Forest Carbon Assessment for the Chequamegon-Nicolet National Forest in the Forest Service's Eastern Region

Contributors:
Alexa Dugan
Duncan McKinley
Sara Amiot - Environmental Coordinator, Region 3
Todd Ontl - Climate Adaptation Specialist, NFS Office of Sustainability and Climate
Lauren Onofrio - Environmental Coordinator, Region 8
Miles Worthen - Resource Assistant, Chequamegon Nicolet National Forest
Jennifer Maziasz - Forest Environmental Coordinator, Chequamegon Nicolet National Forest
Jedd Ungrodt – Planning Forester, Chequamegon Nicolet National Forest

Version 2.0, October 2023[1]

Contents

---

[1] Dugan, A.J., McKinley D.C., Amiot, S., Ontl, T., Onofrio, L., Worthen M., Maziasz, J., and Ungrodt J. 2023. Forest Carbon Assessment for Chequamegon-Nicolet National Forest in the Forest Service's Eastern Region. USDA Forest Service.

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 the Chequamegon-Nicolet 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 or the Forest 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 Chequamegon-Nicolet NF increased by 19,029 ha from 1990 to 2020. Carbon density (forest carbon stocks per unit area) in the Chequamegon-Nicolet NF increased by 19.77 Mg C per ha. Consequently, ecosystem carbon stocks increased by 12.16 percent over this period, suggesting overall carbon volume of the Chequamegon-Nicolet NF is increasing.

Forest stand age, disturbance, climate, and environmental factors collectively impact ecosystem carbon stocks and future trends of the Chequamegon-Nicolet NF. Forests of the Chequamegon-Nicolet NF are mostly (62%) middle-aged or younger (less than 80 years), and few stands are over 100 years old. This suggests that forest carbon stocks of the Chequamegon-Nicolet NF will continue to increase in the coming decades. However, this rate may decrease without additional management to make room for early successional stands.

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 Chequamegon-Nicolet NF was harvest. Model results suggest that non-soil carbon stocks in the Chequamegon-Nicolet NF would have been approximately 2.11 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 increase the rate of increase in forest carbon stocks in younger stands while increased temperature, drought pressure, and insect damage will increase disturbance of mature or older stands. While the effects of future climate conditions are complex and remain uncertain, forests of the Chequamegon-Nicolet NF may be increasingly vulnerable to a variety of stressors and at risk of reduced carbon stocks. Management activities that promote resilience of different stands are therefore increasingly important for future planning.

Overall, the Chequamegon-Nicolet 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 Chequamegon-Nicolet 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 Chequamegon-Nicolet 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.

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

Tonnes				Grams		
Multiple	Name	Symbol		Multiple	Name	Symbol
				10^0	Gram	g
				10^3	Kilogram	Kg
10^0	Tonne	t		10^6	Megagram	Mg
10^3	Kilotonne	Kt		10^9	Gigagram	Gg
10^6	Megatonne, million metric tonnes	Mt, MMt		10^{12}	Teragram	Tg

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

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.

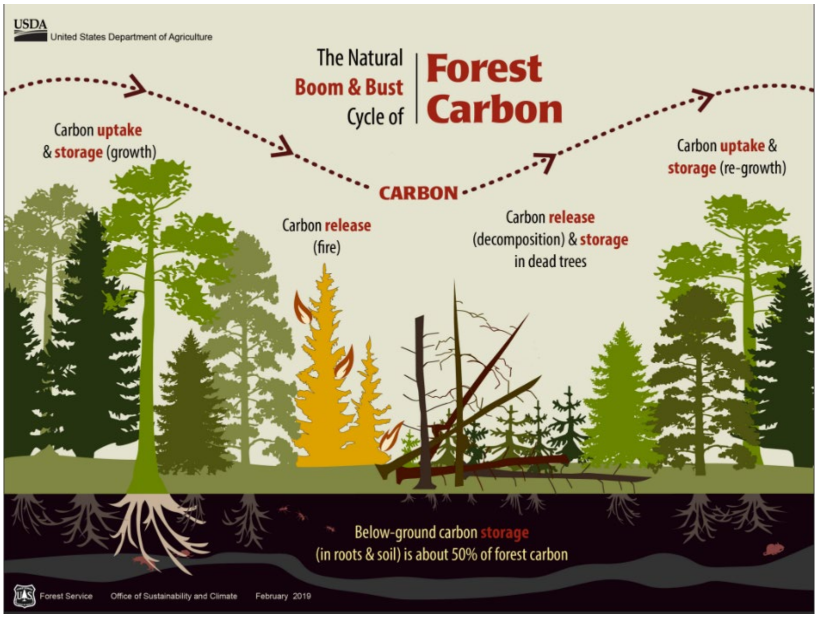
1.3 Carbon Cycling in Forested Ecosystems

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.

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 as drought and growing space, can hinder this ability.

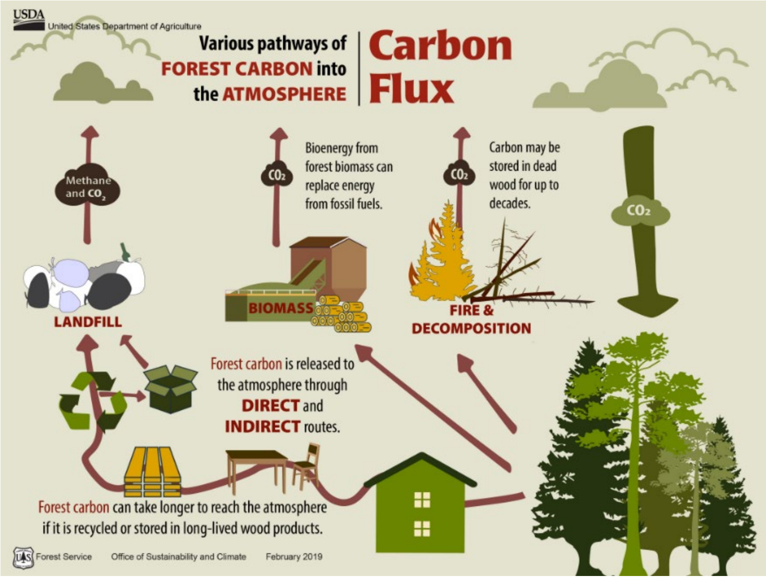


Management activities providing carbon benefits over time include timber harvests to diversify species, structural, or age-class diversity; and thinning and fuel reduction treatments that remove forest carbon and transfer a portion to wood products (Puhlick et al. 2020; Crockett et al. 2023). Silvicultural 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 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 in within the land “sectors” 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 Chequamegon-Nicolet 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; Healey et al. 2023): 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; Healey et al., 2023). 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 Chequamegon-Nicolet NF, located in northern Wisconsin, includes approximately 594,000 ha of forested land. Based on FIA inventory data and its forest type groupings, “maple-beech-birch” and “aspen-birch” types are currently the most abundant types across the Chequamegon-Nicolet NF.

The potential site productivity of forests in the Upper Great Lakes region is largely based on the landforms and surficial deposits left by a series of repeated glacial retreats and advances ending about 10,000 years BP (Fassnacht and Gower 1997; Nave et al 2017). Soils range from coarse, nutrient poor outwash sands to highly productive till-derived loams interspersed with thousands of small lakes, wetlands, and streams. Forest composition and structure on this complex landscape has evolved over time with changes in species ranges and disturbance patterns.

Indigenous people – first nomadic hunter-gatherers, then bands living in seasonal villages – made use of the abundant fish, game, and plant resources and used fire as a land management tool for thousands of years. Grasslands and pine and oak savannas on sandy soils burned frequently, while pine-oak forests were maintained by moderate intensity fires occurring every few decades. Large-scale fire was relatively rare in mesic hardwood-hemlock forests, where wind was the primary disturbance agent. White pine (*Pinus strobus*) up to three feet in diameter occurred as a super-canopy tree across a wide range of soils and landforms.

The arrival of the European fur trade to the region in the 1600s brought massive changes to indigenous ways of life and land use. By the time of the Government Land Office (GLO) surveys in the mid-1800s indigenous populations had been decimated and the liquidation of the white pine resource – beginning near waterways where logs could be driven to downstream mills – had begun. The 1880s and 1890s were a period of intense forest exploitation and catastrophic wildfires caused by the resulting slash. By 1900 most of the pine was gone and the attention of the remaining forest industry shifted to railroad-based logging of hardwoods.

In the early 1900s, settlers bought cutover lands hoping they could support profitable farms, but most found the rocky soil, short growing season, and long distance to markets too much to overcome and many lands reverted to county ownership through tax delinquency. At the same time, wildfires continued to burn out of control, setting the back recovery of forested lands. Conditions at this time favored tree species that could sucker or re-sprout from their root systems (i.e., aspen, oak, and maple) or had very light seeds that could colonize land that was intensely burned, plowed, or eroded (i.e., paper birch and aspen). Species dependent on a source of seeds and low- or moderate-intensity disturbance (i.e. white pine) struggled to re-establish.

In the 1920s the State of Wisconsin began to establish fire control, reforestation, and forest protection programs, and in 1925 legislation allowing the establishment of a national forest, which began with the first land acquisitions in 1928. The Chequamegon and Nicolet National Forest purchase units were formally established in 1933. The next decade saw the establishment of effective fire control and aggressive reforestation, mainly in the form of jack or red pine plantations.

Due to this legacy of exploitation, degradation, and eventual protection, forests of the Chequamegon-Nicolet NF today are relatively young, less diverse, and less structurally complex than what occurred on the landscape historically. A high percentage of stands originated in the 1920s and 1930s, and many of these are made up of early successional tree species with a relatively short lifespan.

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 1933, the Chequamegon-Nicolet National Forest was established.

This legacy of timber harvesting and early efforts to restore the forest is visible today in the homogenous structure and lack of old growth forests; both of which effect the carbon dynamics of these forests.
(Birdsey et al. 2006; ; 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 Chequamegon-Nicolet NF increased from 131.48±5.89 teragrams of carbon (Tg C) in 1990 to 147.47±8.05 Tg C in 2020, a 12 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,147.47 Tg C is equivalent to the emissions from approximately 118 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 Chequamegon-Nicolet NF have been steadily increased from 1990 to 2020 (Fig. 1). The increasing carbon stocks from 1990 to 2020 (Fig. 1) over the 30-year period suggests that the forests of Chequamegon-Nicolet NF are likely a carbon sink. These trends over time on the Chequamegon-Nicolet NF have resulted in categorization as a high carbon density forest.

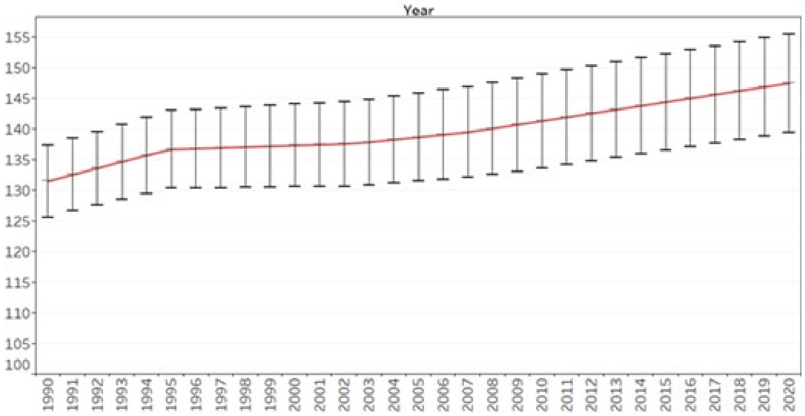


Figure 1. *Total carbon stocks from 1990 to 2020 for Chequamegon-Nicolet National Forest. Estimated using the CCT model using methods described in Smith et al. 2007.*

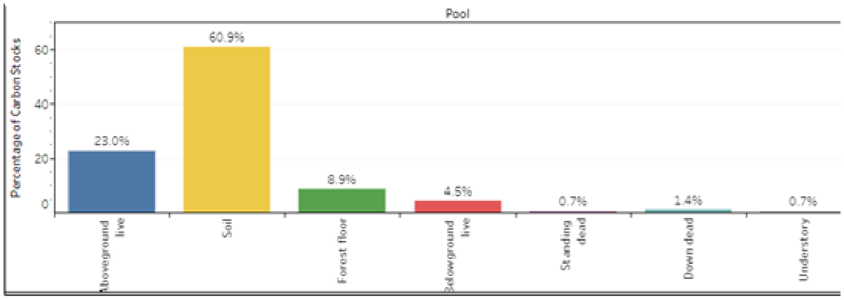


Figure 2. *Percentage of carbon stocks in 2020 in each of the forest carbon pools, for Chequamegon-Nicolet National Forest. Estimated using the CCT model (Smith et al. 2007).*

Soils of the Chequamegon-Nicolet NF and other similar 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 23 percent of forest carbon stocks in the Chequamegon-Nicolet NF are stored in the aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2). Currently available CCT data suggest that about 61 percent of forest carbon stocks are stored in mineral soils to a depth of one meter (excluding roots). Updated, nationally consistent estimates of soil carbon forthcoming from FIA will likely reveal that the amount of carbon stored in soils is larger, exceeding the estimates derived from the CCT model (Domke et al. 2017). Regional forest ecosystem carbon inventory data suggest that mineral soil carbon stocks to 1 m depth account for 50-80% of total ecosystem carbon (Grigal and Ohmann 1992; Powers et al. 2011; Strong 1997; Trettin et al. 2011). The values in Figure 2 are also subject to change because of carbon transfers to different pools over time or as a result of forest disturbances. These transfers can also be referred to as carbon fluxes. For example, as a result of a severe disturbance event such as a windstorm, 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, some of the carbon within downed woody material, forest floor, and standing dead trees can transfer to the soil carbon pool (Rothstein et al. 2018, Santos et al. 2017) which may increase soil carbon stocks over time.

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

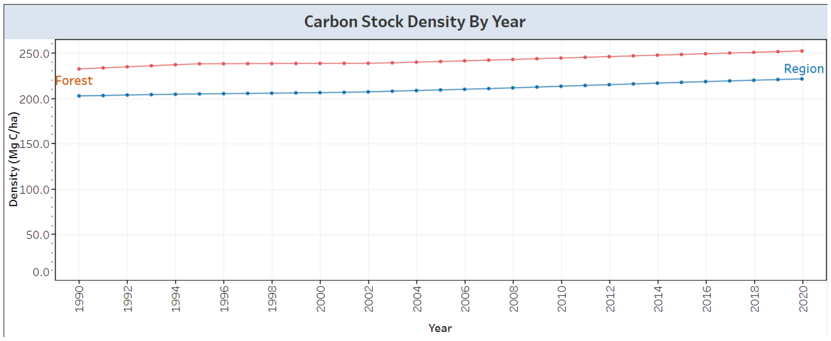


Figure 3. *Average carbon stock density (in megagrams per hectare) in Chequamegon-Nicolet National Forests and for all units in the Eastern Region from 1990 to 2020. Estimates use Forest Inventory and Analysis Data and are derived from the Carbon Calculation Tool (updated in 2020 by the Northern Research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

(Olofsson et al. 2016; Ma et al. 2020). However, because limited non-discretionary undertakings are the primary cause of land conversions on National Forest system lands, National Forests are an important safeguard to 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 Chequamegon-Nicolet NF has increased from 566,668 ha in 1990 to 585,697 ha in 2020, a net change of 19,029 ha. When forest land area increases, total ecosystem carbon stocks typically also increases, indicating the forest land is serving to increasingly store more carbon. 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).

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 Chequamegon-Nicolet NF, carbon density increased from about 232.02 Megagrams of carbon (Mg C) per ha in 1990 to 251.89 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. 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 Chequamegon-Nicolet NF, most national forests in the Eastern Region have experienced increasing carbon densities from 1990 to 2020. Carbon density estimates in the Chequamegon-Nicolet NF have been similar to but slightly higher 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.

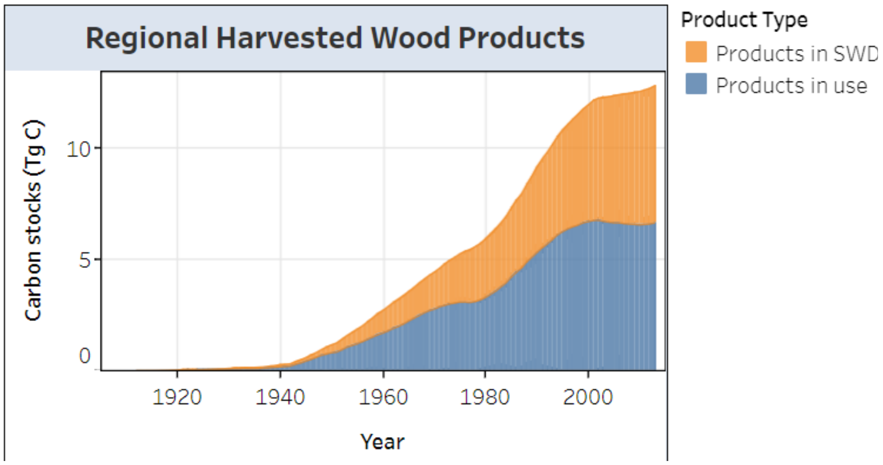


Figure 4. *Cumulative total carbon (in teragrams) stored in harvested wood products (HWP) sourced from National Forest System units in the Eastern Region from 1912 to 2013. This includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production 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.

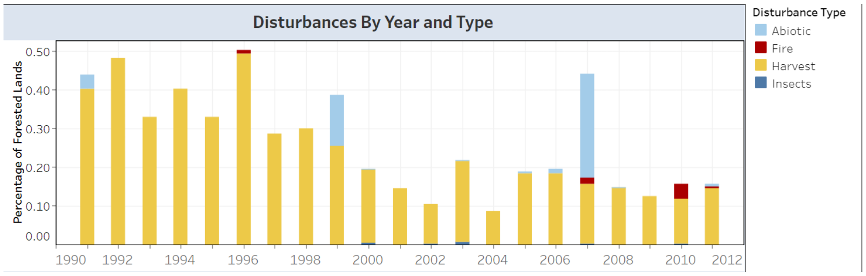


Figure 5. *(a) Percentage of forest disturbed from 1990 to 2011 in Chequamegon-Nicolet National Forest by (a) disturbance type including fire, harvests, insects, and abiotic (wind)*

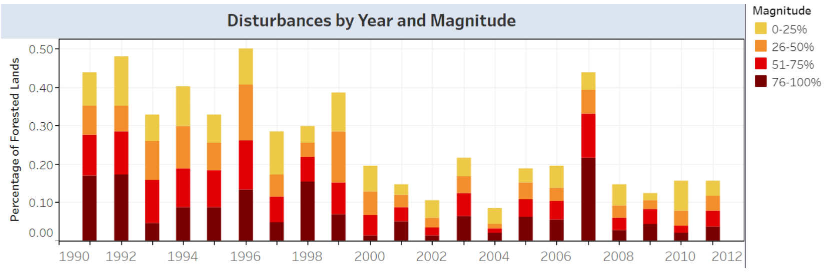


Figure 5. *(b) Percent of forest disturbed by year and magnitude of disturbance (change in canopy cover). Both figures estimated using annual disturbance maps derived from Landsat satellite imagery and a static forest mask (Healey et al. 2018). Note that slower disturbances such as insects may affect the same acreage over multiple years.*

3.0 Factors Influencing Forest Carbon

3.1 Effects of Disturbance

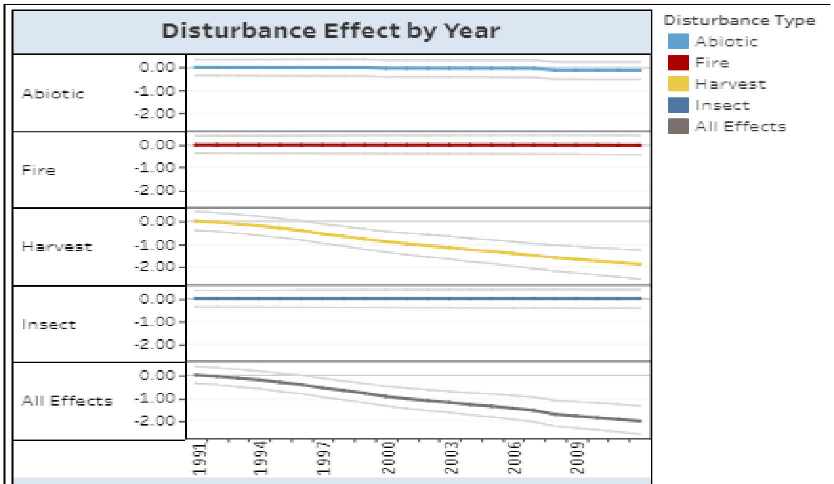
The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually verified, annual disturbance data derived from Landsat satellite imagery (Healey et al. 2018). The Landsat imagery was used to detect canopy cover changes due to disturbances including fires, 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 disturbance graphs indicate that timber harvest has been the dominant disturbance type detected on the Chequamegon-Nicolet NF from 1990 to 2011 in terms of the total percentage of forested area disturbed over the 21-year period (Fig. 5a). In most years, timber harvests affected less than 4 percent of the total forested area of the Chequamegon-Nicolet NF in any single year from 1990 to 2011, and in total around 5 percent (approximately 30,000 ha) of the forested area during this period (594,003 ha). The percentage of the forest harvested annually has varied over this 21-year period. Further, although harvests varied in the proportion of trees removed (i.e., magnitude), they on average removed less than 75 percent of canopy cover (Fig. 5b).

Timber harvesting on the Chequamegon-Nicolet 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, the Chequamegon-Nicolet NF contained 2.01 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 Chequamegon-Nicolet NF would have been approximately 2.27 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).

Other disturbances (wind events, fire and insect mortality) have been infrequent on the CNNF during this recent period of record; longer-term data and studies from other regional landscapes suggest these infrequent events can nonetheless affect significant areas of forestland when they do occur (Frelich and Lorimer 1991; Woods and Kern 2022).

The second most prominent disturbance on the Chequamegon-Nicolet NF is commonly severe windstorms resulting in blowdown of several thousand acres. In 2007 a large tornado caused severe damage to around 4,000 acres of land. Other abiotic disturbances in figure 5 are also attributable to similar weather events.



Cumulative lost potential storage of carbon (in megagrams per hectare) as a result of disturbances in Chequamegon-Nicolet National Forests. 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.

Insect disturbance impacted 0.01 percent or less of forested area, reaching peak percentage disturbed in 2001. According to the report methodology, slower multi-year disturbances, like insects, may be detected as a disturbance until the value no longer exceeds the sensitivity threshold (Healey et al. 2018).

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.

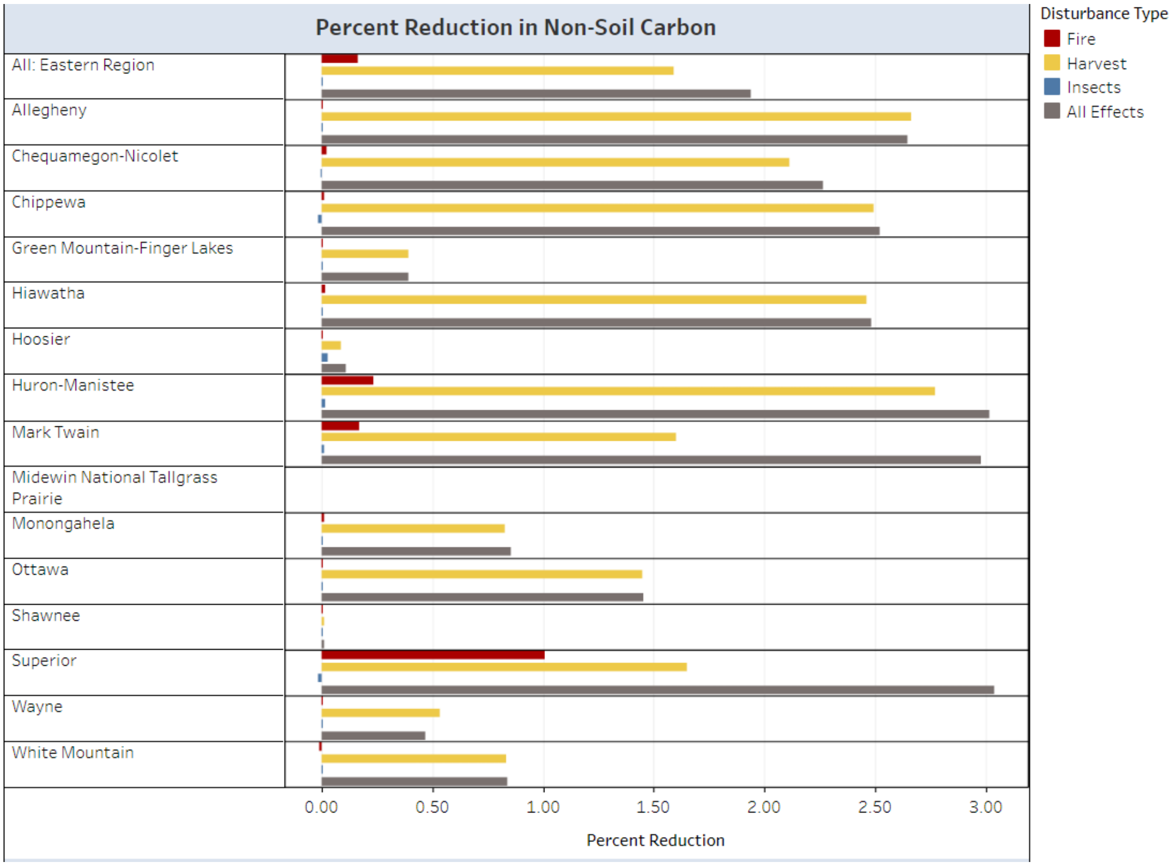


Figure 7. *The degrees to which 2011 carbon storage on each national forest in the Eastern Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from the CCT model (Birdsey et al. 2019, Smith et al. 2007).*

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 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 (Janowiak 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.

There is little research addressing management or disturbance impacts on soil carbon stocks on the Chequamegon-Nicolet NF; available site-specific evidence suggests that typical disturbances related to harvest operations have little to no effect on soil carbon (Alban and Perala 1992; Jurgensen et al. 2012). Recent regional research shows a range of soil carbon responses to harvest and fire. Most importantly, this research points to natural factors, such as soil texture and parent material, as more significant drivers of soil carbon stocks than disturbances such as fire or harvest (Nave et al. 2021b). In addition to controlling the spatial distribution of baseline soil carbon stocks, soil texture and parent material also control how soil carbon stocks respond to harvest in the Lake States. Regionally, carbon stocks in topsoil (the thin, organic-rich mineral horizon beneath the organic horizon) typically increase with harvesting on fine-textured soils such as lake plains and decrease with harvesting on intermediate to coarse-textured soils, especially outwash plains. At the whole-profile level, harvesting does not have a detectable impact on soil carbon stocks.

Generally, fire decreases forest floor carbon stocks, though the magnitude and variability of these changes differ across regions (Nave et al. 2011). 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, in the Lake States, losses of soil organic carbon at the surface of the profile are generally offset by gains deeper in the soil profile, meaning fire generally has no detectable impact on the entire soil profile (Nave et al. 2021b). For these reasons, prescribed burns conducted on the appropriate sites 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). Overall, the science reviewed in this section suggests 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 (hydrology, soils, 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 Chequamegon-Nicolet NF derived in 2023 from forest inventory database indicates very little stand establishment prior to 1830, and more elevated stand establishment around 1930-1960 (Fig. 8a). This period of elevated stand establishment came after decades of intensive logging and in the late 1800s and early 1900s (Whitney, 1987). Policies focusing on restoring forests after decades of overharvesting and conversion of forest to agriculture enabled these stands to establish, survive, and sequester carbon. Similar age trends have been widely observed in eastern U.S. forests, where rates of carbon sequestration have been declining in recent decades as forests age (Birdsey et al. 2006). 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 Lake States and eastern U.S., forests range from modest carbon sinks, to carbon neutral, to modest carbon sources, depending on forest type, regional variation, disturbance, and carbon methodology; generally, older stands tend to be carbon neutral or carbon sources in recent decades (Bradford and Kastendick 2010; Clay et al. 2022; Desai et al. 2022; Finzi et al. 2020; Fraser et al. 2023; Gunn et al. 2014; Halpin and Lorimer 2016; Hollinger et al. 2021; Powers et al. 2011; Woods and Kern 2022).

InTEC model results show that Chequamegon-Nicolet NF accumulated carbon steadily at the start of the analysis in the 1950s through the mid-1970s (Fig. 9). This period is influenced by rapid regrowth following disturbances, as most stands were young (Fig. 8b). As stand establishment declined and more stands reached slower growth rates around the 1980s, aging and disturbance began to reduce carbon sequestration.

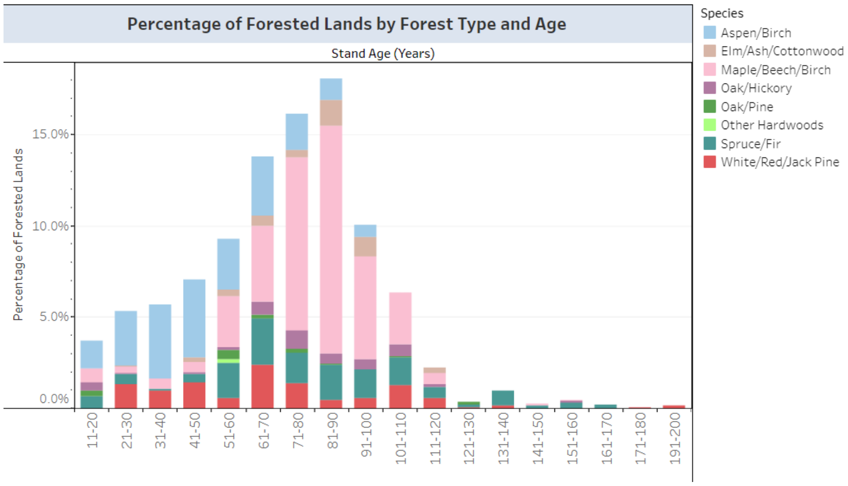


Figure 8. *(a) Stand age distribution in 2023 by forest type group in Chequamegon-Nicolet National Forest. Estimated from FIA data on undisturbed and untreated plots; rare forest type groups may not be represented (Bechtold and Patterson 2005).*

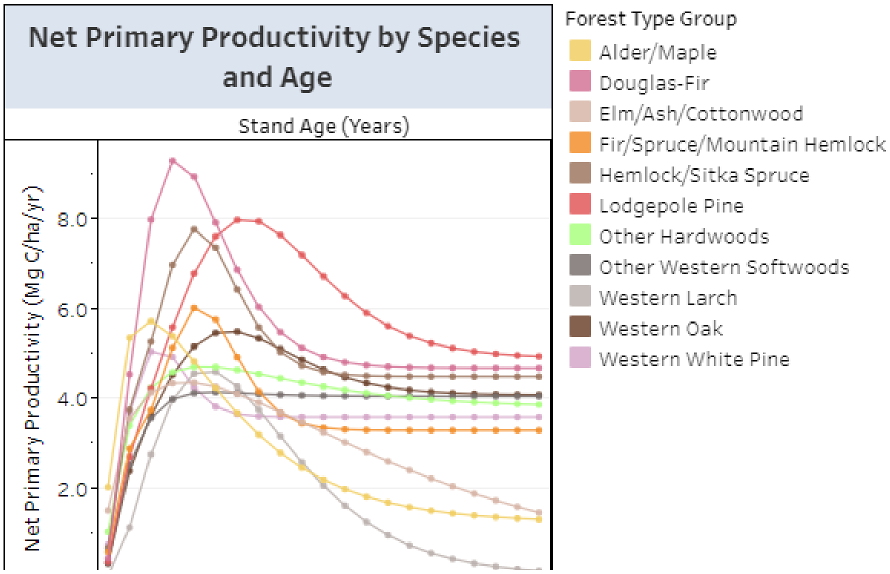


Figure 8. (b) Net primary productivity-stand age curves by forest type group in the Chequamegon-Nicolet National Forest. Derived from FIA data on undisturbed and untreated plots; rare forest type groups may not be represented (Bechtold and Patterson 2005, He et al. 2012).

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 Chequamegon-Nicolet (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).

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 Chequamegon-Nicolet 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).

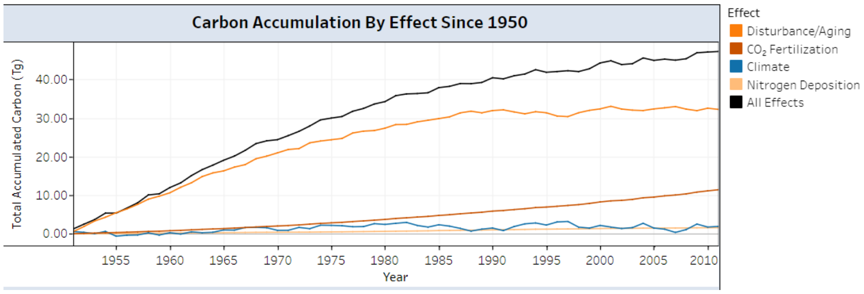


Figure 9. *Excluding carbon accumulated pre-1950, accumulated carbon (Tg) in Chequamegon-Nicolet National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in black line) for1950–2011. Estimated using the InTEC model (Chen et al. 2000)*

Modeled estimates suggest that overall nitrogen deposition had a major positive effect on carbon accumulation in the Chequamegon-Nicolet 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 partially offset 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 Chequamegon-Nicolet NF has a Management Area Designation specifically for old-growth forests via the Land and Resource Management Plan, as stated in the desired conditions (USDA 2004; CNNF Forest Plan, p.3-56). Management Area 8G is characterized by ecosystem complexes and scattered individual stands which feature existing or developing old growth forest, as well as other exemplary natural communities. 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 9,874,337 ha of old-growth forest land and 27,281,219 ha of mature growth forest land. The technical report and accompanying map depict low amounts of old-growth and mature forest on the Chequamegon-Nicolet 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).

A low amount of mature and old-growth stands indicated on the Chequamegon-Nicolet NF by data on the Climate Risk Viewer indicates the acreage of these forest conditions within the various firesheds mapped within the unit. The presence of high/ intermediate classes of old-growth/mature 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 Chequamegon-Nicolet Chequamegon-Nicolet NF are mostly middle-aged or younger (less than 80 years) and few stands are mature or older (Fig. 8a). If the Forest does not maintain early successional stands, more stands will begin to age 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 (Pregitzer and Euskirchen, 2004). 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 forests with large carbon stores (Bradford and Kastendick 2010; Desai et al. 2022; 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 (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.

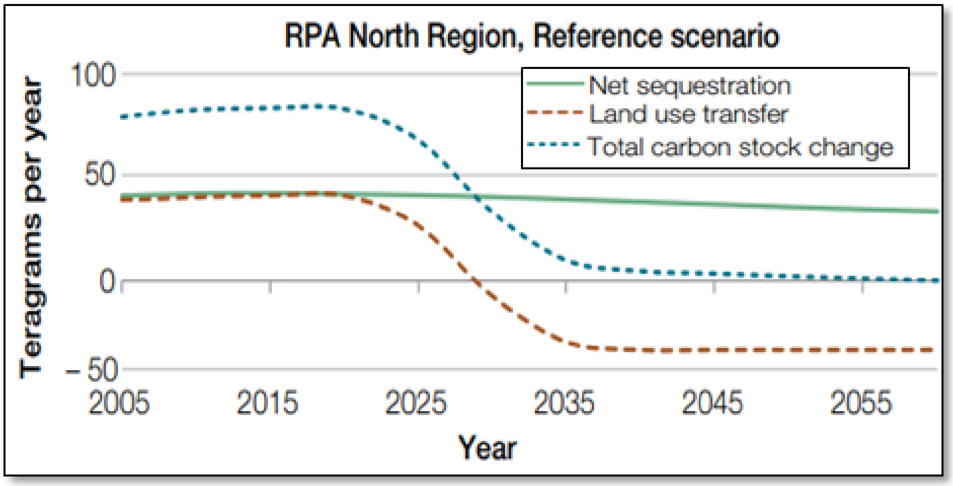


Figure 10. Projections of forest carbon stock changes in the Eastern Region (equivalent to the boundaries of Eastern Region, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.

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 Chequamegon-Nicolet 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 (USGCRP, 2023).

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 Chequamegon-Nicolet 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; Janowiak 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; Janowiak 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 Great Lakes region (USDA 2016), which encompasses the Chequamegon-Nicolet 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; Janowiak et al. 2018; USDA 2016a).

Elevated temperatures may increase soil respiration and reduce soil moisture through increased evapotranspiration, which would negatively affect growth rates and carbon accumulation (Ju et al. 2007; Melillo et al. 2017). Modeled results of recent climate effects using the InTEC model indicate that years with elevated temperatures have generally had a negative effect on carbon uptake in the Chequamegon-Nicolet NF (Fig. 9).

Mean annual precipitation in the Great Lakes region is projected to increase, although seasonal precipitation projections are less certain. Winter precipitation is projected to increase the most, though the amount of precipitation falling as snow is expected to decline as temperatures warm. 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 (D'Amato et al. 2011; Flower et al. 2013).

Changes in climate are expected to drive many other changes in forests through the next century, including changes in forest establishment and composition (Janowiak et al. 2018). 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; Janowiak et al. 2018). Model projections suggest that many northern conifer species, including balsam fir, red spruce, and black spruce, are the most vulnerable to climate change—particularly at more southerly locations and at the end of this century. The potential for future declines of northern 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; Janowiak et al. 2018). Climate-driven failures in species establishment further reduce the ability of forests to recover carbon lost after mortality-inducing events or harvests. Although future climate conditions also allow for other future-adapted species to increase, there is greater uncertainty about how well these species will be able to take advantage of new niches that may become available (Duveneck et al. 2017; Iverson et al. 2017). 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 Chequamegon-Nicolet NF, 9,860 acres are susceptible to high level (>25%) of overall tree mortality and 8 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 Chequamegon-Nicolet NF are maintaining a carbon sink. Forest carbon stocks increased by about 12 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. However, harvests during this period have been relatively small and low intensity. Forest carbon losses associated with harvests have been small compared to the total amount of carbon stored in the Forest, resulting in a loss of about 2.1 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 Chequamegon-Nicolet NF is the legacy of intensive timber harvesting and land clearing for agriculture during the 19th and 20th 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 Chequamegon-Nicolet NF are now mostly middle age or younger. The rate of carbon uptake and sequestration generally declines as forests age.

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, have also influenced carbon accumulation on the Chequamegon-Nicolet NF. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in recent years. 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 Chequamegon-Nicolet 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 Chequamegon-Nicolet NF.

Forested area on the Chequamegon-Nicolet 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 Chequamegon-Nicolet 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. This 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 1 m 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 10-year sampling cycle. It is important to note the Chequamegon-Nicolet 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 Chequamegon-Nicolet 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 (Birdsey 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.

8.0 References

Aber, J., McDowell, W., Nadelhoffer, K., Magill, A., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L. & Fernandez, I. (1998) Nitrogen saturation in temperate forest ecosystems. *BioScience*, 921-934.

Aber, J.D., Ollinger, S.V., Fédérer, C.A., Reich, P.B., Goulden, M.L., Kicklighter, D.W., Melillo, J. & Lathrop, R. (1995) Predicting the effects of climate change on water yield and forest production in the northeastern United States.

Alban DH, Perala DA. 1992. Carbon storage in Lake States aspen ecosystems. Canadian Journal of Forest Research 22: 1107-1110.

Anderegg, W.R.L., C. Wu, N. Acil, N. Carvalhais, T.A.M. Pugh, J.P. Sadler, R. Seidl. 2022. A1570 climate risk analysis of Earth's forests in the 21st century. Science, **377,** 1099-1103.1571

Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciasis, D.Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson. 2020. Climate-driven risks to the climate mitigation potential of forests. Science, **368**, eaaz705.

Baker, J. S., Van Houtven, G., Phelan, J., Latta, G., Clark, C. M., Austin, K. G., ... & Martinich, J. (2023). Projecting US forest management, market, and carbon sequestration responses to a high-impact climate scenario. Forest policy and economics, **147**, 102898.

Bechtold, W. A. and P. L. a. Patterson (2005). "The enhanced forest inventory and analysis program - national sampling design and estimation procedures." Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p. 080.

Berg, A., Sheffield, J. & Milly, P.C.D. (2017) Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44**, 236-244.

Birdsey, R.A., Dugan, A.J., Healey, S.P., Dante-Wood, K., Zhang, F., Mo, G., Chen, J.M., Hernandez, A.J., Raymond, C.L., & McCarter, J. (2019). Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of US national forests. Gen. Tech. Rep. RMRS-GTR-402. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 116.

Birdsey, R.; Pan, Y.; Janowiak, M.; Stewart, S.; Hines, S.; Parker, L.; Gower, S.; Lichstein, J.; McCullough, K.; Zhang, F.; Chen, J.; Mladenoff, D.; Wayson, C.; and Swanston, C. 2014. Past and prospective carbon stocks in forests of northern Wisconsin: a report from the Chequamegon-Nicolet National Forest Climate Change Response Framework. Gen. Tech. Rep. NRS-127. Newtown Square, PA. U.S. Department of Agriculture, Forest Service, Northern Research Station. 52 pp

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

Boggs, J.L., McNulty, S.G., Gavazzi, M.J. & Myers, J.M. (2005) Tree growth, foliar chemistry, and nitrogen cycling across a nitrogen deposition gradient in southern Appalachian deciduous forests. *Canadian Journal of Forest Research*, **35**, 1901-1913.

Bossio, D. A., S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, R. J. Zomer, M. Von Unger, I. M. Emmer & B. W. Griscom (2020) The role of soil carbon in natural climate solutions. Nature Sustainability, 3, 391-398.

Brandt, Leslie; Schultz, Courtney (June, 2016). Climate Change Considerations in National Environmental Policy Act Analysis. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. https://www.fs.usda.gov/ccrc/topics/nepa-environmental-analysis

Bradford, J. B., & Kastendick, D. N. (2010). Age-related patterns of forest complexity and carbon storage in pine and aspen–birch ecosystems of northern Minnesota, USA. Canadian Journal of Forest Research, 40(3), 401-409.

Campbell, J.L., Rustad, L.E., Boyer, E.W., Christopher, S.F., Driscoll, C.T., Fernandez, I.J., Groffman, P.M., Houle, D., Kiekbusch, J., Magill, A.H., Mitchell, M.J. & Ollinger, S.V. (2009) Consequences of climate change for biogeochemical cycling in forests of northeastern North America. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **39**, 264-284.

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

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

Clark, C.M., J. Phelan, J. Ash, J. Buckley, J. Cajka, K. Horn, R.Q. Thomas, R.D. Sabo. 2023. Future climate change effects on US forest composition may offset benefits of reduced atmospheric deposition of N and S. Global Change Biology, 29, 4793-4810.

Clay, C., Nave, L., Nadelhoffer, K., Vogel, C., Propson, B., Den Uyl, J., ... & Gough, C. M. (2022). Fire after clear-cut harvesting minimally affects the recovery of ecosystem carbon pools and fluxes in a Great Lakes forest. Forest Ecology and Management, 519, 120301.

Council on Environmental Quality (2023) National Environmental Policy Act Guidance on Consideration of Greenhouse Gas Emissions and Climate Change. Federal Register, Vol 88, No. 5. 2023-00158.pdf (govinfo.gov)

Crockett, E. T. H., J. W. Atkins, Q. Guo, G. Sun, K. M. Potter, S. Ollinger, C. A. Silva, H. Tang, C. W. Woodall, J. Holgerson & J. Xiao (2023) Structural and species diversity explain aboveground carbon storage in forests across the United States: Evidence from GEDI and forest inventory data. Remote Sensing of Environment, 295, 113703.

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

D’Amato, A.W., Bradford, J.B., Fraver, S. & Palik, B.J. (2011) Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. *Forest Ecology and Management*, **262**, 803-816.

Danneyrolles, V., Boucher, Y., Fournier, R., & Valeria, O. (2023). Positive effects of projected climate change on post-disturbance forest regrowth rates in northeastern North American boreal forests. Environmental Research Letters, **18**(2), 024041.

Davis, K. T., Robles, M. D., Kemp, K. B., Higuera, P. E., Chapman, T., Metlen, K. L., ... & Campbell, J. L. (2023). Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. Proceedings of the National Academy of Sciences, 120(11), e2208120120.

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

Desai A, Murhpy B, Wiesner S, Thom J, Butterworth B, Koupaei-Abyazani N, Muttaqin A, Paleri S, Talib A, Turner J, Mineau J, merrelli A, Stoy P, Davis K. 2022. Drivers of decadal carbon fluxes across temperate ecosystems. Journal of Geophysical Research-Biogeosciences 127:e2022JG007014

Desai, A. R., Bolstad, P. V., Cook, B. D., Davis, K. J., & Carey, E. V. (2005). Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. Agricultural and Forest Meteorology, 128(1-2), 33-55.

Domke, G. M., B. F. Walters, C. L. Giebink, E. J. Greenfield, J. E. Smith, M. C. Nichols, J. A. Knott, S. M. Ogle, J. W. Coulston and J. Steller (2023). Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990–2021. Resource Bulletin WO-101. Washington, D.C., U.S. Department of Agriculture, Forest Service, Washington Office.10 p.

Domke, G., Perry, C., Walters, B., Nave, L., Woodall, C. & Swanston, C. (2017) Toward inventory-based estimates of soil organic carbon in forests of the United States. *Ecological Applications*, **27**, 1223-1235.

Domke et al., 2020 Internal Report. Carbon baseline data was updated from 1990 to 2020 by Grant Domke and others in FIA and a new report is in development. This data update is based off methodology outlined in the following reports/sources: USDA Forest Service 2015 and Smith et al., 2007. .

Dugan, A. J., Lichstein, J. W., Steele, A., Metsaranta, J. M., Bick, S., & Hollinger, D. Y. (2021). Opportunities for forest sector emissions reductions: a state-level analysis. Ecological Applications, **31**(5), e02327.

Dugan, A.J., Birdsey, R., Mascorro, V.S., Magnan, M., Smyth, C.E., Olguin, M. & Kurz, W.A. (2018) A systems approach to assess climate change mitigation options in landscapes of the United States forest sector. *Carbon Balance and Management*, **13**, doi.org/10.1186/s13021-018-0100-x.

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

Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., Cooke, B., Theoharides, K.A., Stange, E.E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R. & Ayres, M. (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research*, **39**, 231-248.

Dupigny-Giroux, L.A., Mecray, E.L., Lemcke-Stampone, M.D., Hodgkins, G.A., Lentz, E.E., Mills, K.E., Lane, E.D., Miller, R., Hollinger, D.Y., Solecki, W.D., Wellenius, G.A., Sheffield, P.E., MacDonald, A.B. & Caldwell, C. (2018) Northeast. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II (ed. by D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock and B.C. Stewart), pp. 669-742. US Global Change Research Program, Washington, DC, USA.

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

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

Fassnacht K, Gower S. 1997. Interrelationships among the edaphic and stand characteristics, leaf area index, and aboveground net primary production of upland forest ecosystems in north central Wisconsin. Canadian Journal of Forest Research 27: 1058-1067.

Finzi, A. C., Giasson, M. A., Barker Plotkin, A. A., Aber, J. D., Boose, E. R., Davidson, E. A., ... & Foster, D. R. (2020). Carbon budget of the Harvard Forest Long-Term Ecological Research site: Pattern, process, and response to global change. Ecological Monographs, 90(4), e01423.

Flower, C.E., Knight, K.S. & Gonzalez-Meler, M.A., 2013. Impacts of the emerald ash borer (Agrilus planipennis Fairmaire) induced ash (Fraxinus spp.) mortality on forest carbon cycling and successional dynamics in the eastern United States. Biol Invasions 15, 931–944. https://doi.org/10.1007/s10530-012-0341-7

.

Foster, D.R. (2006) *Forests in time: the environmental consequences of 1,000 years of change in New England*. Yale University Press.

Franklin, J.; Hemstrom, M.; Van Pelt, R.; Buchanan, J.; Hull, S.; Crawford, R.; Curry, S.; Obermeyer, W. 2007. Extent and distribution of old forest conditions on DNR-managed state trust lands in eastern Washington. Washington Department of Natural Resources. 44p.

Fraser, J. S., Knapp, L. S. P., Graham, B., Jenkins, M. A., Kabrick, J., Saunders, M., ... & Shifley, S. (2023). Carbon dynamics in old-growth forests of the Central Hardwoods Region, USA. Forest Ecology and Management, **537**, 120958.

Frelich L, Lorimer C. 1991. NATURAL DISTURBANCE REGIMES IN HEMLOCK HARDWOOD FORESTS OF THE UPPER GREAT-LAKES REGION. Ecological Monographs 61:145-164.

Goeking, S. A. (2015). "Disentangling Forest Change from Forest Inventory Change: A Case Study from the US Interior West." Journal of Forestry 113(5): 475-483.

Goodwin MJ, North MP, Zald HSJ, Hurteau MD. (2020) Changing climate reallocates the carbon debt of frequent-fire forests. Glob Change Biol. 2020;26:6180– 6189. https://doi.org/10.1111/gcb.15318

Gough, C.M., Vogel, C.S., Harrold, K.H., George, K., & Curtis, P.S. (2007). The Legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. Global Change Biology, 13, 1935-1949.

Gray, A. N., T. R. Whittier and M. E. Harmon (2016). "Carbon stocks and accumulation rates in Pacific Northwest forests: role of stand age, plant community, and productivity." Ecosphere 7(1): e01224.

Grigal, D., Ohmann, L. 1992. Carbon storage in upland forests of the Lake States. Soil Science Society of America Journal 56: 935-943

Gunn, J. S., Ducey, M. J., & Whitman, A. A. (2014). Late-successional and old-growth forest carbon temporal dynamics in the Northern Forest (Northeastern USA). Forest Ecology and Management, 312, 40-46.

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

Halpin, C. R., & Lorimer, C. G. (2016). Long-term trends in biomass and tree demography in northern hardwoods: An integrated field and simulation study. Ecological Monographs, 86(1), 78-93.

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

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

Healey, S.P., Raymond, C.L., Lockman, I.B., Hernandez, A.J., Garrard, C. & Huang, C. (2016) Root disease can rival fire and harvest in reducing forest carbon storage. *Ecosphere*, **7**, Article e01569.

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

Healy et al., 2023. Draft and interim disturbance data and ForCaMF model update from the period of 1990 to 2021 based on the methodology of the following papers: Birdsey, Richard A.; Dugan, Alexa J.; Healey, Sean P.; Dante-Wood, Karen; Zhang, Fangmin; Mo, Gang; Chen, Jing M.; Hernandez, Alexander J.; Raymond, Crystal L.; McCarter, James. 2019. Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests. Gen. Tech. Rep. RMRS-GTR-402. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 116 pages plus appendices; Healey, S.P., Cohen, W.B., Yang, Z., Brewer, C.K., Brooks, E.B., Gorelick, N., Hernandez, A.J., Huang, C., Hughes, M.J., Kennedy, R.E. and Loveland, T.R., 2018. Mapping forest change using stacked generalization: An ensemble approach. Remote Sensing of Environment, 204, pp.717-728.

Hollinger, D. Y., Davidson, E. A., Fraver, S., Hughes, H., Lee, J. T., Richardson, A. D., ... & Teets, A. (2021). Multi-decadal carbon cycle measurements indicate resistance to external drivers of change at the Howland forest AmeriFlux site. Journal of Geophysical Research: Biogeosciences, 126(8), e2021JG006276.

Hoover, C. M., W. B. Leak and B. G. Keel (2012). "Benchmark carbon stocks from old-growth forests in northern New England, USA." Forest Ecology and Management 266: 108-114.

Hoover, C. M. and J. E. Smith (2023). "Aboveground live tree carbon stock and change in forests of conterminous United States: influence of stand age." Carbon Balance and Management 18(1): 7.

Houghton, R.A., House, J.I., Pongratz, J., Van Der Werf, G.R., Defries, R.S., Hansen, M.C., Le Quéré, C. & Ramankutty, N. (2012) Carbon emissions from land use and land-cover change. *Biogeosciences*, **9**, 5125-5142.

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of theIntergovernmental Panel on Climate change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647

IPCC (2022a): Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B.

Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

IPCC (2022b): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.

IPCC (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (ed. by R.K. Pachauri and L.A. Meyer), p. 151. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Iverson, L. R., Peters, M. P., Prasad, A. M., & Matthews, S. N. (2019a). Analysis of climate change impacts on tree species of the eastern US: Results of DISTRIB-II modeling. Forests, 10(4), 302.

Iverson, L. R., Prasad, A. M., Peters, M. P., & Matthews, S. N. (2019b). Facilitating adaptive forest management under climate change: A spatially specific synthesis of 125 species for habitat changes and assisted migration over the eastern United States. Forests, 10(11), 989.

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

Janowiak, M.; Connelly, W.J.; Dante-Wood, K.; Domke, G.M.; Giardina, C.; Kayler, Z.; Marcinkowski, K.; Ontl, T.; Rodriguez-Franco, C.; Swanston, C.; Woodall, C.W.; Buford, M. 2017. Considering Forest and Grassland Carbon in Land Management. Gen. Tech. Rep. WO-95. Washington, D.C.: United States Department of Agriculture, Forest Service. 68 p.

Janowiak, M.K., D'Amato, A.W., Swanston, C., Iverson, L., Thompson III, F., Dijak, W., Matthews, S., Prasad, A., Peters, M., Fraser, J.S., Brandt, L., …Templer, P. (2018) New England and New York forest ecosystem vulnerability assessment and synthesis: a report from the New England Climate Change Response Framework In, p. 234. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Jevon, F. V., D'Amato, A. W., Woodall, C. W., Evans, K.,, Ayres, M. P., Matthes, J. H. (2019). Tree basal area and conifer abundance predict soil carbon stocks and concentrations in an actively managed forest of northern New Hampshire, USA, Forest Ecology and Management, **451**, 117534.

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

Jurgensen M, Tarpey R, Pickens J, Kolka R, Palik B. 2012. Long-term effect of silvicultural thinnings on soil carbon and nitrogen pools. Soil Science Society of American Journal 76:1418-1425.

Ju, W.M., Chen, J.M., Harvey, D. & Wang, S. (2007) Future carbon balance of China's forests under climate change and increasing CO2. *Journal of Environmental Management*, **85**, 538-562.

Kaarakka, Lilli, et al. "Improved forest management as a natural climate solution: A review." Ecological Solutions and Evidence 2.3 (2021): e12090.

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

Keyser, T.L. & Zarnoch, S.J. (2012) Thinning, age, and site quality influence live tree carbon stocks in upland hardwood forests of the southern appalachians. *Forest Science*, **58**, 407-418.

Körner, C., Asshoff, R., Bignucolo, O., Hättenschwiler, S., Keel, S.G., Peláez-Riedl, S., Pepin, S., Siegwolf, R.T.W. & Zotz, G. (2005) Ecology: Carbon flux and growth in mature deciduous forest trees exposed to elevated CO2. *Science*, **309**, 1360-1362.

Krist, Frank J., Jr.; Ellenwood, James R.; Woods, Meghan E.; McMahan, Andrew J.; Cowardin, John P.; Ryerson, Daniel E.; Sapio, Frank J.; Zweifler, Mark O.; Romero, Sheryl A. 2014. 2013-2027 National Insect and Disease Forest Risk Assessment. FHTET-14-01. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team.

Krofcheck, D. J., C. C. Remy, A. R. Keyser and M. D. Hurteau (2019). "Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires." Journal of Geophysical Research: Biogeosciences 124(10): 3075-3087.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T. & Safranyik, L. (2008) Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**, 987-990.

Lippke, B., Oneil, E., Harrison, R., Skog, K., Gustavsson, L. & Sathre, R. (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Management*, **2**, 303-333.

Littlefield, C. E., & D'Amato, A. W. (2022). Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. Conservation Science and Practice, **4**(4), e12631.

Loeffler, D., Anderson, N., Stockmann, K., Skog, K., Healey, S., Jones, J.G., Morrison, J. & Young, J. (2014) Estimates of carbon stored in harvested wood products from United States Forest Service Eastern Region, 1911-2012. Unpublished report. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory. 27 p.

Lorimer, C.G. 2001. Historical and ecological roles of disturbance in eastern North American forests: 9,000 years of change. Wildlife Society Bulletin **29**:425-439.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P. & Grace, J. (2008) Old-growth forests as global carbon sinks. *Nature*, **455**, 213-215.

Ma, W., Domke G.M., Woodall, C. W., D'Amato, A. W. (2020). Contemporary forest carbon dynamics in the northern U.S. associated with land cover changes, Ecological Indicators, 110, 105901.

Magerl, A., Gingrich, S., Matej, S., Cunfer, G., Forrest, M., Lauk, C., et al. (2023). The role of wildfires in the interplay of forest carbon stocks and wood harvest in the contiguous United States during the 20th century. Global Biogeochemical Cycles, 37, e2023GB007813. https://doi.org/10.1029/2023GB007813

Matthews, S. N.; Iverson, Louis R.; Peters, Matthew P.; Prasad, Anantha M. 2018. Assessing potential climate change pressures across the conterminous United States: mapping plant hardiness zones, heat zones, growing degree days, and cumulative drought severity throughout this century. RMAP-NRS-9. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 31 p. https://doi.org/10.2737/NRS-1863 RMAP-9.

Miesel, J. R., Hockaday, W. C., Kolka, R. K., & Townsend, P. A. (2015). Soil organic matter composition and quality across fire severity gradients in coniferous and deciduous forests of the southern boreal region. Journal of Geophysical Research: Biogeosciences, 120(6), 1124-1141.

McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E. & Skog, K.E. (2011) A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications*, **21**, 1902-1924.

McMahon, S.M., Parker, G.G. & Miller, D.R. (2010) Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences*, **107**, 3611-3615.

Melillo, J.M., Frey, S.D., DeAngelis, K.M., Werner, W.J., Bernard, M.J., Bowles, F.P., Pold, G., Knorr, M.A. & Grandy, A.S. (2017) Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science*, **358**, 101-105.

Nave, L.E.; Bowman, M.; Gallo, A.; Hatten, J.A.; Heckman, K.A.; Matosziuk, L.; Possinger, A.R.; SanClements, M.; Sanderman, J.; Strahm, B.D.; Weiglein, T.L.; Swanston, C.W. 2021(a). Patterns and predictors of soil organic carbon storage across a continental-scale network. Biogeochemistry. 375(3): 114472. 22 p. https://doi.org/10.1007/s10533-020-00745-9

Nave, L.E.; DeLyser, K.; Domke, G.M.; Janowiak, M.K.; Ontl, T.A.; Sprague, E.; Walters, B.F.; Swanston, C.W. 2021(b). Land use and management effects on soil carbon in U.S. Lake States, with emphasis on forestry, fire, and reforestation. Ecological Applications. 31(6): e02356. https://doi.org/10.1002/eap.2356.

Nave, Lucas E.; DeLyser, Kendall; Domke, Grant M.; Holub, Scott M.; Janowiak, Maria K.; Kittler, Brian; Ontl, Todd A.; Sprague, Eric; Sucre, Eric B.; Walters, Brian F.; Swanston, Christopher W. 2022. Disturbance and management effects on forest soil organic carbon stocks in the Pacific Northwest. Ecological Applications. 32(6):e2611. 21 p. https://doi.org/10.1002/eap.2611.

Nave, Luke; Marin-Spiotta, Erika; Ontl, Todd; Peters, Matt; Swanston, Chris. 2019. Soil carbon management Chapter 11 . In: Busse, Matt; Giardina, Christian P.; Morris, Dave M.; Page, Dumroese, Deborah S. Global change and forest soils: Cultivating stewardship of a finite natural resource. Developments in Soil Science, Vol. 36. Elsevier. p. 215-257.

Nave, Lucas E.; Vance, Eric D.; Swanston, Christopher W.; Curtis, Peter S. 2011. Fire effects on temperate forest soil C and N storage. Ecological Applications. 21(4): 1189-1201.

Nave, L.E.; Vance, E.D.; Swanston, C.W.; Curtis, P.S. 2010. Harvest impacts on soil carbon storage in temperate forests. Forest Ecology and Management. 259: 857-866.

Norby, R.J., Warren, J.M., Iversen, C.M., Medlyn, B.E. & McMurtrie, R.E. (2010) CO2 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences*, **107**, 19368-19373.

Oliver, C. D., N. T. Nassar, B. R. Lippke & J. B. McCarter (2014) Carbon, fossil fuel, and biodiversity mitigation with wood and forests. Journal of Sustainable Forestry, 33, 248-275.

Ollinger, S., Goodale, C., Hayhoe, K. & Jenkins, J. (2008) Potential effects of climate change and rising CO2 on ecosystem processes in northeastern U.S. forests. *Mitigation and Adaptation Strategies for Global Change*, **13**, 467-485.

Olofsson, P., Holden, C. E., Bullock, E. L., & Woodcock, C. E. (2016). Time series analysis of satellite data reveals continuous deforestation of New England since the 1980s. Environmental Research Letters, 11(6), 064002.

Ontl, Todd A; Janowiak, Maria K; Swanston, Christopher W; Daley, Jad; Handler, Stephen; Cornett, Meredith; Hagenbuch, Steve; Handrick, Cathy; Mccarthy, Liza; Patch, Nancy. 2020. Forest Management for Carbon Sequestration and Climate Adaptation. Journal of Forestry. 118(1): 86-101. https://doi.org/10.1093/jofore/fvz062.

Oswalt, S. N., Smith, W. B., Miles, P. D., & Pugh, S. A. (2019). Forest resources of the United States, 2017. General Technical Report-US Department of Agriculture, Forest Service. Forest Service.

Palik, B.J.; D'Amato, A.W.; Franklin, J.F.; Johnson, K.N. 2020. Ecological silviculture: foundations and applications. Longrove, IL: Waveland Press. 343 p

Pan, Y., Birdsey, R., Hom, J. & McCullough, K. (2009) Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management*, **259**, 151-164.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S. & Hayes, D. (2011a) A large and persistent carbon sink in the world's forests. *Science*, **333**, 988-993.

Pan, Y., Chen, J.M., Birdsey, R., McCullough, K., He, L. & Deng, F. (2011b) Age structure and disturbance legacy of North American forests. *Biogeosciences*, **8**, 715-732.

Pardo, L.H., Fenn, M.E., Goodale, C.L., Geiser, L.H., Driscoll, C. T., Allen, E.B. …Dennis, R.L. (2011) Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. *Ecological Applications*, **21**, 3049-3082.

Patton RM, Kernan DH, Burton JI, Drake JE. 2022. Management trade-offs between forest carbon stocks, sequestration rates, and structural complexity in the central Adirondacks. Forest Ecology and Management 525, 120539.

Powers, M., Kolka, R., Palik, R., MacDonald, R., Jurgensen, M. 2011. Long-term management impacts on carbon storage in Lake States forests.

Pregitzer, K.S. & Euskirchen, E.S. (2004) Carbon cycling and storage in world forests: biome patterns related to forest age. *Global change biology*, **10**, 2052-2077.

Puhlick, J. J., A. R. Weiskittel, L. S. Kenefic, C. W. Woodall & I. J. Fernandez (2020) Strategies for enhancing long-term carbon sequestration in mixed-species, naturally regenerated Northern temperate forests. Carbon Management, 11, 381-397.

Raymond, C.L., Healey, S., Peduzzi, A. & Patterson, P. (2015) Representative regional models of post-disturbance forest carbon accumulation: Integrating inventory data and a growth and yield model. *Forest Ecology and Management*, **336**, 21-34.

Rhemtulla, J. M., D. J. Mladenoff, and M. K. Clayton. 2009. Legacies of historical land use on regional forest composition and structure in Wisconsin, USA (mid-1800s- 1930s-2000s). Ecological Applications **19**:1061-1078.

Ross, D. S. & M. E. Knowles (2023) Partial Harvest Effects on the Forest Floor at Four Northern Hardwood Sites in the Green Mountains of Vermont, USA. fxad032.

Rothstein, D., Toosi, E., Schaetzl, R., Grandy, A. 2018. Translocation of Carbon from Surface Organic Horizons to the Subsoil in Coarse-Textured Spodosols; Implications for Deep Soil C Dynamics. Soil Society of America Journal 82:969-982

Santos, F., Wagner, S., Rothstein, D., Jaffe, R., Miesel, J. 2017. Impact of a Historical Fire Event on Pyrogenic Carbon Stocks and Dissolved Pyrogenic Carbon in Spodosols in Northern Michigan. Frontiers in Earth Science 5:80.

Sathre, R. & J. O'Connor (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental science & policy, 13, 104-114.

Schimel, D., Stephens, B.B. & Fisher, J.B. (2015) Effect of increasing CO2 on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 436-441.

Schulte, L. A., Mladenoff, D. J., Crow, T. R., Merrick, L. C., & Cleland, D. T. (2007). Homogenization of northern US Great Lakes forests due to land use. Landscape Ecology, 22, 1089-1103.

Shands, W. (1992) The Lands Nobody Wanted: The Legacy of the Eastern National Forests. The origins of the National Forests. In. Pinchot Institute for Conservation Studies.

Shifley, S.R. & Moser, W.K. (2016) Future forests of the northern United States. Gen. Tech. Rep. NRS-151. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 388 p.

Skog, K.E., McKinley, D.C., Birdsey, R.A., Hines, S.J., Woodall, C.W., Reinhardt, E.D. & Vose, J.M. (2014) Chapter 7: Managing Carbon. In: *Climate Change and United States Forests, Advances in Global Change Research*, **57**, 151-182.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. http://dx.doi.org/10.2737/NE-GTR-343

Smith, J.E., Heath, L.S. & Nichols, M.C. (2007) US forest carbon calculation tool: forest-land carbon stocks and net annual stock change. Revised. Gen. Tech. Rep. NRS-13. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 34 p.

Stern, Rebecca L.; Schaberg, Paul G.; Rayback, Shelly A.; Murakami, Paula F.; Hansen, Christopher F.; Hawley, Gary J. 2021. Eastern white pine and eastern hemlock growth: possible tradeoffs in response of canopy trees to climate. Canadian Journal of Forest Research. 51(12): 1926-1938. https://doi.org/10.1139/cjfr-2020-0512.

Strong, T. 1997. Harvesting intensity influences the carbon distribution in a northern hardwoo ecosystem. USDA-Forest Service, North Central Forest Experiment Station, Research Paper No. NC-329. 11pp.

Tang, G., Beckage, B. & Smith, B. (2014) Potential future dynamics of carbon fluxes and pools in New England forests and their climatic sensitivities: A model-based study. *Global Biogeochemical Cycles*, **28**, 286-299.

Tang Jianwu, Bolstad Paul V., Desai Ankur R., Martin Jonathan G., Cook Bruce D., Davis Kenneth J., Carey Eileen V., Ecosystem respiration and its components in an old-growth forest in the Great Lakes region of the United States, Agricultural and Forest Meteorology, Volume 148, Issue 2, 2008, Pages 171-185, ISSN 0168-1923

Thomas, R.Q., Canham, C.D., Weathers, K.C. & Goodale, C.L. (2010) Increased tree carbon storage in response to nitrogen deposition in the US. *Nature Geoscience*, **3**, 13-17.

Thompson, J.R., Foster, D.R., Scheller, R. & Kittredge, D. (2011) The influence of land use and climate change on forest biomass and composition in Massachusetts, USA. *Ecological Applications*, **21**, 2425-2444.

Trettin, C., Jurgensen M., Gale, M., Mclaughlin, J. 2011. Recovery of carbon and nutrient pools in a northern forested wetland 11 years after harvesting and site preparation. Forest Ecology and Management 262: 1826-1833.

United States, Executive Office of the President [Joe Biden]. (2022). Executive order 14072 on strengthening the Nation’s forests, communities, and local economies. Washington, DC: White House. https://www.whitehouse.gov/briefing-room/presidentialactions/2022/04/22/executive-order-on-strengthening-the-nations-forests-communities-and-local-economies/US EPA (2015) Executive Summary. *US inventory of greenhouse gas emissions and sinks: 1990 – 2013.* U.S. Environmental Protection Agency, Washington, DC. 27 pp.

U.S. Environmental Protection Agency [U.S. EPA]. 2023. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2023. EPA 430-R-22-003. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle#:~:text=typical%20passenger%20vehicle%3F-,A%20typical%20passenger%20vehicle%20emits%20about%204.6%20metric%20tons%20of,8%2C887%20grams%20of%20CO2

USDA Forest Service. (2023a). Forest Service Climate Risk Viewer (Beta 0.1.3). https://storymaps.arcgis.com/collections/87744e6b06c74e82916b9b11da218d28

USDA Forest Service (2023b). Mature and Old-Growth Forests: Definition, Identification, and Initial Inventory on Lands Managed by the Forest Service and Bureau of Land Management. https://www.fs.usda.gov/sites/default/files/mature-and-old-growth-forests-tech.pdf

USDA Forest Service (2015) Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System Units, Eastern Region. 58 pp.

USDA Forest Service (2016) Future of America's Forests and Rangelands: Update to the 2010 Resources Planning Act Assessment. Gen. Tech. Report WO-GTR-94. Washington, DC. 250 p.

USDA Forest Service. 2013. Forest Management – Cut and Sold Reports: http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml

USDA Forest Service. Chequamegon-Nicolet National Forests. Land and Resource Management Plan; Chapter 3, Management Area Direction. 2004. R9-CN-FP.

USGCRP, 2023: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023

Vance, E. D. (2018). Conclusions and caveats from studies of managed forest carbon budgets. Forest ecology and management, 427, 350-354.

Vose, J.M., Peterson, D.L. & Patel-Weynand, T. (2012) Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 p.

Vose, J.M., Peterson, D.L., Domke, G.M., Fettig, C.J., Joyce, L.A., Keane, R.E., Luce, C.H., Prestemon, J.P., Band, L.E., Clark, J.S., Cooley, N.E., D'Amato, A. & Halofsky, J.E. (2018) Chapter 6: Forests. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (ed. by D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock and B.C. Stewart), US Global Change Research Program, Washington, DC, USA, 232-267.

Walters, B.F., Domke, G.M., Greenfield, E.J., Smith, J.E., & Ogle, S.M. (2023) Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2021: Estimates and quantitative uncertainty for individual states, regional ownership groups, and National Forest System regions. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2023-0020

Wear, D.N., Huggett, R., Li, R., Perryman, B., & Liu, S. (2013) Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service 2012 RPA Assessment. Gen. Tech. Rep. SRS-GTR-170. Asheville, NC: USDA-Forest Service, Southern Research Station. 101 p.

Whitney, G. G. 1987. An ecological history of the Great-Lakes forest of Michigan. Journal of Ecology **75**:667-684.

Woodall, C.W., Smith, J.E. & Nichols, M.C. (2013) Data sources and estimation/modeling procedures for National Forest System carbon stocks and stock change estimates derived from the US National Greenhouse Gas Inventory. U.S. Department of Agriculture, Forest Service, Northern Research Station. 23 p.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Andersen, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagen, S.C., Hanou, I.S., Nichols, M.C., Perry, C.H.H., Russell, M.B., Westfall, J. & Wilson, B.T.T. (2015) The U.S. forest carbon accounting framework: stocks and stock change, 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 p.

Woods K, Kern C. 2022. Intermediate disturbances drive long-term fluctuation in old-growth forest biomass: an 84-yr temperate forest record. Ecosphere 13:e03871.

Wu, C., Coffield, S. R., Goulden, M. L., Randerson, J. T., Trugman, A. T., & Anderegg, W. R. (2023). Uncertainty in US forest carbon storage potential due to climate risks. Nature Geoscience, **16**(5), 422-429.

Xu, W., Yuan, W., Dong, W., Xia, J., Liu, D. & Chen, Y. (2013) A meta-analysis of the response of soil moisture to experimental warming. *Environmental Research Letters*, **8**, 044027 (8pp)

Zaehle, S., Sitch, S., Smith, B. & Hatterman, F. (2005) Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. *Global Biogeochemical Cycles*, **19**, 1-16.

Zhang, F., Chen, J.M., Pan, Y., Birdsey, R.A., Shen, S., Ju, W. & He, L. (2012) Attributing carbon changes in conterminous U.S. forests to disturbance and non-disturbance factors from 1901 to 2010. *Journal of Geophysical Research: Biogeosciences*, **117**, 18 p.

Zhang, F., Chen, J.M., Pan, Y., Birdsey, R.A., Shen, S., Ju, W. & Dugan, A.J. (2015) Impacts of inadequate historical disturbance data in the early twentieth century on modeling recent carbon dynamics (1951-2010) in conterminous U.S. forests. *Journal of Geophysical Research: Biogeosciences*, **120**, 549-569.

Zhao, T. & Dai, A. (2017) Uncertainties in historical changes and future projections of drought. Part II: model-simulated historical and future drought changes. *Climatic Change*, **144**, 535-548.

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S. & Zeng, N. (2016) Greening of the Earth and its drivers. *Nature Climate Change*, **6**, 791-795.