# Forest Carbon Assessment for the Mississippi National Forests in the Forest Service's Southern Region

*August 11, 2023 – SUBJECT TO UPDATES*

For more information contact:
NFMS EC Willard E. Childress

Contents

## 1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services forests provide. Through photosynthesis, growing plants remove carbon dioxide (CO2) from the atmosphere and store it as biomass (plant stems, branches, foliage, roots), and some of this organic material is eventually stored in soils. Carbon uptake and storage from the atmosphere helps modulate greenhouse gas (GHG) concentrations. Forest land harvested wood products (HWP), woodlands, and urban trees within the land sector collectively continue to represent the largest net carbon (C) sink in the United States, offsetting the equivalent of more than 12.4 percent of total (i.e., gross) GHG emissions in 2020 (U.S. EPA 2022; Domke et al., 2023). See Box 1 for a crosswalk of metric measurements used in this document.

**Box 1.** Description of the primary forest carbon models used to conduct this carbon assessment.

**Carbon Calculation Tool (CCT)**

> Estimates annual carbon stocks and stock change from 1990 to 2020 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

**Forest Carbon Management Framework (ForCaMF)**

> Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2021 had not occurred.

**Integrated Terrestrial Ecosystem Carbon (InTEC) model**

> A process-based model that integrates FIA data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric $CO_2$. 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 modeling processes.

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as trees and other vegetation establish and grow, die with age or disturbances, and re-establish and regrow. When long-lived vegetation such as trees die, either through natural aging and competition processes or disturbance events (e.g. storm damage, fires, insects), carbon is transferred from living carbon pools to dead pools that also release CO2 through decomposition or combustion (fires). A portion of the carbon contained within dead biomass can become stabilized within soils and potentially stored centuries to millennia.

For some forest stands, management of forests can be effective for increasing ecosystem carbon over time, enhancing the ability of forests, grasslands, and other ecosystems to mitigate increasing atmospheric carbon dioxide concentrations (see Ontl et al., 2020 and Kaarakka et al., 2021) that are driving a changing climate. Often these management actions 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 forest regrowth that may have simplified the species composition or structural diversity of the ecosystem, or a lack of natural disturbance such as frequent low-intensity fires that altered stand development. Management activities that can provide carbon benefits over time include timber harvests to diversify species, structural, or age-class diversity, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Commodities (e.g., paper, lumber) can then store carbon for days, decades, or even centuries. In the absence of active management, some forests may thin naturally from mortality-inducing disturbances or aging, resulting in accelerated tree mortality that, despite regeneration in canopy gaps, can result in altered carbon balance of the ecosystem that may result in emitting more carbon to the atmosphere than it absorbs.

Following natural disturbances or harvests, regrowing forests slowly absorb and store carbon, often these disturbed stands eventually accumulate the same amount of carbon emitted (McKinley et al., 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics, environmental factors such as atmospheric CO2 concentrations, rainfall, 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).

**Box 2. Carbon Units.** The following table provides a crosswalk among various metric measurements 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 | Mt | | $10^{12}$ | Teragram | Tg |
| $10^9$ | Gigatonne | Gt | | $10^{15}$ | Petagram | Pg |
| $10^{12}$ | Teratonne | Tt | | $10^{18}$ | Exagrame | Eg |
| $10^{15}$ | Petatonne | Pt | | $10^{21}$ | Zettagram | Zg |
| $10^{18}$ | Exatonne | Et | | $10^{24}$ | yottagram | Yg |

1 hectare (ha) = 0.01 $km^2$ = 2.471 acres = 0.00386 $mi^2$
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 passenger vehicle emits about 4.6 tonnes $CO_2$ a year

The Intergovernmental Panel on Climate Change (IPCC) summarized human contributions to climate change by "sectors" (IPCC, 2014) and intends to update this report in 2023.The 2023 Synthesis Report will integrate 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, HWP, woodlands, and urban trees in settlements individually and collectively represent a net GHG sink over the 1990-2020 time series, with interannual variability driven, in large part, by natural and anthropogenic forest disturbances (e.g., wildfire, harvesting), fluxes resulting from land conversions (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 2022; Domke et al., 2023). In 2020, forest land, HWP, woodlands, and urban trees in settlements collectively represented an estimated net increase in C stocks of 768.1 million metric tons of carbon dioxide equivalent (MMT CO2e or 768.1 Tg of CO2e). The forest land remaining forest land category is the largest net sink in the land sector, with an estimated uptake of 584.4 MMT CO2e (or 584 Tg CO2e). The largest source of emissions in the Resource Update report were from the conversion of forest land, with estimated losses of 126.9 MMT CO2e (or 126.9 Tg CO2e (U.S. EPA 2022; Domke et al., 2022).

In this paper, 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 harvested wood products (HWP) for each Forest Service region through 2011.
- Disturbance Report (Birdsey et al., 2019; Healey et al., 2023): provides a national forest-scale evaluation of the influences of disturbances and management activities, 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 (Chen et al., 2000; Zhang et al., 2012). The Southern Region currently supports disturbance data from 1990 to 2011 and is awaiting updated data up to 2020.

These reports used data from Forest Inventory and Analysis (FIA) and validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). Collectively, these reports incorporate advances in data and analytical methods, being the best available data and science to provide comprehensive assessments of NFS carbon trends.

### 1.1 Background

The National Forests in Mississippi, stretch from the pine forest of the Gulf Coastal Plain to the upland hardwood in the northern part of the state coving 1.2 million acres of diverse natural resources and valued public lands. Distributed across the State of Mississippi, National Forest System (NFS) lands include an array of ecological systems that are representative of the ecological diversity of the different portions of the state. Forestwide, pine-dominated stands (many of which resulted from reforestation efforts in the 1930s) are the most common forest communities. Large tracts of loblolly pine represent the most prevalent forest type, but fire-dependent stands of native longleaf pines along the lower Gulf Coastal Plain still occupy a portion of their historic range. Oaks and hickories dominate the dry slopes and ridges in the northern half of the state, where sheltered bluffs and mesic ravines contain a mix of hardwoods that includes American beech, white oak, and Southern magnolia. Along the Mississippi River Delta, approximately 60,000 acres of forested wetlands constitute the only bottomland hardwood national forest in the National Forest System.

The carbon legacy of Mississippi NF's and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. Exploration of the **Southern Region** by Europeans began in the mid-17th century. In the late 18th century, after the Revolutionary War, settlers cleared forests for mixed agriculture and grazing, establishing farming communities with schools, stores, and mills. Many of these farms, and sometimes entire communities, were abandoned in the mid to late 19th century, as farming technology changed and people moved west or to cities for better economic opportunities. Large logging companies bought up the abandoned farmland and woodlots, constructing logging railroads and camps and stripping much of the timber from the mountains. The unregulated practices of these logging companies caused massive forest fires and damaged watersheds. 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 1936, the National Forests in Mississippi was established when the recently established Bienville, Holly Springs, De Soto, and Homochitto National Forests were administratively combined. The restored forests and improved watersheds of today are in stark contrast to the cutover lands and abandoned farms that existed in the 1930s. This legacy of timber harvesting and early efforts to restore the forest is visible today, influencing forest age structures, tree composition, and carbon dynamics (Birdsey *et al.*, 2006).

## 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 stocks in the Mississippi NF increased from 61.6±5.0 teragrams of carbon (Tg C) in 1990 to 82.6±10.0 Tg C in 2020, a 34 percent increase in carbon stocks over this period (Fig. 1). For context, 83 Tg C is equivalent to the emissions from approximately 66 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 Mississippi NF are stable or have increased from 1990 to 2020 (Fig. 1). 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 historic baseline conditions. Previous studies that have attempted to reconstruct historic baseline conditions could not do so without a high degree of uncertainty and are overall inconclusive about how they compare to current conditions (see Keane et al., 2009). It is important to consider both historic and current baseline conditions when evaluating future trends in carbon uptake and storage.

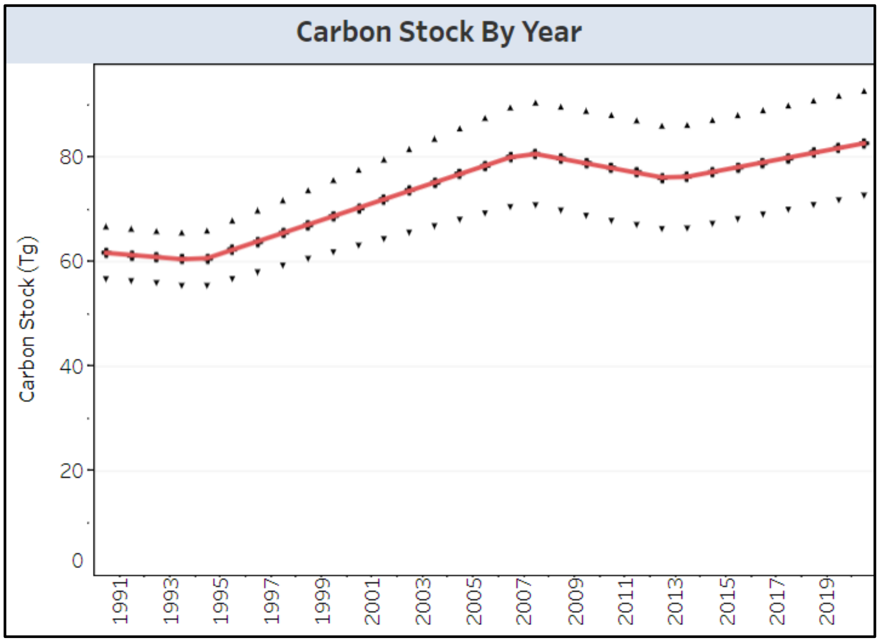

***Figure 1.** Total forest carbon stocks (Tg) from 1990 to 2020 for the Mississippi National Forests, bounded by 95 percent confidence intervals. Estimated using the Carbon Calculation Tool (CCT) model.*

About 28.6 percent of forest carbon stocks in the Mississippi NF are stored in the soil carbon contained in organic material to a depth of one meter (excluding roots). The aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2) is the largest carbon pool, storing another percent 50.7 of the forest carbon stocks. Updated methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke *et al.*, 2017).

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area in the Mississippi NFs has increased from 471,893 ha in 1990 to 475,152 ha in 2020, a net change of 3,259 ha.[1] When forestland area increases, total ecosystem carbon stocks will also increase, indicating a carbon sink. The CCT model used inventory data from two different databases. This may have led to inaccurate estimates of changes in forested area, potentially altering the conclusion regarding whether or not forest carbon stocks are increasing or decreasing, and therefore, whether the National Forest is a carbon source or sink (Woodall *et al.*, 2011).

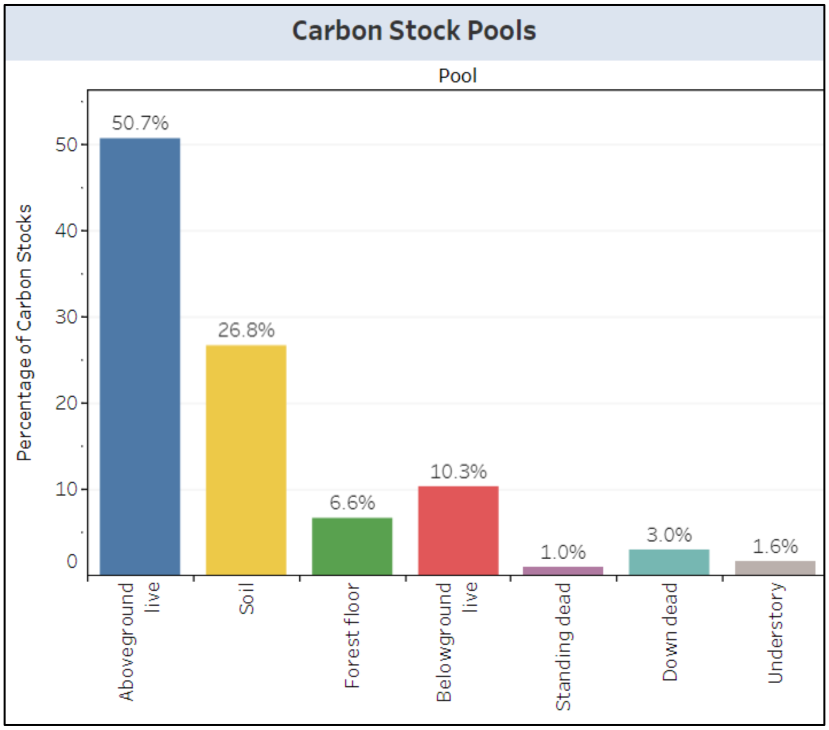

***Figure 2.*** *Percentage of carbon stocks in 2020 in each of the forest carbon pools, for the Mississippi National Forests. Estimated using the Carbon Calculation Tool (2022).*

To help address the influence of changes in forestland area on forest carbon stocks, carbon density is calculated. Carbon density is an estimate of forest carbon stocks per unit area. In the Mississippi NFs, carbon density increased from about 130.6 Megagrams of carbon (Mg C) per ha in 1990 to 173.7 Mg C per ha in 2020 (Fig. 3). This increase in carbon density suggests that the increase in total carbon was not entirely driven by increases in forestland area, but that carbon stocks within the six carbon pools measured by FIA (Fig. 2) have also increased.

Carbon density is also useful for comparing trends among units ownerships with different forest areas. Similar to the Mississippi NFs, most national forests in the Southern Region have experienced increasing carbon densities from 1990 to 2020. Carbon density estimates in the Mississippi NFs have been similar to the average for all national forest units in the Southern 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. These differences may also be affected by disturbance and management regimes (see Section 3.0).

### 2.2 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[2] and shown by the error bars (Fig. 1). These confidence intervals indicate the carbon stock for any given year has a five percent chance of the true value being outside this range. The uncertainties contained in the models, samples, and

---

[1] Forested area used in the CCT model may differ from more recent FIA estimates, as well as from the forested areas used in the other modeling tools.

[2] A Monte Carlo simulation performs an error analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty (e.g., data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

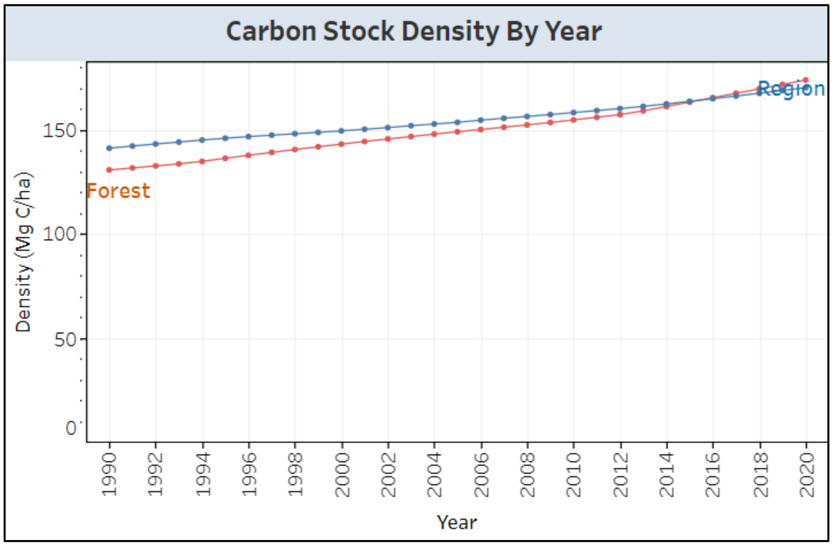

***Figure 3**. Carbon stock density (Megagrams per hectare) in the Mississippi National Forests and the average carbon stock density for all forests in the Southern Region from 1990 to 2020. Estimated using the Carbon Calculation Tool (2022).*

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 over time.

The baseline estimates that rely on FIA data include uncertainty associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). As mentioned in Section 2.1, one such model error has resulted from a change in FIA sampling design, which led to an apparent change in forested area. Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the Mississippi NFs have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artefact of altered inventory design and protocols (Woodall *et al.*, 2013).

In 2005, the inventory design changed from a periodic inventory, in which all plots were sampled in a single year to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year.  As a result, there is a structural anomaly with results for forest floor early in the time series (before 2005) due to 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 (Woodall *et al.*, 2011). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which inventory plots are measured. Forest Inventory and Analysis plots are resampled about every 5 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.

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 mechanisms that alter carbon stocks and provides information on finer temporal scales. Consequently, discrepancies in results may occur between the Baseline Report and the Disturbance Report (Dugan *et al.*, 2017).

### 2.3 Carbon in Harvested Wood Products

Although harvest disturbance transfers carbon out of the forest ecosystem, some of that carbon is not emitted directly back to the atmosphere, but rather stored in wood products. The duration of that carbon stored in products varies depending on the type of commodity produced. Additionally, 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 carbon stored in the products themselves (Gustavsson *et al.,* 2006; Lippke *et al.,* 2011). Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the forest in the affected area regenerates and grows over the decades following harvest.

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report was conducted by incorporating data on harvests on national forests documented in cut-and-sold reports within a production accounting system (Smith *et al.*, 2006; Loeffler *et al.*, 2014). This approach tracks the entire cycle of carbon, from harvest to timber products to primary wood products to disposal. As more commodities are produced and remain in use, the amount of carbon stored in products increases. As more products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

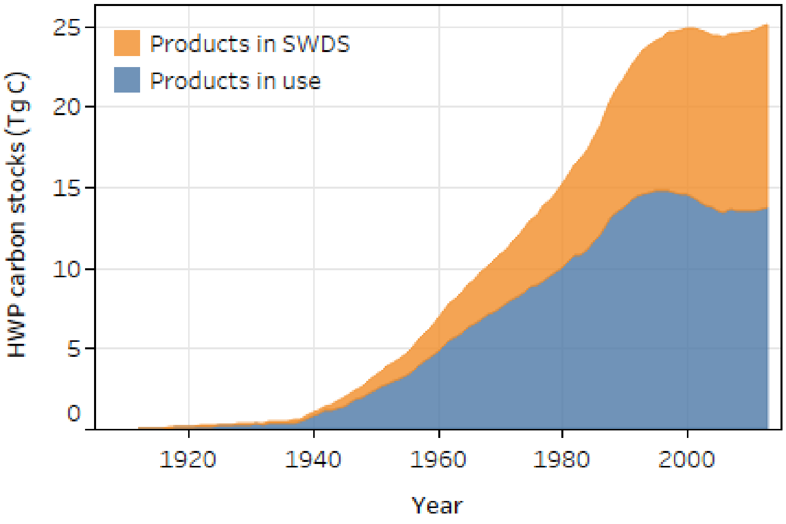

***Figure 4***. *Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the* **Southern Region** *from 1912 to 2013. Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

In national forests in the **Southern 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 anoxic conditions of SWDS.

Carbon storage in products and landfills reached roughly 25 Tg C in 2001. However, because of a significant 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 **Southern 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 2.7 percent of total forest carbon storage associated with national forests in the **Southern Region**.

### 2.4 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of historic harvests to modern national forest boundaries; factors used to convert the volume harvested to biomass; the proportion of harvested wood used for different commodities (e.g., paper products, saw logs); product decay rates; and the lack of distinction between methane and $CO_2$ emissions from landfills. The approach also does not consider the substitution of wood products for emission-intensive materials or the substitution of bioenergy for fossil fuel energy, which can be significant (Gustavsson *et al.*, 2006). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Loeffler *et al.*, 2014).

## 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 from Landsat satellite imagery (Healey *et al.*, 2018). The Landsat imagery was used to detect land cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting disturbance maps indicate that timber harvest has been the dominant disturbance type detected on the Mississippi NFs from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 5a). However, according to the satellite imagery, timber harvests affected a relatively small area of the forest during this time. In most years, timber harvests affected less than 1 percent of the total forested area of the Mississippi NFs in any single year from 1990 to 2011, and in total less than 9 percent (approximately 43,210 ha) of the average forested area during this period (500,040). Although harvest was the dominant disturbance, there were some years where fire and abiotic factors were greater. In total fire and abiotic accounted for 3.3% of the land base of the total forest disturbance from 1990 to 2011.

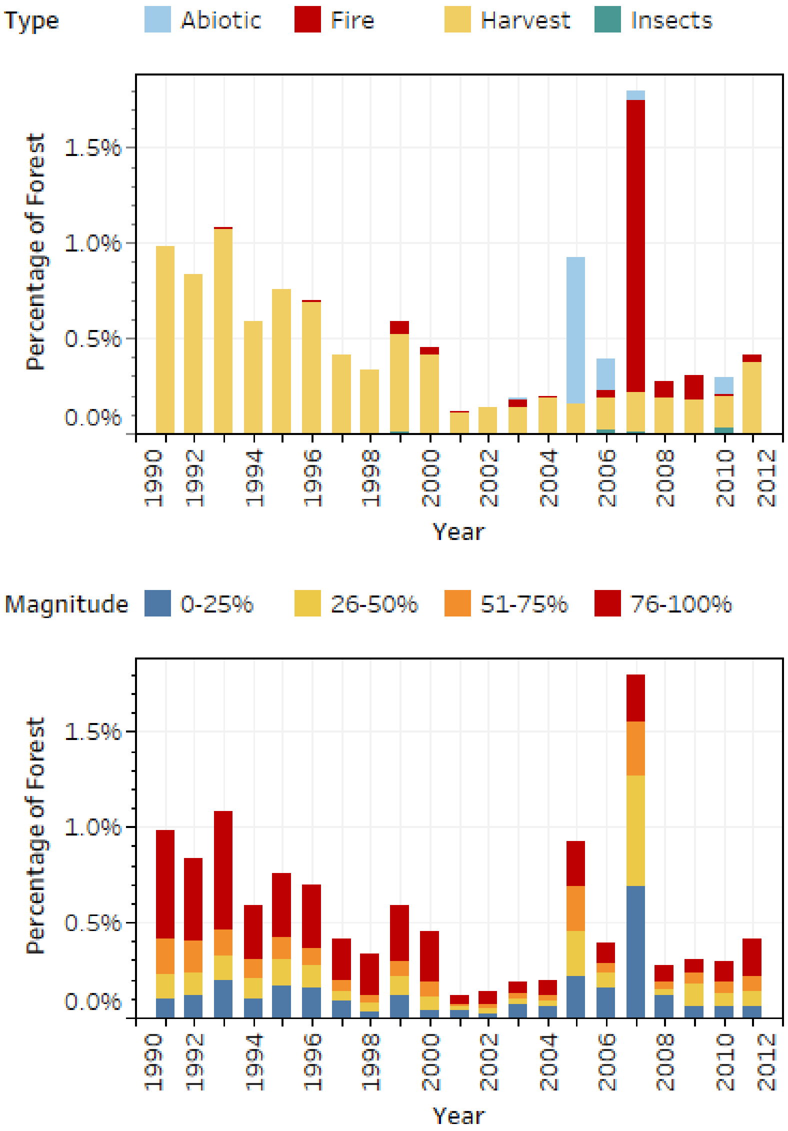

***Figure 5.*** *Percentage of forest disturbed from 1990 to 2011 in the Mississippi National Forests by (a) disturbance type including fire, harvests, insects, and abiotic (wind), and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite*

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 5, along with FIA data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond *et al.*, 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each national forest if the disturbances and harvests during 1990-2011 had not occurred. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey *et al.*, 2014).

Timber harvesting on the Mississippi NFs was the primary disturbance influencing carbon stocks from 1990 to 2011 (Fig. 6). ForCaMF model indicates that, by 2011,the Mississippi NFs contained 6.8 Mg C per ha less non-soil carbon (i.e., vegetation and associated pools) due to harvests since 1990, as compared to a hypothetical undisturbed scenario (Fig. 6). As a result, non-soil carbon stocks in the Mississippi NFs would have been approximately 4.6 percent higher in 2011 if harvests had not occurred since 1990 (Fig. 7).

Across all national forests in the Southern Region, harvest has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 7 percent lower by 2011 (Fig. 8). Considering all national forests in the Southern Region, by 2011, fires accounted for the loss of 2.1 percent of non-soil carbon stocks, insects 0.38 percent, and abiotic factors (wind, ice storms) 0.33 percent (Fig. 7).

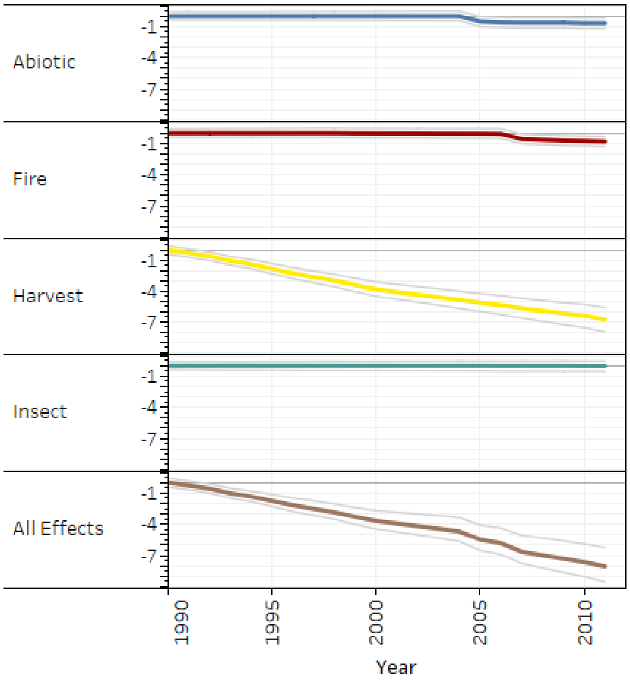

***Figure 6.*** *Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in the Mississippi National Forests. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.*

The ForCaMF analysis was conducted over a relatively short time. After a forest is harvested, it will eventually regrow and recover the carbon removed from the ecosystem in the harvest. However, several decades may be needed to recover the carbon removed depending on the type of the harvest (e.g., clear-cut versus partial cut), as well as the conditions prior the harvest (e.g., forest type and amount of carbon) (Raymond *et al.*, 2015). The ForCaMF model also does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Lippke *et al.*, 2011; McKinley *et al.*, 2011; Skog *et al.*, 2014; Dugan *et al.*, 2018). The IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC, 2000), therefore an assessment of impacts of harvest activities on greenhouse gas emissions is not complete without incorporation of carbon storage estimates from wood products (see Section 2.3).

Quantitative data is not currently available to estimate the carbon impacts of more recent disturbances (from the period of 2011 – 2023). It is likely that the Forest has experienced more frequent and high severity disturbances over the last 10 years. Please see section 4.2 for more discussion regarding climate and carbon. While quantitative data is not yet available from the period of 2011 to 2023, a recent forest health advisory report indicates that approximately 61% of tree biomass across all National Forests in Mississippi is at risk (or termed hazard) (USFS FHA 2023). The forest health advisory system defines risk as “the expectation that, without remediation, at least 25% of standing live basal area greater than one inch in diameter will die over a 15-year time frame (2013 to 2027) due to insects and diseases” (USFS FHA 2023). Southern pine beetle and emerald ash borer are the main pests of concern across all the National Forests in Mississippi. This potential increase in pest activity across the Mississippi NFs may have subsequent carbon implications. Quantitative estimates of carbon impacts from more recent disturbances are forthcoming via an update to the ForCaMF model.

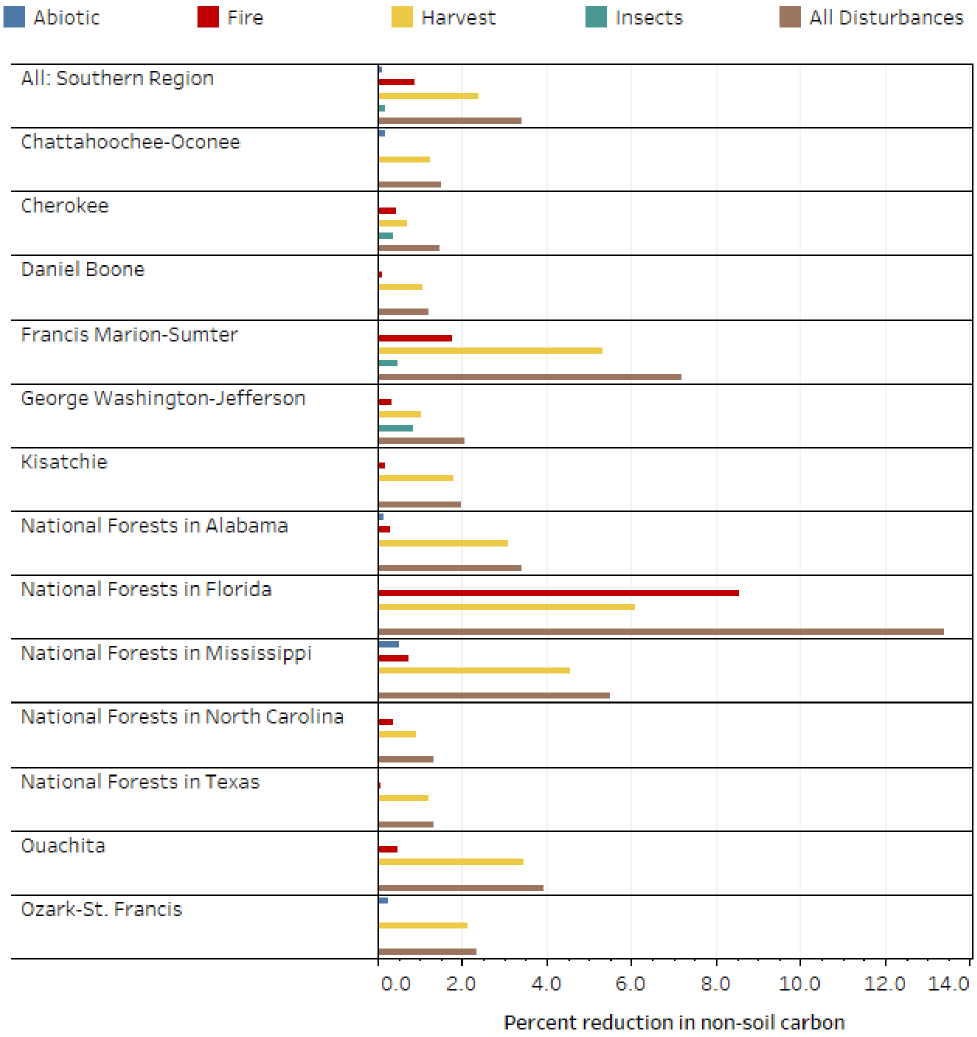

***Figure 7.*** *The degrees to which 2011 carbon storage on each national forest in the* ***Southern Region*** *was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The purple line indicates the effect of all disturbance types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT.*

### 3.2 Effects of Forest Aging

InTEC models the collective effects of forest disturbances and management, aging, mortality, and subsequent regrowth on carbon stocks from 1950 to 2011. 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. The model uses inventory-derived maps of stand age, Landsat-derived disturbance maps (Fig. 6), and equations describing the relationship between net primary productivity (NPP) and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan *et al.*, 2011a). In the model, when a forested stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration.

Stand-age distribution for the Mississippi NFs derived from 2011 forest inventory data indicates elevated stand establishment around 1900-1920 (Fig. 8a). This period of elevated stand regeneration came after decades of intensive logging and large wildfires in the late 1800s and early 1900s (Foster, 2006). Policies focusing on restoring forests after decades of overharvesting and conversion of forest to agriculture enabled these stands to establish, survive, and accumulate carbon. Similar age trends have been widely observed in eastern U.S. forests (Birdsey *et al.*, 2006). Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer & Euskirchen, 2004; He *et al.*, 2012), as indicated by the in NPP-age curves (Fig. 8b), derived in part from FIA data.

InTEC model results show that the Mississippi NFs were accumulating carbon steadily at the start of the analysis in the 1950s through the mid-1970s (Fig. 9) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Fig. 8b). As stand establishment declined and more stands reached slower growth stages around the 1970s, the rate of carbon accumulation declined (negative slope). While forest regrowth and aging following historical disturbances (early 1900s harvesting and land-use change), have collectively played an important role in carbon accumulation trends since 1950 in the Mississippi NFs (Fig. 9), the effects of non-disturbance factors have become more important in influencing carbon trends on the forest.

In the fall of 2022, the U.S. Department of Agriculture's Forest Service and U.S. Department of the Interior's 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). In ordinance with Executive Order 14072, the Forest Service released a Mature and Old Growth Forests technical report and the Climate Risk Viewer (USDA Forest Service 2023a; USDA Forest Service 2023b). The technical report and accompanying dashboard depict potential estimates of old growth and mature forest at the fireshed scale on the Mississippi National Forests. Additional Forest Service guidance on mature and old growth forest is forthcoming. For more information on old and mature forests please see the Forest Service Climate Risk Viewer and technical report (USDA Forest Service 2023a; USDA Forest Service 2023b).

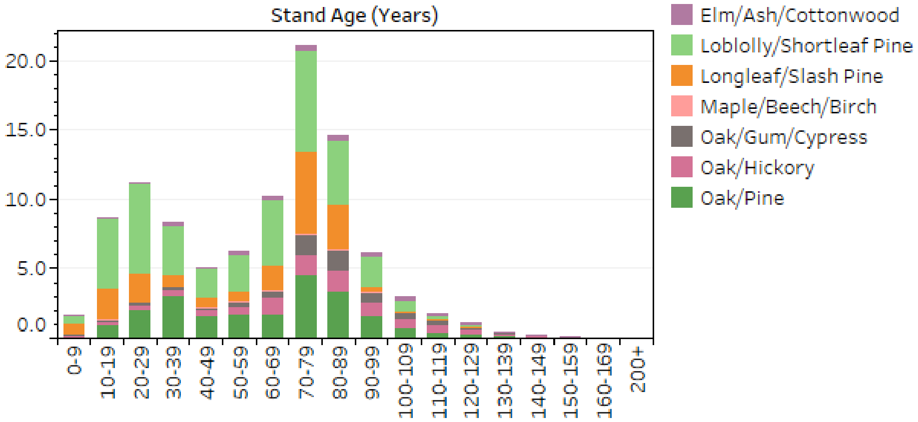

***Figure 8.*** *(a) Stand age distribution in 2011 by forest type group in the Mississippi National Forests. Derived from forest inventory data.*

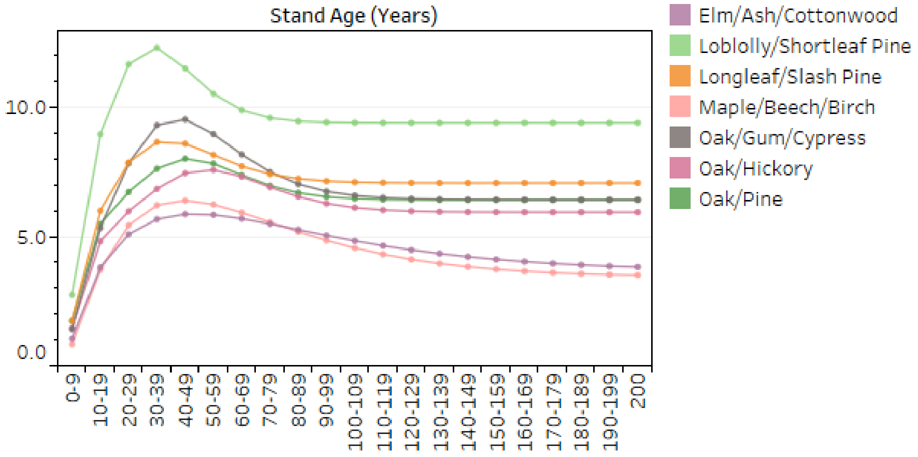

***Figure 8.*** *(b) net primary productivity-stand age curves by forest type group in the Mississippi National Forests. Derived from forest inventory data and He et al. 2012.*

### 3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric $CO_2$ concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year, but overall, since the mid-1950s, climate has had a small positive effect on carbon stocks in the Mississippi (Fig. 9). Warmer temperatures can have negative impacts on ecosystem carbon balance, increasing forest respiration through enhanced soil microbial activity (Ju *et al.*, 2007; Melillo *et al.*, 2017) and reducing forest growth from increased evapotranspiration that causes lowered soil moisture levels, (Xu *et al.*, 2013). InTEC model results suggest that climate had a net negative impact on carbon accumulation rates.

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 a significant 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 $CO_2$ has consistently had a positive effect on carbon stocks in the Mississippi NFs, tracking an increase in atmospheric $CO_2$ concentrations worldwide (Fig. 9). 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). There has been considerable debate regarding the effects of elevated $CO_2$ on forest growth and biomass accumulation, thus warranting additional study (Körner *et al.*, 2005; Norby *et al.*, 2010; Zhu *et al.*, 2016).

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the Mississippi NFs (Fig. 9). Like $CO_2$, the actual magnitude of this effect remains uncertain. 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). The InTEC model results indicate that rates of carbon accumulation associated with nitrogen deposition decreased as deposition rates declined. Overall, the InTEC model suggests that $CO_2$ and nitrogen fertilization partially offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate.

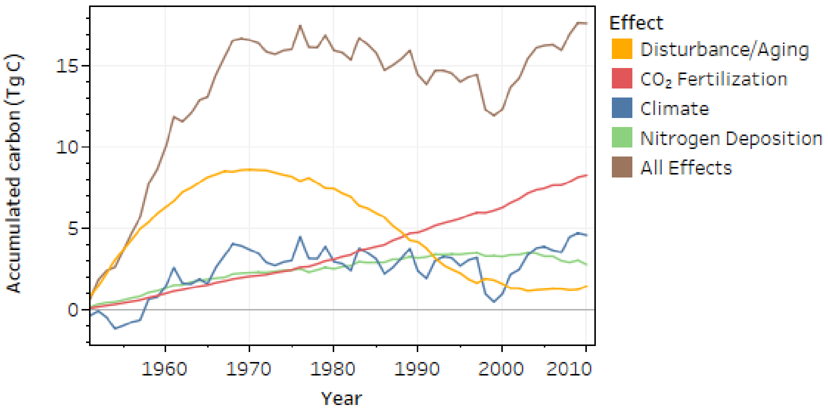

***Figure 9.*** *Accumulated carbon in the Mississippi National Forests due to disturbance/aging, climate, nitrogen deposition,* $CO_2$ *fertilization, and all factors combined (shown in black line) for1950–2011, excluding carbon accumulated pre-1950 Estimated using the InTEC model.*

### 3.4 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, however, they are expected to have minor impacts on results given the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond *et al.*, 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (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.

## 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 Mississippi NFs are nearly equivalent between middle-aged (less than 80 years) and older (greater than 80 years) (Fig. 8a). If the Forest continues this aging trajectory with the majority of stands advancing into older age classes with time, more stands will reach a slower growth stage in coming years and decades (Fig. 8b). This may cause the rate of carbon accumulation to decline over time, with the result of the Forest eventually transitioning first to a steady state (no change in carbon stocks over time) and then into a carbon source (declining carbon stocks over time) in the future. Although NPP curves indicate that live tree biomass carbon accumulation rates may be approaching maximum levels (Fig. 8b), total ecosystem carbon stocks can continue to increase for many decades as dead carbon (forest floor, standing dead, and downed dead) and soil carbon stocks continue to accumulate (Luyssaert *et al.*, 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities or disturbances could affect future stand age and forest growth rates (Davis *et al.*, 2009; Keyser & Zarnoch, 2012).

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

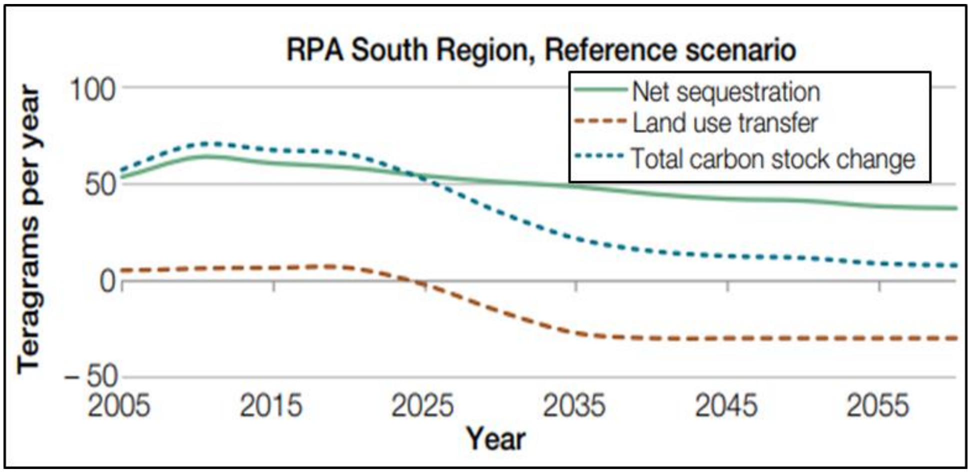

***Figure 10.*** *Projections of forest carbon stock changes in the South Region (equivalent to the boundaries of* ***Southern Region****, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use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

For RPA's South Region (equivalent to Forest Service's Southern Region boundary, but includes all land ownerships), projections indicate that the rate of carbon sequestration began to decline since approximately 2010 and will continue to decline through 2060, but at a slower rate in the middle of the century. This decline in the carbon sink is mostly due to the loss of forestland (land-use transfer), and to a lesser extent through forest aging and increased disturbances, which is shown by the change in net sequestration (total carbon stock change minus losses associated with land-use change) (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.*, 2011b; Houghton *et al.*, 2012). Converting forest land to a non-forest use removes a large amount of carbon from the land and dramatically reduces 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 Mississippi NFs in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 9, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2060.

### 4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major drivers of historic and current forest carbon sequestration occurring on the Mississippi NF and elsewhere across the region. Reforestation through land management practices and post-disturbance recovery has the ability to increase topsoil carbon storage within the National Forest System (Nave *et al.* 2019).

Climate change introduces additional uncertainty about how forests—and forest carbon sequestration and storage—may change in the future. Climate change causes many direct alterations of the local environment, such as changes in temperature and precipitation, and it has indirect effects on a wide range of ecosystem processes (Vose *et al.*, 2012). 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 and aging on forest carbon dynamics.

A climate change fact sheet for the Mississippi NF's indicates forestlands across the region are experiencing increased threats from fire, insect and plant invasions, disease, extreme weather, and drought. Scientists project increases in temperature and changes in rainfall patterns that can make these threats occur more often, with more intensity, and/or for longer durations. Although many of the effects of future changes are negative, natural resource management strategies can help mitigate these impacts. Responses informed by the best current science enable natural resource professionals within the Forest Service to better protect the land, resources, and the region's forestlands into the future.

Stresses from drought and wide-scale pest outbreaks, such as southern pine beetle and Ips bark beetle, have the potential to cause large areas of forest dieback (Allen *et al*, 2010). However, there has been a reduction in southern pine beetle activity in the southeastern United States in the last five years (Fettig et al. 2022). Intensified extreme weather events, such as hurricanes, ice storms, and fire, as well as temperature caused vegetation range shifts, are also expected to lead to changes in plant community composition. Species more resistant to these disturbances, such as shortleaf pine, are expected to be more resilient to a changing climate (Hansen *et al.*, 2001) and may have lower mortality or sustain higher growth under stressed conditions. Populations of other plants, including the threatened large-flowered skullcap, may be particularly vulnerable because invasive species like the Japanese honeysuckle and kudzu out-compete the native plant (McMorrow, 1996). Northern hardwood species in high elevations are especially vulnerable to changing temperatures; species of pine may opportunistically move into areas of higher elevation where past tree species have become stressed. Although many of the effects of future changes are negative, natural resource management can help mitigate these impacts; managers may elect to thin tree densities to increase water availability for remaining trees or, ultimately, shift management focus away from northern hardwood species.

Mean annual precipitation projections across the region vary, with projected decreases is the western part of the region and increases in the Southern Appalachian Mountains, although uncertainty remains relatively high. More intense precipitation and extreme storm events are expected to continue increasing in this region. Across the region, the number of intense (i.e., >2 inches of precipitation within a 24-hour period) precipitation events increased by 22 percent during the 20th century. Higher intensity rainfall leads to greater flooding and soil erosion, which in turn could lead to lower agricultural productivity (McNulty *et al.*, 2015). The potential for reduced soil moisture and drought is also predicted to increase, especially later in the growing season as increased temperatures drive evapotranspiration (Wear and Greis, 2012; Vose and Klepzig, 2013). 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; Miller et al., 2022), which can significantly reduce carbon uptake (Kurz et al., 2008; D'Amato et al., 2011). Drought may also have a detrimental drying effect on the wetlands of the Southeast, leading to reduced carbon stocks.

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC, 2014). The Southern region is projected to face increases in climate driven hazards which escalate with every increment of global temperature rise (IPCC, 2021; IPCC, 2022a; IPCC, 2022b). 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 CO2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions.

## 5.0 Summary

Forests in the Mississippi NFs are stable and may be maintaining a carbon sink. Forest carbon stocks increased by about 34 percent between 1990 and 2020, and negative impacts on carbon stocks caused by disturbances and environmental conditions have been modest and 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. 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.

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

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

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

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

## 6.0 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.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D.McDowell, N., Vennetier, M., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, 259(4), 660-684. doi:10.1016/j.foreco.2009.09.001

Birdsey, R., Dugan, A.J., Healey, S., Dante-Wood, K., Zhang, F., Chen, J., Hernandez, A., Raymond, C., McCarter, J. (2019) Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of United States National Forests. Fort Collins, Colorado: Gen. Tech. Report RM-402.

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.

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.

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.

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.

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, Grant M.; Walters, Brian F.; Nowak, David J.; Greenfield, Eric. J.; .Smith, James, E.; Nichols, Michael C.; Ogle, Stephen M.; Coulston, John. W.; Wirth, Tom C. 2022. Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990–2020. Resource Update FS–382. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 10 p. https://doi.org/10.2737/FS-RU-382

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. Washington, D.C., U.S. Department of Agriculture, Forest Service, Washington Office.

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.

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*.

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.

Fettig, Christopher J; Asaro, Christopher; Nowak, John T; Dodds, Kevin J; Gandhi, Kamal J K; Moan, Jason E; Robert, Jeanne. 2022. Trends in Bark Beetle Impacts in North America During a Period (2000 2020) of Rapid Environmental Change. Journal of Forestry. 120(6): 693-713. https://doi.org/10.1093/jofore/fvac021.

Flanagan, Steven A.; Bhotika, Smriti; Hawley, Christie; Starr, Gregory; Wiesner, Susanne; Hiers, J. Kevin; O'Brien, Joseph H.; Goodrick, Scott; Callaham Jr., Mac A.; Scheller, Robert M.; Klepzig, Kier D.; Taylor, R. Scott; Loudermilk, E. Louise. 2019. Quantifying carbon and species dynamics under different fire regimes in a southeastern U.S. pineland. Ecosphere, 10(6): 1-16.

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

Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iver-son, L. R., Currie, D. J., Bartlein, P. J. (2001). Global change in forests: Responses of species, communities, and biomes. Bio-Science, 51, 765-779.

Hayes, D.J., Vargas, R., Alin, S.R., Conant, R.T., Hutyra, L.R., Jacobson, A.R., Kurz, W.A., Liu, S., McGuire, A.D., Poulter, B. & Woodall, C.W. (2018) Chapter 2: The North American carbon budget. *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* (ed. by N. Cavallaro, G. Shrestha, Birdsey, R. M. A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao and Z. Zhu), pp. 71-108. U.S. Global Change Research Program, Washington, DC.

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.

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 (2000) *Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change, Summary for Policy Makers*, Geneva, Switzerland.

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.

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.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.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.

Jie Zhu, Ge Sun, Wenhong Li, Yu Zhang, Guofang Miao, Asko Noormets, Steve G. McNulty, John S. King, Mukesh Kumar, Xuan Wang. 2017. Modeling the potential impacts of climate change on the water table level of selected forested wetlands in the southeastern United States

Johnson, C. and D. Govatski. 2013. Forests for the people: the story of America's eastern national forests. Island Press, Washington, D.C.

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.

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.

Keane, Robert E., et al. "The use of historical range and variability (HRV) in landscape management." Forest Ecology and Management 258.7 (2009): 1025-1037.

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.

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.

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.

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.

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.

McMorrow, Alex. Tennessee Department of Environment and Conservation for Southeast Region U.S. Fish and Wildlife Ser-vice. Recovery Plan for Large-flowered Skullcap (Scutellaria montana). 1996.

McNulty, S., S. Wiener, E. Treasure, J. Moore Myers, H. Farahani, L. Fouladbash, D. Marshall, R. Steele, D. Hickman, J. Porter, S. Hestvik, R. Dantzler, W. Hall, M. Cole, J. Bochicchio, D. Meriwether, and K. Klepzig, 2015: Southeast Regional Climate Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies, T. Anderson, Ed., United States Department of Agriculture, 61 pp. https://doi.org/10.32747/2015.7279978.ch

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.

Miller, D.R.; Nowak, J.T.; Mayfield, A.E. 2022. Siricid parasitoids (Hymenoptera: Ichneumonidae) from eastern white pine and associated pine species in Southern Appalachia. Journal of Entomological Science. 57(1): 119-122. https://doi.org/10.18474/JES21-08.e

Nave, L.E., G.M. Domke, K.L. Hofmeister, U. Mishra, C.H. Perry, B.F. Walters, and C.W. Swanston. 2018. Reforestation can sequester two petagrams of carbon in US topsoils in a century. Proc. Nat. Acad. Sci. USA 115(11):2776–2781.

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.

Oishi, A. Christopher , Chelcy F. Miniat, Kimberly A. Novick, Steven T. Brantley, James M. Vose, John T. Walker. 2018. Warmer temperatures reduce net carbon uptake, but do not affect water use, in a mature southern Appalachian forest, Agricultural and Forest Meteorology, Volume 252, Pages 269-282, ISSN 0168-1923, https://doi.org/10.1016/j.agrformet.2018.01.011.

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.

Ontl, Todd A., et al. "Forest management for carbon sequestration and climate adaptation." Journal of Forestry 118.1 (2020): 86-101.

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

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. (2011b) A large and persistent carbon sink in the world's forests. *Science*, **333**, 988-993.

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.

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.

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.

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.

Shands 1992. The Lands Nobody Wanted: The Legacy of the Eastern National Forests. The origins of the National Forests. 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. & 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.

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. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H. & et al. (2014) Agriculture, Forestry and Other Land Use (AFOLU). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by O. Edenhofer, R. Pichs-Madruga, Y. Sokona and et al.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stanturf, J.A., Wade, D.D., Waldrop, T.A., Kennard, D.K., Achtemeier, G.L., 2002. Background paper: fires in southern forest landscapes. In Wear, D.N., Greis, J.G. (Eds.), Southern Forest Resource Assessment. Tech. Rep. GTR SRS-53. USDA, For. Serv., Washington, DC, pp. 153–174. URL: http://www.srs.fs.usda.gov/sustain/report/ [Online].

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.

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.

US EPA (2015) Executive Summary. *US inventory of greenhouse gas emissions and sinks: 1990 – 2013.* U.S. Environmental Protection Agency, Washington, DC. 27 pp.

USDA Forest Service (2015). Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System Units, Southern Region. 60 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 (2019). History and Culture. Retrieved from: https://www.fs.usda.gov/main/conf/learning/history-culture. December 17, 2019.

USDA Forest Service FHA. (2023). Forest Health Advisory System. Retrieved June 30, 2023, from https://apps.fs.usda.gov/fhas/CreateAdvisory/2/537.

USDA Forest Service (2023a). Forest Service Climate Risk Viewer. (2023, June 29). ArcGIS StoryMaps. 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

U.S. Environmental Protection Agency [U.S. EPA]. 2022. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2020. EPA 430-R-22-003. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/ ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

Van Lear, D.H.; Waldrop, T.A. 1989. History, Uses, and Effects of Fire in the Appalachians. Gen. Tech. Rep. SE-54. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 20 p.

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.; Klepzig, K.D. (2013). Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystems. CRC Press.

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.

Wear, D.N.; Greis, J.G. 2012. The Southern Forest Futures Project: summary report. Gen. Tech. Rep. SRS-159. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 54 p.

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.

Williams, M. 1989. Americans and Their Forests: An Historical Geography. New York: Cambridge University Press.

White House. 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/

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., Heath, L.S., Domke, G.M. & Nichols, M.C. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 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.

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.

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.

Paper Authors
Alexa Dugan
Duncan McKinley (Duncan.mckinley@usda.gov)
Sara Amiot (sara.amiot@usda.gov)
Lauren Onofrio (lauren.onofrio@usda.gov)
Willard Childress (willard.childress@usda.gov)