Forest Carbon Assessment for the Chattahoochee-Oconee National Forests in the Forest Service's Southern Region

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1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services provided by forests and grasslands. Through the process of photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it in forest biomass (plant stems, branches, foliage, roots) and much of this organic material is eventually stored in forest soils. This uptake and storage of carbon from the atmosphere helps modulate greenhouse gas (GHG) concentrations in the atmosphere. Estimates of net annual storage of carbon indicate that forests in the United States (U.S.) constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan *et al.*, 2011b). Forests in the U.S. remove the equivalent of about 12 percent of annual U.S. fossil fuel emissions or about 206 teragrams of carbon after accounting for natural emissions, such as wildfire and decomposition (US EPA, 2015; Hayes *et al.*, 2018).

The Intergovernmental Panel on Climate Change (IPCC) has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (IPCC, 2014). From 2000 to 2009, forestry and other land uses contributed just 12 percent of human-caused global CO_2 emissions.[1] The forestry sector contribution to GHG emissions has declined over the last decade (FAOSTAT, 2013; IPCC, 2014; Smith *et al.*, 2014). Globally, the largest source of GHG emissions in the forestry sector is deforestation (Pan *et al.*, 2011b; Houghton *et al.*, 2012; IPCC, 2014), defined as the removal of all trees to convert forested land to other land uses that either do not support trees or allow trees to regrow for an indefinite period (IPCC, 2000). However, the United States is experiencing a net increase in forestland in recent decades because of the reversion of agricultural lands back to forest and regrowth of cut forests (Birdsey *et al.*, 2006), a trend expected to continue for at least another decade (Wear *et al.*, 2013; USDA Forest Service, 2016).

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools, which also release carbon dioxide through decomposition or combustion (fires). Management activities include timber harvests, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Carbon can then be stored in commodities (e.g., paper, lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinning, harvest, and fuel reduction treatments, forests will thin naturally from mortality-inducing disturbances or aging, resulting in dead trees decaying and emitting carbon to the atmosphere.

Following natural disturbances or harvests, forests regrow, resulting in the uptake and storage of carbon from the atmosphere. Over the long term, forests regrow and often accumulate the same amount of carbon that was emitted from disturbance or mortality (McKinley *et al.*, 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients, such as nitrogen, can also influence forest growth and carbon dynamics (Caspersen *et al.*, 2000; Pan *et al.*, 2009).

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[1] Fluxes from forestry and other land use (FOLU) activities are dominated by CO_2 emissions. Non-CO_2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate.

In this section, we provide an assessment of the amount of carbon stored on the Chattahoochee-Oconee National Forest (CONF) and how disturbances, management, and environmental factors have influenced carbon storage overtime. This assessment primarily used two recent U.S. Forest Service reports: The Baseline Report (USDA Forest Service, 2015) and Disturbance Report (Birdsey *et al.,* 2019). Both reports relied on Forest Inventory and Analysis (FIA) and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). The Baseline Report 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 2013. The Baseline Report also provides information on carbon storage in harvested wood products (HWP) for each Forest Service region. The Disturbance Report 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). 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). See Box 1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act (RPA) assessment (USDA Forest Service, 2016) and regional climate vulnerability assessments (Wear and Greis, 2012; Vose and Klepzig, 2013; USDA Forest Service, 2016) are used to help infer future forest carbon dynamics. Collectively, these reports incorporate advances in data and analytical methods, representing the best available science to provide comprehensive assessments of NFS carbon trends.

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 2013 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2011 had not occurred.

Integrated Terrestrial Ecosystem Carbon (InTEC) model

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

1.1 Background

The Chattahoochee-Oconee NFs, located across the northern portion (Chattahoochee National Forest (NF)) of the state of Georgia with lands in 18 counties, and in the Central/Piedmont portion of the state of Georgia (Oconee NF) with land in 8 counties. The Chattahoochee-Oconee NFs cover approximately 878,482 acres of forest land across 26 counties. Oak-hickory, loblolly-shortleaf pine and oak-pine forest types are the most abundant across the Chattahoochee-Oconee NFs, according to FIA data.

The carbon legacy of Chattahoochee-Oconee NFs and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. The lands on the Chattahoochee NF are usually found in large blocks on the mountainsides and ridges, with private lands in the valleys. There are occasional, usually small, private parcels that are partly or surrounded by national forest land. Similarly, there are forest parcels that are isolated from the larger blocks and are partially or surrounded by private lands. Features of notable significance on the Chattahoochee NF include Brasstown Bald (the highest point in Georgia), the crest of the Blue Ridge Mountains, most cold-water trout fisheries, and over 150,000 acres of Congressionally designated areas. Chattahoochee NF lands are contained in the headwaters of four major river basins that begin in Georgia: the Tennessee, Chattahoochee, Coosa, and Savannah Rivers. Water from each of these basins provides essential domestic and industrial water supplies for numerous cities and towns downstream of National Forest lands. The Coosa and Chattahoochee basins are part of on-going tri-state negotiations on allocation of surface waters. The Oconee NF is located south of Athens and east of Atlanta, Georgia. The lands are generally in large blocks, but with a generous interspersing of private lands. The private lands are sometimes in fairly large blocks of farmland or lands owned or managed by large timber companies. This forest occurs as two separate sections, a northern section near Madison and Greensboro; and a southern section near Monticello and Eatonton. Interstate Highway 20 creates an east-west boundary between the two sections of National Forest. The Oconee is a Piedmont forest with predominantly pine vegetation on the uplands and wide hardwood bottomlands. Features of notable significance on the Oconee NF include Murder Creek Research Natural Area (RNA), Scull Shoals Historic Area, Scull Shoals Archeological Area, and a threatened and endangered species—the red-cockaded woodpecker. Two major river basins flow through the Oconee National Forest, the Ocmulgee and the Oconee. These two basins include reservoirs managed for hydroelectric power production, recreation and water supply. Much of the private lands surrounding the lakes have experienced increasing development for residential and recreational uses. The two basins flow together south of the Forest to form the Altamaha River which flows to the Atlantic Ocean between Savannah and Brunswick, GA. Before Native Americans arrived, fire occurred mainly in the spring and summer thunderstorm season, ignited by lightning. Most fires were probably limited in extent, as normally humid and still nighttime conditions in the summer tend to extinguish fires in light fuels. Some fires, however, were undoubtedly far ranging because they were associated with dry weather fronts (Stanturf et. al., 2002). Multi-year drought cycles affected the probability of ignition and the general fire behavior much the way it does currently. Prior to the advent of active fire suppression and human-created

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

fuel breaks, during drought cycles it would be expected that fire size was much larger and included those areas on the higher end of fire return intervals (35-200 years). Steep slopes in the mountains also add an additional parameter that influences fire spread (USDA-Forest Service, 2004b).

Prescribe fire has played an important role during the historic period. By the early 1800s, the Piedmont of Georgia was largely claimed, and settlers moved into the mountains for land. The better land along the major streams was settled first. The settlement of Mulky Creek in the mountains of northern Georgia was where the first hay crop was harvested beneath the open timber of a south slope. Broom sedge grew shoulder high on the drier sites, and wild legumes were abundant. The role of fire must have played a role in maintaining open mountain ecosystems, even before grazing of livestock became a supporting factor. Frequent burning by settlers stimulated the production of forage for livestock and retarded the advance of woody undergrowth. As cotton farming increased in the Piedmont, the use of woods fires increased to control the vole weevil. This burning was generally an annual event, even though these fires did little to halt the spread of the weevil" (Van Lear and Waldrop, 1989).

The lands that make up Georgia's beautiful National Forests were once the lands nobody wanted. The early history of Georgia is a tale of abuse and overuse of the fragile ecosystems. Hydraulic mining for gold, cut and leave practices of early timber companies, wildfires, over-grazing and unregulated hunting and fishing led to a forest that needed extensive restoration efforts.

The Forest Service purchased 31,000 acres in four North Georgia counties (Fannin, Gilmer, Lumpkin and Union counties) in 1911 for $7 per acre. In the beginning, the Chattahoochee was part of the Nantahala and Cherokee National Forests in North Carolina and Tennessee. Many of the early purchases were old homesteads and abandoned farm lands.

The Chattahoochee National Forest (NF) takes its name from the Chattahoochee River whose headwaters begin in the North Georgia mountains. The River and the area were given the name by the English settlers who took the name from the Indians living here. In one dialect of the Muscogee, (indian language) Chatta means stone; ho chee, marked or flowered. These marked or flowered stones were in the Chattahoochee River at a settlement near Columbus, Georgia (USDA-Forest Service, 2004a).

The Cherokee and Creek Indians inhabited North Georgia. When the pioneer colonists arrived, the Indians learned new farming skills and lived in harmony with the pioneers. Then, gold was discovered. Indians were driven off their land in the tragic "Trail of Tears" relocation to reservations in Oklahoma. Land was given away in land lotteries. Gold was mined and almost every stream in north Georgia suffered tremendous damage from hydraulic mining. But nothing lasts forever, the gold ran out and the timber companies moved in on steel rails.

In the 1880's, railroads began penetrating the North Georgia Mountains making timber easier to access. Large landowners built these railroads. These companies bought much of this mountain land for as little as $1.00 per acre. Their goal was to cut the timber, sell the land, and move on to another location. They logged the land for lumber and for bark of chestnut, chestnut oak and hemlock trees. Tanic acid was extracted from the bark, which was used in tanning leather. This was big industry in those days as almost every household item was leather or involved leather in its use (USDA-Forest Service, 2019a).

On July 9, 1936, the Chattahoochee National Forest was proclaimed as a separate National Forest. At that time, Forest Service managers began to restore these lands by planting trees, fighting wildfires, controlling erosion and introducing wildlife and fish back into their natural habitat. As a result of a concentrated effort by the Forest Service and the Department of Natural Resources personnel, the deer and trout populations which had been virtually eliminated, were brought back to today's healthy and productive level. Today's estimate of the deer population is more than 30,000 animals and a turkey population of over 6,000 birds.

Likewise, in 1970, the bear population on the Chattahoochee totaled 106 bears. After 20years of continually managing the habitat for this animal, the Chattahoochee today boasts a healthy bear population of more than 650 animals (USDA-Forest Service, 2019b).

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), carbon stocks in the Chattahoochee-Oconee NF increased from 45.03±4.57 teragrams of carbon (Tg C) in 1990 to 62.00±8.19 Tg C in 2013, a 37.68 percent increase in carbon stocks over this period (Fig. 1). For context, 62.00 Tg C is equivalent to the emissions from approximately 49.5 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 Chattahoochee-Oconee NF have been increased from 1990 to 2013 (Fig. 1).

About 34.8 percent of forest carbon stocks in the Chattahoochee-Oconee 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 46.4 percent of the forest carbon stocks. Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke *et al.*, 2017).

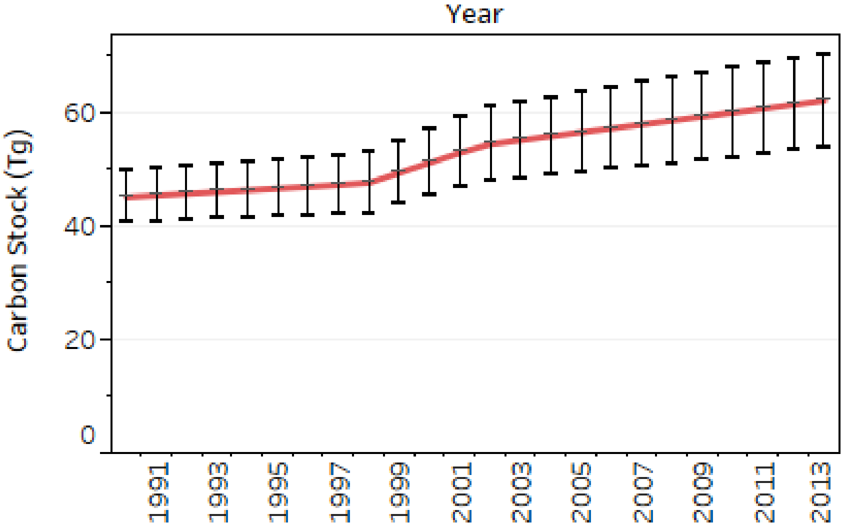

Figure 1. *Total forest carbon stocks (Tg) from 1990 to 2013 for Chattahoochee-Oconee National Forest, bounded by 95 percent confidence intervals. Estimated using the Carbon Calculation Tool (CCT) model.*

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source in a given year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink: the forest is absorbing more carbon from the atmosphere (through growth) than it emits (via decomposition, removal, and combustion). A positive value indicates a source: the forest is emitting more carbon than it takes up.

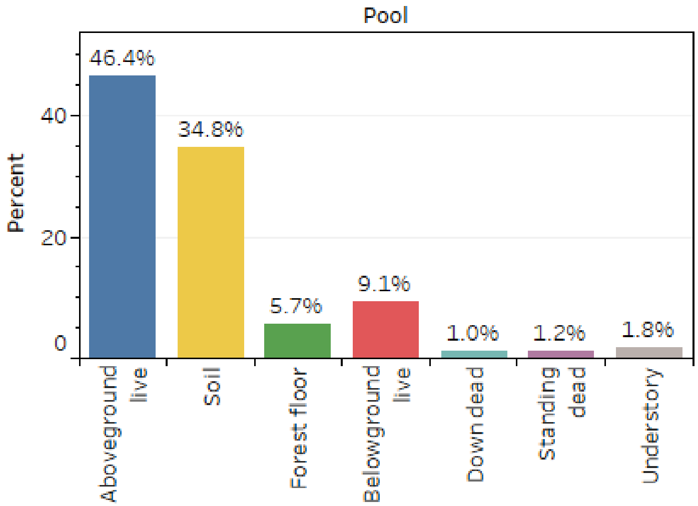

Figure 2. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for Chattahoochee-Oconee National Forests. Estimated using the CCT model.*

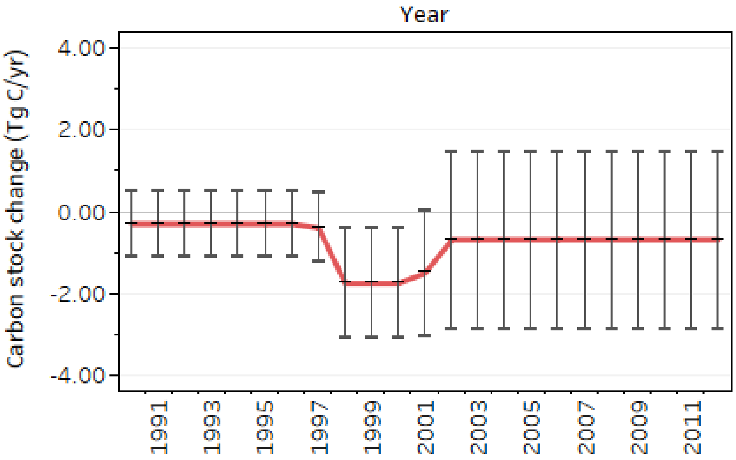

Figure 3. *Carbon stock change in teragrams per year (Tg/yr) from 1990 to 2012 for Chattahoochee-Oconee National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Annual carbon stock changes in the Chattahoochee-Oconee NF were -0.31 ± 0.82 Tg C per year (gain) in 1990 and -0.69 ± 2.17 Tg C per year in 2012 (gain) (Fig. 3). The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Fig. 3). However, the trend of increasing carbon stocks from 1990 to 2013 (Fig. 1) over the 23-year period suggests that the Chattahoochee-Oconee NFs are a modest carbon sink.

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 Chattahoochee-Oconee NF has increased from 321,546 ha in 1990 to 355,509 ha in 2013, a net change of 33,963 ha.[2] When forestland area increases, total ecosystem carbon stocks typically 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).

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[2] 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.

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. In the Chattahoochee-Oconee NFs, carbon density increased from about 140 Megagrams of carbon (Mg C) per ha in 1990 to 174.39 Mg C per ha in 2013 (Fig. 4). This increase in carbon density suggests that total carbon stocks may have indeed increased.

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Similar to Chattahoochee-Oconee NF, most national forests in the Southern Region have experienced increasing carbon densities from 1990 to 2013. Carbon density in the Chattahoochee-Oconee NF has been similar to but slightly higher than the average for all national forest units in the Southern Region (Fig.4). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. These differences may also be affected by disturbance and management regimes (see Section 3.0).

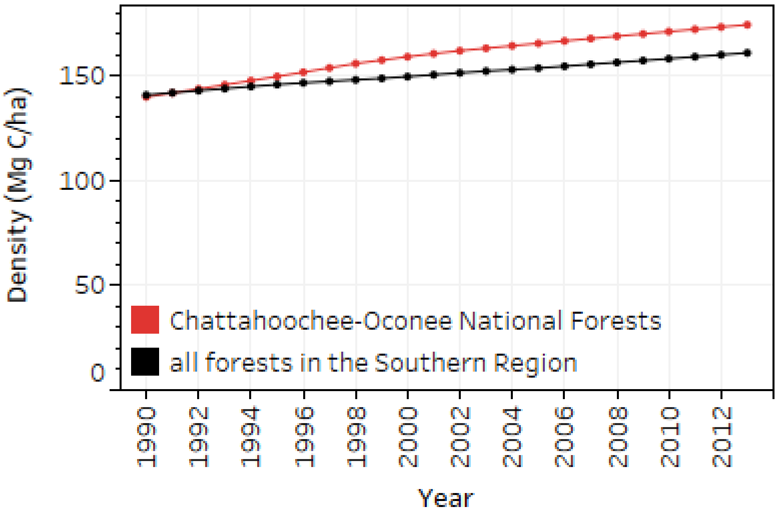

***Figure 4**. Carbon stock density (in megagrams per hectare) in the Chattahoochee-Oconee National Forests and the average carbon stock density for all forests in the **Southern Region** from 1990 to 2013. Estimated using CCT.*

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[3] and shown by the error bars (Figs. 1, 3). These confidence intervals indicate that 19 times out of 20, the carbon stock or stock change for any given year will fall within error bounds. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infer if or how carbon stocks are changing.

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

The inventory design changed from a periodic inventory, in which all plots were sampled in a single year

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

to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (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 transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, it can be stored in wood products for a variable duration depending on the commodity produced. Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect (Gustavsson *et al.,* 2006; Lippke *et al.,* 2011). Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the affected area regrows.

Carbon accounting for harvested wood products (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.

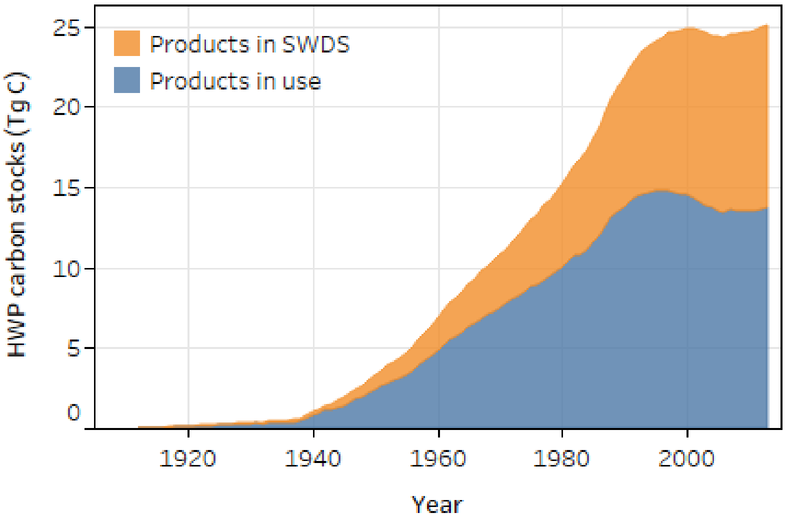

***Figure 5**. Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the* **Southern Region** . *Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting 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. 5). Timber harvesting and subsequent carbon storage later increased rapidly from the 1980s through the 1990s. Storage in products and landfills reached roughly 12 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 1 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).

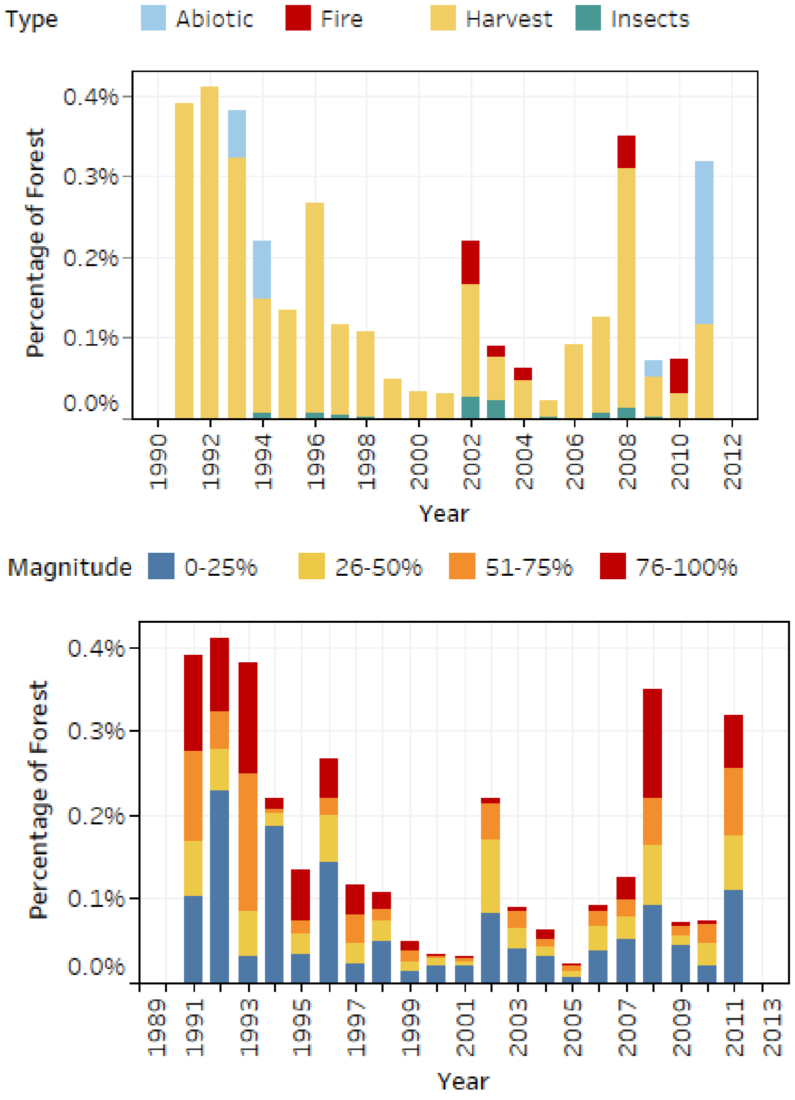

Figure 6. *Percentage of forest disturbed from 1990 to 2011 in Chattahoochee-Oconee National Forest by (a) disturbance type including fire, harvests, insects, and abiotic (wind), and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery.*

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 Chattahoochee-Oconee NF from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 6a). 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 0.3 percent of the total forested area of the Chattahoochee-Oconee NF in any single year from 1990 to 2011, and in total less than 2.96 percent (approximately 9,717 ha) of the average forested area during this period (328,057 ha). The percentage of the forest harvested annually has also decreased slightly over this 21-year period. Although harvests varied in proportion of trees removed, they generally removed less than 25 percent of canopy cover (magnitude) (Fig. 6b). Fire and insects have been detected on the landscape, but were relatively minor influences over this period.

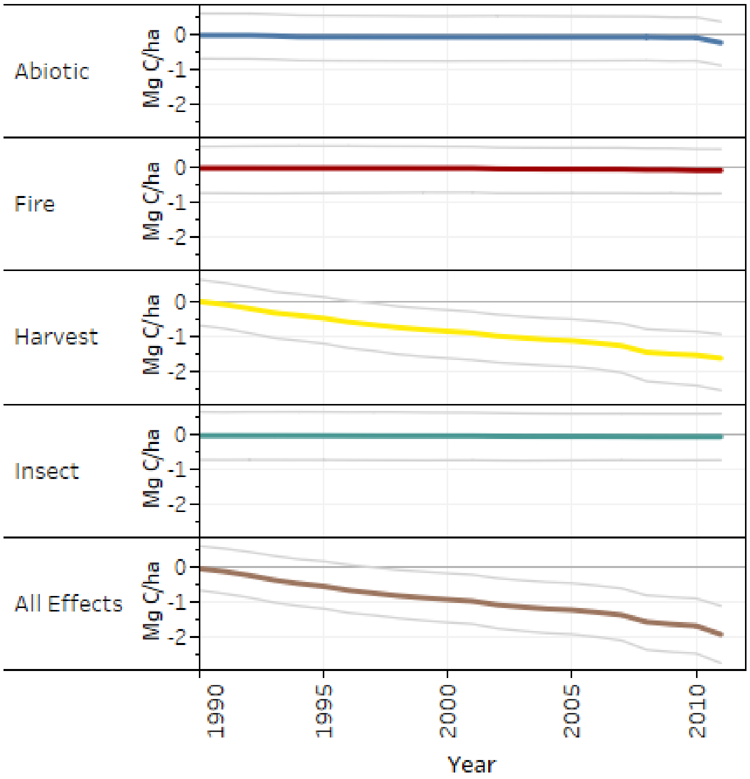

Figure 7. *Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in Chattahoochee-Oconee National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.*

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 6, along with FIA data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond *et al.*, 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each 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 Chattahoochee-Oconee NF was the primary disturbance influencing carbon stocks from 1990 to 2011 (Fig. 7). Harvesting accounted for nearly 85 percent of the total non-soil carbon lost from the forest due to disturbances (USDA Forest Service, 2015). The ForCaMF model indicates that, by 2011, Chattahoochee-Oconee NF contained 1.63 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. 7). As a result, non-soil carbon stocks in the Chattahoochee-Oconee NF would have been approximately 1.24 percent higher in 2011 if harvests had not occurred since 1990 (Fig. 8).

Across all national forests in the **Southern Region** from 1990 to 2011, harvest has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 2.38 percent lower by 2011 (Fig. 8). Considering all national forests in the **Southern Region**, by 2011, timber harvest affected the largest land area (approximately 246,487 ha) and accounted for over two-thirds of carbon stocks losses (average reduction of 2.59 Mg/ha). Fire accounted for the next largest loss, affecting 135,751 ha and accounting for average carbon stock loss of 0.95 Mg/ha. Insects accounted for 0.17 percent of non-soil carbon stock losses and abiotic factors (wind, ice storms) accounted for the loss of 0.13 percent of non-soil carbon stocks.

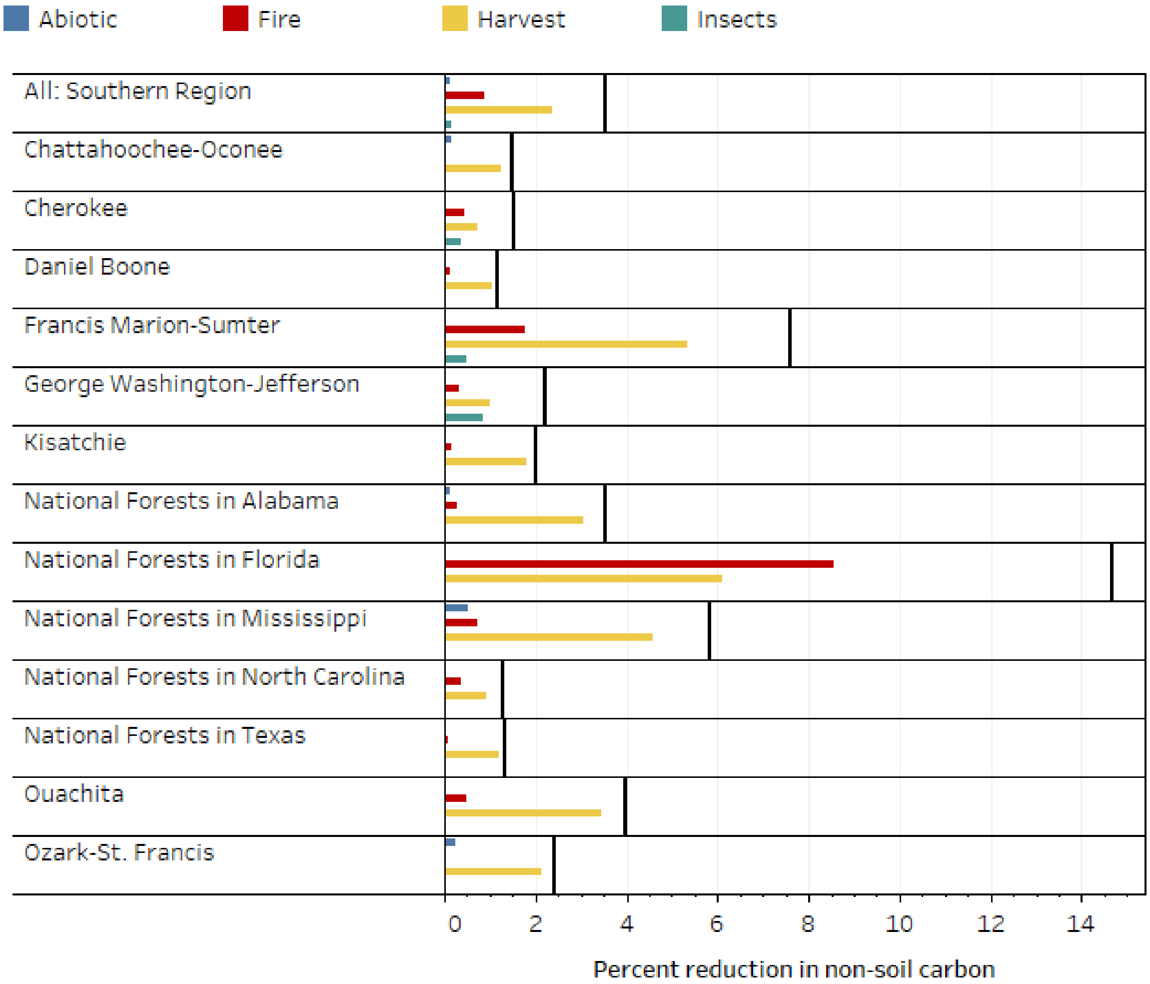

Figure 8. *The degrees to which 2011 carbon storage on each national forest in the* ***Southern Region*** *was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The black line indicates the effect of all disturbances types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT.*

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). Therefore, the IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC, 2000).

ForCaMF helps to identify the biggest local influences on continued carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. The purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors.

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. 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 Chattahoochee-Oconee NF derived from 2011 forest inventory data indicates elevated stand establishment around 1910–1940 (Fig. 9a). This period of elevated stand regeneration came after decades of intensive logging and large wildfires in the late 1800s and early 1900s (Foster, 2006). There was a second pulse in the period of roughly 1970-1990 which likely reflects regrowth following a large increase in timber removals across national forests in the Southern Region. 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. 9b), derived in part from FIA data.

InTEC model results show that Chattahoochee-Oconee NFs was accumulating carbon steadily at the start of the analysis in the 1950s through the mid-1970s (Fig. 10) (indicated by the orange line, positive slope). This trend was a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (20-50 years old) (Fig. 9b). 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 Chattahoochee-Oconee NF (Fig. 10), the effects of non-disturbance factors have become more important in influencing carbon trends on the forest.

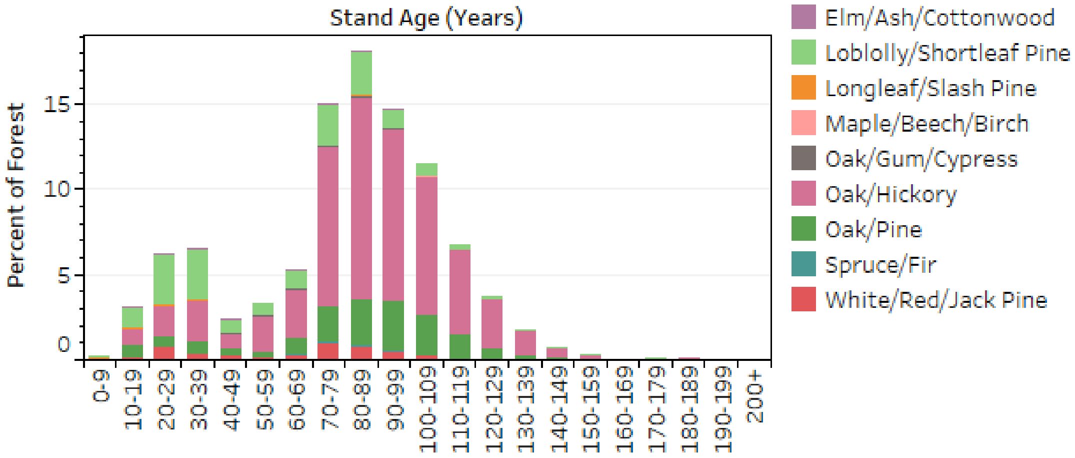

Figure 9. *(a) Stand age distribution in 2011 by forest type group in Chattahoochee-Oconee National Forests. Derived from forest inventory data.*

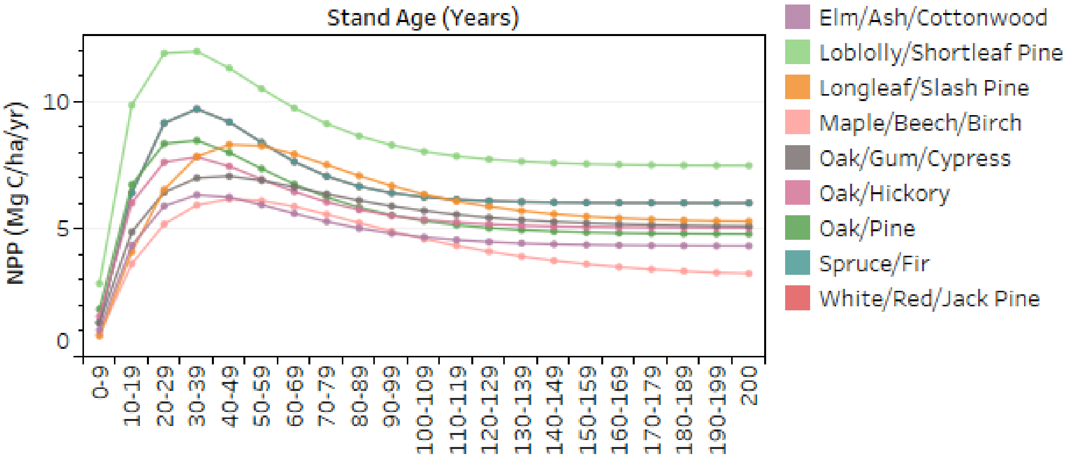

Figure 9. *(b) net primary productivity-stand age curves by forest type group in Chattahoochee-Oconee National Forests. Derived from forest inventory data and He et al. 2012.*

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, climate since 1950 has had a small positive effect on carbon stocks in the Chattahoochee-Oconee (Fig. 10). 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 (Xu *et al.*, 2013).

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 Chattahoochee-

Oconee NF, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 10). 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 Chattahoochee-Oconee NF (Fig. 10). 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 simulated 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.

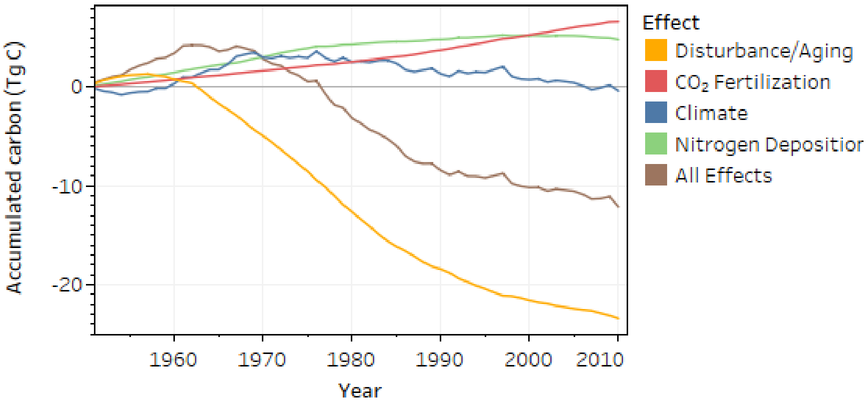

Figure 10. *Accumulated carbon in Chattahoochee-Oconee National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in black line) for1950–2011, excluding carbon accumulated pre-1950 Estimated using the InTEC model.*

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. For example, omission, commission, and attribution errors may exist in the remotely-sensed disturbance maps used in the ForCaMF and InTEC models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond *et al.*, 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (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. 10, “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 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 Chattahoochee-Oconee NF are nearly equivalent between middle-aged (less than 80 years) (43.65%) and older (greater than 80 years) (56.35%) (Fig. 9a). If the Forest continues on this aging trajectory, more stands will reach a slower growth stage in coming years and decades (Fig. 9b), potentially causing the rate carbon accumulation to decline and the Forest may eventually transition to a steady state in the future. Although yield curves indicate that biomass carbon stocks may be approaching maximum levels (Fig. 9b), ecosystem carbon stocks can continue to increase for many decades as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert *et al.*, 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities or disturbances could affect future stand age and forest growth rates (Davis *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. will continue to expand at current rates until 2022, when it will begin 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.

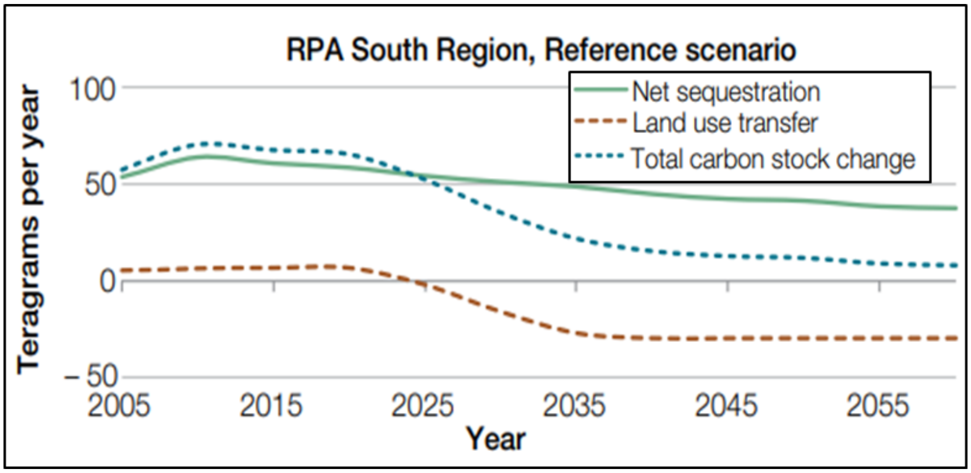

Figure 11. *Projections of forest carbon stock changes in the South Region (equivalent to the boundaries of* ***Southern Region****, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

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 (net sequestration) (Fig. 11). 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 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 Chattahoochee-Oconee NFs in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2060.

4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major driver of historic and current forest carbon sequestration that is occurring at the Chattahoochee-Oconee 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—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 Chattahoochee-Oconee NFs (Treasure et. al., 2014; USDA, 2016) 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 can help mitigate these impacts. For instance, 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 Chattahoochee-Oconee NF (Fig. 10). Heat stress may limit the growth of some southern pines and hardwood species. Stresses from drought and wide-scale pest outbreaks have the potential to cause large areas of forest dieback (Allen *et al*, 2010). Intensified extreme weather events, such as hurricanes, ice storms, and fire, are also expected to lead to changes in plant community composition. Species more resistant to these disturbances, such as shortleaf pine, will be more resilient to a changing climate (Hansen *et al.*, 2001). Populations of other plants, including the threatened large-flowered skullcap, may be particularly vulnerable because invasive species like the Japanese honeysuckle out-compete the native plant (McMorrow, 1996).

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. 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), which can significantly reduce carbon uptake (Kurz et al., 2008; D'Amato et al., 2011).

Changes in climate are expected to drive many other changes in forests through the next century, including changes in forest establishment and composition (Wear and Greis, 2012; Vose and Klepzig, 2013). Some southern 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). 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 lower elevations or more southerly locations and at the end of this century. The potential for future declines of northern species increase the risk of carbon losses in forest communities dominated by these species, particularly under scenarios of greater warming (Wear and Greis, 2012; Vose and Klepzig, 2013). 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 (Iverson et al., 2017).

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 10), 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 CO2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond to novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. As climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions.

5.0 Summary

Forests in the Chattahoochee-Oconee NF are maintaining a carbon sink. Forest carbon stocks increased by about 37.68 percent between 1990 and 2013, 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, resulting in a loss of about 1.24 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 product sector.

The biggest influence on current carbon dynamics on the Chattahoochee-Oconee NF 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 Chattahoochee-Oconee NF 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 Chattahoochee-Oconee NF. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in the 2000s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

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

Forested area on the Chattahoochee-Oconee NF will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. 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 Chattahoochee-Oconee NF will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

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