Wildfires resulted in a range of canopy cover loss, including a high proportion of 76-100 percent loss. Insect disturbances, in contrast, generally resulted in less than 25 percent canopy loss (Figure 6b). It is important to note that the impacts of the widespread mountain pine beetle outbreak (2006-2012) may not be entirely reflected in the data sources used.

Figure 6. Percentage of forest disturbed from 1990 to 2011 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.



(a) Helena National Forest

(a) Lewis & Clark National Forest



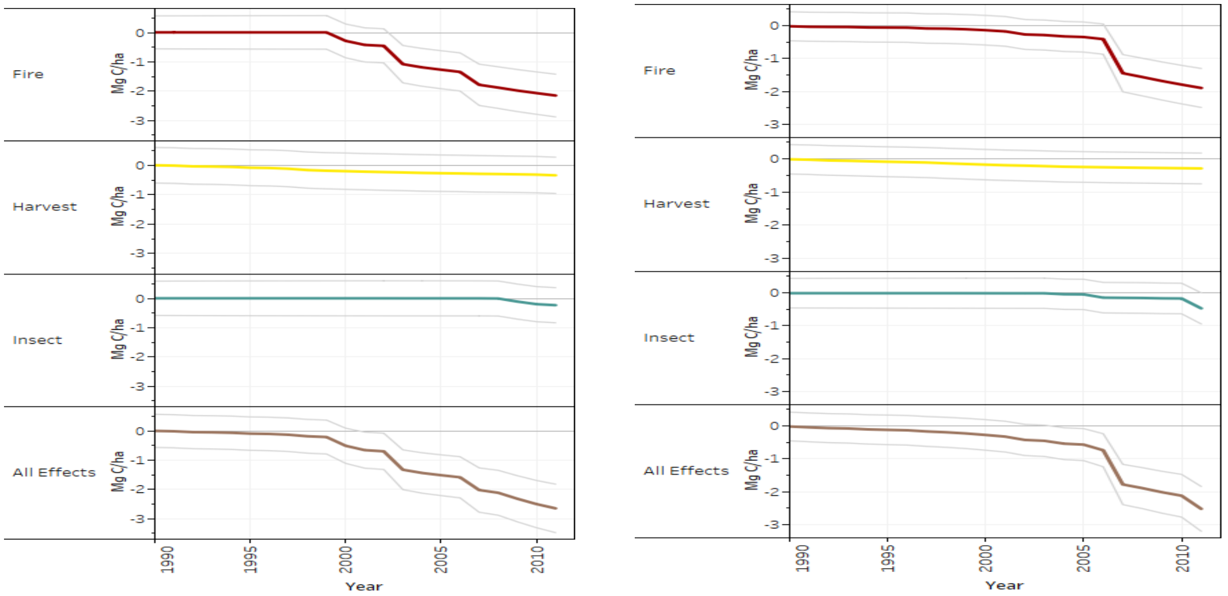
(b) Helena National Forest

(b) Lewis & Clark National Forest

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 & 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 NF 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 (Sean P. Healey et al., 2014).

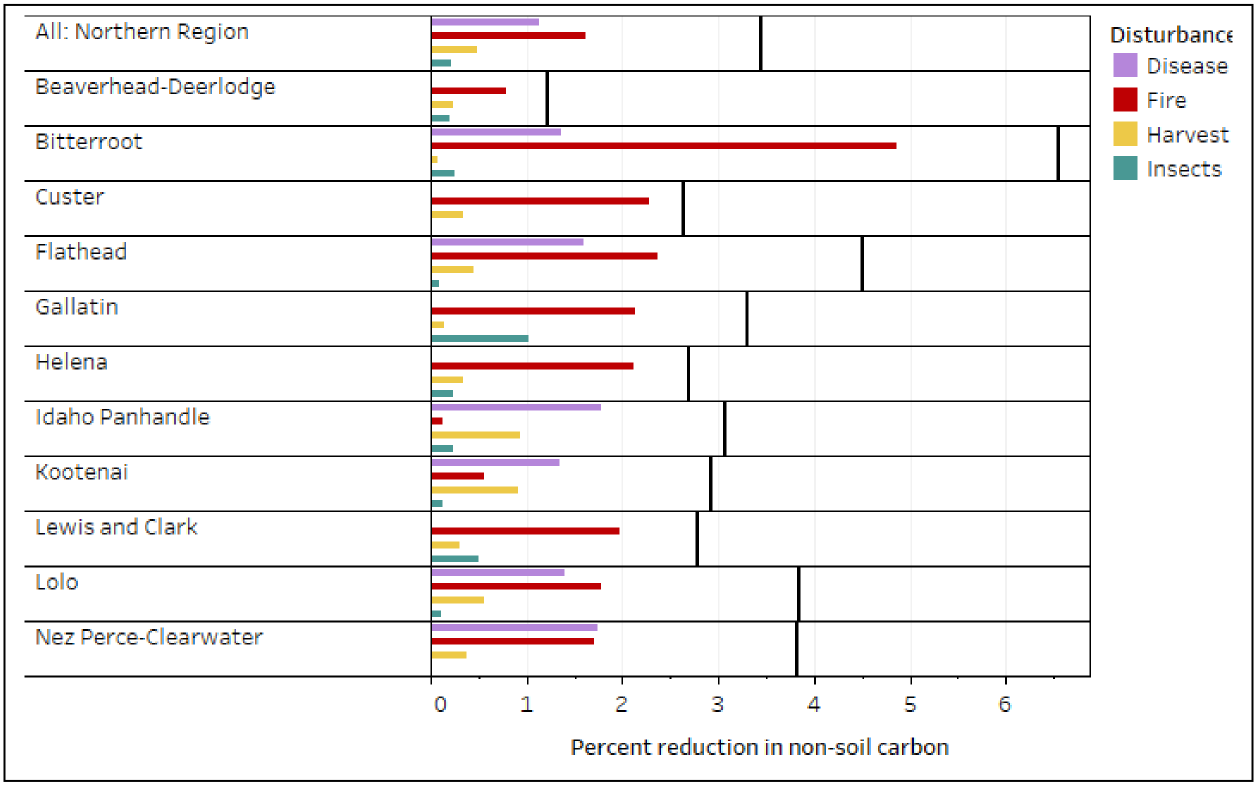
Wildfire on the HLC NF was the primary disturbance influencing carbon stocks from 1990 to 2011 (Figure 7). Wildfire accounted for nearly 82 percent of the total non-soil carbon lost from the forest due to disturbances on the Helena NF, and 76 percent on the Lewis & Clark NF. Losses from insects and harvest made up the remainder of the total non-soil carbon loss, affecting similar proportions(U.S. Department of Agriculture, 2015). The ForCaMF model indicates that, by 2011, the Helena NF contained 2.2Mg 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 (Figure 7). As a result, non-soil carbon stocks in the Helena NF would have been approximately 2.1 percent higher in 2011 if wildfire had not occurred since 1990 (Figure 8). Similarly, the data indicate that, by 2011, the Lewis & Clark NF contained 1.9 Mg 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.

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



Helena National Forest *Lewis & Clark National Forest*

Figure 8. The degrees to which 2011 carbon storage on each NF in the FEIS Appendix J Climate Carbon 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 NFs 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 (Figure 8). Considering all NFs 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 (Dugan et al., 2018; Lippke et al., 2011; McKinley et al., 2011; Skog et al., 2014). 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.

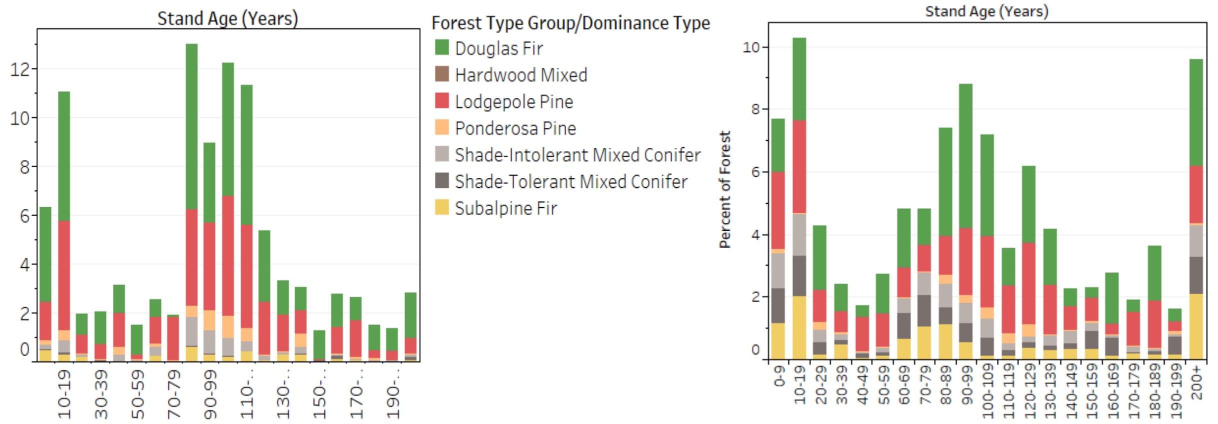
Effects of forest aging

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 (Figure 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 (Y. Pan et al., 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.

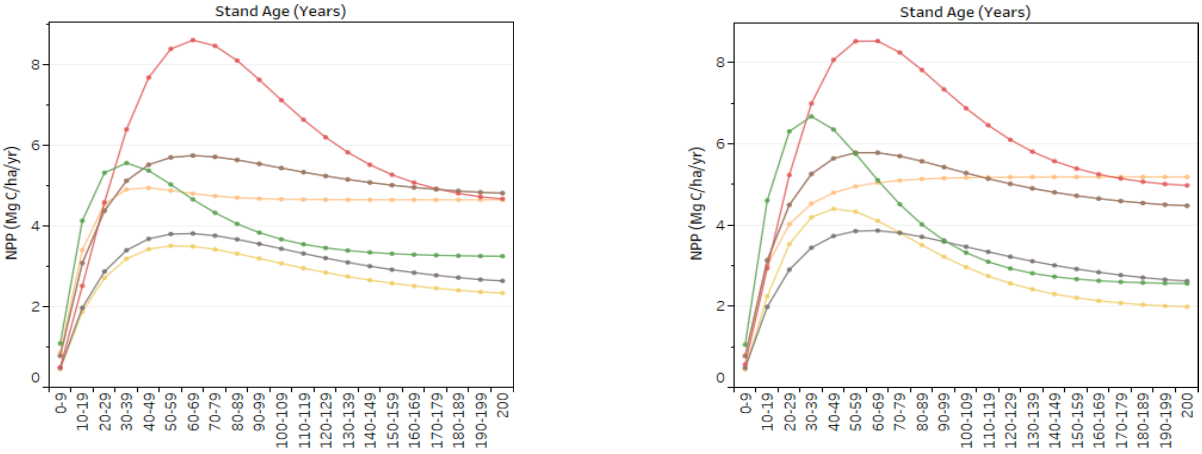
Stand-age distribution for the HLC NF derived from 2011 forest inventory data indicates elevated stand establishment around 1880-1930 (Figure 9a) in both Forests. This period of elevated stand regeneration came after large wildfires in the late 1800s and early 1900s, as well as harvest activities associated with railroad and mining developments, followed by moist climate conditions conducive to forest establishment. Both portions of the HLC NF 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 (He, Chen, Pan, Birdsey, & Kattage, 2012; Pregitzer & Euskirchen, 2004), as indicated by the in net primary productivity-age curves (Figure 9b), derived in part from FIA data.

InTEC model results show that the HLC NF was accumulating carbon steadily at the start of the analysis in the 1950s through the mid-1970s (Figure 10) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old). As stand establishment declined and more stands reached slower growth stages around the 1980s, the rate of carbon accumulation declined (negative slope). Of all the factors modeled in InTEC, forest regrowth and aging following historical disturbances (early 1900s harvesting and land-use change), have collectively been responsible for the majority of carbon accumulation since 1950 in the HLC NF (Figure 10).

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

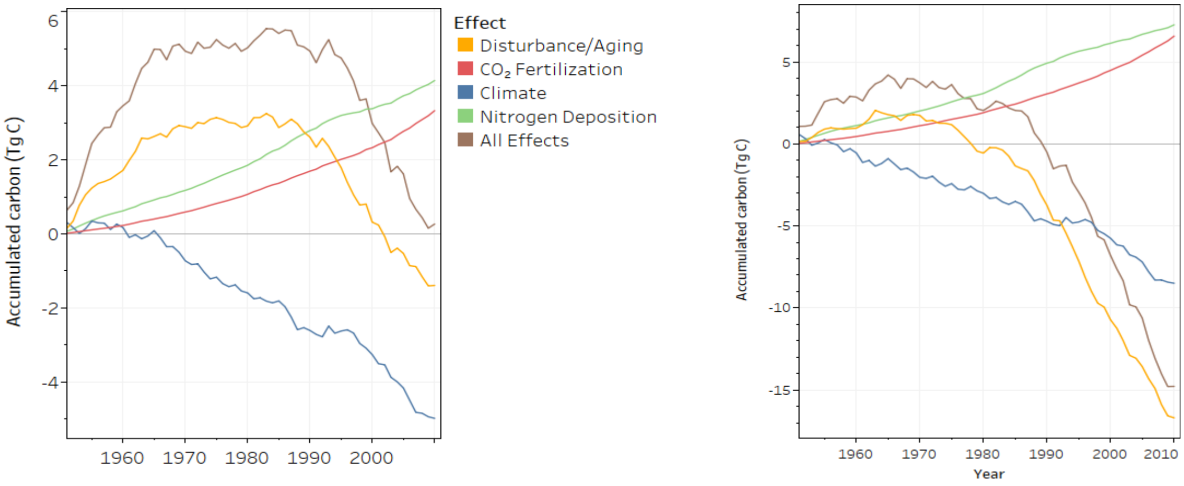


(a) Helena National Forest *(a) Lewis & Clark National Forest*



(b) Helena National Forest *(b) Lewis & Clark National Forest*

Figure 10. Accumulated carbon in the HLC NF due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined for 1950–2011, excluding carbon accumulated pre-1950.



Helena National Forest *Lewis & Clark National Forest*

Estimated using the InTEC model.

Effects of climate and environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO2 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 HLC NF relative to other factors (Fig. 10). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju, Chen, Harvey, & Wang, 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 CO2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen et al., 2000; Yude Pan et al., 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused a significant increase in both CO2 and nitrogen emissions (W. Chen, J. Chen, & J. Cihlar, 2000);(F. M. Zhang et al., 2012). According to the InTEC model, higher CO2 has consistently had a positive effect on carbon stocks in the HLC NF, tracking an increase in atmospheric CO2 concentrations worldwide (Figure 10). However, a precise quantification of the magnitude of this CO2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones, Scullion, Ostle, Levy, & Gwynn-Jones, 2014; F. Zhang et al., 2015). Long-term studies examining increased atmospheric CO2 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 CO2 on forest growth and biomass accumulation, thus warranting additional study (Korner et al., 2005; Norby, Warren, Iversen, Medlyn, & McMurtie, 2010; Zhu et al., 2016).

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the HLC NF (Figure 10). Like CO2, the actual magnitude of this effect remains uncertain. Elevated nitrogen deposition can also decrease growth in some species for a variety of reasons, such as leaching of base cations in the soil, increased vulnerability to secondary stressors, and suppression by more competitive species (Pardo, Robin-Abbott, & Driscoll, 2011). The InTEC model simulated that rates of carbon accumulation associated with nitrogen deposition decreased as deposition rates declined. Overall, the InTEC model suggests that CO2 and nitrogen fertilization only partially offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate.

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 (Sean P. 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, Sitch, Smith, & Hatterman, 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, Stephens, & Fisher, 2015), as well as calibration with observational datasets (F. M. Zhang et al., 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Figure 10). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., NF 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 (F. M. 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.

Carbon on non-forest lands

The HLC NF contains 178,000 hectares of non-forest lands. Grasslands, shrublands, and riparian and wetland areas cover most of these lands, accounting for approximately 15 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 (M. Janowiak et al., 2017; McKinley & Blair, 2008). 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, Briggs, Harnett, & Collins, 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 & 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, Houghton, Mustard, & Hamburg, 2006; Koteen, Baldocchi, & Harte, 2011). The Forest supports relatively low amounts of invasive annual species, such as *Bromus tectorum*, 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., 1998). 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). 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.

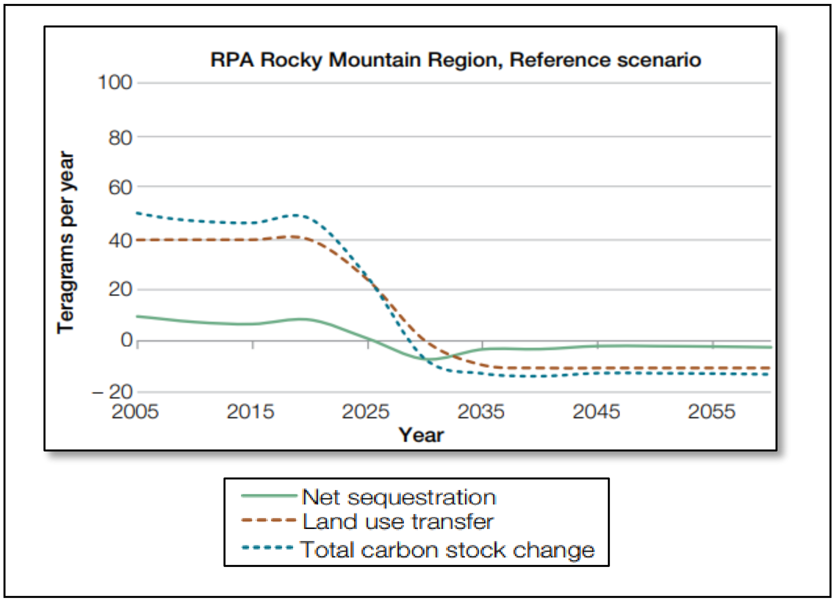
Future carbon conditions

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, 60 and 68 percent of the Helena and Lewis & Clark 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 (Figure 9a). There is also a pulse of stands over 200 years old on the Lewis & Clark NF. If the Forests continues on this aging trajectory, the pulse of middle-aged stands will reach a slower growth stage in coming years and decades (Figure 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 (Figure 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 or disturbances could affect future stand age and forest growth rates (Davis, Hessl, Scott, Adams, & Thomas, 2009; Keyser & Zarnoch, 2012).

For RPA's Rocky Mountain Region (equivalent to a combination of the FS'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 (Figure 11).

Figure 11. Projections of forest carbon stock changes in the North Region[1] for the RPA reference scenario.[2]



1 Equivalent to a combination of the Forest Service's Northern, Rocky Mountain, Intermountain West, and Southwest Region boundaries, but includes all land tenures.
2 Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.

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 these NF 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 (James M. Vose, Peterson, & Patel-Weynand, 2012). Further, disturbance rates are projected to increase with climate change (J. M. 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., 2018b), which encompasses the HLC NF indicates that average warming across the five Northern Region Adaptation Partnership 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 HLC NF (Figure 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 HLC NF 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 HLC NF, the species expected to be most vulnerable to climate change on the HLC NFs 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 (Maria K. 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, Thompson, Gustafson, Liang, & de Bruijn, 2017; Iverson et al., 2017).

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 CO2 fertilization effect is included in modeling (Aber et al., 1995; Ollinger, Goodale, Hayhoe, & Jenkins, 2008; Yude Pan et al., 2009; F. M. Zhang et al., 2012). However, the effect of increasing levels of atmospheric CO2 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 CO2 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 CO2 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.

Summary

The HLC NF may be functioning as a slight carbon source, although the confidence interval overlaps zero. This determination is also unclear because the modeling and uncertainty analyses were split based on the historical Helena and Lewis and Clark National Forests, which are now combined. Forest carbon stocks decreased by about 14 percent between 1990 and 2013 on the Helena NF, and by about 2.44

percent on the Lewis & Clark NF. This trend is also observed in the carbon density data although less pronounced. The negative impacts on carbon stocks have primarily been caused by disturbances and environmental conditions, and have been greater than the gains from forest growth. 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 2.1 and 1.2 percent of non-soil carbon from 1990 to 2011 on the Helena and Lewis & Clark 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 HLC NF 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 HLC NF 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 CO2 and nitrogen deposition, have also influenced carbon accumulation on the HLC NF. Climate conditions along with disturbance and aging have had a negative impact on carbon accumulation since the 1950s. Conversely, increased atmospheric CO2 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 HLC NF 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 CO2 concentrations. However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the HLC NF.

Forested area on the HLC NF 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 HLC NF will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

Additional description of potential effects on carbon

This section provides additional discussion of how the proposed management objectives management direction may potentially affect forest carbon.

All action alternatives provide the same desired conditions for terrestrial ecosystems, and the standards and guidelines that help achieve or maintain those conditions. Using management activities to achieve this desired mix of conditions would enhance the overall ecological integrity of the forest ecosystems, improving their ability to adapt to potential stressors. These activities would help maintain critical ecosystem functions into the future, in part by balancing the maintenance of carbon stocks and rates of carbon uptake.

One desired condition in the 2020 Forest Plan is to provide for old growth on the landscape. Older forest stands are desirable because they provide a range of ecosystem services, including storing more carbon than do younger stands. The current stand-age structure on the HLC NF indicates over half of the forests are middle-aged and older, with a pulse of young stands that have established after large fires in the early 2000's. As the middle-aged forests age, rates of carbon uptake may decline after several decades, although carbon stocks will continue to increase.

Under all alternatives, management activities involving timber harvesting and thinning can result in both long-term carbon storage off site and substitution effects through the use of harvested wood products. Carbon can be stored in wood products for days to centuries, depending on the commodity produced and end use. As more commodities are produced and remain in use, the amount of carbon stored in products increases, creating a cumulative benefit when considered with forest regrowth. Even as more wood products are discarded, the carbon stored in solid waste disposal sites also increases. Harvested wood products can also substitute for more fossil fuel-intensive materials like steel, concrete, and plastic, resulting in a net decline in emissions (Dugan et al., 2018; Gustavsson et al., 2006; Lippke et al., 2011; McKinley et al., 2011). Likewise, harvested wood and discarded wood products can be burned to produce heat or electrical energy, also producing a benefit by substituting for more carbon-producing energy sources. The IPCC recognizes wood and fiber as a renewable resource that can provide lasting climate-related mitigation benefits that with active management can accrue over time (IPCC 2000).

Prescribed fires would also be conducted under all alternatives, which typically target surface and ladder fuels and are less severe than wildfires (Agee & Skinner, 2005), because they are conducted within predetermined conditions. Fire-dependent forest types that are targeted for prescribed burning also typically contain species with thicker bark, which offers protection from heat-related damage. Thus, in some situations, prescribed fires and thinning can lower overstory tree mortality (Hurteau & North, 2009), potentially reducing amounts of carbon emissions that might be emitted if the same area were to burn in a high-severity wildfire (Wiedinmyer & Hurteau, 2010). By promoting natural fire-adapted vegetation through the use of thinning and prescribed burns, thereby reducing the threat of wildfire, all alternatives might create more advantageous conditions to support long-term forest health in a changing climate (adaptation) and reduce carbon emissions and maintain carbon stocks (mitigation) (Intergovernment Panel on Climate Change (IPCC), 2007).

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