USDA Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Forest Carbon Assessment for the Allegheny National Forest in the Forest Service's Eastern Region

Version 2.0, March 2024[1]

Old growth eastern hemlock and white pine in Hearts Content Scenic Area. USDA Forest Service photo by Todd Ristau, Research Ecologist

[1] USDA Forest Service. 2024. Forest Carbon Assessment for Allegheny National Forest in the Forest Service's Eastern Region. USDA Forest Service.

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Executive Summary

Forests play an important role in regulating the global carbon cycle by taking up (sequestering) and storing carbon. Forests sequester CO_2 from the atmosphere through the process of photosynthesis and store this carbon in plant biomass. Over time, plant biomass carbon moves to other carbon pools in the forest and is eventually emitted back to the atmosphere through decomposition or combustion (fire). To interpret assessments of how much carbon is held in a forest at a given time and how forest carbon changes over time, a basic understanding of how carbon cycles within a forest is needed.

Carbon sequestration is the process by which plants take up atmospheric CO_2 and convert it to biomass (total plant biomass is approximately 50 percent carbon). The rate of carbon sequestration is commonly measured as the net amount of carbon uptake (Tg, Mg; see Box 1) per hectare per year.

Once carbon is sequestered, it is held in the forest as a *carbon stock*, the amount of carbon stored at any one time. Carbon is stored in different reservoirs or zones, called *carbon pools*. Typically, and in this assessment, forest carbon is divided into five carbon pools: live aboveground biomass, live belowground biomass, dead standing biomass or downed woody debris, forest floor, and soil.

Carbon is initially sequestered by plants and stored in the live aboveground biomass carbon pool, with some of this carbon quickly moving into live belowground biomass to build roots and acquire soil resources. Over time, carbon in the live biomass pools will be transferred into the dead biomass and forest floor pools. As this organic matter decomposes, most of its carbon is released back into the atmosphere while a fraction of its carbon is transferred into the soil carbon pool where the decomposition process continues but generally at a much slower rate. The stability, or residence time, of carbon varies among these pools and with environmental conditions. Generally live and dead tree carbon stocks have a mean residence time of decades to centuries, forest floor carbon stocks have a shorter residence time of months to decades, and soil carbon stocks have the greatest stability, often persisting for decades to millennia. Therefore, understanding forest carbon dynamics requires consideration of both carbon pool size and stability over time.

The long-term capacity of forest ecosystems to sequester and store carbon depends in large part on their health, productivity, resilience, and ability to adapt to changing conditions. Some specific factors that affect forest carbon include:

- Forest age: young forests generally have higher rates of carbon sequestration while older forests have greater carbon stocks.
- Forest structure and diversity: forests with more complex structure will generally be more resilient and adaptive to changing conditions.
- Site conditions: some sites will be more productive than others, regardless of management actions, resulting in higher rates of carbon sequestration and greater carbon stocks. For example, sites with nutrient-rich soils and adequate soil moisture generally have higher productivity and store more carbon in both vegetation and soil pools.

This document provides an assessment of forest carbon for Allegheny National Forest (NF). This assessment describes how fluctuations of carbon on the unit-level relate to environmental factors and past human and natural disturbances. The assessment also considers future carbon trends in the context of climate change and disturbance. The assessment focuses solely on biogenic carbon, hereafter 'carbon'.

By providing high-quality, consistent, and transferable information, this assessment can help land managers to understand carbon stocks, fluxes, and impacts of disturbances at the forest level and can inform project and programmatic NEPA analyses. This analysis uses baseline carbon stocks, assessed from the Forest Inventory and Analysis (FIA) Program data, to estimate ecosystem carbon stocks at the unit scale. In addition, a combination of data, models, and qualitative analysis based on the best available science and information are used to assess how disturbance and environmental factors have impacted forest carbon in the past and are projected to affect forest carbon in future decades.

Any forest level analysis of carbon should be considered within the context of carbon stewardship and the Forest Service's holistic approach to land management, which supports our multi-use mission to steward national forests and grasslands for the benefit of current and future generations. Carbon stewardship seeks to optimize carbon within the context of ecosystem integrity and climate adaptation, not to maximize carbon at the expense of forest health or habitat.

Across the contiguous United States, forest land is the largest net carbon sink in the land sector, and conversion of forest land to non-forested land is the largest source of carbon emissions from this system. Forested area in the Allegheny NF increased by 21,436 ha from 1990 to 2020. Carbon density (forest carbon stocks per unit area) in Allegheny NF increased by 28.86 Mg C per ha. Consequently, ecosystem carbon stocks increased by 28.49 percent over this period, suggesting the forests of Allegheny NF are remaining stable.

Forest stand age, disturbance, climate, and environmental factors collectively impact ecosystem carbon stocks and future trends of Allegheny NF. Forests of the Allegheny NF are mostly (67 percent) middle-aged and older (greater than 80 years), and few stands are young. This suggests that while forest carbon stocks of the Allegheny NF have increased in recent decades, carbon stocks may decline due to forest aging in the coming decades without additional disturbance. Assessment of disturbance effects (harvests, fires, insects, and abiotic factors such as wind and ice storms) on forest carbon stocks from 1990 to 2011 indicate that the primary disturbance to non-soil carbon stocks in the Allegheny NF was timber harvest. Model results suggest that non-soil carbon stocks in the Allegheny NF would have been approximately 2.7 percent higher in 2011 if harvests had not occurred since 1990.

Natural disturbance frequency is expected to increase in the future, but it is difficult to predict how future disturbances will affect forest carbon. Model results suggest that environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, may have enhanced growth rates and helped to counteract forest carbon stock declines due to historical disturbances, aging, and climate. While the effects of future climate conditions are complex and remain uncertain, forests of the Allegheny NF may be increasingly vulnerable to a variety of stressors and at risk of

reduced carbon stocks. Overall, the Allegheny NF will continue to serve an important role in sequestering carbon, contributing to the regional and national-scale forest carbon sink for decades to come.

1.0 Introduction

1.1 Background and Purpose

On January 9th, 2023, the Council on Environmental Quality (CEQ) published the *National Environmental Policy Act (NEPA) Guidance on Consideration of Greenhouse Gas (GHG) Emissions and Climate Change*. The guidance provides numerous recommendations that pertain to land and resource management projects. These include the recommendation that agencies consider the projected GHG emissions or reductions for proposed actions and their reasonable alternatives (Section IV) and use this information to assess potential climate change effects (Section V). The CEQ guidance also advises agencies to assess the potential future state of the affected environment in NEPA analyses (Section VI), including considering the impacts of climate change on project actions and alternatives (for more information on incorporating climate change into NEPA Environmental Analysis, see Brandt and Schultz 2016). To do so, it recommends the use of the best available science, including relevant data and quantification tools where appropriate, to guide these analyses. However, CEQ advises agencies should be guided by a rule of reason and the concept of proportionality in determining the appropriate depth of analysis. This includes a recognition of the inherent complexities and uncertainties associated with analyzing projected biogenic carbon sources and carbon stocks that are associated with land and resource management actions under uncertain future climate conditions, including localized carbon impacts. This current carbon assessment focuses solely on biogenic carbon, hereafter 'carbon'.

This carbon assessment provides a framework to support carbon analysis at the National Forest (unit) scale. This document provides high-quality, consistent, and transferable information to inform project and programmatic NEPA analyses, as well as forest and landscape-level carbon analyses. The information within this assessment can help land managers understand carbon stocks, fluxes, and impacts of disturbances at the forest level.

This assessment of carbon stocks and fluxes uses both quantitative and qualitative data and a programmatic approach to analyze carbon sources and carbon stocks. Within this framework, this assessment is appropriate for proposed land and resource management actions occurring under a Land and Resource Management Plan as well as for the development of a Land and Resource Management Plan. Detailed analyses of impacts to carbon are site and practice specific and may require assessment of impacts to carbon over long time periods, which may be complex. Such an approach presents challenges for analyzing the effects on carbon for any given project, because of the complexity and uncertainty of ecosystem dynamics under changing climatic and environmental conditions. Nevertheless, evaluating current and future trends of forest carbon is vital for understanding the role of forests in the context of global change.

This assessment describes how fluctuations of carbon at the scale of the Allegheny NF relate to environmental factors and to past human and natural disturbance. This assessment also considers projected future changes in carbon under multiple changing climate scenarios and associated socioeconomic pathways. By attributing current carbon stock and flux data to past management

actions, this assessment projects how proposed actions similar in scope and scale may affect carbon. For proposed actions anticipated to be outside of the scope and scale of past actions; for example, if a management action results in forest loss outside the range of that exhibited within the period of the analysis (1990 to 2011), further assessment of its effects on carbon may be needed.

The components of this qualitative and programmatic carbon analysis provide a consistent, efficient, and unbiased approach. These components include:

Use of baseline carbon stocks: Forest Inventory and Analysis (FIA) Program data provide a nationally-consistent assessment of baseline carbon stocks across the National Forest System (NFS), which permit accurate estimation of ecosystem carbon stocks at the National Forest scale. FIA data are typically unsuitable for estimation at finer spatial scales, such as at the project scale, because of both the variability of forest stand conditions at the project scale that impact carbon stocks, and the spatial density of the FIA plot network, which typically consists of one plot per approximately 3,000-6,000 acres. Although technical capabilities will improve over time (e.g., advancements in small-area estimation), an appropriate and robust scale at which to evaluate project impacts remains the entire National Forest unit.

Assessment at the unit scale*:* Project boundaries can be somewhat flexible or altered to include or exclude non-impacted areas. Unit-scale analyses reflect a consistent frame of reference for project goals because the unit scale is used for land management planning. This approach recognizes that the desired benefits associated with a given proposed action may be realized beyond a particular project's boundaries. Assessing carbon at the scale of the Allegheny NF also allows for an unbiased comparison across landscapes that may vary in their carbon storage and sequestration capacities and provides necessary context for estimating carbon gains or losses from proposed activities and past disturbances.

Consistent analysis approaches that incorporate the best available science: Carbon assessments at the scale of the National Forest System unit help to inform project-level carbon analysis in a consistent, efficient, and unbiased approach that reflects the CEQ NEPA Guidance. Forest Service (FS) policies and CEQ recommendations require the use of best available science and data in NEPA analyses. There is strong scientific agreement that future carbon sequestration, storage, and stability on both forested and non-forested lands will be affected by changing climate conditions (Dupigny-Giroux et al. 2018). Changing climate condition impacts on forest health can include disturbance frequency and severity, as well as to tree growth, mortality, and regeneration. The current generation of tools used to quantify projected carbon stocks is unable to accurately incorporate these known impacts to ecosystem carbon dynamics over time and across all regions, particularly at fine (e.g., stand-level) spatial scales. Computer simulation models, such as the Forest Vegetation Simulator (FVS), can compare predicted future tree carbon stocks for proposed project actions, alternative actions, or a no-action alternative. However, these models are designed to be applied at the forest stand scale, not across multiple stands and landscapes, and require further refinement to accurately capture carbon flows across all relevant carbon pools (e.g., soil) in a consistent manner. Qualitative analyses performed at broader spatial scales using rigorous, objective methods remain the most robust way to integrate known climate impacts into carbon analyses (see, e.g., The United Nation's (UN) Climate Change secretariat's

Annual Reports highlighting achievements in addressing the climate emergency, and towards achieving the long-term objectives of the UN Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris Agreement).

1.2 Principles of Carbon Stewardship

Intentional and explicit analysis of effects of land and resource management on carbon dynamics forms the basis for carbon stewardship. While completion of this unit-level carbon assessment does not address all components needed to identify carbon stewardship as a project purpose, the information contained within this assessment can inform additional analyses of underlying carbon stewardship.

The Forest Service defines carbon stewardship as "actions informed by carbon science that provide for increased carbon uptake and storage or increased stabilization through land use and vegetation management strategies" (Janowiak et al. 2017). Thoughtful carbon stewardship seeks to optimize carbon within the context of ecosystem integrity and climate adaptation, not to maximize carbon at the expense of forest health or habitat. Carbon stewardship involves:

- The intentional analysis of the effects of management actions on carbon uptake, storage, and stability.
- Balancing carbon benefits with other ecosystem benefits.
- Considering landscape-scale ecosystem function and resilience.
- Enhancing net ecosystem carbon uptake and storage.
- Avoiding emissions from disturbance or tree mortality (carbon stabilization).

Carbon stewardship principles align with the Forest Service's holistic approach to land management (Janowiak et al. 2017), which supports the multi-use mission to steward national forests and grasslands for the benefit of current and future generations. These principles include:

1. Emphasize ecosystem function and resilience.
2. Recognize carbon sequestration as one of many ecosystem services.
3. Support diversity of approach.
4. Consider system dynamics and scale in decision making.
5. Use the best information and analysis methods.

Carbon stewardship requires a broad definition because ecosystem carbon responses to land management actions may be different across site conditions and ecosystems. The following elements of carbon stewardship are further described to help determine if proposed actions that can reasonably be expected to provide carbon benefits over the life of the project.

Carbon optimization: While national forests and grasslands can play an important role in climate change mitigation through land management, balancing the numerous environmental benefits provided by healthy ecosystems is paramount to achieving our mission. Carbon stewardship aims to optimize carbon benefits on the landscape in a way that recognizes the importance of achieving other management objectives. Maximizing ecosystem carbon stocks can create undesirable tradeoffs with other environmental benefits (Littlefield and D'Amato 2022), and in some landscapes may result in lower carbon benefits where carbon stability is compromised.

Maximizing carbon is therefore not necessary for, and is often counter to, achieving effective carbon stewardship.

Carbon stability: Carbon stewardship actions may be in response to assessments that indicate current conditions are out of alignment with ecosystem dynamics. Projects in alignment with carbon stewardship actions may involve reducing carbon stocks to restore and maintain ecosystem conditions that reflect historical reference conditions. For example, reducing tree densities in overstocked stands will decrease carbon to lower the risk of carbon losses from mortality and wildfire. These actions can provide carbon benefits since the remaining ecosystem carbon is expected to have greater stability and a longer landscape residence time. Carbon stewardship actions that increase carbon stocks in live vegetation, dead wood, and soils, should not elevate the risk of disturbance that would cause widespread carbon emissions back to the atmosphere. *Carbon stabilization* refers to the reductions in the risk of either carbon emissions or reduced sequestration capacity from natural disturbance or biotic stressors resulting from carbon stewardship actions that increase the residence time of carbon in the ecosystem.

Climate adaptation: Actions that provide adaptation benefits through reduced risk of unintended climate impacts can provide carbon benefits through avoided carbon emissions. Some disturbances or forest health issues may also decrease carbon uptake through plant growth. While not all adaptation-related actions provide carbon benefits, there are many actions, such as planting climate-resilient, productive species or genotypes, that address risks to ecosystem health while sustaining or improving the capacity of ecosystems to sequester carbon.

Time scale of carbon benefits: Carbon benefits are not limited to immediate increases in carbon stocks, but instead may be realized over a variety of time scales and patterns. Carbon responses may even include near-term decreases in carbon stocks, whereas carbon benefits in the form of increases may take many decades to occur.

1.3 Carbon Cycling in Forested Ecosystems

Carbon uptake and storage are some of the many ecosystem services forests provide. Through photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it as biomass (plant stems, branches, foliage, roots), and much of this organic material is eventually stored in forest and grassland soils and considered carbon. The amount of carbon stored is referred to as a carbon stock. The reservoir or zone, such as soil, live aboveground biomass, or downed dead wood, containing an accumulation of carbon is considered a carbon pool. Carbon uptake and storage from the atmosphere helps modulate GHG concentrations. See Box 1 for a crosswalk of metric measurements used in this document.

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. The rate of carbon removal by plants from the atmosphere is influenced by many factors, including natural disturbances, management, forest age and successional pathways, climate and environmental factors, and availability of nutrients and water. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools that also release CO_2 through decomposition or combustion (fires). Carbon within forest systems is therefore part of a

cycle, where carbon emitted to the atmosphere through fire and decomposition is eventually removed from the atmosphere by growing forests and vegetation. The long-term capacity of ecosystems to sequester and store carbon depends in large part on their health, productivity, resilience, and ability to adapt to changing conditions. Net non-soil carbon storage over a full successional cycle is zero.

Box 1. Carbon Units. The following table provides a crosswalk among various metric measurement units used in the assessment of carbon stocks and emissions.

Multiple	Name	Symbol
10^0	Tonne	t
10^3	Kilotonne	Kt
10^6	Megatonne	Mt
10^6	Million metric tonnes	MMt
10^0	Gram	g
10^3	Kilogram	Kg
10^6	Megagram	Mg
10^9	Gigagram	Gg
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 a year.

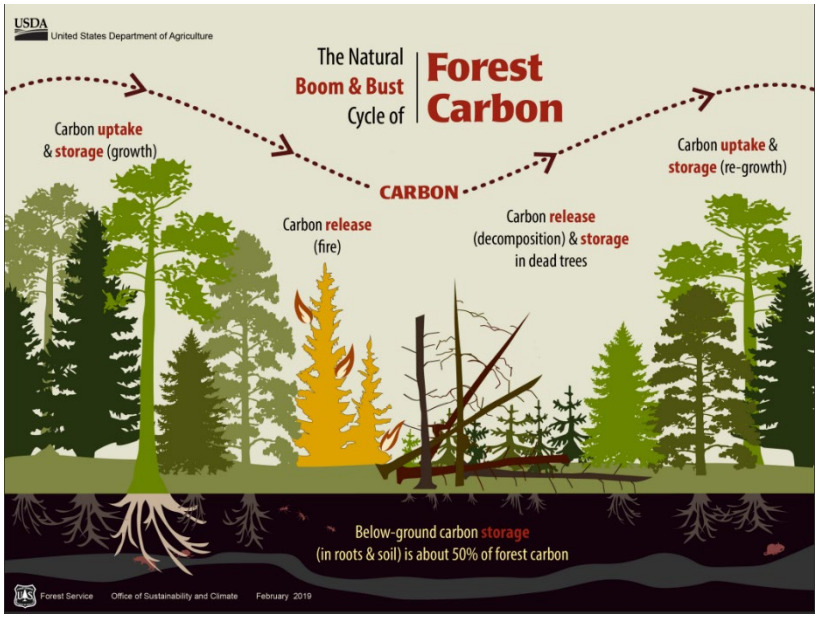
1.4 Forest Management for Carbon Optimization

For many forest stands, managing for carbon can be an effective approach for mitigating increasing atmospheric carbon dioxide concentrations (see Ontl et al. 2020 and Kaarakka et al. 2021) that are driving a changing climate. Carbon management can sometimes, but not always, align with overall forest resilience goals. Carbon management actions can address vulnerabilities of forest ecosystems to climate change impacts, chronic stressors, or other forest health concerns that put sustained forest productivity at risk of decline. These vulnerabilities can stem from past land use, such as past clearing and subsequent forest regrowth, that may simplify the species composition or structural diversity of the ecosystem, or from a shift away from natural disturbance regimes such as frequent low-intensity fires, resulting in altered stand development and the buildup of hazardous fuels. Other disturbances such as insect epidemics, and drought, can undercut efforts to maintain or increase carbon storage (Goodwin et al. 2020). Carbon stabilization can be enhanced by forest management actions which contribute to forest resilience and adaptability, although several factors, such a drought and growing space, can hinder this ability.

Management activities providing carbon benefits over time include timber harvests to diversify species, structural, or age-class diversity; and thinning and fuel reduction treatments that remove forest carbon and transfer a portion to wood products (Puhlick et al. 2020; Crockett et al. 2023). Silvicultural tools for addressing vulnerabilities include removing hazardous fuels and reducing live tree density, thereby increasing resiliency to climate-driven disturbances. Timber harvest

initially reduces the amount of forest carbon but can transfer carbon to wood products or energy use, while increasing the productivity and health of remaining trees (Sathre and O'Connor 2010, D'Amato et al. 2011, Oliver et al. 2014). Careful planning of treatments can have longer-term benefits that reduce the risk of future wildfires and tree mortality, thus optimizing carbon benefits (Krofcheck et al. 2019). Globally, scientists agree that reducing conversion of forested land to non-forest can avoid carbon emissions (Vance 2018). National Forest System lands thus may provide a buffer against land use change by keeping forests as forests.

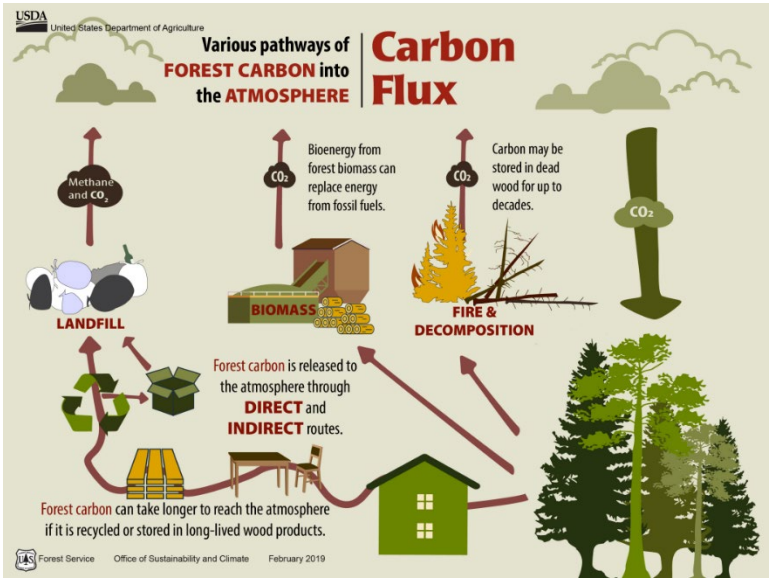
Following natural disturbance or harvest, regrowing forests sequester carbon, eventually accumulating the same amount of carbon initially emitted, in the absence of further disturbance or climate change (McKinley et al. 2011). Although disturbance, forest aging, and management are often the primary drivers of forest carbon dynamics, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients such as nitrogen can influence forest growth and carbon dynamics (Caspersen et al. 2000; Pan et al. 2009). Additional resources may be found in the Adaptation Workbook, an online tool supported by the US Forest Service and the Northern Institute of Applied Climate Science. The Adaptation Workbook takes users through a structured process designed to consider the potential effects of climate change and design land management and conservation actions that can help prepare for changing conditions.



1.5 Role of Forest Management at the National Level

The Intergovernmental Panel on Climate Change (IPCC) summarized human contributions to climate change by "sectors" (IPCC, 2014) and updated this report in 2023. The 2023 Synthesis Report (IPCC, 2023) integrates findings from recent publications (IPCC, 2021; IPCC, 2022a; IPCC, 2022b). According to the 2022 Resource Update from the USDA Forest Service Northern Research Station, forest land, harvested wood products (HWP), woodlands, and urban trees within the land "sector" represent a net GHG sink over the 1990-2020 time series, both individually and collectively. Interannual variability in GHGs was primarily driven by disturbance (e.g., wildfire, harvest), land conversion (e.g., forest land converted to cropland and

settlements, reforestation/afforestation), and changes in HWP stocks in use and transfers to solid waste disposal sites (U.S. EPA 2023; Domke et al. 2023). Forest land, harvested wood products, woodlands, and urban trees, combined within the land sector, continue to represent the largest net carbon (C) sink in the United States, offsetting the equivalent of more than 12.4 percent of total (gross) GHG emissions in 2023 (U.S. EPA 2023; Domke et al., 2023). In 2020, forest land, HWP, woodlands, and urban trees in settlements collectively represented a net increase in C stocks. The forest land remaining forest land category is the largest net sink in the land sector and the conversion of forest land to non-forested land is the largest source of emissions, according to the 2022 Resource Update report.



1.6 Carbon Assessment Report Description on the Unit Level

For the Allegheny NF, we use two reports to estimate how disturbances, management, and environmental factors have influenced carbon storage.

- **Baseline Report** (USDA Forest Service, 2015; Domke et al. 2020): applies the Carbon Calculation Tool (CCT) (Smith et al. 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the national forest from 1990 to 2020. The Baseline Report also provides information on carbon storage in HWP for each Forest Service region through 2013.
- **Disturbance Report** (Birdsey et al. 2019): provides a national forest-scale evaluation of the influences of disturbances and management activities from 1990 to 2011, using the Forest Carbon Management Framework (ForCaMF) (Healey et al. 2014; Raymond et al. 2015; Healey et al. 2016). This report also contains estimates of the long-term relative effects of disturbance and non-disturbance factors on carbon stock change and accumulation, using the Integrated Terrestrial Ecosystem Carbon (InTEC) model for 1950 to 2011 (Chen et al. 2000; Zhang et al. 2012).

These reports used FIA data in combination with validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System. Collectively, these reports incorporate advances in data and analytical methods, and are

currently the best data and science available to provide comprehensive assessments of NFS carbon trends.

This carbon assessment provides a framework to support carbon analysis at the forest level. This document provides high-quality, consistent, and transferable information to inform project and programmatic NEPA analyses, as well as forest- and landscape-level carbon analyses. This information can help land managers to better understand carbon stocks, fluxes, and impacts of disturbances at the forest level.

1.7 Unit Description

The Allegheny NF, located on the Allegheny Plateau in Pennsylvania, contains approximately 207,499 ha of forest land. Maple-beech-birch and oak-hickory forest types are the most abundant across the Allegheny NF, according to FIA data. The carbon legacy of Allegheny NF and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. The Allegheny Plateau was once a vast forest dominated by eastern hemlock and American beech on the ridgetops and white pine and oak growing along the slopes and bottoms of the Allegheny River and Clarion River. The Allegheny Plateau was profoundly transformed by industrialization and consequent unregulated logging beginning in the early 1800s when the first European settlers reached the area and continuing into the 1900s with the advent of the wood chemical industry. The once vast forest of the Allegheny Plateau was almost completely removed, leaving barren, brush covered hillsides as far as the eye could see. Deer and their predators were almost eliminated due to unregulated hunting and loss of habitat. (USDA-FS, 2007).

As the need for sustainable forest management became evident, the U.S. government began purchasing large areas of these overharvested and often submarginal lands in the eastern United States in the early and mid-20th century to be established as national forests (Shands, 1992). In September 1923, the Allegheny NF was established under the authorities of the Weeks Act of 1911 as one of the first national forests in the eastern United States. This legacy of timber harvesting and early efforts to restore the forest is visible today in the relatively homogenous age structure, composition, and carbon dynamics of these forests (Birdsey et al. 2006; Ducey et al. 2023; Foster et al. 1998; Lorimer 2001; Rhemtulla et al. 2009; Schulte et al. 2007; Whitney 1987).

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

According to results of the Baseline Report (USDA Forest Service, 2015, Domke et al. 2020), carbon stock estimates in the Allegheny NF increased from 35.33±3.68 teragrams of carbon (Tg C) in 1990 to 45.33±5.92 Tg C in 2020, a 28.5 percent increase in carbon stocks over this period (Fig. 1). This includes carbon stocks for all carbon pools, including live and dead vegetation and soils. For context, 45.33 Tg C is equivalent to the emissions from approximately 36.17 million passenger vehicles in a year. Despite some uncertainty in annual carbon stock estimates, reflected by the 95 percent confidence intervals, there is a high degree of certainty that carbon stocks on the Allegheny NF have increased from 1990 to 2020 (Fig. 1). The trend of increasing carbon stocks from 1990 to 2020 (Fig. 1) over the 30-year period suggests that the forests of

Allegheny NF may be a carbon sink. These trends over time on Allegheny NF have resulted in categorization as a high carbon density forest with greater than 10% increases in carbon stocks from 2000 to 2020

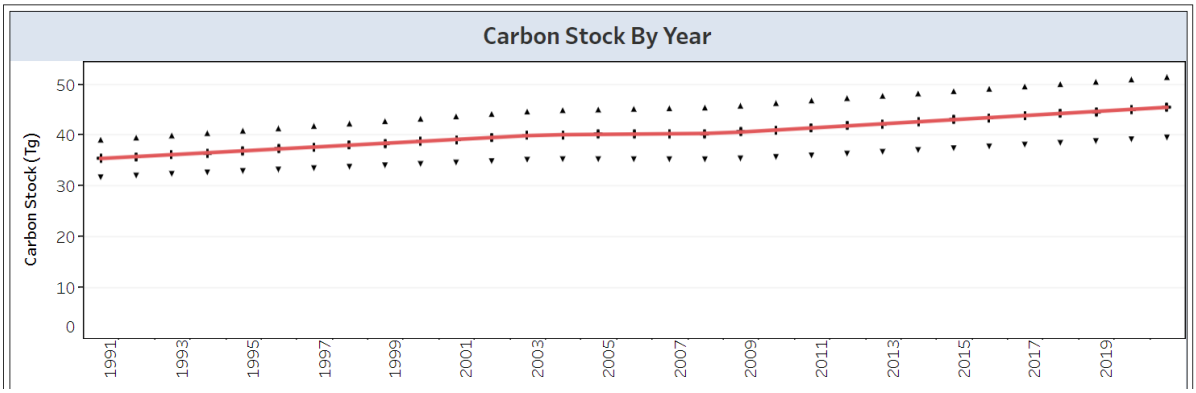


Figure 1. *Total forest carbon stocks (in teragrams) from 1990 to 2020 for Allegheny National Forest, bounded by 95 percent confidence intervals. Estimates use Forest Inventory and Analysis Data and are derived from the Carbon Calculation Tool (updated in 2020 by Northern Research Station), following methods in Smith et al., 2007.*

on the Climate Risk Viewer (Climate Risk Viewer Beta 0.1.3, USDA Forest Service, 2023). Soils of the Allegheny NF and most temperate forests are the largest ecosystem carbon pools (Jevon et al. 2019; Walters et al. 2023) and represent an opportunity to mitigate rising atmospheric carbon dioxide concentrations through both their protection and management (Bossio et al. 2020). About 45 percent of forest carbon stocks in the Allegheny NF are stored in the aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2). About 30 percent of forest carbon stocks are stored in mineral soils to a depth of one meter (excluding roots). Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke et al. 2017). The values in Figure 2 are subject to change, as carbon can transfer to different carbon pools over time or as a result of forest disturbance; this can also be referred to as carbon flux. For example, as a result of background tree mortality or a severe disturbance event, carbon stocks within dead wood pools (downed dead, standing dead) may temporarily represent a greater percentage of total forest carbon relative to that which is stored in the aboveground live pool. Additionally, carbon within downed woody material, forest floor, and standing dead trees can transfer to the soil carbon pool (Janowiak et al. 2017) which may increase flux to soil carbon stocks over time.

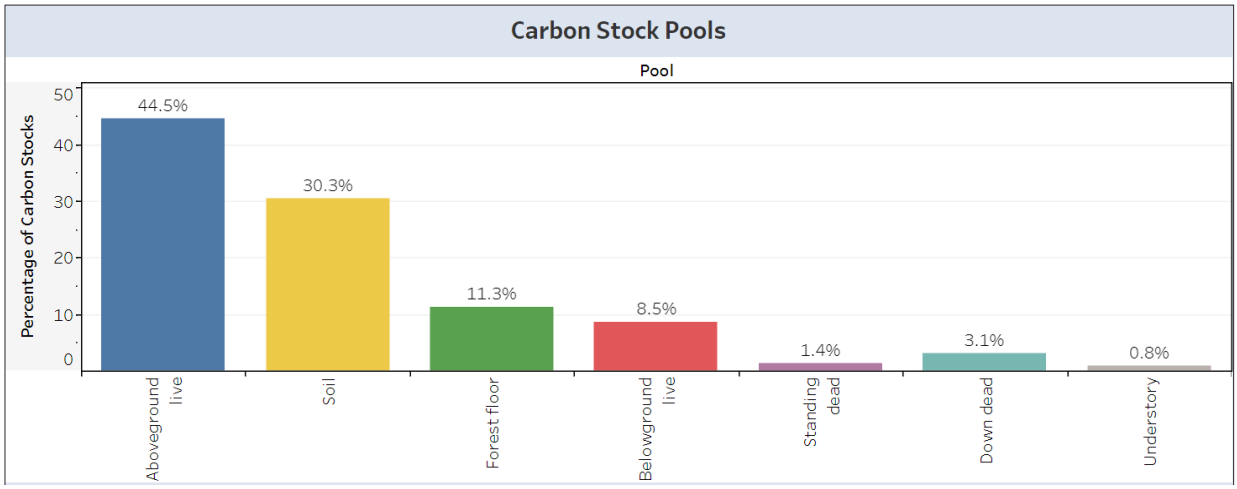


Figure 2. *Percentage of carbon stocks in 2020 in each of the forest carbon pools for Allegheny National Forest. Estimates use Forest Inventory and Analysis Data and are derived from the Carbon Calculation Tool (updated in 2020 by the Northern Research Station), following methods described in Smith et al., 2007.*

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. In the eastern U.S., land development is an important landscape driver, and conversion of forest to non-forest land is one of the largest contributions to reduction of the forest carbon pool (Olofsson et al. 2016; Ma et al. 2020). However, National Forest lands are protected from land conversion, and therefore are an important safeguard of the long-term forest carbon pool in this region. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area in Allegheny NF has increased from 186,062 ha in 1990 to 207,499 ha in 2020, a net change of 21,436 ha[2]. When forest land area increases, total ecosystem carbon stocks typically also increase, indicating the forest land is serving as a carbon sink. It should be noted that FIA plot layouts, methods for assigning forest conditions, and requirements for the definition of forest land have changed regionally and over time (Goeking et al. 2015). Measured forested area may change as an artifact of these changes in definitions and sampling designs. This may alter the assessment of whether forest carbon stocks are increasing or decreasing, and therefore, whether the national forest is considered to be serving as a carbon source or sink (Smith et al. 2007).

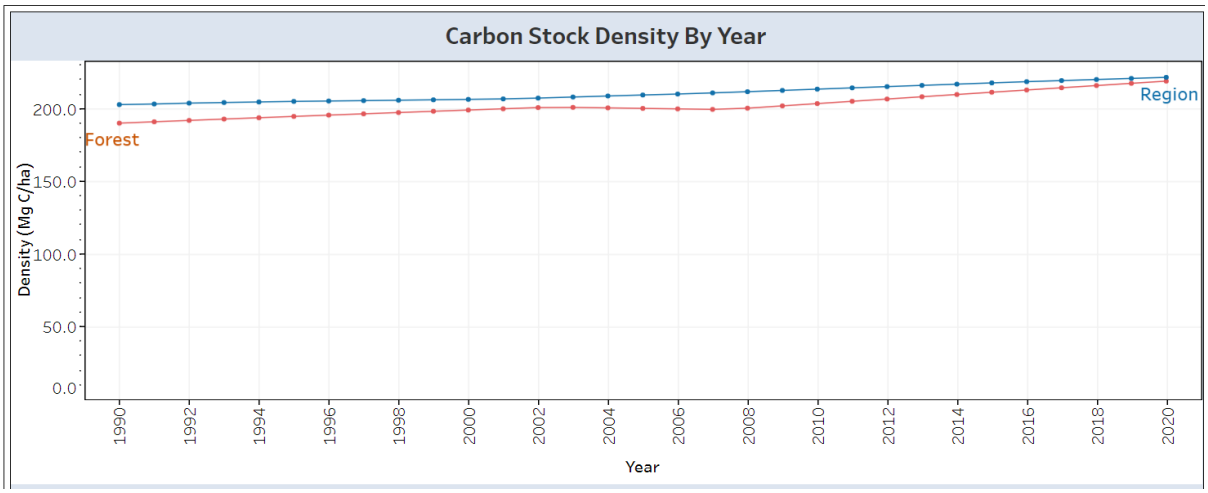


***Figure 3**. Average carbon stock density (in megagrams per hectare) in the Allegheny National Forest and for the Eastern Region from 1990 to 2020. Estimates use Forest Inventory and Analysis Data and are derived from the Carbon Calculation Tool (updated by the Northern Research Station), following methods described in Smith et al., 2007.*

Carbon density is used to assess how changes in forested area affect forest carbon stocks. Carbon density is an estimate of forest carbon stocks per unit area. In the Allegheny NF, carbon density increased from about 189.61 Megagrams of carbon (Mg C) per ha in 1990 to 218.47 Mg C per ha in 2020 (Fig. 3). This increase in carbon density suggests that total carbon stocks may have increased. Analysis of changes in carbon stocks and density on the forest unit level is only appropriate in analysis at the forest scale, not at the project level scale within a forest. Such analyses, such as the values within the total carbon stock change figure, serve to provide context for future land management activities conducted on the forest level, such as thinning, fuels reduction, or insect spread prevention.

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Similar to Allegheny NF, most national forests in the Eastern Region have experienced increasing carbon densities from 1990 to 2020. Carbon density estimates in the Allegheny NF have been similar to but slightly lower than the average for all national forest units in the Eastern Region (Fig. 3). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. Differences may also be affected by disturbance and management regimes as well as data limitations at localized scales (see Section 3.0).

2.2 Carbon in Harvested Wood Products

Harvest disturbance transfers carbon out of the forest ecosystem, but some of that carbon is not emitted directly back to the atmosphere; rather, it is stored in wood products. The duration of carbon stored in products varies depending on the type of commodity produced. For example, short-lived forest products such as paper, pulp, or biomass will not store carbon on a long-term scale comparable to keeping the carbon within timber. In the eastern US, the proportion of long-lived timber products is lower than in other regions (e.g., Pacific region; Oswalt et al., 2019), which means the HWP C turnover time tends to be shorter. Instead, the eastern market is dominated by short-lived pulp and bioenergy products (Dugan 2021). This means that current

impact of long-lived wood products in reducing net carbon emissions is less than in other regions of the U.S. As more wood-based commodities are produced and remain in use, the amount of carbon stored in harvested wood products increases. As more forest products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Forest products stored in solid waste disposal sites may continue to store carbon for many decades.

Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect that provides added benefits for greenhouse gas emissions reductions, beyond the carbon stored in the products themselves (Gustavsson et al. 2006; Lippke et al. 2011). Increasing the proportion of bioenergy products in the eastern Region may be a viable option for reducing carbon emissions in the eastern region (Dugan 2021). Wood products are often disposed of in solid waste disposal sites (SWDS) at the end of their useful lifetime. Carbon can continue to be stored for long periods, as decomposition proceeds at a very slow rate under the oxygen-excluded conditions of SWDS. Much of the amount of harvested carbon that is initially transferred out of the forest can also be recovered with time, as the forest in the affected area regenerates and grows over the decades following harvest.

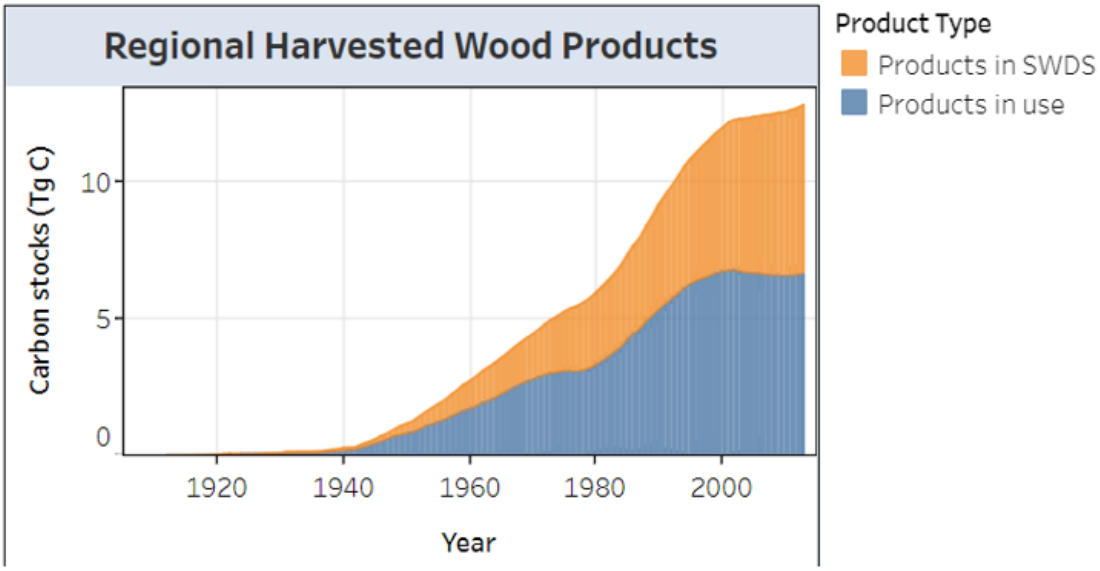


Figure 4. *Cumulative total carbon (in teragrams) stored in harvested wood products sourced from National Forest System units in the Eastern Region from 1912 to 2013. This includes products that are still in use and carbon stored at Solid Waste Disposal Sites (SWDS). Estimated using the Intergovernmental Panel on Climate Change production accounting approach (Smith et al. 2006).*

In national forests in the Eastern Region, harvest levels remained low until after the start of World War II in the late 1930s, when they began to increase, which caused an increase in carbon storage in HWP (Fig. 4). Timber harvesting and subsequent carbon storage later increased rapidly from the 1980s through the 1990s. Wood products are often disposed of in solid waste disposal sites (SWDS) at the end of their useful lifetime. Carbon can continue to be stored for long periods as decomposition proceeds at a very slow rate under the oxygen-excluded conditions of SWDS. Storage in products and landfills reached roughly 12 Tg C in 2001. However, because of a decline in harvesting in the early 2000s (to 1950s levels), carbon accumulation in the product sector has slowed, and carbon storage in products in use has

declined slightly since 2002. In the Eastern Region, the contribution of national forest timber harvests to the HWP carbon pool exceeds the decay of retired products, causing a net increase in product-sector carbon stocks from 1912 to 2013. In 2012, the carbon stored in HWP was equivalent to roughly 1 percent of total forest carbon storage associated with national forests in the Eastern Region.

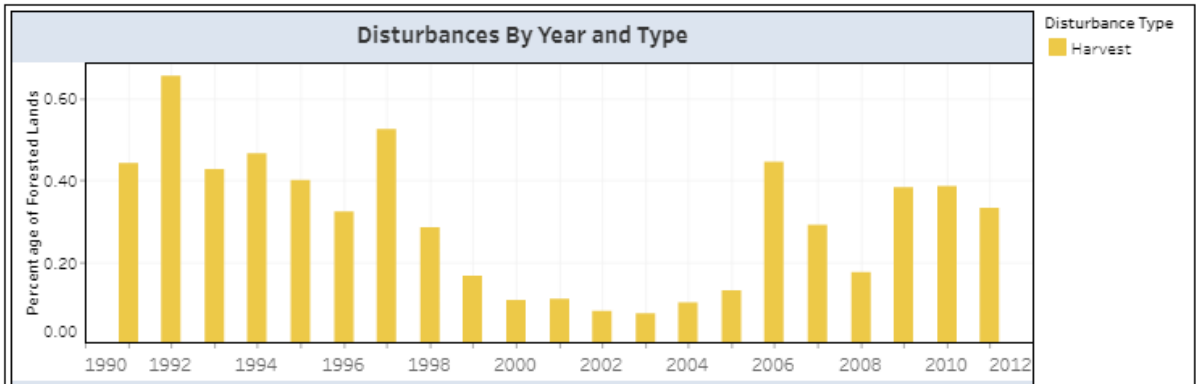


Figure 5a. *Percent of forest disturbed, by year and type of disturbance, for the Allegheny National Forest. Estimated using annual disturbance maps derived from land satellite imagery, following methods described in Haeley et al., 2018.*

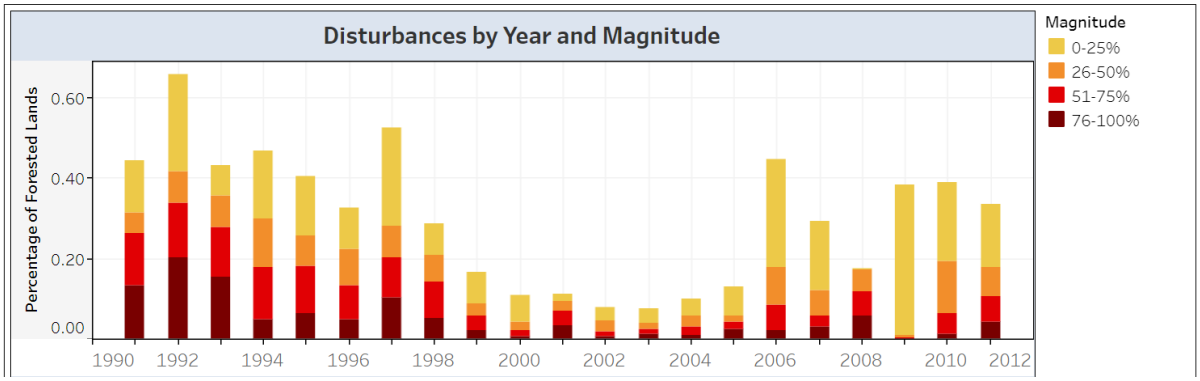


Figure 5b *Percent of forest disturbed, by year and magnitude of disturbance (change in canopy cover), for Allegheny National Forest. Estimated using annual disturbance maps derived from land satellite imagery, following methods described in Healey et al. 2018.*

3.0 Factors Influencing Forest Carbon

3.1 Effects of Disturbance

The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually verified, annual disturbance data derived from Landsat satellite imagery (Healey et al. 2018). The Landsat imagery was used to detect canopy cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting satellite-imagery-derived disturbance maps indicate the type of disturbance and the year that the disturbance was detected (which, in some cases, may be the year *after* the disturbance actually occurred, because the timing of the imagery data capture may not align with the disturbance event).

The method used to produce the disturbed forested area and carbon impact, ForCaMF, is no longer being updated. This method used manually-verified remote sensing data to accurately attribute forested pixels to disturbance type up to 2011. Currently, there is no viable substitute for this method. Office of Sustainability and Climate is currently working with Rearch and Development to use an FIA-based method of disturbance attribution and estimation; however, we estimate that these results will not be available until 2025.

The disturbance graphs indicate that timber harvest has been the dominant disturbance type detected on the Allegheny NF from 1990 to 2011 in terms of the total percentage of forested area disturbed over the 21-year period (Fig. 5a). However, timber harvests affected a relatively small area of the forest during this time. In most years, timber harvests affected less than 0.6 percent of the total forested area of the Allegheny NF in any single year from 1990 to 2011, and in total 6.31 percent (approximately 12,518 ha) of the forested area during this period (198,427 ha). The percentage of the forest harvested annually has oscillated over this 21-year period. Further, although harvests varied in the proportion of trees removed (i.e., magnitude), they on average removed less than 50 percent of canopy cover (Fig. 5b).

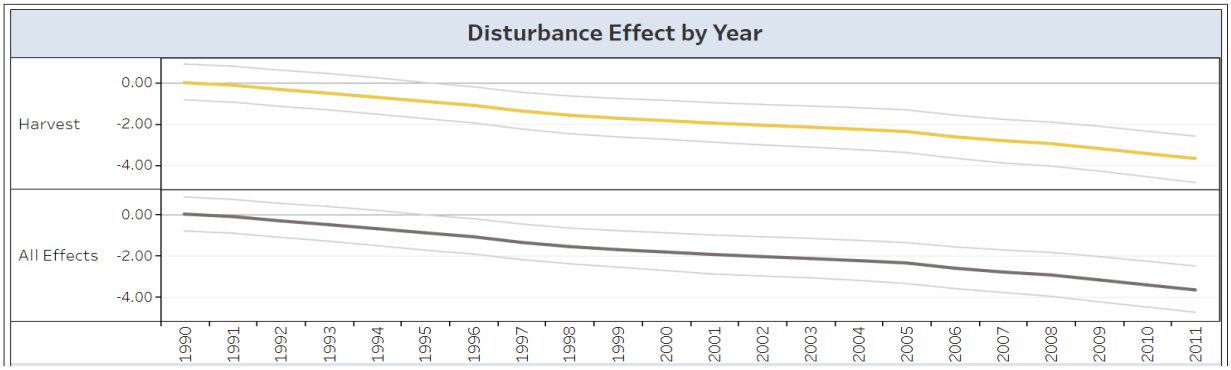


Figure 6. *Cumulative lost potential storage of carbon (in megagrams per hectare) as a result of disturbances in Allegheny National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the Forest Carbon Management Framework following methods described in Birdsey et al. 2019.*

Timber harvesting on Allegheny NF was also the primary disturbance influencing non-soil (i.e., vegetation and associated pools) carbon stocks from 1990 to 2011. The ForCaMF model indicates that, by 2011, Allegheny NF contained 3.69 Mg C per ha less non-soil carbon due to harvests since 1990, as compared to a hypothetical undisturbed scenario (Fig. 6). As a result, non-soil carbon stocks in the Allegheny NF would have been approximately 2.7 percent higher in 2011 if harvests had not occurred since 1990 (Fig. 7). By comparison, across all land ownerships nationally from 1926 to 2017, fire and harvest reduced total forest stocks on average by 14 percent and 51 percent respectively (Magerl et al. 2023).

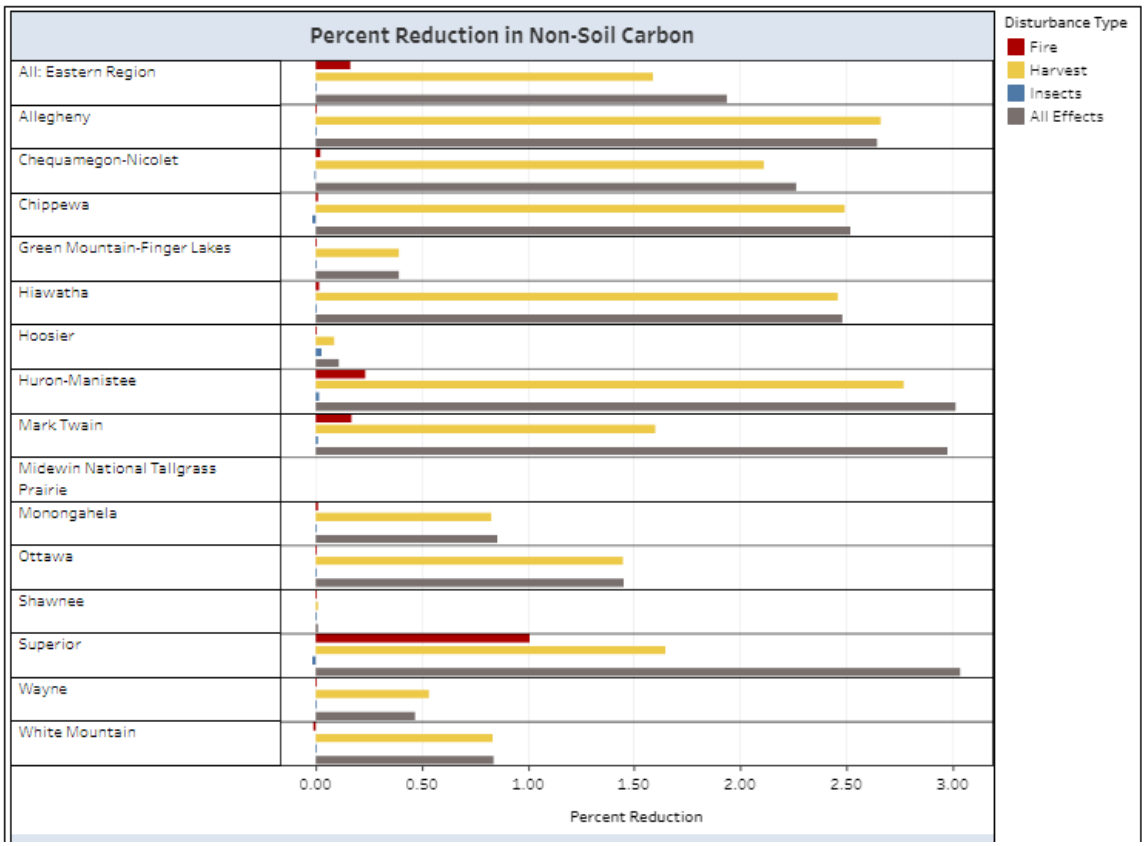


Figure 7. *The percentage by which the 2011 carbon storage on each National Forest System in the Eastern Region was reduced by disturbances from 1990 to 2011 relative to a hypothetical baseline with no disturbance. Estimated using the Forest Carbon Management Framework following methods described in Birdsey et al. 2019, and non-soil carbon stock estimates from the Forest Inventory and Analysis Data derived from the Carbon Calculation Tool, following methods described in Smith et al., 2007.*

Across all national forests in the Eastern Region harvest has been the greatest disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 1.59 percent lower by 2011 (Fig. 7). Considering all national forests in the Eastern Region, by 2011 fire accounted for the loss of 0.16 percent of non-soil carbon stocks and insects only 0.01 percent. The ForCaMF-based disturbance analysis was conducted over a short time period relative to those of forest development and successional processes. After a forest is harvested, it will eventually regrow and recover the carbon removed from the ecosystem in the harvest. However, several decades may be needed to recover the carbon removed depending on the type of the harvest (e.g., clear-cut versus partial cut), as well as the conditions prior to the harvest (e.g., forest type and amount of carbon) and after the harvest (e.g., herbivory, disturbance, and climate) (Raymond et al. 2015). Also, ForCaMF does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, if carbon stored in wood products, substitution effects, and forest regrowth is considered (Lippke et al. 2011; McKinley et al. 2011; Skog et al. 2014; Dugan et al. 2018). However, the proportion of long-lived wood products tends to be lower in the eastern region as compared to other areas of the country (Oswalt et al., 2019); therefore, there is less of an impact from long-lived wood products on net carbon emissions reductions in this region. The IPCC

recognizes wood as a renewable resource that can provide a mitigation benefit to climate change if sustainably managed (IPCC, 2022b). Therefore, an assessment of impacts of harvest activities on GHGs is not complete without incorporation of carbon storage estimates from wood products (see Section 2.3). Lastly, in the eastern region, non-harvest disturbances are projected to increase with climate change, such as fire (Miesel et al. 2015) and extreme weather events (Butler-Leopold et al. 2018). Therefore, the hypothetical "no-disturbance" scenario is highly unlikely, though it is useful and valid for basis of comparing relative impacts of disturbance.

While the ForCaMF model can detect various disturbances and estimate resulting carbon losses from multiple forest carbon pools, it does not estimate impacts of these disturbances on soil carbon stocks. While there are not currently analyses of disturbance impacts on soil carbon stocks specific to Allegheny NF, recent studies provide insights into patterns among ecoregions, which show varying soil carbon responses to harvest and fire. Overall, these studies point 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. 2019, 2021a, 2021b, 2022). For example, whereas harvest generally does not affect soil carbon in the Pacific Northwest (Nave et al. 2021a), in the Lake States of the eastern region, it can have positive or negative effects on topsoil carbon storage depending on soil texture and parent material. However, these effects are not significant for ecosystem level carbon accounting (Nave et al. 2021b). These ecoregional analyses provide greater detail and specificity than broadscale literature reviews and also broader inferences than individual site-level studies. To date, these analyses in the eastern region suggest that total soil carbon stocks are not significantly affected by harvest. This highlights the importance of careful soil management, especially in the portion of the managed area where soil physical impacts occur (e.g., due to traffic). At a continental scale, after a disturbance, the forest floor is more likely to exhibit changes in carbon than is mineral soil with fire having a greater impact than harvest (Nave et al. 2010, 2011).

Generally, fire decreases forest floor carbon stocks in all regions, though the magnitude and variability of these declines differ across regions. In the eastern region, fire can change the composition of soil organic matter, with greatest impacts on the forest floor (Miesel et al. 2015). However, losses of soil organic carbon in topsoil are generally offset by gains deeper in the soil profile, meaning fire generally has no net impact on the entire soil profile (Nave et al. 2021b). In most regions, mineral soils are not affected by fire, and distinct types of fire influence forest floor responses variably, with prescribed fire producing smaller carbon losses than unintentional or unmanaged wildfires. Legacy impacts of fire on aboveground forest carbon storage vary with fire frequency, severity, and recovery time. In the eastern region, fire history at stand establishment has little impact on carbon storage of late successional forests (Clay et al. 2022); however, repeated fire events have been shown to decrease carbon storage through potential site quality impacts (Gough et al. 2007). For these reasons, prescribed burns conducted under expert guidance, may serve as 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). Other than severe wildfires or forest to non-forest land use change, no type of disturbance or harvest is likely to cause a change in soil carbon that is detectable throughout the entire soil profile. Site-level research papers relevant to typical management actions on the Allegheny NF (e.g., Jevon et

al. 2019; Ross and Knowles 2023) and quantitative reviews suggest that harvesting does note detectably alter soil C stocks, and that implementing existing soil quality standards, protection guidelines, and monitoring protocols is an effective way to promote soil carbon stewardship.

3.2 Effects of Forest Aging

Typically, forests follow a four-stage model of 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 and disease 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 (moisture, substrate, or climate) or intermediate disturbances, making the stand origin or endpoint difficult to determine (e.g., Franklin et al. 2007, Palik et al. 2020). Stand age serves as a proxy for past disturbances and management activities (Pan et al. 2011b). When a forest stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration (peaks in Figures 8a and 8b).

Stand-age distribution for the Allegheny NF derived in 2023 from forest inventory database indicates elevated stand establishment around 1910-1930 (Fig. 8a). This period of elevated stand establishment came after decades of intensive logging and large wildfires in the late 1800s and early 1900s (Foster, 2006). Policies focusing on restoring forests after decades of overharvesting enabled these stands to establish, survive, and accumulate carbon. Similar age trends have been widely observed in eastern U.S. forests (Birdsey et al. 2006). Stands regrow and recover at different rates depending on forest type, site conditions, and regional climate, for example, forest NPP tends to peak earlier and decline more slowly in the Southeast, whereas long-lived species in the California mixed conifer group results in increasing NPP for >125 tears (He et al. 2012). Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer & Euskirchen, 2004; He et al. 2012), as indicated by NPP-age curves (Fig. 8b), derived in part from FIA data. In the eastern U.S., old-growth forests are likely small carbon sinks, though some may be neutral or potentially small carbon sources, depending on forest type, regional variation, disturbance, and carbon methodology (Bradford and Kastendick 2010; Desai et al. 2005; Finzi et al. 2020; Gunn et al. 2014; Halpin and Lorimer 2016; Hollinger et al. 2021).

InTEC model results show that Allegheny NF accumulated carbon steadily at the start of the analysis in the 1950s through the 1980s (Fig. 9) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Fig. 8b). As stand establishment declined and more stands reached slower growth stages around the 1990s, the rate of carbon accumulation declined (negative slope).

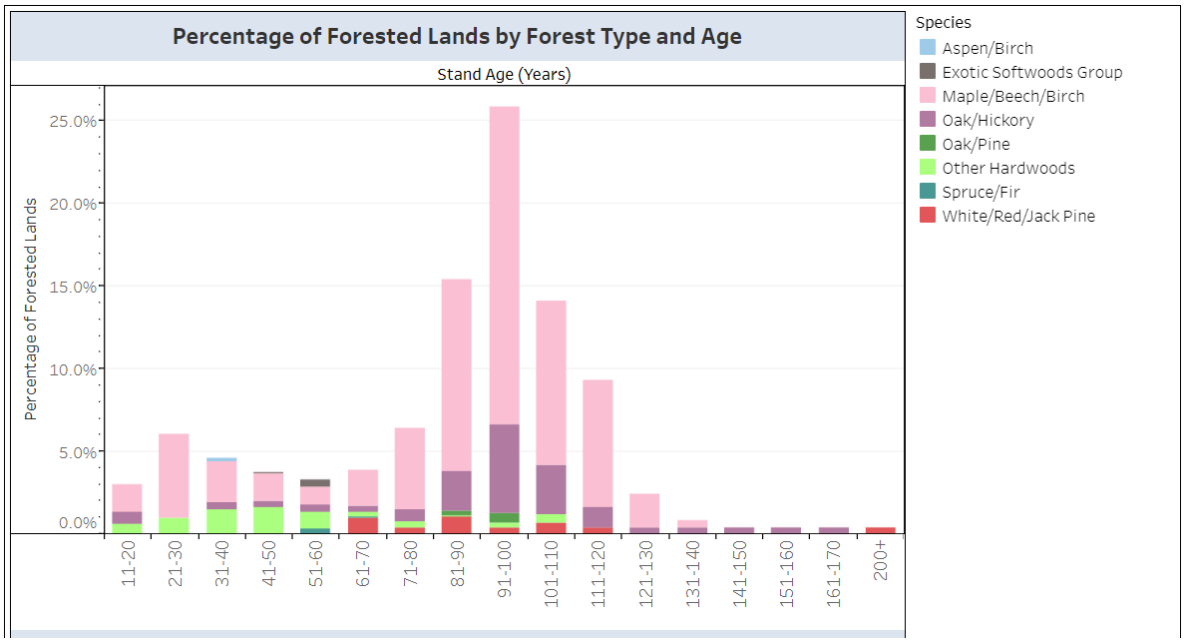


Figure 8a. *Stand age in 2023 by forest type group in Allegheny National Forest, from Forest Inventory and Analysis (FIA) data (USDA Forest Service, FIA Program, 2023) using methods of Bechtold and Patterson (2005).*

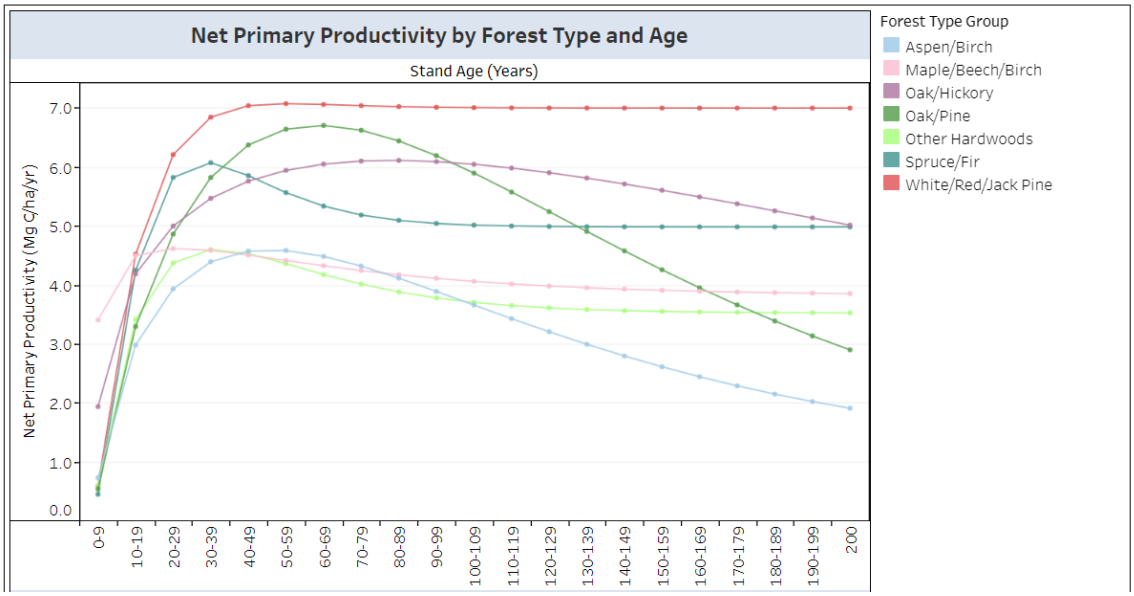


Figure 8b. *Net primary productivity-stand age curves (in megagrams of carbon per hectare per year) by forest type group in Allegheny National Forest. Derived from Forest Inventory and Analysis (FIA) data (USDA Forest Service, FIA Program, 2023) using methods of Bechtold and Patterson (2005) and He et al., (2012).*

3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO_2 concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally, annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year, but overall, climate since 1950 has had a small positive effect on carbon

stocks in the Allegheny (Fig. 9). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju et al. 2007; Melillo et al. 2017), but warming temperatures can also reduce soil moisture through increased evapotranspiration, causing lower forest growth and reduced emissions, especially in semiarid and low elevation forests (Xu et al. 2013). When moisture conditions are not limiting, increases in temperature can positively impact forest growth by lengthening the growing season in temperate, high elevation ecosystems (Stern et al. 2021; Vose et al. 2018).

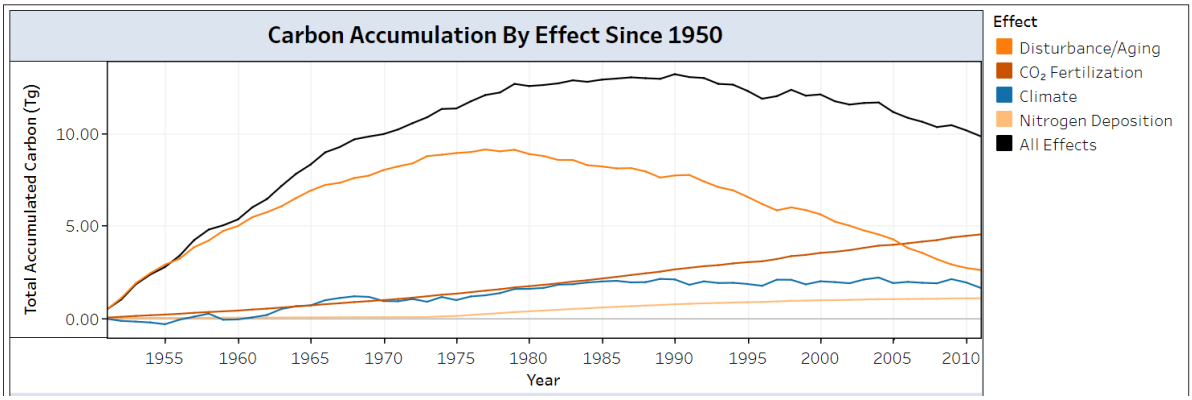


Figure 9. *Accumulated carbon since 1950 (in teragrams) in Allegheny National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all these factors combined (shown in black line) for 1950–2011, excluding carbon accumulated pre-1950. Estimated using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen et al. 2000).*

In addition to climate, the availability of CO_2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen et al. 2000; Pan et al. 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused an increase in both CO_2 and nitrogen emissions (Chen et al. 2000; Keeling et al. 2009; Zhang et al. 2012). According to the InTEC model, higher atmospheric CO_2 concentrations have consistently had a positive effect on carbon stocks in Allegheny NF, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 9). This effect is commonly referred to as carbon dioxide fertilization, where the increased availability of carbon dioxide in the atmosphere can result in increased photosynthesis. However, a precise quantification of the magnitude of this CO_2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones et al. 2014; Zhang et al. 2015). Long-term studies examining increased atmospheric CO_2 show that forests initially respond with higher productivity and growth, but the effect is greatly diminished or lost within 5 years in most forests (Zhu et al. 2016). Uncertainty surrounding increased forest growth rates in response to elevated CO_2 is also related to nutrient availability in the soil (Vose et al. 2018). There has been considerable debate regarding the effects of elevated CO_2 on forest growth and biomass accumulation, thus warranting additional study (Körner et al. 2005; Norby et al. 2010; Zhu et al. 2016).

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the Allegheny NF (Fig. 9). Like CO_2, the actual magnitude of this effect remains uncertain. Estimates from inventory data in the northeast and north-central United States confirm that nitrogen deposition has enhanced growth among most tree species, subsequently increasing forest carbon accumulation (Thomas et al. 2010). However, elevated nitrogen deposition can also

decrease growth in some species for a variety of reasons, such as leaching of base cations in the soil, increased vulnerability to secondary stressors, and suppression by more competitive species (Pardo et al.2011). Some regional studies have documented negative effects on forest productivity associated with chronically high levels of nitrogen deposition in the eastern United States (Aber et al. 1998; Boggs et al. 2005; Pardo et al. 2011). Overall, the InTEC model suggests that CO_2 fertilization and nitrogen deposition offset the declines in carbon accumulation associated with disturbance and aging.

3.4 Mature and Old-Growth Forests

In the fall of 2022, the U.S. Department of Agriculture Forest Service and the U.S. Department of the Interior Bureau of Land Management (BLM) set out to develop mature and old-growth forest definitions and a national inventory of forests on interagency lands in response to Executive Order 14072 (White House 2022). The mature and old-growth forest initial inventory relies on the FIA field plot network; estimates used data from the most recent inventory cycle for each state as of December 2022 (https://www.fia.fs.usda.gov/library/database-documentation/).

The Allegheny NF manages specifically for old-growth forests via the Land and Resource Management Plan, as stated in the desired conditions. In alignment with Executive Order 14072, the Forest Service released a Mature and Old-Growth Forests map and technical report (USDA Forest Service 2023a; USDA Forest Service 2023b). Nationally, the Forest Service contains 24,400,019 acres of old-growth forest land and 67,413,361 acres of mature growth forest land.

Approximately 4,000 acres of remnant, original forest remains on the Allegheny NF in the Tionesta Scenic and Research Natural Area. Although it makes up less than 1 percent of the total Allegheny NF acreage, it comprises approximately 12 percent of the total old growth forest in Pennsylvania and is the largest contiguous old growth beech-hemlock forest in the Northern United States. Hearts Content Recreation Area, A National Natural Landmark, also contains old growth forest. Mature and old growth species on the Allegheny NF include eastern white pine, eastern hemlock, American beech, and white oak. The technical report and accompanying map depict low amounts of old-growth and high amounts of mature forest on the Allegheny NF, aligning with the data presented in Figure 8a.

Mature forests are the stage of forest development immediately before old-growth. In general, mature forests contain more complexity in tree size and arrangement than younger forests but lack larger tree sizes and the structural complexity often found in old-growth. Old-growth forests typically have abundant large-diameter trees, complex vertical structure, and abundant dead wood in both snags and/or downed woody materials, and a thick litter layer on the forest floor that results in carbon stocks that are often, but not always, higher compared to mature forests (Hoover et al. 2012). Depending on forest type, mature and old-growth forests may have greater species diversity as well as variable complexity in structure than younger age classes present in the landscape mosaic in which mature and old growth forests typically occur (Fraser et al. 2023). Even though the oldest forests take up carbon more slowly than younger forests, decades of carbon accumulation make these forests hotspots of carbon stocks, especially in the forest floor and downed woody components (Hoover et al. 2012; Hoover and Smith, 2023; Gray et al. 2016).

A continual adaptive management process integrating new science, local conversations, and

social processes will refine old-growth and mature forest working definitions over time. It is important to note that any inventory represents a snapshot in time, resulting from the legacy of past events that has led to the present, not a prediction of future conditions. Mature and old-growth forest inventory results provide information about the status of these forests; they do not present any information about their sustainability, climate-informed management, or desired conditions for any given forest type or location. More information on old and mature forests can be found in the Forest Service Climate Risk Viewer and technical report (USDA Forest Service 2023a; USDA Forest Service 2023b).

The Climate Risk Viewer suggests that there arehigh amounts of mature and low amounts of old growth stands in the Allegheny NF. This signifies the presence of conditions associated with the definitions of old-growth/mature forest, including abundant large diameter trees and associated high carbon stocks in the live tree carbon pools. Additionally, high/intermediate classes correlate to a greater proportion of forest floor and downed woody carbon relative to standing tree carbon.

4.0 Future Carbon Conditions

4.1 Prospective Forest Aging Effects

The retrospective analyses presented in the previous sections can provide an important basis for understanding how various factors may influence carbon storage in the future. For instance, the forests of the Allegheny NF are mostly middle-aged and older (greater than 80 years) and few stands are young (Fig. 8a). If the Forest continues on this aging trajectory, more stands will reach a slower growth stage in coming years and decades (Fig. 8b), potentially causing the rate of carbon accumulation to decline. Although NPP curves indicate that biomass growth may be approaching peak levels (Fig. 8b), ecosystem carbon stocks can continue to increase for many decades as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert et al. 2008). Forests can remain carbon sinks into old age for some forest types; the trajectory of carbon stocks depends on the balance of NPP with respiration. Therefore, managers may find it beneficial to balance young forests with high sequestration rates and mature forest with large carbon stores (Bradford and Kastendick 2010; Patton et al. 2022). Furthermore, while past and present aging trends can inform future conditions, their applicability may be limited, because potential changes in management activities, disturbances, and future climate conditions could affect future stand age and forest growth rates (Davis et al. 2009; Keyser & Zarnoch, 2012).

The Resource Planning Act (RPA) assessment provides regional projections of forest carbon trends across forest land ownerships in the United States based on a new approach that uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (Woodall et al. 2015; USDA Forest Service, 2016). The RPA reference scenario assumes forest area expansion rates began to decline due to land use change starting in 2022. However, national forests tend to have higher carbon densities than private lands and may have land management objectives and practices that differ from those on other lands.

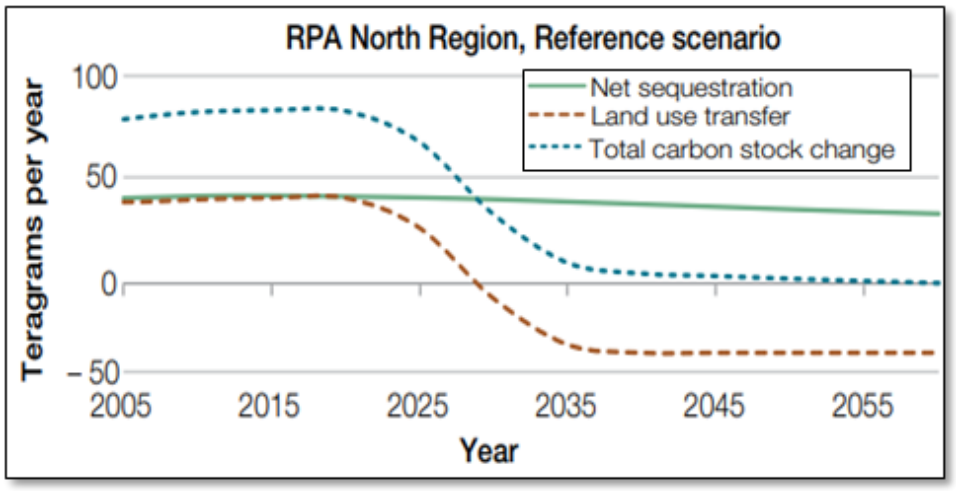


Figure 10. *Projections of forest carbon stock changes in the Eastern Region (equivalent to the boundaries of Eastern Region, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

For RPA's North Region (equivalent to Forest Service's Eastern Region boundary, but includes all land ownerships), projections indicate that the rate of carbon sequestration may rapidly decline in the 2020s and 2030s and then stabilize towards the middle of the century. This decline is mostly due to the loss of forest land (land-use transfer), and to a lesser extent through forest growth, aging, and disturbances (net sequestration) (Fig. 10). At the global and national scales, changes in land use—especially the conversion of forests to non-forest land (deforestation)—have a substantial effect on carbon stocks (Pan et al. 2011a; Houghton et al. 2012). Converting forest land to a non-forest use removes a large amount of carbon from the forest and inhibits future carbon sequestration. National forests tend to experience low rates of land-use change, and thus, forest land area is not expected to change substantially within the Allegheny NF in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 10, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2060.

4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major driver of historic and current forest carbon stock change and sequestration that is occurring at the Allegheny NF and elsewhere in across the region. Several other modeling studies that have been conducted across the region simulate future changes in forest growth, biomass, and carbon through the middle or end of the 21st century (Ollinger et al. 2008; Thompson et al. 2011; Tang et al. 2014; Duveneck et al. 2017; Bulter-Leopold et al. 2018). Although these studies may include multiple ownerships and vary in the degree that they incorporate the potential for carbon changes from forest harvest and natural disturbances, they all include scenarios of climate change. From this robust collection of work, the collective evidence points to continued forest growth and recovery from past disturbances as the major driver of landscape-scale forest carbon gains for many decades into the future, in the absence of major disturbances from climate change or other causes (Shifley & Moser, 2016; Duveneck et al. 2017; Bulter-Leopold et al. 2018).

Climate change introduces additional uncertainty about how forests—including the stability of forest carbon sequestration and storage—may change in the future due to climate risks from stress, insects, and fire (Anderegg et al. 2022; Wu et al. 2023). Climate change causes many direct alterations of the local environment, such as changes in temperature and precipitation (Matthews et al. 2018), and it has indirect effects on a wide range of ecosystem processes (Vose et al., 2012). The collective effects of these changes are anticipated to impact growth rates, mortality, and reproduction of individual tree species in unique ways (Baker et al. 2023; Clark et al. 2023) that may shift the growth (Danneyrolles et al. 2023) or suitability of a location for a species (Iverson et al. 2019a, 2019b) either positively or negatively, depending on the traits of that species. Further, disturbance rates are projected to increase with climate change (Vose et al. 2018) making it challenging to use past trends to project the effects of disturbance, aging, and tree regeneration on forest carbon dynamics (Anderegg et al. 2020, 2022; Davis et al. 2023).

A climate change vulnerability assessment of Mid-Atlantic region (Butler-Leopold, et al. 2018), which encompasses the Allegheny NF indicates that climate change is expected to cause temperatures to continue to rise in all seasons, increasing mean temperatures as well as the frequency of heat waves. Growing season length is expected to increase by several weeks under various climate scenarios, and a longer growing season may enhance forest growth and carbon sequestration, where water supply is adequate, and temperatures do not exceed biological thresholds (McMahon et al. 2010; Butler-Leopold, et al. 2018). Elevated temperatures may increase soil respiration and reduce soil moisture through increased evapotranspiration, which would negatively affect growth rates and carbon accumulation (Ju et al. 2007; Melillo et al. 2017).

Mean annual precipitation in Mid-Atlantic region is projected to increase slightly during the next century, with much of the increase shifting to winter and spring with reduced growing season precipitation in some parts of the region during the next century. More intense precipitation and extreme storm events are expected to continue increasing in this region. The potential for reduced soil moisture and drought is also predicted to increase, especially later in the growing season as increased temperatures drive evapotranspiration (Campbell et al. 2009; Zhao & Dai, 2017; Berg et al. 2017). Although a longer growing season may increase annual biomass accumulation, droughts could offset these potential growth enhancements and increase the potential for other forest stressors. Drought-stressed trees may also be more susceptible to insects and pathogens (Dukes et al. 2009), which can reduce carbon uptake (Kurz et al. 2008; D'Amato et al. 2011). Shorter winters and warmer temperatures mean that a greater proportion of that precipitation is falling as rain rather than snow. The number of days with snowfall and with snow cover have decreased across the region, and these trends are expected to continue. Snow cover is important in many forests for protecting tree roots and storing water (Butler-Leopold, et al. 2018).

Changes in climate are expected to drive many other changes in forests through the next century, including changes in forest establishment and composition (Butler-Leopold, et al. 2018). Some northern tree species are expected to be particularly vulnerable in the future as climate conditions drive declines or failures in species establishment or habitat suitability (Iverson et al. 2017; (Butler-Leopold, et al. 2018). Model projections suggest northern species like quaking aspen and

yellow birch, are generally expected to decline as the climate warms over the next century and beyond, even with a low amount of change. Other tree species, such as northern red oak, black cherry, and sugar maple, are expected to decline only under the high emissions scenario, suggesting that future changes in temperature and soil moisture may not be tolerable to seedlings and young saplings. The potential for future declines of tree species increases the risk of carbon losses in forest communities dominated by these species, particularly under scenarios of greater warming (Ollinger et al. 2008; Duveneck et al. 2017; Butler-Leopold, et al. 2018). Climate-driven failures in species establishment further reduce the ability of forests to recover carbon lost after mortality-inducing events or harvests. Although future climate conditions also allow for other future-adapted species to increase, there is greater uncertainty about how well these species will be able to take advantage of new niches that may become available (Duveneck et al. 2017; Iverson et al. 2017). Vulnerabilities facing forests include drought, warming temperatures, and long-term fire exclusion which can increase forest density and reduce vigor (capacity to resist stress) and resistance to disturbance. Forest hazards, such as insect disturbance, may also have a greater impact on forested areas with increased vulnerability by interacting with other disturbances and creating a compounding impact on ecosystem health. Damage from native insect species on forests with reduced vigor is expected to be one of the most prominent effects of a warming climate (Vose et al. 2018). According to the Forest Health Advisory System, within the Allegheny NF, 4,882 acres are susceptible to high level (>25%) of overall tree mortality and 7 percent of the tree biomass is at risk to forest pests (Krist *et al.* 2014).

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC, 2014). Several models, including the InTEC model (Figure 9), project greater increases in forest productivity when the CO_2 fertilization effect is included in modeling (Aber et al. 1995; Ollinger et al. 2008; Pan et al. 2009; Zhang et al. 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is transient and can be limited by the availability of nitrogen and other nutrients (Norby et al. 2010). Productivity increases under elevated CO_2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond to novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. As climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO_2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions. 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 in order to meet desired management goals (Ontl et al. 2020).

5.0 Summary

Forests in the Allegheny NF are maintaining a carbon sink. Forest carbon stocks increased by about 28.5 percent between 1990 and 2020, and negative impacts on carbon stocks caused by disturbances and environmental conditions have been exceeded by forest growth. According to satellite imagery, timber harvesting has been the most prevalent disturbance detected on the Forest since 1990. Forest carbon losses associated with harvests have been small compared to the total amount of carbon stored in the Forest, resulting in a loss of about 2.66 percent of non-soil carbon from 1990 to 2011. These estimates represent an upper bound because they do not account for continued storage of harvested carbon in wood products or the effect of substitution. Carbon storage in HWPs sourced from national forests increased since the early 1900s. Recent declines in timber harvesting have slowed the rate of carbon accumulation in the harvested wood product sector.

The biggest influence on current carbon dynamics on the Allegheny NF is the legacy of intensive timber harvesting during the 19th century, followed by a period of forest recovery and more sustainable forest management beginning in the early to mid-20th century, which continues to promote a carbon sink today (Birdsey et al. 2006). However, stands on the Allegheny NF are now mostly middle- to older-aged. The rate of carbon uptake and sequestration generally declines as forests age. Accordingly, projections from the RPA assessment indicate a potential age-related decline in forest carbon stocks in the Eastern Region (all land ownerships) beginning in the 2020s.

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, have also influenced carbon accumulation on the Allegheny NF. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in the 2000s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

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

Forested area on the Allegheny NF will be maintained as forest under Forest Service management in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. Across the broader region, land conversion for development on private ownerships is a concern (Shifley & Moser, 2016) and this activity can cause substantial carbon losses (FAOSTAT, 2013; USDA Forest Service, 2016). The Allegheny NF will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

6.0 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 types 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: live aboveground biomass (trees, shrubs, herbs, grasses), live belowground biomass (roots), dead wood (standing dead trees, stumps, logs), forest floor (leaves, small branches), and soil (mineral soil, decaying organic matter).

Carbon sequestration - The process of plants using sunlight to capture 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 in order 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), and

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 considered to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity.

7.0 Appendix – Models and Associated Uncertainty in this Assessment

7.1 Description of Models Used to Inform Carbon Assessment

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.

Carbon Calculation Tool

Estimates annual carbon stocks and stock change from 1990 to 2020 by summarizing data from two or more FIA survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon. The carbon pools associated with the CCT can be described as:

I. **Live trees**, which includes 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.
II. **Belowground live-tree** carbon is based on the difference between whole trees and above ground only
III. **Understory**, which includes all live herbaceous vegetation and woody vegetation up to 1 inch (2.54 cm) d.b.h.
IV. **Standing dead trees**, which are nonliving but otherwise follow the same definition as live trees, including coarse nonliving roots more than 2 mm in diameter
V. **Down dead wood**, also known as coarse woody debris, includes 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
VI. **Forest floor**, which includes the litter, fumic, and humic layers and all nonliving biomass with a diameter less than 7.5 cm at transect intersection lying on the ground above the mineral soil
VII. Soil organic carbon, including all organic material in soil to 20 cm depth

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, inventory-derived maps of stand age, equations describing the relationship between net primary productivity (NPP) and stand age, Landsat-derived maps of disturbance type and severity (Figures 5a and 5b), and an empirical forest dynamics model, the Forest Vegetation Simulator (FVS), to assess the relative impacts of

disturbances (harvest, insects, fire, abiotic, disease). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Crookston & Dixon, 2005; Raymond et al. 2015). ForCaMF estimates how much more carbon (non-soil) would be on each National Forest if disturbances from 1990 to 2011 (2021 for select regions) had not occurred. ForCaMF helps to identify the biggest local influences on continued non-soil carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. Therefore, the purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors. While this model will not be updated in the future, it provides an important overview of how past stand dynamics and land use legacies impact present carbon dynamics. It is important to note that any carbon losses resulting from disturbance that are estimated by ForCaMF will not be accounted for in the carbon baseline (see Figure 1) until up to 5 years after the disturbance occurred. This time lag is a result of FIA's 5-year sampling cycle. It is important to note the Allegheny NF, 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. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., live trees, standing dead trees, understory vegetation, down dead wood, and forest floor). Like the CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey et al. 2014).

Harvested Wood Products Carbon Model

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report uses the Intergovernmental Panel on Climate Change (IPCC) production accounting approach to estimate HWP carbon storage from 1911 to 2012 (https://www.fs.usda.gov/research/treesearch/22954). This approach tracks the entire cycle of carbon from harvest to timber products to primary wood products to end use to disposal. These calculations were carried out using an online HWP carbon accounting tool (http://maps.gis.usu.edu/HWP). Carbon accounting in HWP also 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 2013). The carbon in HWP from timber products to primary products is based upon the methodology in Smith et al. 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).

Net Primary Productivity Curves

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. 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 ecoregion subsection and forest type group, 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.

Integrated Terrestrial Ecosystem Carbon (InTEC) Model

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

7.2 Uncertainty associated with baseline forest carbon estimates

All results reported in this assessment are estimates that are contingent on models, data inputs, assumptions, and uncertainties. Baseline estimates of total carbon stocks and carbon stock change include 95 percent confidence intervals derived using Monte Carlo simulations and shown by the error bars (Fig. 1). The carbon stock or stock change for any given year will fall within error bounds; these confidence intervals indicate that there is a 5 percent chance of the true value being outside of this range. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infer if or how carbon stocks are changing.

The baseline estimates that rely on FIA data include uncertainty and bias associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the Allegheny NF have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artifact of altered inventory design and protocols (Woodall et al. 2013). This potential error emphasizes the need to compare both carbon stock and carbon density data.

In the early 2000s, FIA changed from a periodic inventory, in which all plots were sampled in a single year, to a standardized, national, annual inventory, in which a proportion of all plots in an area is sampled every year. At the same time, protocols were altered for soil, forest floor and downed wood collection. As a result, there is a structural anomaly with those data early in the time series due to the model's use of different data sets and model limitations. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (Smith et al. 2007). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which

inventory plots are measured. Forest Inventory and Analysis plots are resampled about every five years in the eastern United States, and a full cycle is completed when every plot is measured at least once. However, sampling is designed such that partial inventory cycles provide usable, unbiased samples annually but with higher errors. These baseline estimates may lack some temporal sensitivity because plots are not resampled every year, and recent disturbances may not be incorporated in the estimates if the disturbed plots have not yet been sampled. For example, if a plot was measured in 2009 but was clear-cut in 2010, that harvest would not be detected in that plot until it was resampled in 2014. Therefore, effects of the harvest would show up in FIA/CCT estimates only gradually as affected plots are re-visited and the differences in carbon stocks are interpolated between survey years (Woodall et al. 2013). In the interim, re-growth and other disturbances may mute the responsiveness of CCT to disturbance effects on carbon stocks. Although CCT is linked to a designed sample that allows straightforward error analysis, it is best suited for detecting broader and long-term trends, rather than annual stock changes due to individual disturbance events.

It is important to note that the data presented in Figure 1 represents the carbon baseline from 1990 – 2020 and may not be representative of historical baseline conditions. It is important to consider both historical and current baseline conditions when evaluating future trends in carbon uptake and storage.

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

7.3 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of 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). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Loeffler et al. 2014).

7.4 Uncertainty associated with disturbance effects and environmental factors

As with the baseline estimates, there is also uncertainty associated with estimates of the relative effects of disturbances, aging, and environmental factors on forest carbon trends. Various types of errors may exist in the remotely sensed disturbance maps used in the ForCaMF and InTEC models. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond et al., 2015). To quantify uncertainties, the

ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey et al. 2014).

Uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC because of significant computational requirements. However, process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle et al. 2005). InTEC is highly calibrated to FIA data and remotely-sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel et al. 2015), as well as calibration with observational datasets (Zhang et al. 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Fig. 9, "All effects"). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., national forest scale) are likely to be considerably higher.

Results from the ForCaMF and InTEC models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Zhang et al. 2012; Dugan et al. 2017). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas ForCaMF and InTEC involve additional data inputs and modeling, adding significant complexity beyond summarizing ground data.

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