United States Department of Agriculture

Administrative Change

Helena – Lewis and Clark National Forest

2021 Land Management Plan

The Helena – Lewis and Clark National Forest is in central Montana and includes approximately 2,883,227 acres in portions of the following counties: Broadwater, Cascade, Chouteau, Fergus, Gallatin, Glacier, Golden Valley, Jefferson, Judith Basin, Lewis and Clark, Meagher, Park, Pondera, Powell, Sweet Grass, Teton, and Wheatland.

Forest Service Region 1 [April 2025]

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List of Acronyms

EIS	Environmental Impact Statement
HLC NF	Helena-Lewis and Clark National Forest
USDA	United States Department of Agriculture
USFS	United States Forest Service

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Overview

The Helena-Lewis and Clark National Forest is making minor administrative changes to the 2021 Land Management Plan. These changes are minor in the context of the 2.8+ million-acre forest and do not alter conclusions made in the programmatic EIS supporting the land management plan. The administrative change is summarized below. This change will be effective as of April 4, 2025.

Change to be made

Appendix J of the 2021 Land Management Plan FEIS

The Forest Carbon Assessment portion of Appendix J (beginning on page 4) was updated in March of 2025. This report is periodically updated to incorporate advances in data and analytical methods and represents the best information, science, and data available at the time of each update cycle.

Contact Person

For additional information concerning these changes, please contact Deborah Entwistle, Planning and Resources Staff Officer at Helena – Lewis and Clark National Forest- Forest Supervisor's Office, 2880 Skyway Drive, Helena, MT or by phone at (406) 449-5201.

Signature and Date

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Helena-Lewis and Clark National Forest

2021 Land Management Plan FEIS

Appendix J. Climate and Carbon, Supplemental Information

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; Halofsky et al. 2018b). These publications, and the references cited therein, represent the current state of the science on climate change in the region and on the Helena-Lewis and Clark National Forest.

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. 2018a; 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 (Halofsky et al. 2018a; Halofsky et al. 2018b).

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 Helena-Lewis and Clark National Forest (Halofsky et al. 2018a; Halofsky et al. 2018b). The Helena-Lewis and Clark National Forest 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
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 2021 Land Management Plan and Environmental Impact Statement 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 Environmental Impact Statement describes specific future expectations for temperature, precipitation, and potential resource effects based on information found in Halofsky et al. (2018). 2021 Land Management 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 and Stephenson 2015).

As noted by Halofsky and Others (2018), a warming climate will rarely be the direct agent of change for terrestrial vegetation on the Helena-Lewis and Clark National Forest. 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 mega disturbances, regeneration failures, or shifts to novel ecosystems may occur on the Helena-Lewis and Clark National Forest. 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 et al. 2015; Anderegg et al. 2013; Wong and Daniels 2016).

To the extent feasible, the Simulating Patterns and Processes at Landscape Level Scales (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 et al. 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; Halofsky et al. 2018c; Holling 1973; 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 and Stewart 2003).

For the development of the programmatic management direction in the 2021 Land Management 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 Helena-Lewis and Clark National Forest. Rather than attempting to predict and quantify the unknowable, the 2021 Land Management Plan prepares the vegetation on the Helena-Lewis and Clark National Forest 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 Forest Service control, as well as Forest Service responses to events that are outside Forest Service 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 Helena-Lewis and Clark National Forest, 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 natural range of variation (see appendix H of the Environmental Impact Statement). 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 et al. 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 2021 Land Management 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 mega disturbances 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, Halofsky et al. 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 2021 Land Management 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 non-native 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.

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Forest Carbon Assessment[1]

Helena-Lewis and Clark National Forest

Northern Region

Prepared By: Tanya Murphy, Forest Silviculturist

For: 2021 Helena-Lewis and Clark Land Management Plan

Date: October 17, 2024 (*Updated March 17, 2025, to reflect 2025 Executive Orders*)

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Executive Summary

Total ecosystem biogenic carbon in the Helena-Lewis and Clark National Forest has decreased in recent decades. Carbon density, the carbon stocks by unit area, in the Helena-Lewis and Clark National Forest decreased by 9.53 Mg C per ha from 2005 to 2023. Total ecosystem carbon stocks decreased by 3.33 percent over this period. Soil biogenic carbon values have high uncertainty because of data and modeling limitations and are likely underestimated.

Forest stand development dynamics, myriad disturbances, climatic patterns, and environmental fluctuations have impacted ecosystem carbon uptake and storage in the Helena-Lewis and Clark National Forest. Forest types are mainly Douglas-fir, lodgepole pine, and fir/spruce with lesser quantities of ponderosa pine, limber pine, whitebark pine, and aspen/hardwoods. Stand ages range from 0 to 200+ years old, with about 59 percent of the forest greater than 80 years old and about 20 percent of stands less than 30 years old. Forest carbon stocks decreased in recent decades. From 1990 to 2011, the primary disturbance types influencing carbon uptake and storage, excluding soil carbon, were fire, insects, and harvest. Carbon stocks, excluding soil carbon, in Helena-Lewis and Clark National Forest would have been approximately 2.60 percent higher in 2011 if fire, insects, and harvest had not occurred since 1990.

Disturbances such as fire and insects are likely to increase, with consequent effects on forest carbon. Carbon uptake and storage in the Helena-Lewis and Clark National Forest may be increasingly vulnerable to numerous threats related to climate change and its interactions with forest patterns and processes. The Helena-Lewis and Clark National Forest will continue to serve an important role in taking up and storing carbon, contributing to its holistic approach to land management.

1.0 Overview

1.1 Introduction and Consistency with Relevant Laws, Regulations, and Policy

This carbon assessment report focuses solely on biogenic carbon, hereafter 'carbon.' This report provides a framework to support carbon reporting at the national forest scale. Results and information are derived from a variety of models, data sources, and qualitative analyses. It describes how carbon dynamics relate to environmental factors and human and natural disturbances. It also considers projected future changes in carbon under multiple changing climate scenarios and associated socioeconomic pathways. The stock data sampling design and models whose results are described here were developed for use across broader areas such as the national forest. This allows for direct comparison among landscapes (national forests) that may vary in carbon uptake, storage capacity, and disturbance history. This report provides a broader context for estimating carbon gains or losses at finer scales such as the project level, but direct interpretation of results at these finer scales is not advised. The USDA Forest Service uses carbon assessments at the scale of the national forest to inform project-level carbon analysis in a consistent, efficient, and unbiased manner.

1.2 The Carbon Cycle in Forest Ecosystems

Forests play an important role in the global carbon cycle. Through photosynthesis, plants absorb carbon dioxide from the atmosphere and store some of it as carbon: this process is referred to as carbon uptake. The rate of carbon uptake is commonly measured as the net amount of carbon uptake per hectare per year. The carbon stock is the amount of carbon stored at any one time. Carbon is stored in different reservoirs or zones, called carbon pools. Forest carbon can be categorized into seven carbon pools: aboveground live tree, belowground live tree, understory, standing dead, downed dead wood, litter, and soil organic carbon. These seven pools together comprise the biologically sourced carbon (biogenic carbon) considered in forest management. Carbon density quantifies forest carbon stocks per unit area. The stability of carbon storage, called the residence time, quantifies the duration carbon is stored in each pool.

The biogenic carbon cycle describes the movement of carbon among carbon pools and between these pools and the atmosphere. Forest carbon stocks are dynamic, with carbon frequently transferring among pools. When plants remove carbon from the atmosphere, they store some of this carbon in live aboveground plant biomass. Much of this carbon remains in the aboveground live tree pool. Some carbon rapidly moves into the belowground live tree pool, where plants use it to build roots and acquire soil nutrients. Carbon stored in live tree and understory pools may migrate via decomposition and disturbance into the standing dead, downed dead wood, litter, and soil carbon pools over time or be emitted to the atmosphere. The balance of carbon storage versus emission to the atmosphere determines the total amount of forest carbon, which fluctuates over longer time periods.

1.3 Principles of Carbon Stewardship

Carbon stewardship: Carbon stewardship involves: 1) the intentional analysis of the effects of management actions on carbon uptake, storage, and stability; 2) balancing carbon benefits with other ecosystem benefits; 3) considering landscape-scale ecosystem function and resilience; 4) enhancing net ecosystem carbon uptake and storage; and 5) avoiding emissions from disturbance or tree mortality. These factors contribute to carbon stability.

Carbon stewardship principles align with the Forest Service's holistic approach to land management (Janowiak et al. 2017), which supports its multi-use mission to steward national forests and grasslands for the benefit of current and future generations. Therefore, carbon stewardship would not maximize biogenic carbon storage at the expense of ecosystem health or habitat.

Carbon stewardship requires a broad definition because ecosystem carbon responses to land management actions may differ across site conditions and ecosystems. Evaluation of the following components of carbon stewardship can help managers determine whether proposed actions can reasonably be expected to provide carbon benefits over the life of the project.

Carbon stabilization: Carbon stabilization involves assessing the risk of either carbon emissions or reduced uptake and storage capacity from natural disturbance or biotic stressors in an ecosystem across spatial and temporal scales and taking actions to increase or maintain the residence time, or stability, of carbon in the ecosystem. Forest managers may undertake actions in response to assessments indicating that current conditions are out of alignment with ecosystem dynamics and impinge on carbon stability. Projects in alignment with carbon stewardship actions may involve reducing carbon stocks in the short term to restore and maintain ecosystem conditions in the long term that are consistent with the natural range of variation or that reduce threats to ecosystems from climate change. For example, reducing tree densities in overstocked stands will decrease carbon in the short term but may lower the risk of carbon losses from mortality and wildfire, thus resulting in greater stability and a longer landscape-level residence time of carbon. Carbon stabilization also involves evaluation of carbon residence times, which vary among pools and according to environmental conditions. Aboveground live tree, belowground live tree, standing dead, and downed dead wood carbon stocks have residence times of decades to centuries. Litter carbon stocks have shorter residence times, of months to decades.

Climate change adaptation: Actions that provide adaptation benefits through reduced risk of unintended climate impacts can provide carbon benefits through avoided carbon emissions. Some disturbances may also decrease carbon uptake through reductions in plant growth rates and related carbon uptake and storage. While not all adaptation actions provide carbon benefits, many actions, such as planting climate-resilient, productive species or genotypes, address threats to ecosystem health while sustaining or improving ecosystem carbon uptake and storage capacity.

1.4 Carbon Considerations in Forest Ecosystems

Forests are dynamic ecosystems that undergo fluctuations in carbon as forests establish, grow, die, and regenerate. Forest plants remove carbon dioxide from the atmosphere and store some of it as biomass. Forest managers, policymakers, and scientists typically consider that 50 percent of wood biomass in trees is carbon. Carbon uptake and storage from the atmosphere help to modulate greenhouse gas concentrations. The rate of carbon uptake by plants from the atmosphere is influenced by many factors, including natural disturbance, management, forest age, successional pathways, climate, environmental factors, and availability of water and nutrients.

The long-term capacity of forest ecosystems to uptake and store carbon depends in large part on their health, productivity, resilience, and adaptability to changing conditions. Major factors influencing the long-term capacity of forest ecosystems to gain and store carbon include: 1) forest age: younger forests generally have higher rates of carbon uptake and storage, while older forests have greater carbon stocks; 2) forest structure and diversity: forests with more complex structure are generally more resilient and better able to acclimate and adapt to changing conditions; 3) disturbance regimes: disturbance intensity and frequency vary across forest ecosystems, from individual tree-based gap dynamics to landscapes characterized by large, high severity, stand-replacing wildfires at low to high frequencies; a forest's disturbance dynamics will affect its carbon uptake and storage rates and total carbon stocks over time; and 4) land cover type changes: across all ownerships in the conterminous United States, within the land sector, forest land has the greatest capacity to gain and store carbon. Conversion of forest land to non-forest land is the largest source of carbon losses (Vance 2018).

1.5 Forest Management for Ecological Integrity and Climate Resilience

Forest management for ecological integrity and climate resilience can help mitigate increasing atmospheric carbon dioxide concentrations while aligning with forest adaptability objectives (Ontl et al. 2020; Kaarakka et al. 2021). Management actions can address vulnerabilities of forest ecosystems to climate change, chronic stressors, or other disturbances such as insect outbreaks or drought (Goodwin et al. 2020) that put sustained forest productivity at risk of decline with consequences to carbon stewardship and stability. Management can also address effects of previous land uses, such as past clearing with subsequent forest regrowth or fire suppression resulting in dense stands. These past actions may reduce carbon stability via simplified species composition or structural diversity, as well as modify disturbance regimes.

Many management activities may have short-term carbon emissions but yield long-term carbon benefits through enhancing forest resiliency and, therefore, carbon stabilization. For example, timber harvest aimed at removing hazardous fuels and reducing live tree density can yield short-term carbon emissions but ultimately reduce risk of high severity wildfire, yielding long-term increases to carbon stability (Krofcheck et al. 2019). For projects involving forest harvest, some removed carbon can be stored for long time periods if converted to harvested wood products. Woody biomass for energy production can also decrease greenhouse gas emissions if it is substituted for more fossil fuel-intensive energy sources (Sathre and O'Connor 2010; D'Amato et al. 2011; Oliver et al. 2014). Management activities enhancing species, structural, or age-class diversity can also result in long-term carbon stabilization (Puhlick et al. 2020; Crockett et al. 2023). The use of silvicultural tools such as removing hazardous fuels and reducing live tree density in stands outside the natural range of variation can increase resiliency to disturbance. Timber harvest initially reduces the amount of carbon in a forest stand, but carbon may be transferred to harvested wood products or used for energy production, while increasing longer-term forest productivity and health (Sathre and O'Connor 2010; D'Amato et al. 2011; Oliver et al. 2014). Treatments may have benefits such as reducing the risk of wildfire and tree mortality, thereby contributing to long-term carbon stewardship (Krofcheck et al. 2019). National forests tend to remain in the forest land cover type, and, thus, may provide a buffer against land use change and subsequent carbon losses. Factors such as atmospheric carbon dioxide concentrations, climatic variability, and the availability of growth-limiting forest nutrients such as nitrogen can also influence carbon dynamics (Caspersen et al. 2000; Pan et al. 2009).

1.6 National Role of Forest Management in Climate Change Mitigation

Forest land harvested wood products, woodlands, and urban trees in settlements, both individually and collectively, represent a net greenhouse gas sink (reduction in atmospheric greenhouse gases by storing them) over the 1990-2020 time series (2022 Resource Update, USDA Forest Service Northern Research Station). These sectors, combined within the land sector, represent the largest net carbon sink in the United States, offsetting the equivalent of more than 12.4 percent of total gross greenhouse gas emissions in 2023 (US EPA 2023; Domke et al. 2023). Interannual variability in greenhouse gases was driven primarily by disturbance (e.g., fire, insects/disease, harvest), land conversion (e.g., forest land converted to cropland and settlements, reforestation/afforestation), and changes in harvested wood products stocks in use and transfers to solid waste disposal sites (US EPA 2023; Domke et al. 2023). Forest land harvested wood products, woodlands, and urban trees in settlements collectively showed a net increase in carbon stocks in 2020.

2.0 About the Helena-Lewis and Clark National Forest Carbon Assessment

2.1 Report Description

This report relies on models and data to characterize carbon dynamics at the national forest level. In general, these forest-level analyses use Forest Inventory and Analysis data in combination with validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon. This report is periodically updated to incorporate advances in data and analytical methods and represents the best information, science, and data available at the time of each update cycle.

This carbon assessment describes a suite of results, some at the national forest level and others at the USDA Forest Service region level. At the national forest level, this report characterizes carbon stocks and fluxes, drivers of non-soil carbon dynamics, and stand dynamics. Estimates of aboveground live tree, belowground live tree, understory, standing dead, downed dead wood, litter, and soil organic carbon are estimated for the years 2005 to 2023 for key forest ecosystem carbon pools using Forest Inventory and Analysis data. The impact of disturbances, including harvest, are estimated for 1990 to 2011 using the Forest Carbon Management Framework (ForCaMF; Birdsey et al. 2019; Healey et al. 2014; Raymond et al. 2015; Healey et al. 2016). The long-term, relative effects of disturbance and other factors on the rate of carbon accumulation for the years 1950 to 2011 are estimated using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (InTEC; Chen et al. 2000; Zhang et al. 2012). The most recent Forest Inventory and Analysis inventories were used to analyze stand-age structure (10-year age bins) and net primary productivity by forest type group. At the USDA Forest Service region level, this report characterizes carbon storage in harvested wood products through 2013 and projects potential future climate change impacts using Climate Vulnerability Assessments (CVAs) and Resource Planning Act (RPA) Assessments.

2.2 Helena-Lewis and Clark National Forest Description

The Helena-Lewis and Clark National Forest, located in the Rocky Mountains of central and north-central Montana, encompasses roughly 1,173,588 hectares (ha) (<2.9 million acres) of National Forest System land with approximately 1,050,817 ha supporting forest (Table 1). Prior to the December 11, 2015, administrative consolidation, this land mass was administered as two individual national forests: Helena National Forest and Lewis and Clark National Forest. The Helena-Lewis and Clark National Forest spans 17 counties and is made up of a distinct series of island mountain ranges bisected by the Continental Divide and Missouri River. The Forest is administered by two Forest Supervisor's offices located in Helena and Great Falls and six ranger districts: Lincoln, Helena, Townsend, Judith-Musselshell, Rocky Mountain, and Belt Creek-White Sulphur Springs. For planning purposes, the Helena-Lewis and Clark National Forest is described in terms of ten 'geographic areas' with unique ecological and social context. The southwest portion (30,973 acres) of the Elkhorns geographic area falls within the Beaverhead-Deerlodge National Forest.

According to the 2021 Forest Plan (USDA Forest Service 2021a), Douglas-fir and lodgepole pine forest types are the most abundant, representing 29 and 27 percent of land area respectively, across the Helena-Lewis and Clark National Forest. Grass and shrub cover types represent 14 percent of the forest's vegetation. Spruce, subalpine fir, ponderosa pine, limber pine, whitebark pine, and aspen/hardwood comprise about 25 percent. Cover type distribution is variable within and between the geographic areas. The carbon legacy of this and other national forests in the Northern Region is tied to the history of American Indian use, Euro-American settlement, disturbances, and land management, as described in the 2021 Forest Plan Appendix I Natural Range of Variation Analysis and Results (USDA Forest Service 2021c).

Human occupancy and use of the area managed by the Helena-Lewis and Clark National Forest has occurred over an 11,000 year or more time span. Central Montana was the ancestral homeland and travel way of various indigenous American Indian cultures: the most prominent groups with an active culture and unbroken tie to the area are the Blackfeet, Gros Ventre, Salish, Shoshone, and Kootenai (Aaberg et al. 2007; Knight 1989; Deaver 1995). These cultures hunted; fished; gathered plants for food, medicinal purposes, and fuel; used trees for lodges and travois; implemented anthropogenic burning; and created trails connecting western Montana to the bison country of central and eastern Montana. The Forest's topography and seasonal timing of resource availability, along with acquisition of horses in the late 1700s, influenced indigenous movement and resource exploration.

The Lewis and Clark Corps of Discovery in 1805 brought a dramatic change to American Indian culture and movement due to implementation of the reservation system. Following the Corps' 1806 departure, central Montana began to experience steamboat travel, fur trappers and traders, explorers, missionaries, ranching, and mining. The discovery of gold in and around Helena, Montana, ushered in a wave of settlement and land use that transformed the area's natural and political landscape (Beck 1989). Makeshift towns and an emerging transportation system were established. Accessible trees were used for rail ties or cordwood, and extensive mining created an on-going demand for timber. Today, thousands of mining features can be found in central Montana with their associated ecological and social implications. Open-range cattle and sheep use dominated the rural landscapes in the 1800s. The rich agricultural and cattle industry present in low elevation valley floors firmly established by the late 1860s and flourished with the arrival of the railroads (Beck 1989). Due to conservation-related concerns on public lands, the Forest Reserve Act of 1891 established the Elkhorn, Big Belt, Little Belt, Snowy Mountains, and Little Rockies Forest reserves. In 1908, these reserves were incorporated into the Helena National Forest and the Lewis & Clark National Forest. Central Montana in the 20th century experienced devastating fires, increased access to the forest, a change of forest landscapes from intensive resource extraction to support a booming post-war economy. Modern vegetation management (since 1940) has influenced composition and structure on a relatively small proportion of the Helena-Lewis and Clark National Forest.

Wildfire is the most influential disturbance on the Helena-Lewis and Clark National Forest, as lightning storms are common. Island mountain ranges (mountain ranges that exist in total or almost total isolation from a larger change of ranges), like many of the geographic areas on the Helena-Lewis and Clark National Forest, support distinct fire regimes (Murray et al. 1998). The protruding prominence of these ranges may attract a greater frequency of lighting-ignited fire, and more fire can result from the adjacency to steppe ecosystems where grass fires are common (Murray et al. 1998). Coincident with a warm dry climate period, numerous reports indicate that large acreages on the Helena-Lewis and Clark National Forest burned in the late 1800s in many of the geographic areas (Barrett 2005; Janssen 1949; Stickney 1907, Hatton 1904; Hatton 1904b; USDA Forest Service 1926; Losensky 1993, Murray et al. 1998; Ayers 1904). Some early settlers and surveyors recognized the importance of forest cover not only for timber value but to protect water resources needed for downstream uses (Griffith 1904; Hatton 1904b). When the forest reserves were established in the early 1900s, fire suppression was considered necessary to protect resources. Fire suppression along with cooler, wetter climate conditions and grazing uses contributed to an era of fire exclusion that was prominent from that time until the 1980s. At that point, warmer and drier conditions began to prevail and, along with a build-up of fuels in some areas, contributed to an increase in the acreages burned.

Insects and diseases also historically played an important role in shaping vegetation. Climate and weather play a major role in controlling insects, as does availability and quality of food and breeding habitat. Historically, insect populations would periodically build to high levels under favorable climatic and host conditions; cool climate conditions were not conducive to outbreaks. The Helena National Forest experienced mountain pine beetle population increases in 1919 through 1944. A recent mountain pine beetle outbreak, with the main pulse of tree mortality occurring between 2007 and 2011, impacted the majority of pine forests (lodgepole, ponderosa, limber, and whitebark pine) across the Helena-Lewis and Clark National Forest (Milburn 2015). Specifically on the western part of the forest, roughly two-thirds of the lodgepole pine forests were impacted with the most common change being a reduction in tree density.

3.0 Helena-Lewis and Clark National Forest Carbon Stocks and Fluxes

3.1 Carbon Stocks and Stock Change

Total carbon stocks in the Helena-Lewis and Clark National Forest decreased from 228.35 teragrams of carbon (Tg C) in 2005 to 220.75 ± 12.7 Tg C in 2023, a net decline of 7.6 Tg or 3.3 percent (Fig. 1; see Box 1 for carbon unit description) (USDA Forest Service 2015d). This estimate incorporates carbon stocks for all pools, including live and dead vegetation and soils. The total decline in carbon stocks in the Helena-Lewis and Clark National Forest (7.6 Tg) from 2005 to 2023 (Fig. 1) is less than the confidence interval around the carbon stock estimate in 2023 (± 12.7); therefore, over the 19-year period, forest lands in the Helena-Lewis and Clark National Forest have been stable or potentially a small carbon source.

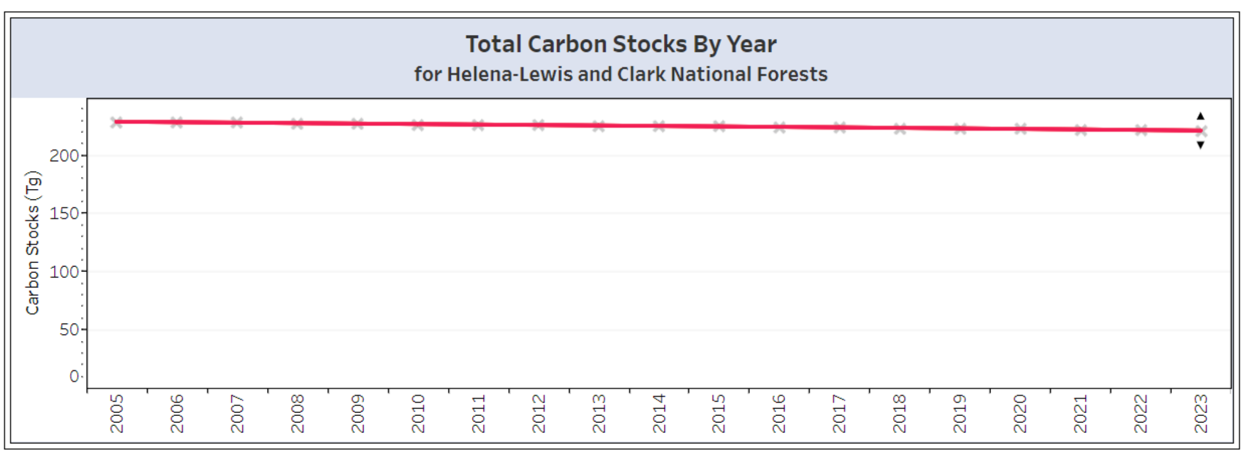


Figure 1. Total forest carbon stocks (Tg) for the years 2005 to 2023. Triangles represent a 95% confidence interval (only available for 2023).

Live and dead vegetation may be a substantial proportion of total carbon stocks in the Helena-Lewis and Clark National Forest. Live vegetation, including aboveground live trees, belowground live trees (roots), and understory vegetation comprise about 20.5 percent of the carbon in the Helena-Lewis and Clark National Forest (Fig. 2). Standing dead wood, downed dead wood, and litter together make up about 20.9 percent of total forest carbon there. The high percentage in the dead wood pool is due to competition induced mortality, fire, and insects.

In conifer forests of the Northern Region, the nature of the litter and the cold limited environment leads to buildup of needle and woody material whereby decomposition works from the bottom up (DeLuca et al. 2019). It is important to note that the speed of decomposition and integration of material into the soil depends on the climate for microbes to thrive, the quality of the litter, and the suite of the microbial composition (DeLuca et al. 2019; Pierson et al. 2021). Adequate water and temperature impose strong controls on decomposition.

Box 1. Carbon 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, million metric tonnes	Mt, MMt		10^{12}	Teragram	Tg

1 hectare (ha) = 0.01 km^2 = 2.471 acres = .00386 mi^2
1 Mg carbon = 1 tonne Carbon = 1.1023 short tons (U.S.) carbon
1 General Sherman Sequoia Tree = 1,200 Mg (tonnes) carbon
1 Mg carbon mass = 1 tonne carbon mass = 3.67 tonnes CO_2 mass
A typical traditional combustion engine passenger vehicle emits about 4.6 tonnes of CO_2 per year

In the Helena-Lewis and Clark National Forest, approximately 58.7 percent of forest carbon is stored in mineral soils (Fig. 2). This is a modeled estimate using data from Forest Inventory and Analysis soil samples and reflects the total soil organic carbon in the soil profile (Domke et al. 2016; Domke et al. 2017; Domke et al. 2023). The current uncertainty associated with the soil carbon estimate is unknown but includes both model uncertainty and sample uncertainty. In most temperate forest ecosystems, soils represent the largest ecosystem carbon pool (Walters et al. 2023) and offer, through their protection and management, an opportunity to mitigate rising atmospheric carbon dioxide concentrations (Bossio et al. 2020).

Future disturbance events may result in changes to the values in carbon stocks and flux among pools. For example, high severity fire can decrease aboveground live stocks and increase dead wood stocks. Some dead material may be transferred via disturbance to the soil carbon pool (Rothstein et al. 2018; Santos et al. 2017).

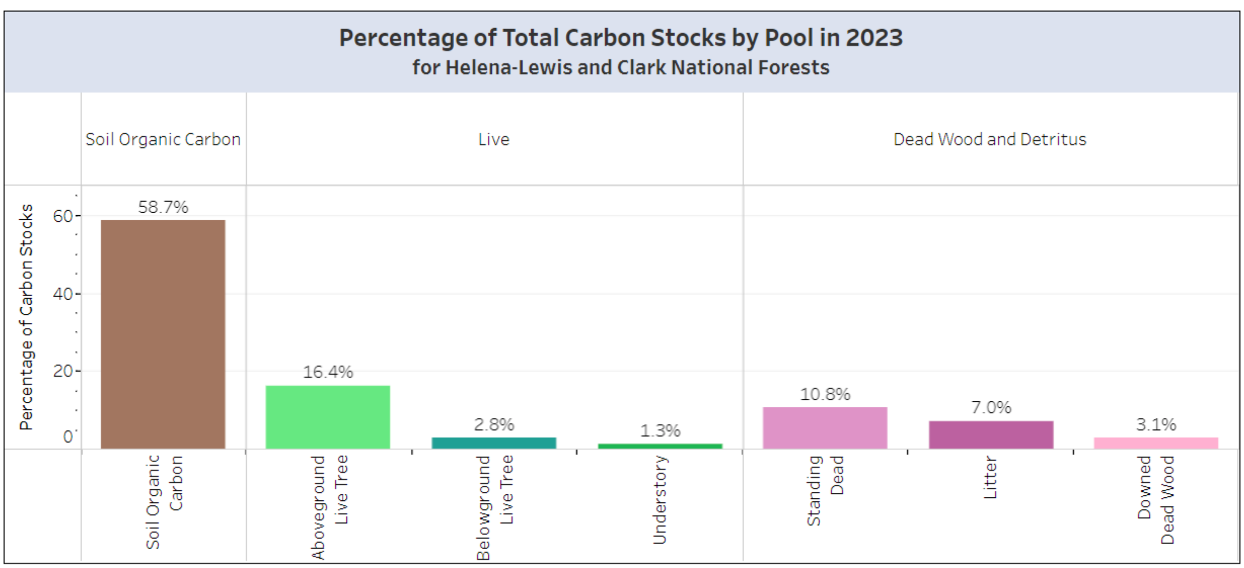


Figure 2. Percentage of total carbon stocks by pool in 2023.

Changes in total carbon storage and forested area collectively determine changes in carbon density. Forested area in the Helena-Lewis and Clark National Forest was 1,039,852 ha in 2005 and increased to 1,050,817 ha in 2023, a net change of 10,965 ha (Table 1). Minor changes in forested area may result from sampling intensity issues or weighting strata rather than actual changes in forested area. Given decreasing stocks of total ecosystem carbon and increasing trends in forested area in the Helena-Lewis and Clark National Forest, carbon density decreased from about 219.60 Mg C/ha in 2005 to 210.07 Mg C/ha in 2023 (Table 1.). This decrease in carbon density suggests the potential decrease of total carbon stocks.

Table 1. Carbon stocks and forested area estimates.

Carbon Stocks and Forested Area Estimates
for Helena-Lewis and Clark National Forests

Variable	Value
Carbon stocks in 2005	228.35 Tg
Carbon stocks in 2023	220.75 Tg
Standard error (+/-) of carbon stock estimates in 2023	12.70 Tg
Percentage of Carbon Stocks: Live	20.50 %
Percentage of Carbon Stocks: Down Dead and Detritus	20.84 %
Percentage of Carbon Stocks: Soil Organic Carbon	58.66 %
Carbon stocks, estimated in million passenger vehicles (MPV), in 2023	176.12 MPV
Percent change in carbon stocks, 2005–2023	-3.33%
Carbon density in 2005	219.60 Mg/ha
Carbon density in 2023	210.07 Mg/ha
Change in carbon density, 2005–2023	-9.53 Mg/ha
Forested area in 2005	1,039,852 ha
Forested area in 2023	1,050,817 ha
Change in forested area, 2005–2023	10,965 ha
Percent of 2013 regional carbon stocks in use as harvested wood products	1.54%

The average carbon density in the national forests of the Northern Region remained stable from 2005 to 2023. Carbon density in the Helena-Lewis and Clark National Forest was lower than the average for all national forests combined in the Northern Region (Fig. 3). Differences in carbon density among national forests may be related to differences in biophysical factors that influence growth and productivity, such as climate, elevation, and forest type, as well as disturbance and management.

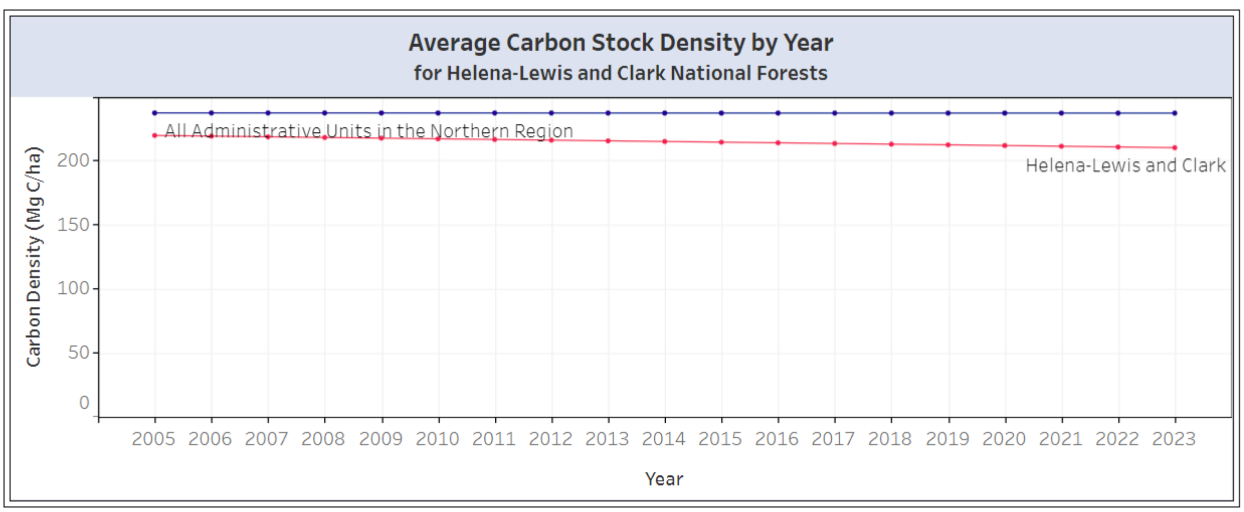


Figure 3. Average carbon stock density (Mg/ha) from 2005 to 2023.

Evaluations of changes to carbon stocks and density are applicable at the national forest level, not the project level, given the methods used in this assessment. These results, thus, provide a broad context for potential national forest land management activities. They are also useful for comparison among national forests, which typically have different amounts of forested area.

3.2 Carbon in Harvested Wood Products

Carbon stored in harvested wood products may result in lower net greenhouse gas emissions relative to unmanaged forests if carbon stored in harvested wood products, substitution effects, and forest regrowth are collectively considered (Lippke et al. 2011; McKinley et al. 2011; Skog et al. 2014; Dugan et al. 2018). Assessing impacts of harvest on greenhouse gases thus should include carbon storage estimates from wood products.

The duration of carbon persistence in harvested wood products depends on the commodity type. For example, paper, pulp, or small-piece biomass will not retain carbon as long as timber does. Carbon stored in harvested wood products increases with harvested wood products commodity production. Landfills (also known as solid waste disposal sites or SWDS) also store discarded forest products and may continue to store carbon for many decades, as decomposition is slowed under oxygen-poor conditions. Wood products used in place of steel or concrete, as well as wood-derived biomass used in energy production in place of coal and natural gas, may reduce net greenhouse gas emissions as well via their substitution for higher greenhouse gas-emitting products (Gustavsson et al. 2006; Lippke et al. 2011).

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 (Fig. 4) (Stockmann et al. 2014). 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 (reduced 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.

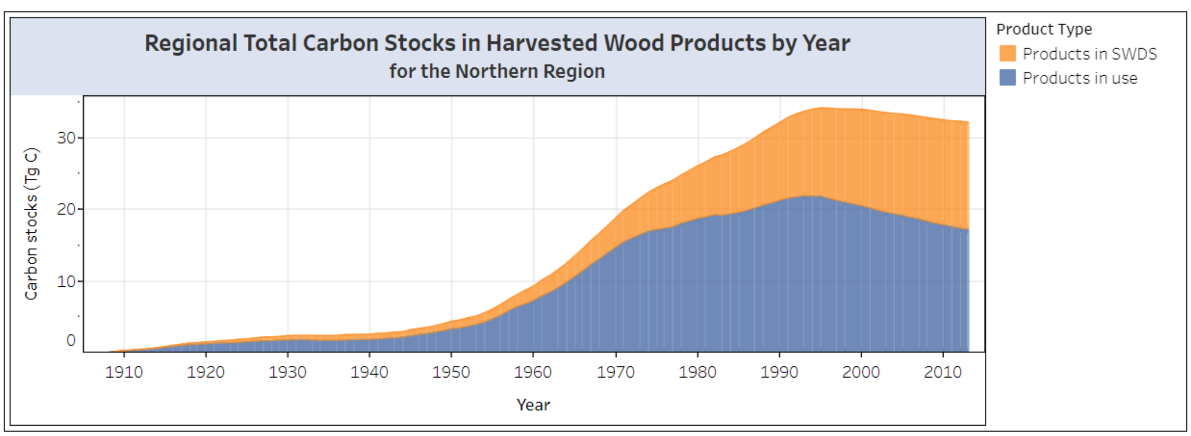


Figure 4. Total region-wide carbon stocks (Tg) in harvested wood products in use and at solid waste disposal sites (SWDS) from 1910 to 2013.

4.0 Factors Influencing Forest Carbon Dynamics

4.1 Disturbance

From 1990 to 2011, fire was the most widespread disturbance type in forested areas of the Helena-Lewis and Clark National Forest (Fig. 5; Table 2). Fire affected less than 5 percent (approximately 48,099 ha) of total forest area over this period. In most individual years, fire affected less than 0.2 percent of the total forested area with the annual range from 0 to 2.83 percent. Fire impacted the greatest area in 2000, 2001, 2002, 2003, and 2007 representing 4.3 percent of forested land. Insect activity began to impact a larger area around 2004 and peaked between 2009 and 2011; in total, insects impacted 1.60 percent of the total forested area (range of 0.02% to 0.70% annually) (Fig. 5; Table 2). This enhanced detection of insect disturbance coincided with an outbreak of mountain pine beetle. Chronic western spruce budworm defoliation and Douglas-fir bark beetle-caused tree mortality have also likely contributed to the insect activity estimate at a much lower level than mountain pine beetle. Chronic lower-severity forest disturbances such as insect effects, however, may be overestimated in this framework because the same incidence may be recorded in multiple years, depending on duration and intensity of canopy impact (Healey et al. 2018). The percentage of forest harvested annually remained stable from 1990 through 2004 (0.03-0.11 percent) and was not a factor from 2005 through 2011.

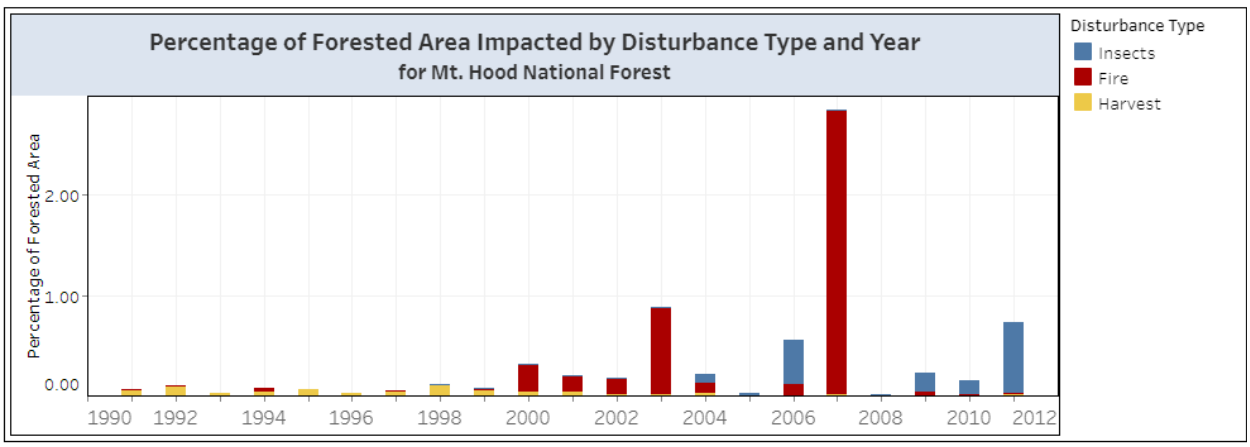


Figure 5. Percentage of forested area disturbed from 1990 to 2011 by disturbance type.

Intensity of canopy cover loss across all disturbances was generally evenly distributed from 1990 to 2002 (Fig. 6; Table 2). The magnitude of canopy cover loss starting in 2003 varied based on the primary disturbance agent; large fire years exhibited 50 to 100 percent canopy loss over 75 percent of the burned area while high insect years had less than 25 percent canopy loss.

Fire on the Helena-Lewis and Clark National Forest also had the greatest impact on carbon stocks, representing an estimated loss of 1.98 Mg/ha of non-soil carbon compared to a hypothetical undisturbed scenario. This loss occurred primarily from 2000 to 2007. Insect activity and harvest resulted in 0.39 and 0.31 Mg C/ha less non-soil carbon, respectively, between 1990 and 2011 compared to a hypothetical undisturbed scenario (Fig. 7; Table 2). Across the Helena-Lewis and Clark National Forest, carbon stocks were 2.6 percent lower by 2011 than they might have been in the absence of disturbance (Fig. 8). Fire accounted for the reduction of 2.02 percent of carbon stocks, insect activity 0.40 percent, and harvest 0.32 percent relative to the no disturbance scenario (Fig. 8; Table 2). Soil carbon is not included in the estimates of carbon related to disturbance from 1990 to 2011. Lower-severity fires and other low-grade disturbances would also not be detected unless they affected canopy closure given the disturbance estimation methods used (Healey et al. 2018).

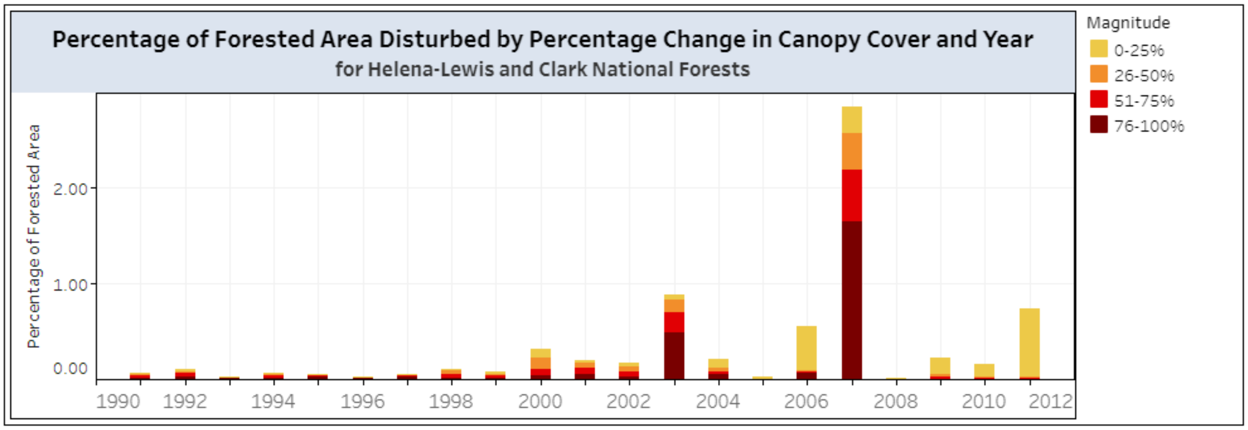


Figure 6. Percentage of forest area disturbed by percentage change in canopy cover and year for Helena-Lewis and Clark National Forest.

Table 2. Disturbance effects for Helena-Lewis and Clark National Forest.

Disturbance Effects
for Helena-Lewis and Clark National Forests

Category	Variable	Value
Reduction in carbon (Mg/ha), by disturbance type, 1990-2011*	Disease	0.00 Mg/ha
	Fire	-1.98 Mg/ha
	Harvest	-0.31 Mg/ha
	Insects	-0.39 Mg/ha
	Abiotic factors	0.00 Mg/ha
	All disturbances	-2.56 Mg/ha
Percentage change in carbon, by disturbance type, 1990-2011*	Disease	0.00%
	Fire	-2.02%
	Harvest	-0.32%
	Insects	-0.40%
	Abiotic factors	0.00%
	All disturbances	-2.60%
Total forest area impacted, by disturbance type, 1990-2011	Fire	48,097 ha
	Harvest	6,925 ha
	Insects	16,578 ha
	Abiotic factors	
	All disturbances	71,599 ha
Percentage of forest impacted, by disturbance type, 1990-2011**	Fire	4.66%
	Harvest	0.67%
	Insects	1.60%
	Abiotic factors	
	All disturbances	6.93%
Percentage of forest impacted, by percentage canopy loss, 1990-2011**	0-25% canopy loss	2.18%
	26-50% canopy loss	0.99%
	51-75% canopy loss	1.26%
	76-100% canopy loss	2.50%
Forest Age***	Percent of forest <= 80 years old	41.14%
	Percent of forest > 80 years old	58.86%
	Percent of forest with age not available	
Other	Forested area****	1,033,167 ha

*Soil carbon was not included.
**Percentage of forest disturbed is the sum of percentage disturbed each year. Some areas may have experienced repeated disturbance over the time period assessed; therefore, total area disturbed may be an overestimate of the actual footprint of the disturbed area.
***Stand age is unavailable for FIA plots which contain only tree species that cannot be aged according to FIA protocol.
****Forested landcover type area was held constant from 1990 to 2011.

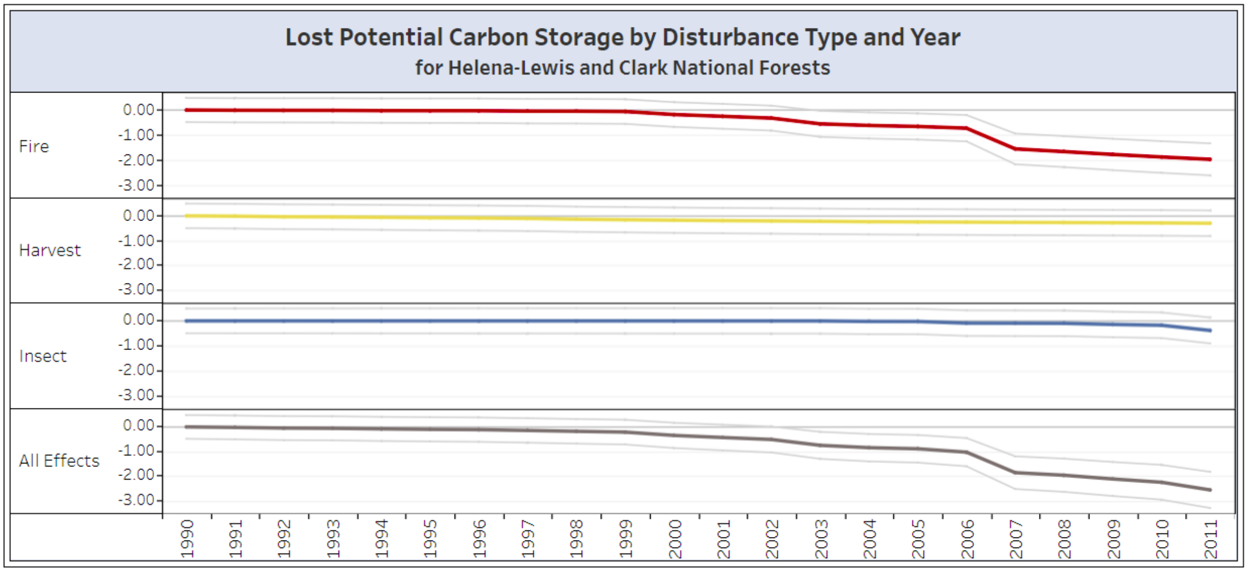


Figure 7. Lost potential storage of carbon (Mg/ha) relative to a hypothetical no-disturbance baseline (zero line), resulting from disturbances from 1990 to 2011. Gray lines are 95% confidence intervals. Soil carbon is not included.

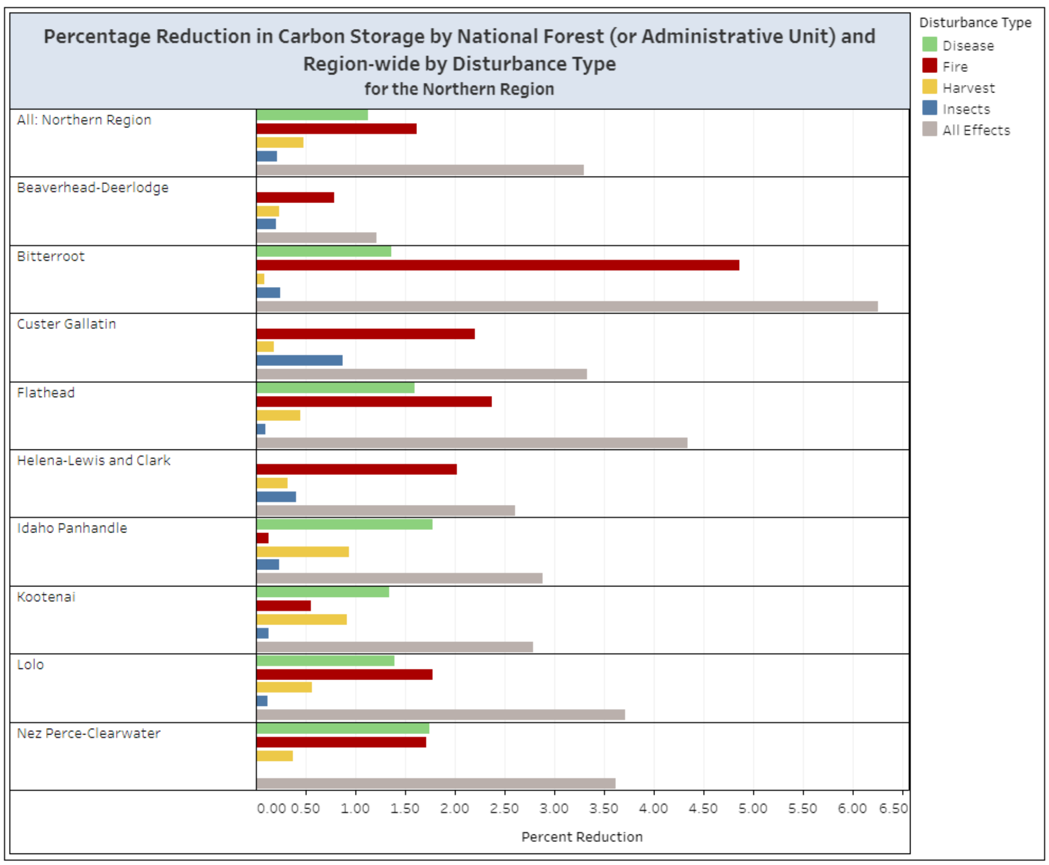


Figure 8. Percentage reduction in carbon storage relative to a hypothetical no-disturbance baseline by disturbance type, administrative unit, and region-wide from 1990 to 2011. Soil carbon is not included.

Based on scientific literature, climate change and land use history have resulted in unusually dense forests in the Northern Region which are increasingly at risk to disturbance, including fire, insects, and disease. These drivers, along with management, play an important role in shaping regional carbon dynamics.

Fire: In the western United States, fire intensity and occurrence have been increasing over the last several decades, particularly since the 1980s (Parks and Abatzoglou 2020; Westerling et al. 2006). Both climate and live fuel loads have been main drivers contributing to the emergence of high-severity fire in the Northern Region (Page-Dumroese and Jurgensen 2006; Parks et al. 2018). Increasing wildfire activity in the Region has been linked to warming temperatures and earlier spring snowmelt (Westerling 2016). Fire produces important by-products such as pyrogenic carbon and charcoal, which ameliorate soil by increasing nutrient and water retention (DeLuca and Aplet 2008; DeLuca et al. 2020). Management can promote this attribute through prescribed burning and underburn treatments after timber treatments.

The Helena-Lewis and Clark National Forest follows the regional trend and has seen nearly 1,126,000 acres burned since 1886. The number of acres burned annually due to natural causes has substantially increased since 1980 with the highest annual acreages burned occurring since 2000. Increasingly large fires can be attributed to 1) fuel buildup in low severity fire regime areas, 2) the influence of a warm, dry climate on vegetation, fire behavior, and suppression, and 3) fire policies that have allowed natural fires to burn in some areas (USDA Forest Service 2021b). The largest fire recorded on the Forest was the 2006 Canyon Creek fire which burned about 84,200 acres. Stand-alone or post-harvest prescribed burning has been reported on the forest since 1946 (143,095 acres). The largest quantity of acres receiving a broadcast burn, underburn, or jackpot burn occurred between about 1985 and 2005.

Insects: Increasingly dry and dense forests are generally more susceptible to insects. Bark beetles (*Curculionidae, Scolytinae*) are an important driver of carbon dynamics in the Northern Region. Fire and bark beetles affect similar spatial extents in Montana and Idaho and, in the western United States, cumulatively impact an area similar to harvesting (Hicke et al. 2016). Mountain pine beetle is a major driver of carbon dynamics in the Northern Region. Native to western North America and co-evolved with pine trees (*Pinus* spp.), mountain pine beetle periodically rises to large-scale outbreaks. In the Northern Region, notable outbreaks have occurred in the 1920s to 1930s (Jenne and Egan 2019), from 1971 to 1989 (Harley et al. 2019), and from 1999 to 2015 (Lestina et al. 2019). During severe infestation, past studies estimate carbon loss of 36 g carbon per meter square per year, which can transition a forest from a net sink to a large source (Kurz et al. 2008).

Insect activity in the Helena-Lewis and Clark National Forest has impacted an area more than twice that of harvesting and about one-third of the area impacted by fire (Table 2). Several mountain pine beetle outbreaks were recorded on the Helena National Forest between 1916 and 1944 and to a lesser extent on the Lewis and Clark National Forest (Jenne and Egan 2019). In the early 2000s, the Forest experienced a mountain pine beetle outbreak covering nearly one million acres with peak mortality from 2007 to 2011. The outbreak was fueled by a warm climate and vast areas of susceptible forest (USDA Forest Service 2021b). Although ponderosa pine, limber pine, and whitebark pine were impacted, lodgepole pine stands experienced the greatest level of stand mortality. Chronic, widespread, western spruce budworm defoliation due to a warm, dry climate and the availability of dense, layered forest of host species has led to reduced productivity in Douglas-fir dominated forest stands and increased susceptibility to Douglas-fir bark beetle (Kegley and Sturdevant 2006; USDA Forest Service 2021b). Douglas-fir beetle, present at endemic levels across the Helena-Lewis and Clark National Forest, has exhibited population spikes following large wildfires since 2000 as the insect capitalizes on fire-weakened trees. Douglas-fir beetle infestation is also present in areas suffering from chronic western spruce budworm activity. Insect-caused tree mortality increases the quantity of standing and down dead wood which retains carbon that eventually transitions to soil carbon through decomposition (USDA Forest Service 2021b).

Disease: National forests in the Northern Region are also impacted by root disease, with area infected ranging from 9 percent of the forested area in Beaverhead-Deerlodge National Forest to 45 percent of the Nez Perce-Clearwater National Forest (Bennett et al., 2022). According to Forest Inventory and Analysis data, nearly 22 percent of forested area on the Helena-Lewis and Clark National Forest is impacted by root disease (Bennett et al. 2022). The most common root pathogens on the Forest are armillaria root disease and schweinitzii root and butt rot. Root disease can rival the effects of fire and harvest in affecting forest carbon storage in the Region (Healey et al. 2016). White pine blister rust is generally present and affecting whitebark pine and limber pine across the forest.

Management: Carbon impacts of management practices can be nuanced depending on site and prescription details, which are likely not captured in coarse, remotely sensed data. For timber harvests, rotation length (Harmon and Marks 2002; Smithwick et al. 2007), retention of legacy logs/slash (Page-Dumroese and Jurgensen 2006; Schaedel et al. 2017; Trettin et al. 2021), and species retention (Bormann et al. 2015) will all affect post-harvest biomass and carbon through impacts on regeneration or carbon transfer. Studies indicate that common timber harvesting regimes in the Northern Region can quickly recover removed biomass (within a couple of decades) and combining harvest with prescribed burning can reduce fuel loads and risk of wildfire (Clyatt et al. 2017). Ultimately, various timber management regimes can balance carbon storage with other desirable ecosystem services (DeLuca and Hatten, 2024). Management, including thinning and prescribed fire, can reduce likelihood of high-intensity wildfire, thereby improving carbon stability (Halofsky et al. 2020; Hood et al. 2024). Other studies in the Northern Region have explored using biochar amendment to increase soil carbon stocks (Sarauer et al. 2019). Emphasizing the importance of site, management practices should be carefully selected on any sites with root disease present to avoid unintended effects (Rippy et al. 2005).

Since 1940, commercial harvest has occurred on about 5 percent (137,300 acres) of the Helena-Lewis and Clark National Forest (USDA Forest Service 2021b). Approximately 78 percent of the harvested acres received a regeneration harvest method. Clearcutting in lodgepole pine has been the most significant harvest method with seed tree and shelterwood systems occurring in early seral, warm-dry habitat forest types, such as ponderosa pine and Douglas-fir. Five-year post-harvest regeneration success across the forest is 99 percent for planting and about 96 percent for natural regeneration (Regeneration Timeframe Report, USDA Forest Service 2021b) which indicates that forest stands are quickly recovering. Commercial thinning has occurred on 12 percent of harvested acres, primarily in Douglas-fir Forest types. Managed stands across the forest are relatively free from mountain pine beetle, western spruce budworm, and Douglas-fir beetle activity, which is impacting adjacent, unmanaged, dense, mature to over-mature stands.

By comparison nationally across all land ownerships from 1926 to 2017, fire and harvest reduced total forest stocks on average by 14 percent and 51 percent respectively (Magerl et al. 2023). For example, across the western United States from 1940 to 2017, fire, harvest, and other disturbance (e.g., insect, drought) reduced carbon stocks on average by 14 percent, 81 percent, and 7 percent, respectively (Magerl et al. 2023). The Helena-Lewis and Clark National Forest’s impact on carbon stocks (1990-2011) has been substantially less than the national average with an average reduction from fire, harvest, and insects of 2.02 percent, 0.32 percent, and 0.40 percent, respectively.

The disturbance history information reported here does not describe past disturbance effects on carbon stocks and fluxes over long time periods and, therefore, does not capture the full range of successional processes. Further, conditions such as herbivory, chronic disturbance, climate fluctuations prior to and after harvest, and the type of harvest (selective vs regeneration harvest, for example) are not assessed, but these factors also affect the timing of recovery of ecosystem carbon. Because of these factors, it may take several decades for carbon emissions to be offset by subsequent uptake and storage (Raymond et al. 2015). This disturbance information also does not account for harvest-related retention of carbon stored in harvested wood products.

4.2 Soil Carbon and Disturbance

Disturbance impacts on soil carbon stocks and fluxes are not evaluated within this assessment. National forests can choose to use a national protocol, Forest Soil Disturbance Monitoring Protocol, for collecting data on soils impacted by management activity (Page-Dumroese et al. 2009a; Page-Dumroese et al. 2009b). However, impacts on soil carbon are not directly quantified unless individual national forests collect those data. Data collected by individual national forests following Forest Soil Disturbance Monitoring Protocol may help to augment national soil stock data lacking soil-related disturbance information. In the Forest Soil Disturbance Monitoring Protocol, the presence or absence of the organic horizon and detrimental physical soil disturbance (effect of disturbance on specific soil types to subsequent tree growth) are measured, giving individual national forests information on the extent to which biogenic carbon could be impacted by management activities. Recent scientific research suggests that typical disturbance related to harvest operations has little to no effect on soil carbon (Curzon et al. 2022). A recent meta-analysis of research conducted in Great Lakes states points to natural factors, such as soil texture and parent material, forest type, and climate, as more significant drivers of soil carbon stocks than disturbances such as fire or harvest (Nave et al. 2021b).

Generally, fire decreases litter carbon stocks though the magnitude and variability of these declines differ across regions (Nave et al. 2011). For example, in the Pacific Northwest, wildfires drive large carbon losses from litter and in mineral soil horizons, while prescribed fires primarily diminish litter carbon (Nave et al. 2022). In most regions, mineral soils are not affected by fire, but fire may impact microbial activity and the quantity and quality of organic matter inputs into the soil, thus potentially affecting soil carbon (Knelman et al. 2015). Different types of fire may influence litter responses variably, with prescribed fire producing smaller carbon losses than unintentional or unmanaged wildfires. For these reasons, prescribed burns can be an effective tool for reducing aboveground fuel loads while mitigating soil carbon and nitrogen losses that would otherwise occur in wildfire (Nave et al. 2011). Implementing existing soil quality standards, protection guidelines, and monitoring protocols are effective ways to promote soil carbon stewardship following disturbance.

4.3 Stand Development and Dynamics

Forests are generally considered to follow a multi-stage model of progressive stand development after a severe disturbance: stand initiation, stem exclusion, understory re-initiation, and old growth. However, in a stand affected by frequent low- to moderate-severity disturbance (such as frequent fires or insect outbreaks) trees may cycle between intermediate stages for centuries (standing dead trees and/or old living trees of low abundance). While these stands generally follow the four stages of development, progressing from seedling to old growth, the period spent in each stage varies. Setbacks to earlier stages may result from limitations in site conditions (hydrology, soils, or climate) or intermediate disturbances, making the stand origin or endpoint difficult to determine (Franklin et al. 2007; Palik et al. 2020).

Stand age can serve somewhat as a proxy for past disturbances and management activities (Pan et al. 2011). When a forest stand is impacted by a high severity disturbance, stand age returns to zero until regeneration commences. Relative percentages of forested area in given age classes might reflect stand-replacing disturbance events in situations where a given stand age class predominates. Uneven-aged stands may reflect lower severity disturbance regimes and have more complex patterns.

For the Northern Region, site history can affect current stand dynamics. In particular, retention of logs and downed woody material play an important role in forest regeneration and nutrient cycling (Graham 1994; Trettin et al. 2021). History of wildfire also influences soil carbon through formation of pyrogenic carbon (Bird et al. 2015; DeLuca and Aplet 2008) which is generated as the result of incomplete combustion of organic material during a fire. Both wildfire and prescribed fire can generate substantial amounts of pyrogenic carbon, varying dependent on fire and fuel conditions, with some regional estimates of 5-12 percent of combusted biomass (DeLuca et al. 2020). Therefore, stand history can have a large influence on current carbon stocks.

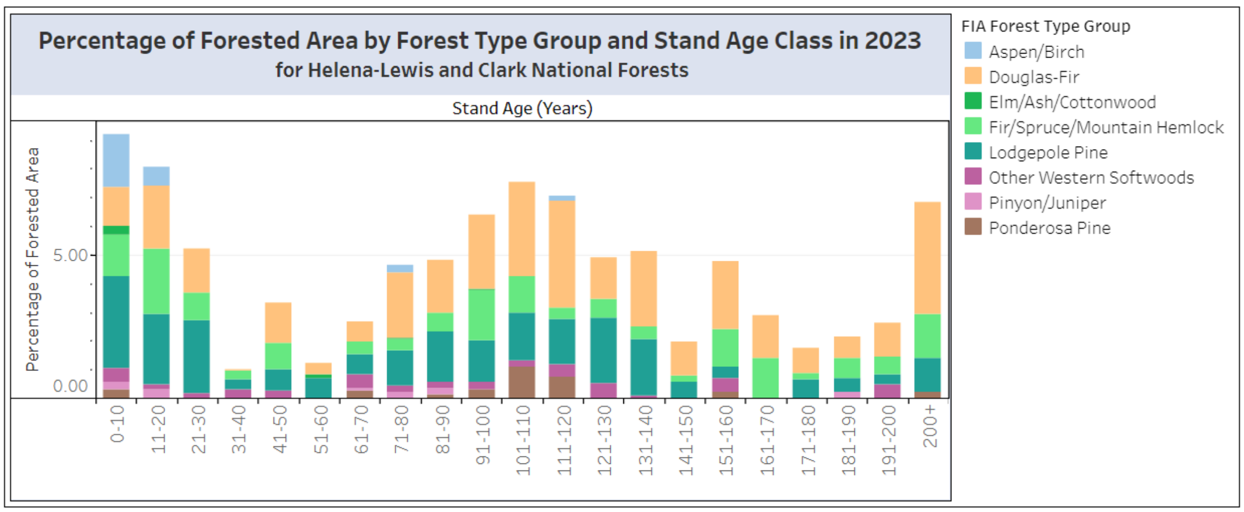


Figure 9. Percentage of forested area by Forest Inventory and Analysis Forest type group and stand age class in 2023.

Stand-age distribution for the Helena-Lewis and Clark National Forest derived from 2023 Forest Inventory and Analysis data indicates stands which established prior to 1820 are still present today (about 7 percent of all stands); elevated stand establishment occurred between 1880 and 1930, and from 2003 to present (Fig. 9). These periods of elevated stand regeneration were the result of large wildfires and harvest activities associated with railroad or mining developments and stand management followed by moist climate conditions conducive to forest establishment. Between 1886 and 1930, nearly 340,000 acres burned primarily in the wilderness on the Rocky Mountain Front, in the Highwood Mountains, and the north end of the Little Belt Mountains. Timber harvest was most prevalent between 1960 and 2000, although at a much lower quantity than wildfire. The greatest pulse of stand establishment was experienced in the last two decades following wildfires (~529,000 acres) in the early 2000s. With the exception of the 2021 Woods Creek fire, individual fires larger than 20,000 acres occurred around 2007. Douglas-fir and lodgepole pine are the primary forest types regenerating, followed by fir/spruce and ponderosa pine. Quaking aspen forest types have flourished (~2.5% of forest land) with the recent mountain pine beetle outbreak and wildfires.

Net primary productivity curves describe changes in productivity over time that reflect shifts in growth rates. Stand growth rates rely on forest type and site conditions. In general, productivity is highest for young to mid-aged stands across forest types. Productivity then peaks and either declines or stabilizes as the forest canopy closes, respiration rates increase, and some tree mortality occurs (Pregitzer and Euskirchen 2004; He et al. 2012). Lodgepole pine on the Helena-Lewis and Clark National Forest has the highest net primary productivity followed by other softwoods (whitebark pine and limber pine) and Douglas-fir (Fig. 10). Lodgepole pine productivity tends to peak around age 60-69 (8.3 MgC/ha/yr) prior to gradually declining to 6.1 MgC/ha/year. Productivity for other softwoods peaked at 50-59 years (7.1 MgC/ha/yr) and rapidly declined to 3.7 MgC/ha/year by age 100-109. Maximum Douglas-fir productivity (6.2 MgC/ha/yr) was expressed at 30-39 years of age with a gradual reduction to 3.1 MgC/ha/yr at the end of the analysis period. Productivity for ponderosa pine peaked at 20-29 years and remained stable over time (~4.8 MgC/ha/year). The fir/spruce forest group experienced maximum productivity at age 40-59 and then followed a curve almost identical to Douglas-fir.

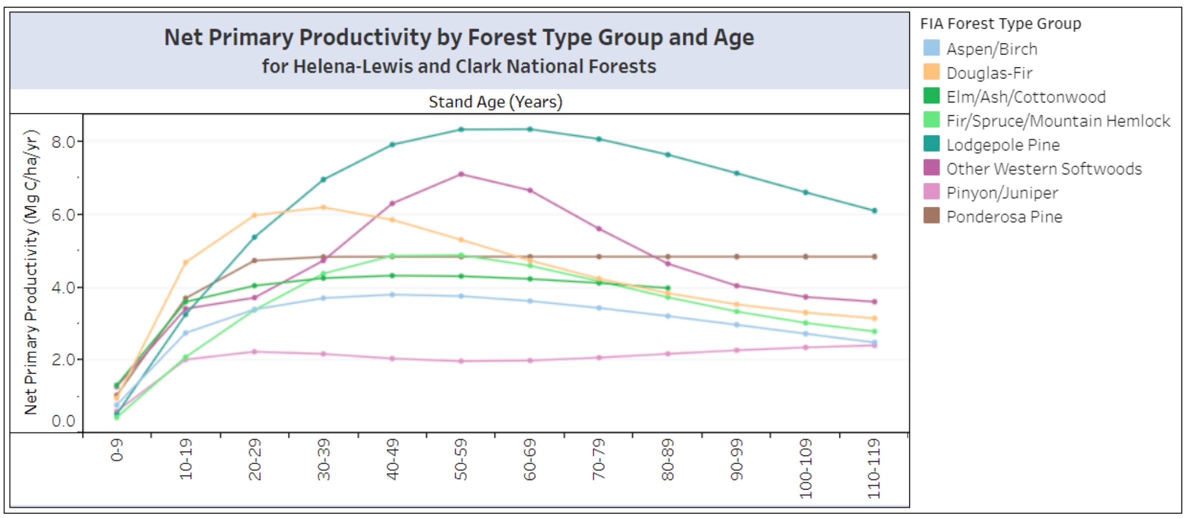


Figure 10. Net primary productivity (Mg C/ha/yr) by Forest Inventory and Analysis forest type group and stand age.

4.4 Effects of Climate and Environment on Recent Carbon Dynamics

For the Northern Region, the Continental Divide drives stark contrasts in climate, particularly precipitation and water availability. West of the Divide there is greater winter precipitation, while east of the Divide there is greater summer precipitation (Shinker and Bartlein 2010). Seasonal precipitation is a main driver of tree biomass production (Crawford et al. 2015).

At smaller spatial scales, topography plays an enormous role in dictating micro-climates and carbon stocks. Studies indicate that carbon density is generally higher on the north-facing aspects (Coble et al. 2001; Hicke et al. 2004). Elevation also impacts the dominant forest type (Pfister 1977) which, therefore, impacts carbon storage (see section 4.3). Site-specific characteristics are likely to influence the impact of changing disturbance regimes under climate change, including wildfire, insects, pathogens, and drought. For example, low elevation, dry sites are likely to be increasingly stressed by wildfire and pathogens (Halofsky et al. 2018).

Disturbance and aging, carbon dioxide fertilization, climate, and nitrogen deposition had combined effects on the accumulation of carbon from 1950 to 2010 in the Helena-Lewis and Clark National Forest (Fig. 11). Combined effects were modest, with positive changes in carbon accumulation of about 9.2 Tg between 1950 and 1965. This accumulation was the result of forest regrowth and aging following historical disturbances in the early 1900s and heightened productivity of the young to middle-aged forests (30-60 years old), primarily lodgepole pine. Accumulated carbon then remained stable for the next decade before experiencing a gradual decline. As stand establishment declined and more stands reached slower growth rate stages around the 1980s, the rate of accumulation declined until the cumulative effect became negative in 1997. The cumulative carbon trajectory closely follows that of the disturbance and aging curve for the Forest. Climate, influencing fire, insects, and tree productivity, was a secondary factor influencing carbon flux resulting in decreases in carbon accumulation. Nitrogen deposition and carbon dioxide fertilization were factors that saw continued increases in carbon accumulation for the analysis period, representing about 0.18 Tg and 0.15 Tg carbon increase per year, respectively. Over the 60-year time period, combined effects resulted in a net negative accumulation of carbon of about 14.52 Tg.

The effects of climate on carbon stocks in the Helena-Lewis and Clark National Forest varied over time, but in general, climate fluctuations since 1950 tended to have a strongly negative effect on carbon stocks (Fig. 11). Climate change can have variable effects on carbon dynamics. 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 may also reduce soil moisture via increased evapotranspiration leading to slower forest growth and reduced emissions, especially in semiarid and low elevation forests (Xu et al. 2013).

Carbon dioxide fertilization and nitrogen deposition can alter forest growth rates, influencing carbon uptake and accumulation (Caspersen et al. 2000; Pan et al. 2009; Thomas et al. 2010). Carbon dioxide fertilization may result in higher productivity, but this effect is transitory for most forests (Zhu et al. 2016). In the Helena-Lewis and Clark National Forest, carbon dioxide fertilization increased carbon stocks (Fig. 11). Quantification of the magnitude of the effect of carbon dioxide fertilization on terrestrial carbon storage and forest growth rates has high uncertainty (Jones et al. 2014; Zhang et al. 2015), however, and is also related to soil nutrient availability (Vose et al. 2018). These topics require additional research (Körner et al. 2005; Norby et al. 2010; Zhu et al. 2016). Nitrogen deposition may have had a positive effect on carbon accumulation in the Helena-Lewis and Clark National Forest (Fig. 11); uncertainty in these estimates is also high. Increased insect activity noted above has decreased forest productivity and ability to take advantage of increased carbon dioxide fertilization and nitrogen deposition.

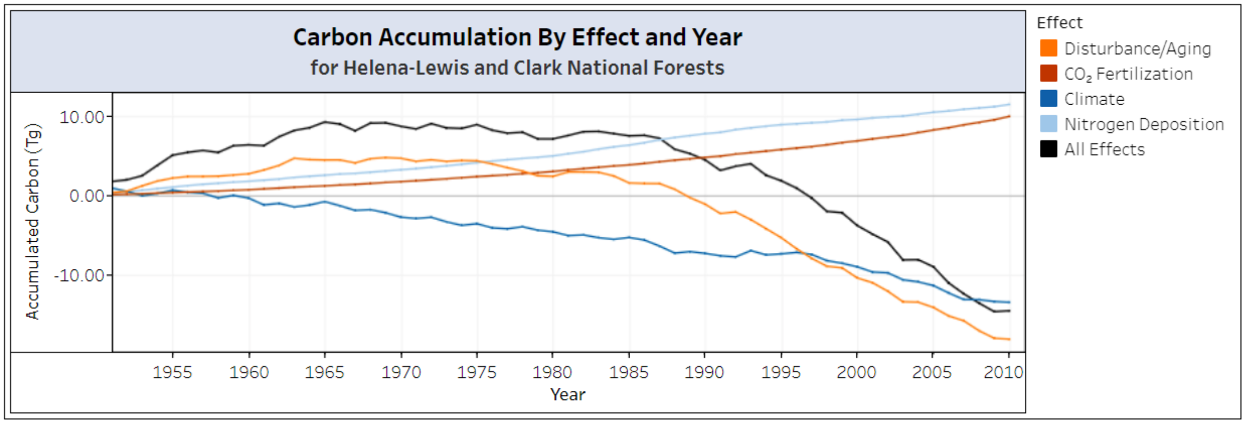


Figure 11. Carbon accumulation (Tg) over time from disturbance/aging, carbon dioxide fertilization, climate, nitrogen deposition, and all effects combined, initialized at zero, from 1950 to 2010.

4.5 Mature and Old-Growth Forest Carbon

Mature and old-growth forest ecosystems take up carbon more slowly than younger forests. However, longer periods of carbon accumulation result in these forests having higher carbon stocks, especially in forest floor and downed dead wood components (Hoover et al. 2012; Hoover and Smith, 2023; Gray et al. 2016).

The Helena-Lewis and Clark National Forest specifically manages for mature and old-growth forest via the 2021 Land and Resource Management Plan (USDA Forest Service 2021a). The Forest Plan contains the following desired condition and guideline pertaining to old growth management.

- *Desired Condition FW-VEGF-DC 05*: Forest conditions support an abundance and distribution of old growth that is dynamic over time. All vegetation desired conditions help ensure that an appropriate array of conditions is present to provide old growth. The amount of old growth is similar to or greater than that of the 2018 existing condition. Forest-wide, the Forest supports 11 percent (9-13%) old growth conditions.
- *Guideline FW-VEGF-GDL 04*: To promote the retention of old growth and contribute to biodiversity, vegetation management activities in old growth stands should only occur for one or both of the following purposes. Management activities conducted for these purposes should retain all minimum quantitative old growth characteristics as well as qualitative attributes to the extent possible. 1) Maintain or restore old growth habitat characteristics and ecosystem processes. 2) Increase resistance and resilience to disturbance or stressors that may have negative impacts on old growth characteristics or abundance (such as drought, wildfire, and bark beetles). Two exceptions to this guideline are allowed.

The Helena-Lewis and Clark National Forest has adopted definitions of old growth developed by the Regional Old Growth Task Force and documented in Green and others (1992, errata corrected 2011). The definitions are specific to forest types and habitat type groups for the East Side Zone (Table 3) and provide a consistent definition. Old growth is defined in the Forest Plan as "an ecosystem distinguished by old trees and related structural attributes. For the [Helena-Lewis and Clark National Forest], old growth stands are specifically defined as those that meet the definitions in Green et al. 1992 (errata corrected 12/11). Those definitions include the discussion in that document titled Use of Old Growth Type Definitions."

Overall, moderate amounts of mature forest and low quantities of old growth (11%) (USDA Forest Service 2021a) are distributed across the Helena-Lewis and Clark National Forest. Old growth represents an array of cover types; however, Douglas-fir is the most common (31%) followed by lodgepole pine (27%) (USDA Forest Service 2021a). Warm dry potential vegetation types tend to support a lower proportion of old growth compared to cool moist and cold vegetation types. The abundance and distribution of old growth across the Forest varies based on disturbance history. Disturbances in the last 120 to 150 years had the potential of impacting old growth quantities and development. Wildfire influences old growth development; therefore, long-lived, early successional, fire tolerant tree species such as ponderosa pine, Douglas-fir, and whitebark pine have the best chance of surviving wildfires and persisting into the late successional stage. The Highwood Mountains, which burned at the beginning of the previous century, lacks an old growth component. Insect activity can also eliminate old growth or impede its development. The recent mountain pine beetle outbreak reduced vast acres of pine-dominated old growth stands. Old growth forest stands reflect areas of past long-term carbon storage and stability in changing forest landscapes.

Management should provide for a succession of young forests into old growth forests in light of their depletion due to natural events (e.g., wildfire and insects) or harvest. With a projected warm and dry climate, old growth is expected to be subjected to increased disturbances and, therefore, represents important areas for the retention of biological legacies seed sources, late successional forest habitat features, and carbon storage (USDA Forest Service 2021b).

Table 3. Eastern Montana zone old growth type characteristics.

DESCRIPTION		MINIMUM CRITERIA			ASSOCIATED CHARACTERISTICS							
OLD GROWTH TYPE	HABITAT TYPE GROUP	MINIMUM AGE OF LARGE TREES	MINIMUM NUMBER TPA/DBH	MINIMUM BASAL AREA (FT^2/AC)	DBH VARIA-TION 2/	PERCENT DEAD/ BROKEN TOP 1/	PROBABILITY OF DOWN WOODY 2/	PERCENT DECAY 1/	NUMBER CANOPY LAYERS 3/	SNAGS ≥9” DBH 1/	NUMBER OF SAMPLES
1 – DF	A	200	4 ≥ 17”	60	M	9 7-10	L-M	5 4-9	SNGL/MLT	6 4-18	989
2 – DF	B,C,D,E,F,H	200	5 ≥ 19”	60	M	7 2-14	L-M	6 3-15	SNGL/MLT	10 3-29	3,439
3 – DF	G	180	10 ≥ 17”	80	M	8 2-15	L-M	8 6-10	SNGL/MLT	32 15-50	18
4 – PP	A,B,C,K	180	4 ≥ 17”	40	M	8 5-10	L-M	4 3-10	SNGL/MLT	7 5-10	92
5 – PF	A,B	120	6 ≥ 09”	50	M	9 0-14	L	10 0-14	SNGL/MLT	12 6-24	24
6 – LP	A,B,C,D,E, F,G,H,I	150	12 ≥ 10”	50	L	7 0-26	L-M	3 0-18	SNGL/MLT	16 3-56	9,633
7 – SAF	C	160	12 ≥ 17”	80	M	1	M	18	SNGL/MLT	50	8
8 – SAF	D,E	160	7 ≥ 17”	80	M	4 0-11	M	5 1-15	SNGL/MLT	28 0-44	664
9 – SAF	F,G,H,I	160	10 ≥ 13”	60	M	5 0-16	L-M	8 0-30	SNGL/MLT	31 20-59	1,360
10 – SAF	J	135	8 ≥ 13”	40	M	5 2-7	L-M	5 0-10	SNGL/MLT	43 8-84	38
11 – WBP	D,E,F,G,H,I	150	11 ≥ 13”	60	M	4 0-11	L-M	7 2-17	SNGL/MLT	24 0-65	953
12 – WBP	J	135	7 ≥ 13”	40	M	4 0-16	L	9 3-27	SNGL/MLT	17 0-34	173

1/ These values are not minimum criteria. They are the range of means for trees ≥9” DBH across plots within forests, forest types, or habitat type groups.

2/ These are not minimum criteria. They are Low, Moderate, and High probabilities of abundant large down woody material or variation in diameters based on stand condition expected to occur most frequently.

3/ Not a minimum criteria. Number of canopy layers can vary within an old growth type with age, relative abundance of different species and successional stage

5.0 Factors Influencing Potential Future Carbon Dynamics

5.1 Forest Aging

Future carbon uptake, storage, and stability are influenced by forest stand age dynamics. As stands in the Helena-Lewis and Clark National Forest age, an increasing proportion of the stands may have slower growth rates since net primary productivity declines as a forest stand ages across some forest type groups (Fig. 10). Landscape-wide, this may result in declining rates of carbon uptake. Although live biomass may approach peak levels and stabilize or decline, ecosystem carbon stocks may continue to increase as dead wood and detritus, as well as soil carbon stocks, accumulate (Pregitzer and Euskirchen 2004). Some forest types may have the tendency to remain carbon sinks for many decades in the absence of disturbance and with increasing forest age. Stand structural heterogeneity, as individual trees die via gap dynamics, can increase over time with resulting shifts of carbon among pools and total carbon stocks. Past and present aging trends can inform future conditions with respect to carbon uptake, storage, and stability. However, the interpretations of past stand and landscape dynamics effects on carbon uptake, storage, and stability may be limited because potential changes in management activities, disturbance, and future climate variability are likely to affect future stand age distributions and forest growth rates (Davis et al. 2009; Keyser and Zarnoch 2012) as well as their variability across broader areas.

Natural forest development (aging, mortality, and regrowth) and succession are the major drivers of historic and current forest carbon uptake. Although stand age and size class are not always highly correlated, size class distribution can give a general trend of structural diversity and forest aging. While a size class is dominated by trees of that size, trees from other size classes may also be present adding to diversity. The Helena-Lewis and Clark National Forest is composed of 13 percent seedlings/saplings, 39 percent small trees (5-9.9” dbh), 21 percent medium trees (10-14.9” dbh), and 7 percent large and very large trees (>15” dbh) (USDA Forest Service 2021a). This distribution is represented in Figure 9, where sixty percent of the Forest is middle-aged (>80 years old) with seedling/sapling and old growth forest at low quantities. If the forest continues on this aging trajectory, the pulse of middle-aged stands will reach a slower growth stage in coming years and decades, potentially causing the rate of carbon accumulation to decline. Forests may eventually transition to a steady accumulation state in the future. Young forest stands (seedlings/saplings) have a high rate of productivity, but low levels of carbon stocks due to small tree stature. To a degree, this productivity may offset the declines evident in middle-aged stands. Wildfires under warming and drying conditions would continue to convert mature stands into highly productive seedling/sapling stands. Insect activity could cause individual tree or stand mortality. In both instances, carbon storage would shift from the live, aboveground component to the standing dead, down dead wood, and soil components as well as to the atmosphere. Following disturbance, lodgepole pine would quickly regenerate to restart carbon accumulation while establishment of other species may be slower. Without disturbance, middle-aged forest stands would continue to grow and accumulate carbon with stable to declining net primary productivity. Carbon stocks can continue to increase for many decades in these stands as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert et al. 2008). The Forest supports approximately 11 percent (9-13%) old growth, primarily in Douglas-fir and lodgepole pine forest types with minimum age requirements of 200 and 120 years, respectively (see Table 3). The old growth age group is represented in the medium, large, and very large size classes and is susceptible to loss from wildfire and insect. 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 et al. 2009; Keyser and Zarnock 2012).

5.2 Potential Carbon Stock Changes within the Resource Planning Act Assessment-Defined Region of the National Forest

The 2020 Resource Planning Act (RPA) Assessment (USDA Forest Service 2023a) is the sixth assessment prepared in response to a mandate by the Forest and Rangeland Renewable Resources Planning Act of 1974 (P.L. 93-378, 88 Stat. 475, as amended). Among other metrics, it provides a snapshot of current forest conditions and projects future trends in forest carbon across all forest land ownerships in the U.S., using the annual Forest Inventory and Analysis inventory to estimate carbon stocks (Woodall et al. 2015). For future trends, the 2020 Resource Planning Act Assessment uses the annual Forest Inventory and Analysis inventory to estimate carbon stocks for four Resource Planning Act-defined regions (i.e., North, South, Rocky Mountains, Pacific Coast) in relation to a set of scenarios. The Helena-Lewis and Clark National Forest is within the Rocky Mountains Region. The 2020 Resource Planning Act Assessment incorporates four combinations of alternative future climate and socioeconomic scenarios: High global warming (RCP (Representative Concentration Pathway) 8.5) and high (SSP5) U.S. growth (scenario "HH"); high global warming and moderate (SSP2) U.S. growth ("HM"); high global warming and low (SSP3) U.S. growth ("HL"); and lower global warming (RCP 4.5) and moderate (SSP 1) U.S. growth ("LM") (Fig. 12; Langner et al. 2020; Coulston et al. 2023). High global warming is positively associated with high future emissions. Lower warming is associated with low future emissions. Because the Resource Planning Act Regions are very large and represent all types of land ownership and management strategies, this information should be used only as broad context of potential future changes across the quadrant of the United States in which a given USDA Forest Service national forest resides.

For each scenario, five individual climate models were simulated to capture uncertainty in future climate estimates under different emissions scenarios. Potential future carbon stocks and stock change are described in relation to these four scenarios (HL, HM, HH, LM) for 2019 to 2070 (Fig. 13; Coulston et al. 2023). These climate models capture the magnitude of change in precipitation and temperature that occurred across a wider range of climate models assessed for potential use in each Resource Planning Act Assessment scenario. Responses were similar across individual climate models within the RCP for each scenario for both carbon stocks and carbon stocks change.

The Resource Planning Act Rocky Mountain Region had lower initial carbon stocks in 2019 than the other Resource Planning Act Regions, approximately 7.8 billion metric tons or gigatons (Gt) (Fig. 13), and total carbon stocks are projected to slowly decline until 2070 (Fig. 14a) (Coulston et al. 2023). Rates of decline in carbon stocks (MMT C) are projected to increase until about 2040 then be fairly stable until 2070 (Fig 14b) (Coulston et al. 2023). All scenarios showed similar results. Uncertainty in carbon flux estimates is high and increases over time, and differences among scenarios for carbon stocks are not significant. The Resource Planning Act Rocky Mountain Region is projected to remain a carbon source between 2019 and 2070.

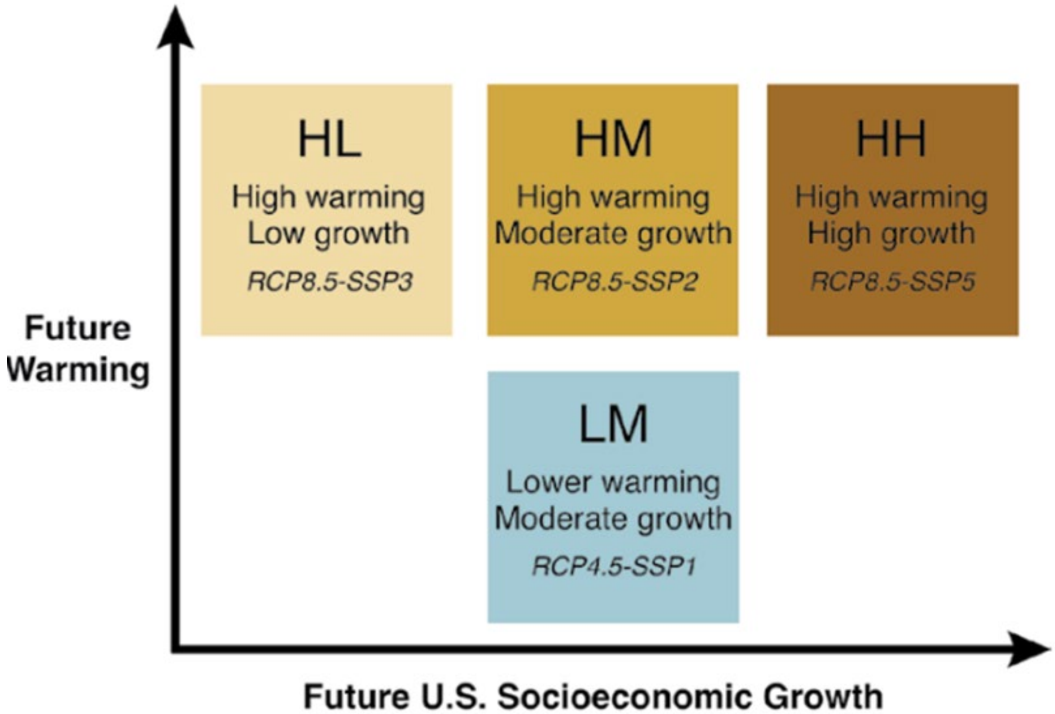


Figure 12. Characterization of global warming and U.S. socioeconomic growth characteristics of the four Representative Concentration Pathway (RCP)-Shared Socioeconomic Pathway (SSP) combinations underpinning the 2020 Resource Planning Act (RPA) Assessment scenarios (Fig. 8 in Langner et al. 2020).

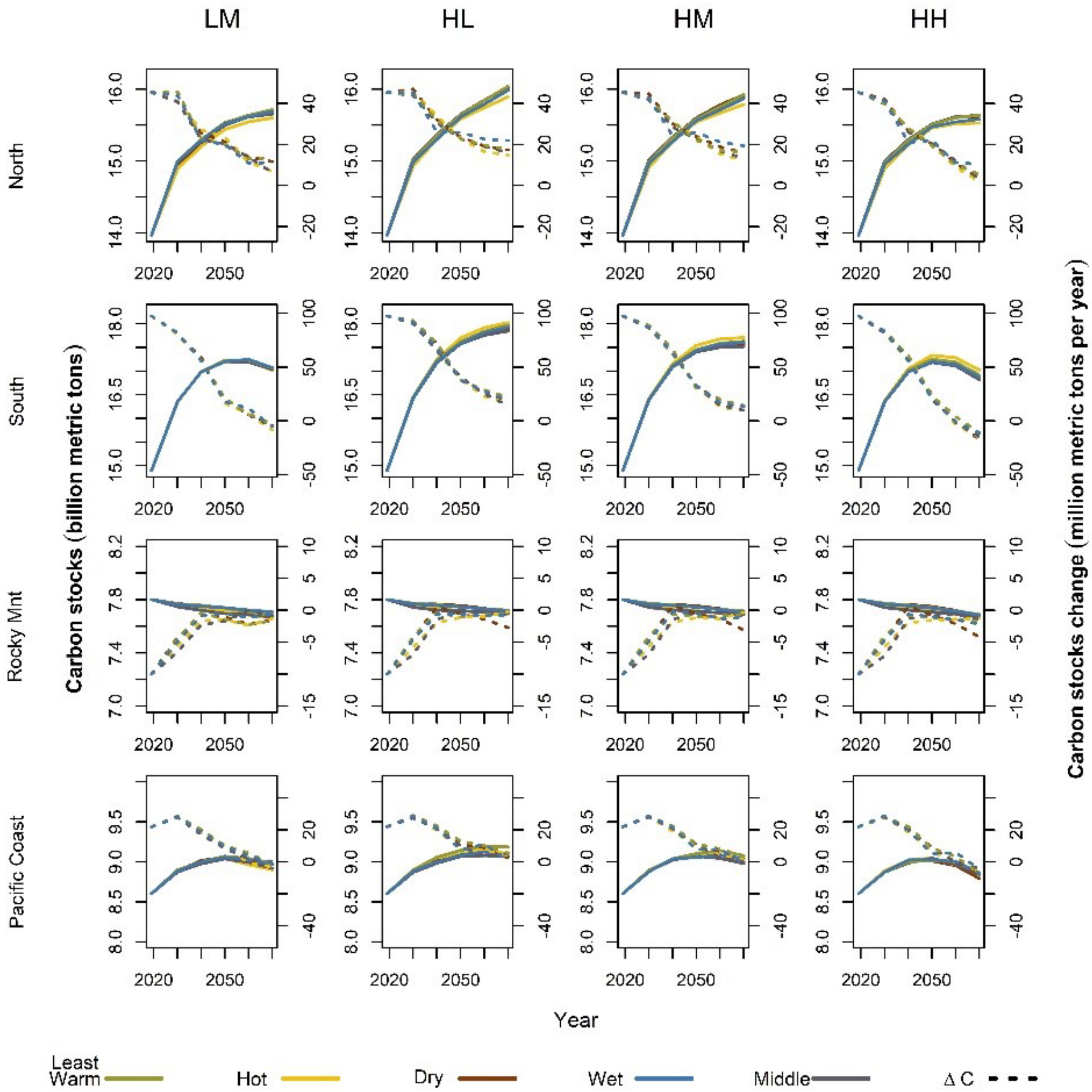
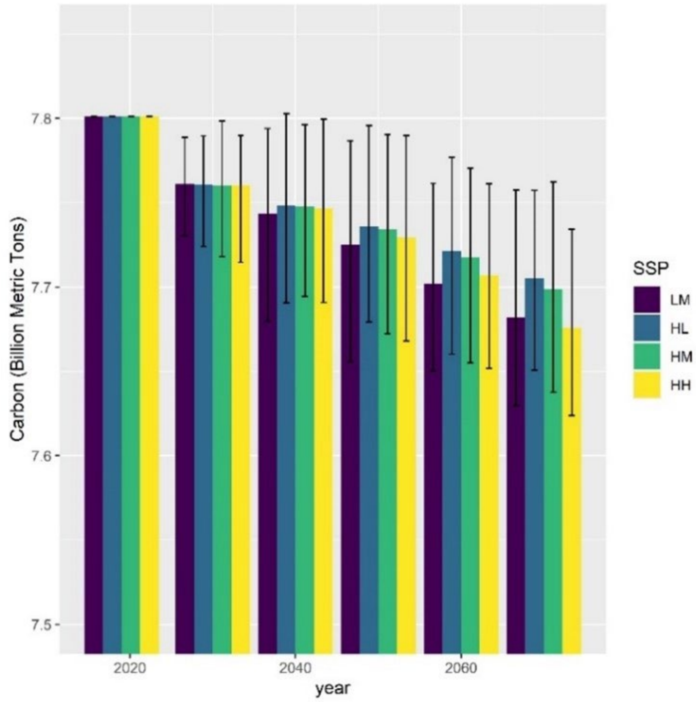
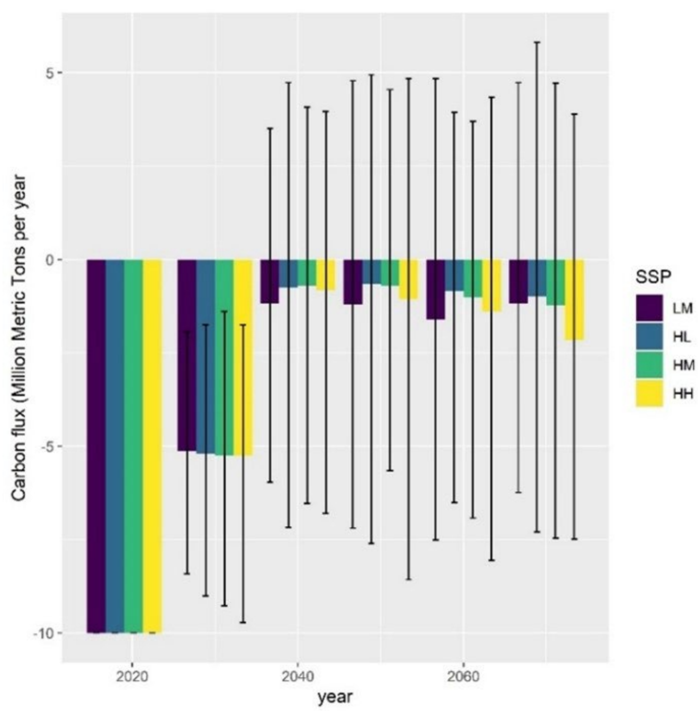


Figure 13. Forest remaining forest total forest ecosystem carbon stocks and stock changes for 2019 and projections to 2070 for each 2020 RPA Assessment scenario-climate future by RPA region. Projected forest ecosystem carbon stock and stock change are based on averaging decadal projection results by 2020 RPA Assessment scenario-climate future. Multiple solid lines indicate carbon stocks projections for the five individual climate models selected for each RCP; dotted lines indicate carbon stocks change (Fig. 6-34 in Coulston et al. 2023).



(a)



(b)

Figure 14. Forest remaining forest total forest ecosystem carbon stocks (a) and stock changes (b) for 2019 and projections to 2070 for each 2020 RPA Assessment scenario-climate future for the RPA Rocky Mountain Region.

5.3 Climate Change and Environmental Effects on Potential Future Carbon Dynamics

Climate change introduces additional uncertainty about how forests may change in the future due to climate-exacerbated risks from stress, insects, and fire (Anderegg et al. 2022; Wu et al. 2023), as well as its direct effects on the local environment, such as changes in temperature and precipitation (Matthews et al. 2018) and its indirect changes to many ecosystem processes (Vose et al., 2012). The uncertain levels of resilience of individual tree species to climate change (Baker et al. 2023; Clark et al. 2023) and projected increases in disturbance make future conditions uncertain. In some cases, using past trends to project the effects of disturbance, aging, and tree regeneration on forest carbon dynamics (Anderegg et al. 2020; Anderegg et al. 2022; Davis et al. 2023) may be erroneous and even irrelevant as there are many pathways to forest change, climate adaptation, and the maintenance of ecosystem integrity.

A climate change vulnerability assessment for the Forest Service Northern Rockies Region (Halofsky et al. 2018a), including the Helena-Lewis and Clark 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. The Helena-Lewis and Clark National Forest is situated primarily in the Eastern Subregion with the western-most portion of the Forest in the Central Subregion. Maximum annual temperature is projected to increase by 5-11 ^{o}F by 2100 in both subregions, and minimum annual temperature is projected to increase by 6-11 ^{o}F by 2100 in the Eastern Subregion and 6-12 ^{o}F in the Central Subregion. Minimum and maximum temperatures are projected to increase in all seasons and may rise above freezing. In the Region, the frequency of summer days with extreme heat is likely to increase (Halofsky et al. 2018a).

The Northern Rockies Region is expected to see slight increases in precipitation in winter and spring and slightly lower precipitation in summer (Easterling et al. 2017; Halofsky et al. 2018a), although projections for precipitation are much more uncertain than those for temperature. However, in the winter months, snowfall may decrease, particularly in warmer locations (e.g., middle to low elevation) (Klos et al. 2014 2014) suggesting potential changes in the form of precipitation. Precipitation extremes (i.e., high precipitation days and consecutive dry days) are projected to increase in frequency and intensity across the United States (Easterling et al. 2017).

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 decrease plant productivity and, therefore, carbon uptake and storage and increase effects of other stressors. Drought is also associated with increased wildfire area burned in the western United States (McKenzie and Littell 2017). The area burned by wildfires (Kitzberger et al. 2017; McKenzie et al. 2004) 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.

Projected temperature and precipitation changes may cause disjunct and isolated ponderosa pine populations on the Helena-Lewis and Clark National Forest to be vulnerable to loss. Future mountain pine beetle outbreaks would remain a threat to ponderosa pine, as well as to lodgepole, limber, and whitebark pine. Because the species is able to 'avoid' drought through effective stomatal closure, ponderosa pine has the potential to move upslope into areas occupied by Douglas-fir and lodgepole pine. The recent history of fire exclusion created dense stands that are now succumbing to mortality from competition, climate change, and high-severity fire. Increased fire frequency and severity has the potential to kill regeneration before it can develop into mature individuals or eliminate relict mature ponderosa pine seed sources (Halofsky et al. 2018a).

Increasing wildfire events in dense (vertical and horizontal cover) stands has the potential to kill the majority of Douglas-fir or be frequent enough that Douglas-fir seedlings are unable to become fire-resistant or reach reproductive maturity. Natural Douglas-fir regeneration on hot, drought-stressed, lower elevation sites and steep, southwest slopes would be less successful than historically witnessed, especially in areas experiencing cone damage from chronic western spruce budworm feeding. Ponderosa pine may replace Douglas-fir on these sites due to its ability to tolerate moisture deficits. Douglas-fir may be better able to survive on higher elevation, southerly slopes (Halofsky et al. 2018a).

As previously stated, lodgepole pine stands would be vulnerable to more frequent and severe mountain pine beetle outbreaks under a warming climate. Without disturbance, competition-induced mortality, insects and diseases, and succession could cause lodgepole pine stands to be replaced by subalpine fir. Lodgepole pine has the potential to expand its range with increased fire occurrence and extent. However, the species is also at risk of being removed in areas where fire is too frequent for stands to become reproductively mature and produce serotinous cones.

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. This includes impacts to individual species as well as forest type groups (Halofsky et al. 2018a). More drought- and fire-tolerant species, such as Douglas-fir or ponderosa pine, will likely increase in abundance (Halofsky et al. 2018a; Keane et al. 2018). The combination of individual tree species and forest type group characteristics and their vulnerability to climate change (Halofsky et al. 2018a; Keane et al. 2018) are likely to interact with site-specific characteristics, for example aspect and soil water holding capacity, to determine site-specific impacts of climate change (Lutz et al. 2010).

Vegetation shifts are most likely to occur after disturbance. For example, drought stress may preclude the establishment of tree species after high-severity disturbance, such as fire, allowing dominance by non-forest vegetation (e.g., grasses and shrubs) (Davis et al. 2019; Davis et al. 2023; 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.

According to the Forest Health Advisory System, within the Helena-Lewis and Clark National Forest, 876,798 acres are susceptible to high levels (≥25%) of total tree mortality, and 26-27 percent of tree biomass is at risk from forest pests (Krist et al. 2014). Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC 2023). Several models, including the InTEC model (Fig. 11), project greater increases in forest productivity when carbon dioxide fertilization is included in modeling (Aber et al. 1995; Ollinger et al. 2008; Pan et al. 2009; Zhang et al. 2012). However, the effect of increasing levels of atmospheric carbon dioxide 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 carbon dioxide could also be offset by losses from climate-related stress or disturbance.

The myriad effects of disturbance, aging, climate change, nitrogen deposition, and carbon dioxide fertilization are likely to affect carbon uptake and storage amounts of forest carbon and may also modify the rate of change in carbon stocks. Temperature and precipitation fluctuations will also impact carbon stocks and fluxes. Drought-stressed trees may also be more susceptible to insects and pathogens (Dukes et al. 2009), which can both reduce carbon uptake (Kurz et al. 2008; D'Amato et al. 2011) and increase emissions.

Forest regeneration failure associated with climate change and warming temperatures may also reduce soil carbon stocks (Nave et al. 2022). Changes in temperature and precipitation may impact soil organic carbon as well by affecting organic matter inputs and decomposition rates (Clark et al. 2016; D'Amore and Kane 2016). Soil microbial activity, which contributes to soil organic carbon formation, may alter via shifts in soil temperature and moisture, especially in water-limited ecosystems (Alster et al. 2016). The effects that temperature and precipitation impose on soil carbon vary (Nave et al. 2021b) and depend on local and regional soil type and vegetation composition (Nave et al. 2021a). A Menu of Adaptation and Mitigation Strategies and Approaches for Forest Carbon Management is available to help translate broad carbon management concepts into actionable tactics that help managers reduce risk from expected climate impacts to meet desired management goals (Ontl et al. 2020).

6.0 Conclusion

Forests in the Helena-Lewis and Clark National Forest have taken up and stored less carbon than they have emitted during the period covered by this assessment. Forest carbon stocks decreased by about 3.33 percent between 2005 and 2023, and reductions in carbon stocks caused by fire, insects, harvest, and environmental conditions have exceeded forest growth. Soil biogenic carbon values have high uncertainty because of data and modeling limitations and are likely underestimated in this assessment.

Disturbance has contributed to forest dynamics in the Helena-Lewis and Clark National Forest. Fire, impacting 4.66 percent of the forest, was the most prevalent disturbance type detected between 1990 and 2011, according to the methods used in this assessment. Lesser disturbances from 1990 to 2011 tended to be insects and harvest which impacted 1.6 and 0.67 percent of the forest, respectively. Forest carbon reductions associated with fire were low relative to total landscape carbon stocks. This disturbance type resulted in a reduction of about 2.02 percent of carbon from 1990 to 2011 with insects reducing carbon by 0.40 percent and harvest by 0.32 percent. Soil carbon was not included in the disturbance assessment. These estimates of disturbance effects on forest carbon losses represent an upper bound because they do not account for continued storage of carbon in harvested wood products, or the effect of forest products substitution for other more highly-greenhouse-gas-emitting building materials such as brick or metal. Carbon storage in harvested wood products sourced from national forests across the United States has increased since the early 1900s. Recent declines in timber harvest rates have slowed the rate of carbon accumulation in the harvested wood products sector.

The biggest influence on recent carbon dynamics in the Helena-Lewis and Clark National Forest was forest regrowth and aging following historic disturbances (wildfire, harvest, and land-use changes). Forest stands of the Helena-Lewis and Clark National Forest are now mainly middle- to old-aged (70-160 years old) with about 59 percent of the forest greater than 80 years old. Forest types consist primarily of Douglas-fir, lodgepole pine, and fir/spruce. Approximately 7 percent of stands are greater than 200 years old. According to the 2020 Resource Planning Act Assessment, forest carbon stocks are projected to decrease under future climate and socio-economic scenarios across that part of the United States with the broad area serving as a source by 2070.

Climate and environmental factors, including elevated atmospheric carbon dioxide and nitrogen deposition, have also influenced carbon uptake and storage in the Helena-Lewis and Clark National Forest in recent decades. Recent shifts in climate have probably increased forest vulnerability to stressors and decreased resilience. Increased carbon dioxide fertilization and nitrogen deposition likely have increased growth rates that increased carbon uptake and storage.

The interactions of climate effects with other components of forest dynamics such as disturbance and socioeconomic factors are complex and uncertain. Under changing climate and other conditions, the Helena-Lewis and Clark National Forest may be increasingly vulnerable to a variety of stressors. There may also be positive effects of a longer growing season, greater precipitation, and elevated atmospheric carbon dioxide concentrations, but those effects vary according to site conditions and may be transitory. How interactions among these factors will affect future carbon dynamics of the Helena-Lewis and Clark National Forest remains unknown.

The forested land cover type of the Helena-Lewis and Clark National Forest likely will be maintained in the future, barring disturbance-related conversions to non-forest cover and shifts in ownership. This is likely to result in continued forest carbon uptake and storage, with effects on broader-scale greenhouse gas levels. Projected continuing land conversion for development on private ownerships remains a potentially negative influence on forest carbon uptake and storage.

The Helena-Lewis and Clark National Forest will continue to play an important role in the USDA Forest Service mission to sustain the health, diversity, productivity, and climate resiliency of the Nation’s Forests and Grasslands to meet the needs of present and future generations. Careful stewardship of carbon uptake, storage, and stability while assessing multiple uses and benefits is part of an intentional approach to integrating climate adaptation and increasing ecosystem integrity under management that is consistent with the USDA Forest Service mission.

7.0 Glossary

Adaptation - Adjustments, both planned and unplanned, in natural and human systems in response to climatic changes and subsequent effects. Ecosystem-based adaptation activities use a range of opportunities for sustainable management, conservation, and restoration.

Biogenic carbon - carbon which cycles through living organisms, such as soil carbon, carbon stored in trees, or other plant parts.

Biomass - The mass of living organic matter (plant and animal) in an ecosystem. Biomass also refers to organic matter (living and dead) available on a renewable basis for use as a fuel; biomass includes trees and plants (both terrestrial and aquatic), agricultural crops and wastes, wood and wood wastes, forest and mill residues, animal wastes, livestock operation residues, and some municipal and industrial wastes.

Carbon flux - The transfer of carbon from one carbon pool to another.

Carbon pool - Different classes of biomass found within forests. The amount of carbon stored in pools changes over time and in response to various factors. Any natural region or zone, or any artificial holding area, containing an accumulation of carbon or carbon-bearing compounds or having the potential to accumulate such substances. Pools can be defined in several ways, but generally include the following: aboveground live biomass (trees, shrubs, herbs, grasses), belowground live biomass (roots), dead wood (standing dead trees, stumps, downed dead wood), forest floor (litter, leaves, small branches), and soil (mineral soil, decomposing organic matter).

Carbon sequestration - The process of plants using sunlight to uptake CO_2 from the air and convert it into plant biomass, including wood, leaves, and roots. The process of increasing the carbon content of a carbon reservoir other than the atmosphere; often used narrowly to refer to increasing the carbon content of carbon pools in the biosphere and distinguished from physical or chemical collection of carbon followed by injection into geologic reservoirs, which is generally referred to as “carbon storage.”

Carbon sink - In general, any process, activity, or mechanism that removes a greenhouse gas or a precursor of a greenhouse gas or aerosol from the atmosphere; in this report, a sink is any regime or pool in which the amount of carbon is increasing (i.e., is being accumulated or stored).

Carbon source - In general, any process, activity, or mechanism that releases a greenhouse gas or a precursor of a greenhouse gas or aerosol into the atmosphere; in this report, a source is any regime or pool in which the amount of carbon is decreasing (i.e., is being released or emitted).

Carbon stock - The amount or quantity of carbon contained in the inventory of a pool or reservoir.

Carbon uptake/storage - The amount of carbon retained long-term within the forest, stored in “carbon pools.”

Council on Environmental Quality (CEQ) - An advisory council to the President established by the National Environmental Policy Act (NEPA) of 1969. The council reviews federal programs for their effects on the environment, conducts environmental studies, and advises the President on environmental matters.

Climate change - A change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external factors, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Coarse woody debris - Any piece(s) of dead woody material, including dead boles, limbs, and large root masses, that are on the ground in forest stands or in streams.

Deforestation - the conversion of forest to non-forest use.

Disturbance - Stresses and destructive agents such as invasive species, diseases, and fire; changes in climate and serious weather events such as hurricanes and ice storms; pollution of the air, water, and soil; real estate development of forest lands; and timber harvest. Some of these are caused by humans, in part or entirely; others are not.

Ecosystem - A system of living organisms interacting with each other and their physical environment. The boundaries of an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

Emissions scenario - A plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on demographic, technological, or environmental developments.

Forest type - A classification of forest vegetation based on the dominant and commonly occurring associated tree species.

Greenhouse gases - Gases that absorb heat in the atmosphere near the Earth's surface, preventing it from escaping into space. If the atmospheric concentrations of these gases rise, the average temperature of the lower atmosphere will gradually increase, a phenomenon known as the greenhouse effect. Greenhouse gases include, for example, carbon dioxide, water vapor, and methane.

Land-use change - The conversion of forest land into different land use systems, often for anthropogenic uses such as cultivated land or horticulture systems.

Management goal - Broad statements, usually not quantifiable, that express a desired state or process to be achieved. Goals are often not attainable in the short term and provide context for more specific objectives.

Management objective - Concise, time-specific statements of measurable planned results that correspond to preestablished goals in achieving a desired outcome.

Mitigation - In the context of climate change, actions that reduce the amount of heat-trapping greenhouse gases, such as $CO2$, in the atmosphere to minimize changes in the Earth's climate. Actions can include avoiding or reducing emissions of greenhouse gases into the atmosphere, as well as removing greenhouse gases that are already present in the atmosphere.

National Environmental Policy Act (NEPA) - An act to declare a national policy which will encourage productive and enjoyable harmony between humankind and the environment, to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of humanity, to enrich the understanding of the ecological systems and natural resources important to the nation, and to establish a Council on Environmental Quality.

Net primary productivity (NPP) - The net increase (i.e., photosynthesis minus respiration) in total plant carbon, including above and below ground.

Projection - An estimate of something in the future, based on data or trends. Projections are distinguished from predictions to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Resilience - The capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly.

Structural diversity - The amount of three-dimensional variation within a forest stand. This is influenced by a combination of plant species diversity and height classes (vertical structure). It is often used as an indicator for biodiversity of forest ecosystems.

Vulnerability - The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. A system may be vulnerable if it is at risk of a composition change leading to a new type, or if the system is anticipated to suffer substantial declines in health or productivity.

8.0 Appendix

The following provides a description of the primary forest carbon models used to conduct this carbon assessment. The Carbon Dashboard, hosting all figures within this assessment, also contains descriptions and accompanying publications in support of each model.

8.1 Carbon Stocks and Pools

Estimates annual carbon stocks and stock change are estimated for the years 2005 to 2023 by summarizing data from Forest Inventory and Analysis (FIA) plots, using methods described in " Inventory of U.S. greenhouse gas emissions and sinks "(EPA 2024). FIA relies on allometric models to convert tree measurements to biomass and carbon.

The carbon pools are described as follows:

1. Live trees - all live woody vegetation at least 1 inch (2.54 cm) in diameter at breast height (d.b.h., 1.3 m). Separate estimates are made for both aboveground and whole-tree biomass, which includes all living biomass of coarse living roots more than 2 mm in diameter.

2. Belowground live-tree carbon - based on the difference between whole trees and above ground only.

3. Understory - all live herbaceous vegetation and woody vegetation up to 1-inch (2.54 cm) d.b.h. Estimates of understory are modeled from NFS Region and forest type as well as plot-level measurements of live-tree carbon density.

4. Standing dead trees - nonliving trees but otherwise follow the same definition as live trees, including coarse nonliving roots more than 2 mm in diameter

5. Downed dead wood (also known as down dead wood or coarse woody debris) - all nonliving woody biomass with a diameter of at least 7.5 cm at transect intersection lying on the ground. Th is pool also includes stumps and coarse roots more than 2 mm in diameter. Nonliving vegetation that otherwise would fall under the definition of understory is included in this pool

6. Litter - the litter layer including all nonliving biomass with a diameter less than 7.5 cm at transect intersection lying on the ground above the mineral soil. The litter estimation uses the FIA litter sample data to build a model relating a suite of biophysical parameters to the observed litter pool at each plot (Domke et al. 2016).

7. Soil organic carbon - all organic material in the soil and excludes the coarse roots of other pools. The soil organic carbon pool estimation utilizes FIA soil sample data to build a model relating a suite of biophysical parameters to observed SOC (Domke et al. 2017). The soil organic carbon pool estimation harmonizes FIA soil samples (0-20 cm) with other national soil carbon data collected at deeper intervals (ISCN 2012a, 2012b) to obtain a modeled SOC to a depth of one meter per FIA plot location.

8.2 Carbon Stock and Stock Change Estimates

Summary: Estimates annual carbon stocks and stock change from 2005 to 2023 by summarizing data from Forest Inventory and Analysis (FIA), following methods described in " Inventory of U.S. greenhouse gas emissions and sinks "(U.S. EPA 2024).

Description: The Forest Inventory and Analysis Program systematically inventories the nation's forested resources, with roughly one plot per 3,000 – 6,000 acres. Sampling intensity is lower for non-tree components (including soil, coarse woody debris, and litter), with a minimum of one plot per 96,000 acres. Although FIA sampling commenced in 1928, significant changes in sampling design began in 1999, making it difficult to reconcile earlier data with recent measurements. The analyses in this assessment include data collected from 2005 onward, when standardized data became available for all states. FIA summarizes data from forested plots within national forest administrative units and federally administered lands. FIA annually estimates total forested area and forest carbon within seven pools (described above).

Note: Many of the underlying models supporting estimates of biomass, volume, and carbon were updated in September 2023, collectively referred to as the National Scale Volume and Biomass Estimators (NSVB; Westfall et al. 2023). Therefore, FIA carbon estimates calculated before versus after this update are not directly comparable. Updated equations were applied retroactively to the entire FIA database, such that the current database now includes updated estimates across the entire time series.

Uncertainty: Potential sources of uncertainty with FIA data include 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). Forest Inventory and Analysis plots are resampled about every five years in the eastern US and every 10 years in the western US; therefore, estimates may lack temporal sensitivity as FIA data is designed for large-scale (e.g., regional) estimation. Additionally, estimates of change in forested area may reflect an actual change in land use due to reforestation or deforestation or may result from variation in weighting schemes and sampling intensity, making it important to consider both carbon stock and density (Woodall et al. 2013). Currently, the estimate of 2023 total ecosystem carbon includes a 95 percent confidence interval; updated confidence intervals for other pools and years are forthcoming. A 95 percent confidence interval reflects that there is a five percent chance that the true value falls outside of the range.

8.3 Regional Harvested Wood Products Carbon Model

Description: This model tracks the entire cycle of carbon from harvest to timber products to primary wood products to end use to disposal. The analysis incorporates regional harvests documented in detailed cut-and-sold reports that are available online and include the value and volume of timber sold and harvested in the region (USDA Forest Service 2023a). The carbon in HWP from timber products to primary products is based upon the methodology in Smith et al. (2006). For the purposes of this report, the HWP carbon pool includes both products in use and products that have been discarded to solid waste disposal sites (SWDS).

Uncertainty: Potential uncertainty in the harvested wood products carbon model include: adjustment of historical 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); site-specific variation such as how much residue is left onsite and how it is used; 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 (Gustavsson et al. 2006). Uncertainty was assessed using a Monte Carlo approach, which indicates a 90 percent confidence interval of ±0.05 percent for 2013, suggesting uncertainty is small at regional scales.

8.4 Disturbance Models

Forest Carbon Management Framework (ForCaMF)

Summary: Estimates how much more carbon (non-soil) would be on each National Forest if disturbances (harvest, insects, fire, abiotic, disease) from 1990 to 2011 had not occurred (Birdsey et al. 2019).

Description: ForCaMF relies on three underlying spatial datasets (maps) for each NF:

1. Annual disturbance maps for 1990 to 2011 (Healey et al. 2014), generated using the Vegetation Change Tracker algorithm (Huang et al. 2010) on Landsat data and manually verified using independent data.
2. Initial forest type maps (derived from Ruefenacht et al. (2008)).
3. Aboveground carbon in 1990 maps, based on Landsat imagery from 1992 and FIA data (Healey et al. 2014; Healey et al. 2016).

Based on the range of observed disturbance by region, FIA plots were iteratively simulated in the Forest Vegetation Simulator (FVS) for a variety of likely disturbance pathways. After simulation, similar plots (based on initial carbon/plot conditions) were grouped together to develop region-level carbon storage models for different forest types and disturbance pathways (disturbance types, magnitudes, and timing, as well as no disturbance). Carbon storage models were applied to the map of initial carbon and forest type, and each national forest was modeled forward in time from 1990 to 2011. Disturbance events reset the carbon trajectory of a given pixel to an appropriate post-disturbance pathway.

ForCaMF distinguishes between the effects of 1) individual types of disturbance, 2) cumulative effects of all disturbance, and 3) a hypothetical no-disturbance scenario, which can be used as a reference point to estimate relative carbon lost to different types of disturbance. To contextualize estimates of carbon lost to disturbance, we used estimates of total ecosystem carbon stocks in 2013 from the Carbon Calculation Tool (CCT; Smith et al. 2007) to calculate the percent by which carbon stocks had been reduced by disturbance (USDA FS 2015a-i). Updated estimates of carbon stocks could not be used to compare with results from ForCaMF because ForCaMF was modeled using FIA data accessed prior to 2023, which contain different underlying allometric equations.

There are a few important caveats for this model. Any National Forest, regardless of land management actions, would not experience an undisturbed scenario under any realistic conditions outside of the modelled ForCaMF framework; the model simply provides context for the total percent disturbance values. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends; therefore, ForCaMF is not exhaustive in analyzing all factors which contribute to changes in carbon. ForCaMF also simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., live trees, standing dead trees, understory vegetation, downed dead wood, and litter). Lastly, carbon losses resulting from disturbance that are estimated by ForCaMF may not be reflected in the carbon stock and flux estimates, due to FIA inventory cycles of 5 years (for eastern states) and 10 years (for western states).

Uncertainty: Various types of errors may exist in the remotely sensed disturbance maps used in the ForCaMF. ForCaMF results may incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond et al. 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey et al. 2014).

Integrated Terrestrial Ecosystem Carbon (InTEC) Model

Summary: Estimates the effects of climate, nitrogen deposition, CO_2 fertilization, and disturbance on carbon accumulation from 1950 to 2011 (Birdsey et al. 2019; Pardo et al. 2011).

Description: The Integrated Terrestrial Ecosystem Carbon model (InTEC; Chen et al. 2000) is a process-based biogeochemical model driven by monthly climate data, vegetation parameters, and forest disturbance information to estimate annual forest C and fluxes in C pools at regional and local scales. InTEC relies on empirical FIA datasets containing variables such as stand age, forest (or dominance) type, and net growth, resulting in a hybrid approach which combines a process-based biogeochemical model with empirical models. Specifically, the FIA-based stand age, dominance (or forest) types, and net primary productivity (NPP)-stand age relationships determine when stands were initially disturbed and, depending on forest (or dominance) type, how the productivity changes with stand age over time. As with ForCaMF, carbon stock and stock change estimates reported by InTEC are likely to differ from estimates of carbon stocks and flux because of the different data inputs and modelling processes.

Uncertainty: Process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle et al. 2005). InTEC is highly calibrated to FIA data and remotely sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel et al. 2015), as well as calibration with observational datasets (Zhang et al. 2012) suggest that model results produce a reasonable range of estimates of the total effect. 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. Due to significant computational requirements, uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC.

8.5 Net Primary Productivity Estimates

Summary: NPP-stand age curves were fit using methods described in He et al. 2012, combining FIA data on net woody forest growth and He et al. (2012) data on foliage and fine root turnover rates.

Description: FIA data were obtained from tables estimated using EVALIDator (https://apps.fs.usda.gov/fiadb-api/evalidator), where stand age and net woody growth (aboveground and belowground) were estimated by plot, excluding disturbed and treated plots from the population. Nonlinear curves were then fit by forest type group and ecoregion in R (www.R-project.org/). Curves for each National Forest Unit were assigned based on which ecoregions the Units are located in. Rare forest type groups may not be represented in FIA data (Bechtold and Patterson 2005).

8.6 Stand Age Distribution by Forest Type Estimates

Summary: Stand age distribution by forest type group was estimated from FIA data on undisturbed and untreated plots.

Description: Number of plots by forest type group and ten-year stand age class were obtained from EVALIDator (https://apps.fs.usda.gov/fiadb-api/evalidator) using the most recent inventory available in July 2023. Rare forest type groups may not be represented in FIA data (Bechtold and Patterson 2005).

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