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

Theresa Davidson (theresa.davidson@usda.gov
Patricia Coffman (patricia.coffman@usda.gov)
Paul Whitworth (paul.whitworth@usda.gov)
Kimberly Frier (kimberly.frier@usda.gov)
Jason Loos (jason.loos@usda.gov)
Casey Hawes (casey.hawes@usda.gov)
Alexa Dugan (alexa.dugan@usda.gov)
Duncan McKinley (duncan.mckinley@usda.gov)

May 16, 2022

Contents

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 (that is plant stems, branches, foliage, and roots). 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. 2011a). 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 (Hayes et al. 2018, US EPA 2015).

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 (such as fires and insects), carbon is transferred from living carbon pools to dead pools. Carbon is also released via 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 (such as paper and lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinnings, harvests, 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). Disturbance, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems (Caspersen et al. 2000, Pan et al. 2009). Environmental factors such as atmospheric carbon dioxide 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).

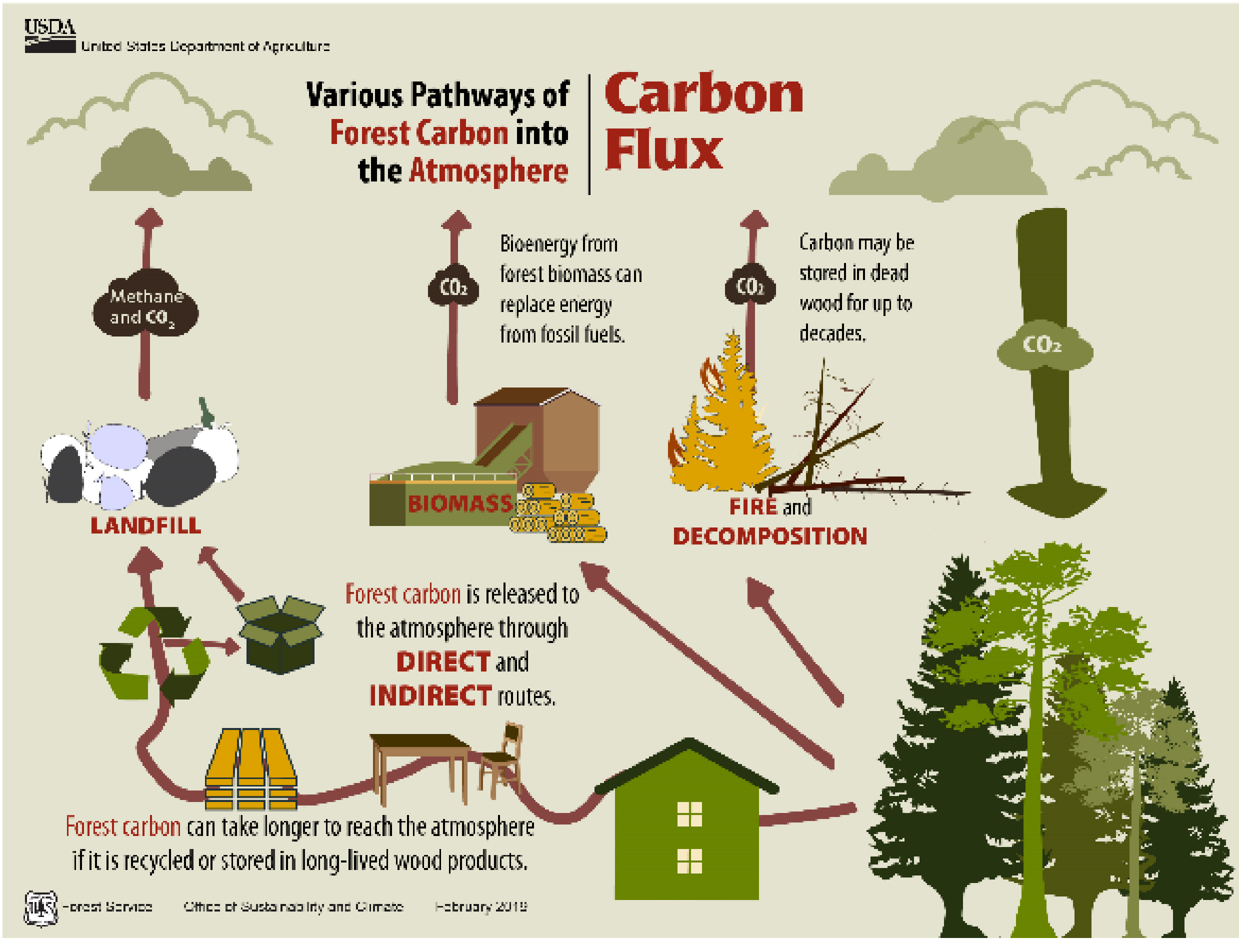


Figure 1. Carbon Flux Diagram - *Forests remove carbon dioxide (CO_2) from the atmosphere and store it in trees, vegetation, and forest soils. Carbon can be stored as forest products (such lumber). Dead and decaying trees release carbon as does forest fires.*

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 carbon dioxide emissions.[1] The forestry sector contribution to greenhouse gas emissions has declined over the last decade (FAOSTAT 2013, IPCC 2014, Smith et al. 2014).

Globally, the largest source of greenhouse gas emissions in the forestry sector is deforestation (Houghton et al. 2012, IPCC 2014, Pan et al. 2011a;). Deforestation is 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).

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).

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

This trend is expected to continue for at least another decade (USDA Forest Service 2016, Wear et al. 2013).

Photo 1. *This photo exemplifies the Mark Twain National Forest's Collaborative Forest Landscape Restoration Project (CFLRP) that is restoring over 100,000 acres of shortleaf pine-oak woodlands in the Eleven Point and Poplar Bluff Ranger Districts with mature trees in a wide range of sizes.*

In this section, we provide an assessment of the amount of carbon stored on the Mark Twain National Forest. The assessment estimates how disturbances, management, and environmental factors have influenced carbon storage over time. This assessment is primarily based on two recent U.S. Forest Service reports that are commonly referred to as the “Baseline Report” (USDA Forest Service 2015) and “Disturbance Report” (Birdsey et al. In press). These 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 Forest Inventory and Analysis 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, Healey et al. 2016, Raymond et al. 2015). 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).

Additional reports, including the most recent Resource Planning Act (RPA) assessment (USDA Forest Service 2016) and regional climate vulnerability assessments (Brandt et al. 2014, Dupigny-Giroux et al. 2018, Janowiak et al. 2018) 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 National Forest System carbon trends.

See box 1 for descriptions of the carbon models used for these analyses.

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.

Box 2. Carbon Units. The following table provides a crosswalk among various metric measurement units used in the assessment of carbon stocks and emissions.

Multiple	Name	Symbol		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

1.1 Background

The Mark Twain National Forest, located in the Ozark Mountains of Missouri, covers approximately 601,282 hectares of forestland. The Mark Twain National Forest administers approximately 1,485,800 acres in southern Missouri. This constitutes approximately 10 percent of the forested land and 84 percent of the publicly owned forested land in Missouri (Spencer et al 1992).

The Mark Twain National Forest is composed of nine separate geographic units in 29 counties which span the state, 200 miles east to west and 175 miles north to south. Private land parcels are scattered throughout the Mark Twain National Forest boundary. On average, Federal ownership within the boundary of the Mark Twain National Forest is about 49 percent, and ranges from a low of 24 percent in the Cedar Creek unit to a high of 71 percent in the Eleven Point unit (USDA Forest Service 2005).

The Mark Twain National Forest lies mostly within the Ozark Highlands, a region long distinguished for its extraordinary geological, hydrological, and ecological diversity. Signature features include crystal-clear springs, over 5,000 caves, rocky barren glades, ancient volcanic mountains, and nationally recognized streams. The Ozarks have been continuously available for plant and animal life since the late Paleozoic period, constituting perhaps the oldest continuously exposed landmass in North America (Yatskievych 1999).

Photo 2. *Rockpile Mountain Wilderness Area in the Fredericktown unit. Areas of federally designated wilderness allow natural processes to occur over time without human manipulation. Carbon cycles occur in wilderness areas just as they do in general forest areas.*

Natural disturbance regimes changed with European settlement and the associated human activities such as widespread deforestation and overgrazing. Human activities disrupted natural disturbance systems and processes for decades prior to modern forest management. Existing natural vegetative communities differ substantially from the natural communities that were historically present in the area (Nelson 2005). Many forest areas now contain more trees, a more closed canopy, and less ground vegetation than that which existed pre-settlement (Nelson 2005).

By around 1930, much of the land within the national forest area had been stripped of timber, burned, and overused as pasture or tilled until productivity was impaired (Halpern 2012). Erosion was a serious problem and many lands had been abandoned. Following acquisition of these lands by the Forest Service in the mid-1930s, workers in the Civilian Conservation Corps performed erosion control, tree planting and reforestation, and timber stand improvement; developed water impoundments; and fought fire (Halpern 2012).

The Forest Service has completed nearly a century of conservation and forest management efforts seeking to repair this previously damaged land and restore properly functioning forests and ecosystems within the Mark Twain National Forest.

In the Ozarks, eastern oak hardwood and southern pine woodlands converge with the drier western tallgrass prairie, creating a distinctive array of open grassy woodlands and savannas. This rich mixture of unique, diverse, and ecologically complex natural communities provides a high level of habitat diversity. The high level of habitat diversity, influx of biota from divergent regions through thousands of years of climatic events, effects of past glaciation to the north, and extreme antiquity of the landscape have combined to support relict populations and allow for development of at least 160 endemic species (USDA Forest Service 2005).

The Mark Twain National Forest occurs in five of the seven major river basins in the Missouri portion of the Ozark Highlands. Eleven primary streams and rivers course through these basins, portions of which occur within the Mark Twain National Forest. Because of the region's karst topography, the Ozarks are home to the world's largest collection of first magnitude springs (those with over 65 million gallons of water flow daily) (USDA Forest Service 2005).

Photo 3. *Eleven Point National Scenic River. The Mark Twain National Forest manages forest lands to provide multiple use benefits, including a variety of ecosystems services, such as clean water, fish and wildlife habitat, forest products, and recreation settings and opportunities.*

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

Carbon stocks on the Mark Twain National Forest are displayed in figure 2 for the period from 1990 through 2013. Carbon stocks are expressed as teragrams of carbon or Tg C. Carbon stocks in the Mark Twain National Forest increased from 66.6 ± 2.4 teragrams of carbon in 1990 to 79.0 ± 3.7 teragrams of carbon in 2013 (USDA Forest Service 2015). This represents an 18.6 percent increase in carbon stocks (fig. 2). For context, 79.0 teragrams of carbon is equivalent to the emissions from approximately 63 million passenger vehicles in a year.

Despite some uncertainty in annual carbon stock estimates, reflected by the 95 percent confidence intervals shown in the figure as the black upper and lower bounding limits, there is a high degree of certainty that carbon stocks on the Mark Twain National Forest have increased from 1990 to 2013 (fig. 2).

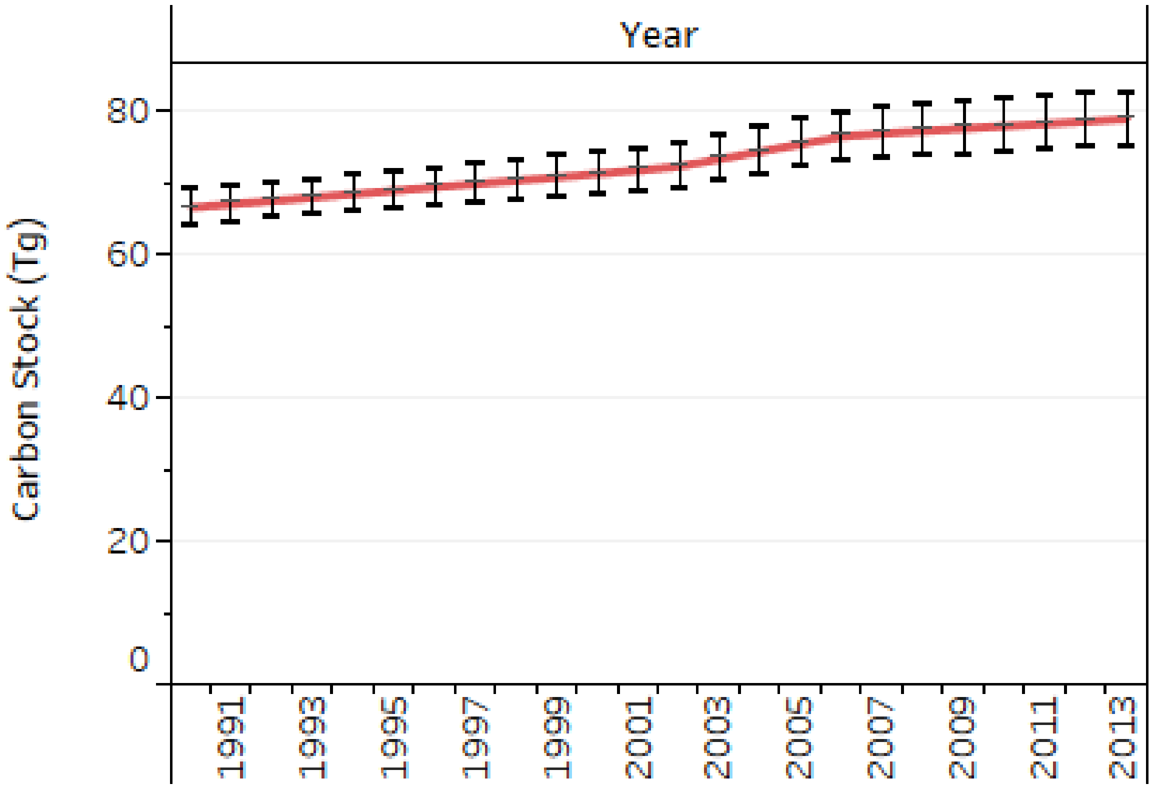


Figure 2. *Total forest carbon stocks (Tg) from 1990 to 2013 for Mark Twain National Forest, bounded by 95 percent confidence intervals. Estimated using the CCT model.*

Figure 3 displays carbon stocks in each forest carbon pool on the Mark Twain National Forest. Carbon stored in the soil and in the forest floor is the second largest carbon pool, storing approximately 45.5 percent of the forest carbon stocks. This component includes carbon contained in organic material to a depth of one meter, excluding roots. About 41 percent of forest carbon stocks are stored in the aboveground portion of live trees and vegetation. This component includes all live woody vegetation at least one inch in diameter. Recent methods for measuring soil carbon have found the amount of carbon stored in soils generally exceeds the Carbon Calculation Tool model derived estimates by roughly 12 percent across forests in the United States (Domke et al. 2017).

Vegetative and leaf debris and organic matter account for approximately 9 percent of carbon stocks. Below ground live components make up about 8 percent of carbon stocks. Down dead and standing dead wood and the understory collectively account for the remaining 6 percent of carbon stock.

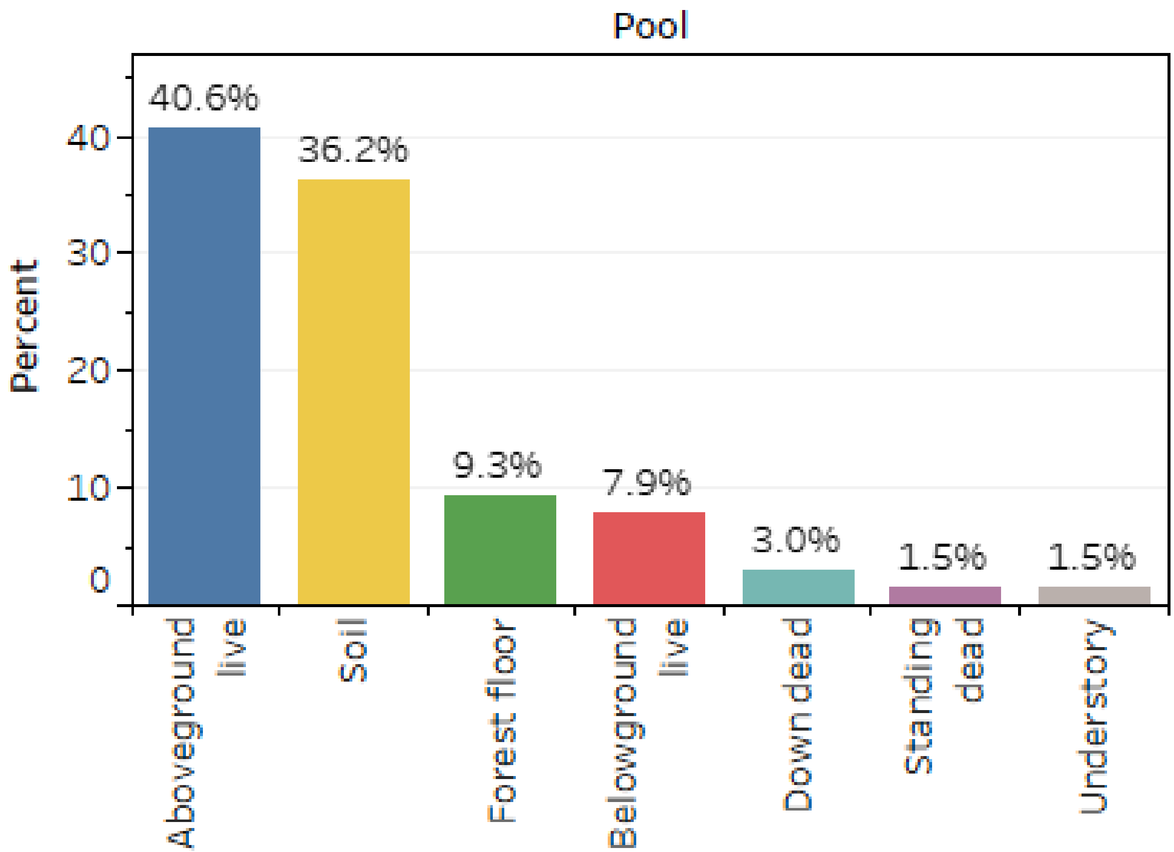


Figure 3. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for Mark Twain National Forest. Estimated using the CCT model.*

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source each year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink which means 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 which means the forest is emitting more carbon than it takes up.

Carbon stock change for the Mark Twain National Forest is displayed in figure 4. Annual carbon stock changes in the Mark Twain National Forest were -0.5 ± 0.3 teragrams of carbon per year (gain) in 1990 and -0.3 ± 0.8 teragrams of carbon per year in 2012 (gain).

The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (that is uncertainty bounds overlap zero) (fig. 4). However, the trend of increasing carbon stocks from 1990 to 2013 (fig. 2) over the 23-year period suggests that the Mark Twain National Forest is a modest carbon sink.

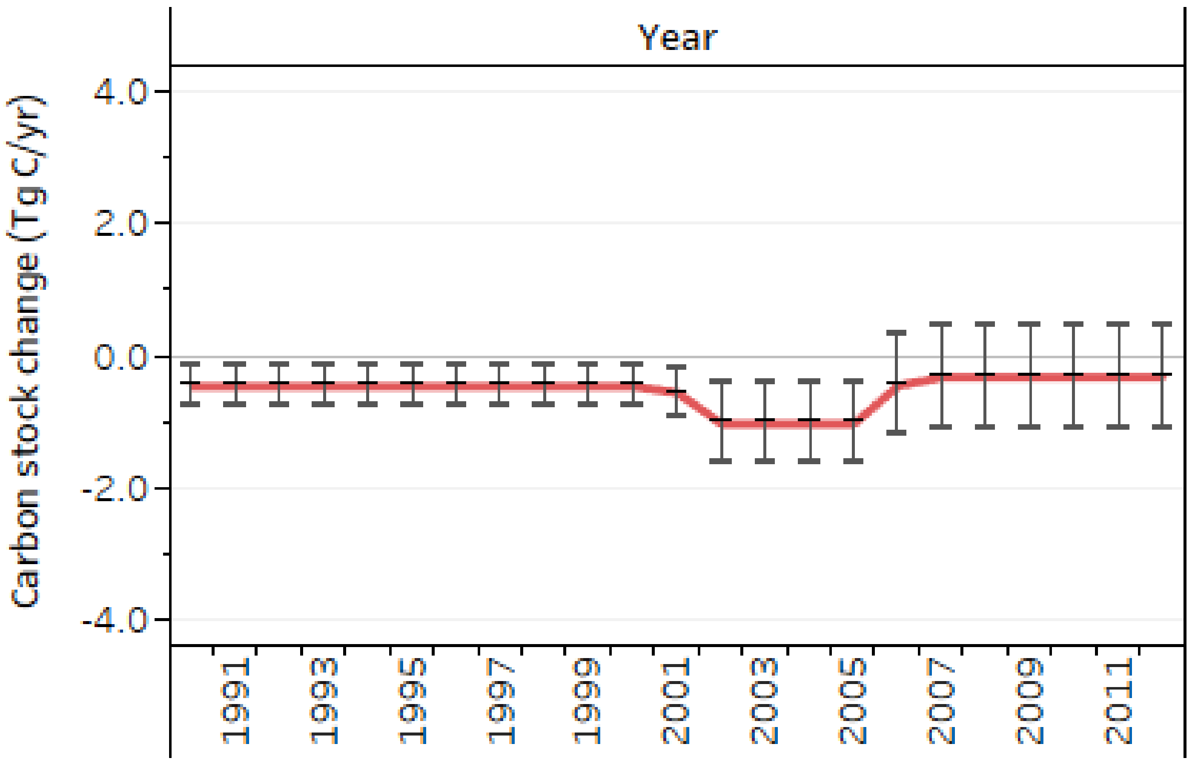


Figure 4. *Carbon stock change (Tg/yr) from 1990 to 2012 for Mark Twain National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Changes in the total forested area may affect whether forest carbon stocks are increasing or decreasing. The Carbon Calculation Tool estimates from the Baseline Report are based on Forest Inventory and Analysis data, which may indicate changes in the total forested area from one year to the next. According to the Forest Inventory and Analysis data used to develop these baseline estimates, the forested area in the Mark Twain National Forest has increased from 582,448 hectares in 1990 to 608,501 hectares in 2013, a net change of 26,053 hectares[2]. When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon sink.

The Carbon Calculation Tool used inventory data from two different databases. This may have led to inaccurate estimates of changes in total forested area. According to Woodall et. Al (2011), such an approach can potentially alter the conclusion regarding whether forest carbon stocks are increasing or decreasing, and therefore, whether the national forest is a carbon source or sink.

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. Carbon density is often expressed as Megagrams of carbon (Mg C) at the forest-scale. Carbon density increased from about 114 Megagrams of carbon per hectare in 1990 to 130 Megagrams of carbon per hectare in 2013 across the Mark Twain National Forest as shown in figure 5. During this period, carbon density increased by 15.4 Megagrams of

[2] Forested area used in the Carbon Calculation Tool may differ from more recent Forest Inventory and Analysis estimates, as well as from the forested areas used in the other modeling tools.

carbon per hectare or approximately 13 percent. This increase in carbon density suggests that total carbon stocks may have indeed increased.

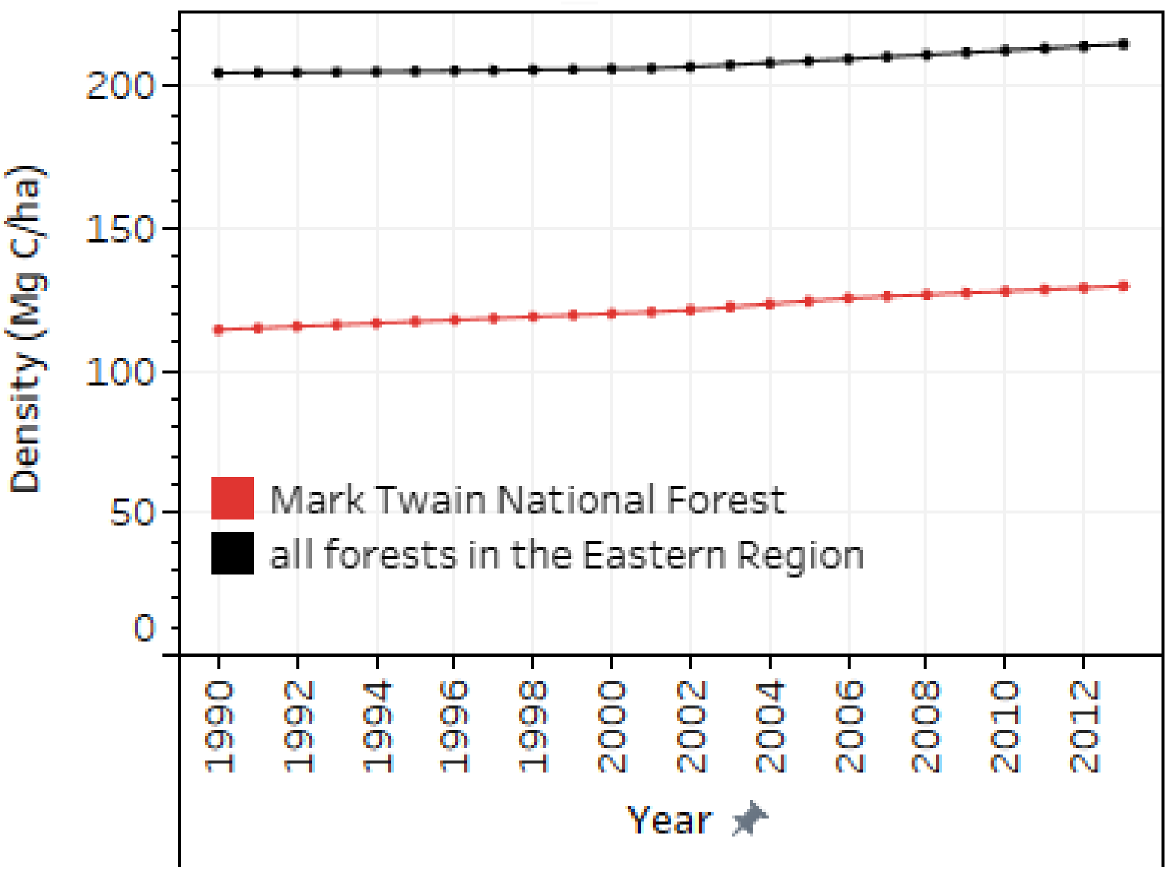


Figure 5*. Carbon stock density (Mg/ha) in the Mark Twain National Forest and the average carbon stock density for all forests in the Eastern Region from 1990 to 2013. Estimated using CCT.*

Carbon density is useful for comparing trends among units or ownerships with different forest areas. Most national forests in the Eastern Region have experienced increasing carbon densities from 1990 to 2013. Changes in carbon density in the Mark Twain National Forest has been like that across all national forest units in the Eastern Region as shown in figure 5. 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[3] and shown by the error bars (figs. 2 and 4). 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. These uncertainties sometimes make it difficult to infer if or how carbon stocks are changing.

Baseline estimates that rely on Forest Inventory and Analysis data include uncertainty. Uncertainty is associated with sampling error (for example area estimates are based on a network of plots, not a census). Uncertainty is associated with measurement error (like species identification and data entry errors). Uncertainty is associated with and model error (associated with volume, biomass, and carbon equations, and interpolation between sampling designs). As mentioned in section 2.1, one such model error has resulted from a change in Forest Inventory and Analysis 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.

The Mark Twain National Forest has experienced minimal changes in land use or adjustments to the boundaries of the national forest in recent years. Change in forested area incorporated in the Carbon Calculation Tool is more likely a data artifact 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, 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. Data gaps identified in the periodic surveys 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. The change in definition may also have contributed to apparent changes in forested area.

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. 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 Forest Inventory and Analysis and the Carbon Calculation Tool estimates only gradually as affected plots are re-visited and the differences in carbon stocks are interpolated between survey years (Woodall et al. 2013). Re-growth and other

---

[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 (for example data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

disturbances may mute the responsiveness of the Carbon Calculation Tool to disturbance effects on carbon stocks.

Although the Carbon Calculation Tool 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 in national forests. The carbon accounting data documented cut-and-sold reports within a production accounting system (Loeffler et al. 2014, Smith et al. 2006). 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 (like landfills and dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

In national forests in the Eastern Region, harvest levels remained low until after the start of World War II in the late 1930s. Around the 1940s, harvest levels began to increase, which caused an increase in carbon storage in harvested wood products as shown in figure 6. Timber harvesting and subsequent carbon storage later increased rapidly from the 1980s through the 1990s.

Products in solid waste disposal sites increased rapidly over time from around 1940 through 2000. Storage in products and landfills reached roughly 12 teragrams of carbon in 2001. A significant decline in harvesting began in the early 2000s (to 1950s levels). Correspondingly, carbon accumulation in the product sector has gradually slowed over time. Carbon storage in products in use has declined slightly since 2002.

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

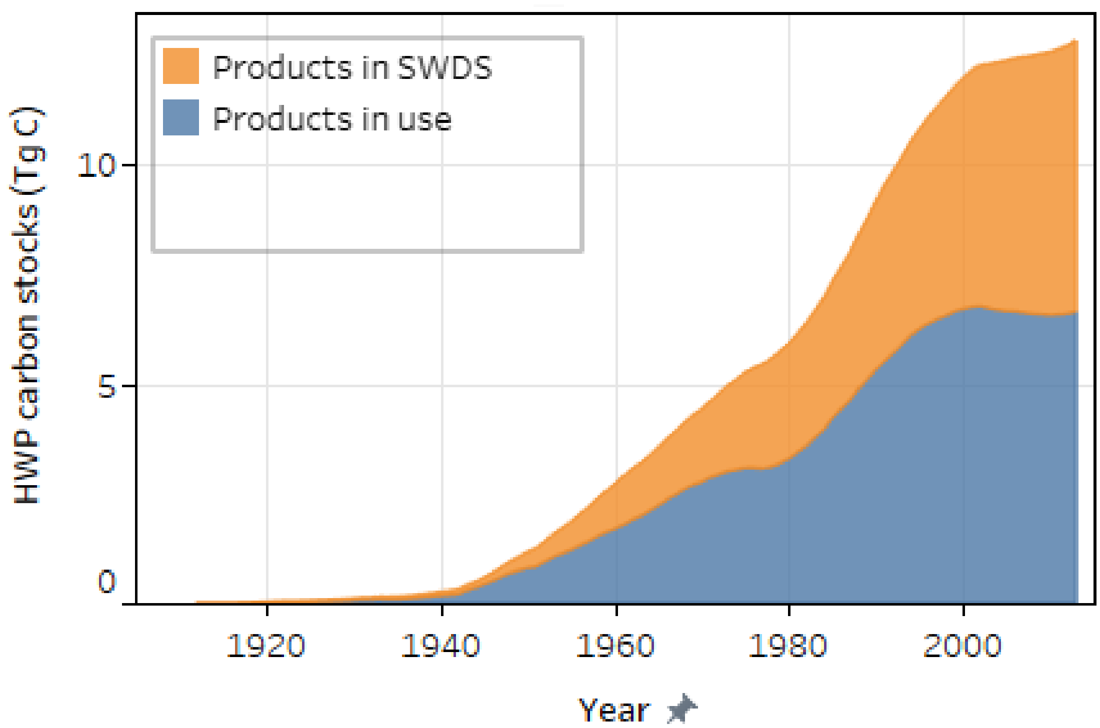


Figure 6. *Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the Eastern Region . Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

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 harvested wood products 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 (like paper products and saw logs); product decay rates; and the lack of distinction between methane and carbon dioxide emissions from landfills. The analysis of carbon storage in harvested wood products 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 (for example wind and ice storms).

Disturbance maps indicate that timber harvest has been the dominant disturbance type detected on the Mark Twain National Forest from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (fig. 7a). 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 Mark Twain National Forest in any single year from 1990 to 2011, and in total less than 3.3 percent (approximately 37,167 hectares) of the average forested area during this period (596,746 hectares). The percentage of the forest harvested annually has been relatively steady 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. 7b).

Disturbances from fire and insects were very small in the Mark Twain National Forest. While insect disturbance has likely occurred, it has had minimal impact and was not detected with satellite imagery.

Beginning around 2000, abiotic disturbance from wind and ice events has been an increasing source of disturbance. Note that in 2009, a derecho wind event occurred that disturbed nearly 2 percent of the Mark Twain National Forest (fig. 7). A Derecho is a widespread, long lived, straight-line windstorm associated with a group of thunderstorms that cause tornadoes and tornadic-force winds, heavy rains, and floods. In most years, abiotic disturbances affected less than two percent of the total forested area of the Mark Twain National Forest in any single year from 1990 to 2011, and in total less than 2.3 percent (approximately 13,956 hectares) of the average forested area during this period (596,746 hectares).

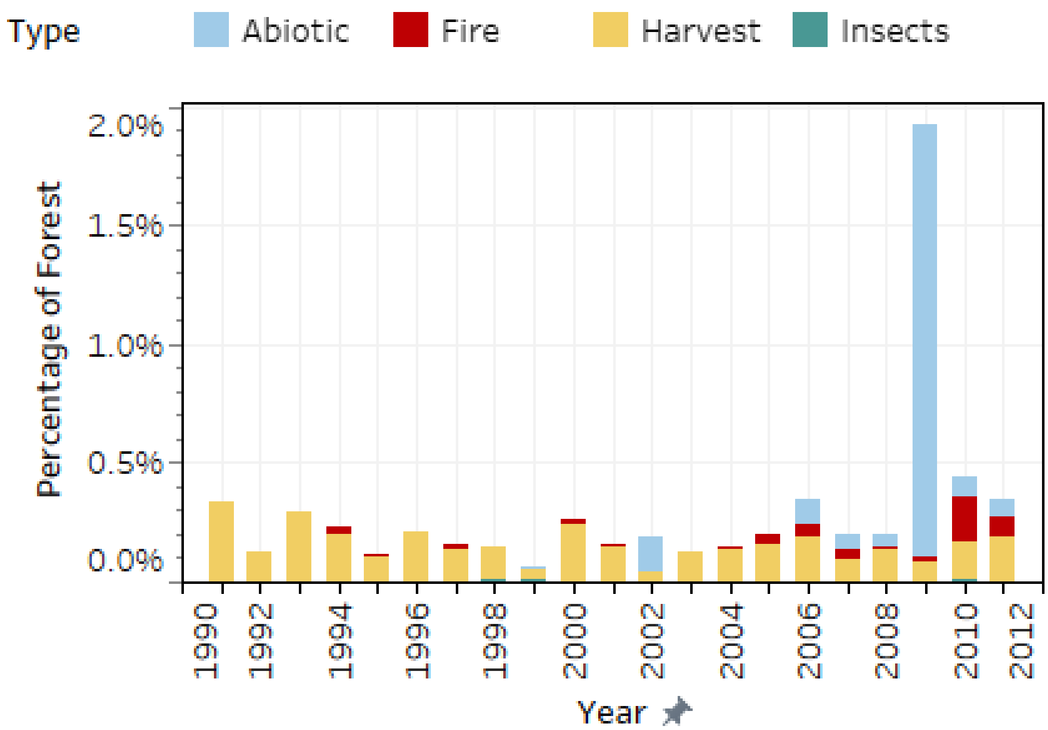
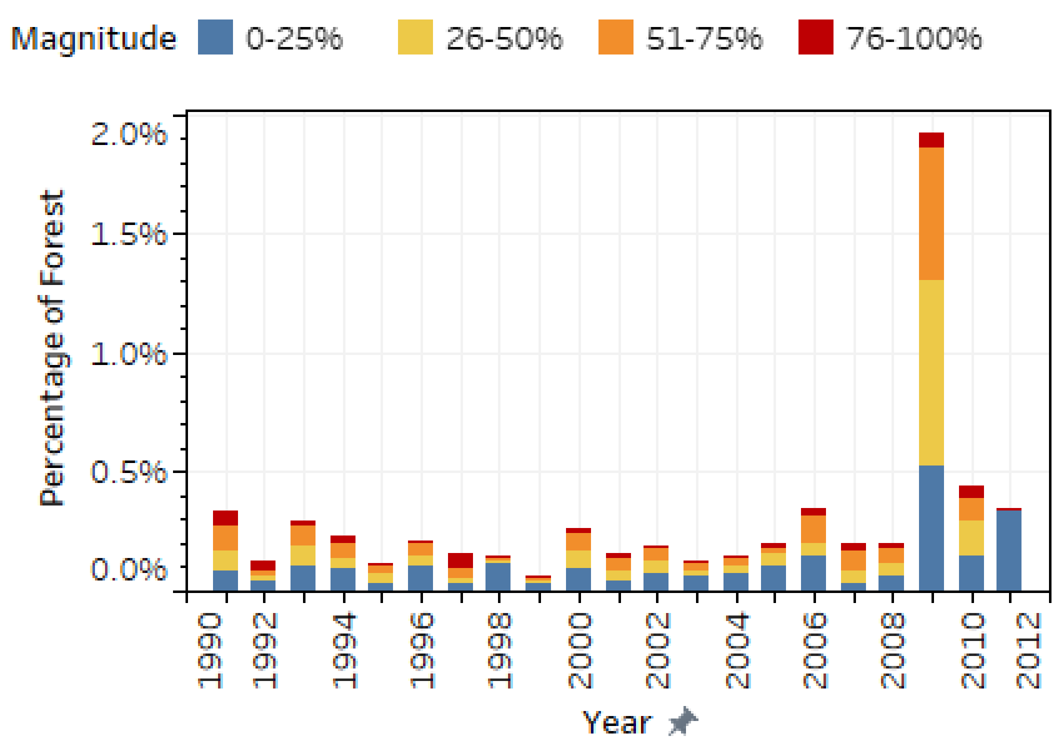


Figure 7. *Percentage of forest disturbed from 1990 to 2011 in Mark Twain National Forest by (a) disturbance type including fire, harvests, insects, and abiotic (wind), and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery.*



The Forest Carbon Management Framework model incorporates Landsat disturbance maps summarized in figure 7, along with Forest Inventory and Analysis data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The Forest Vegetation Simulator 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 Forest Carbon Management Framework 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 to 2011 had not occurred. The Forest Carbon Management Framework model simulates the effects of disturbance and management only on non-soil carbon stocks (like vegetation, dead wood, and forest floor). Like the Carbon Calculation Tool, the Forest Carbon Management Framework model results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey et al. 2014).

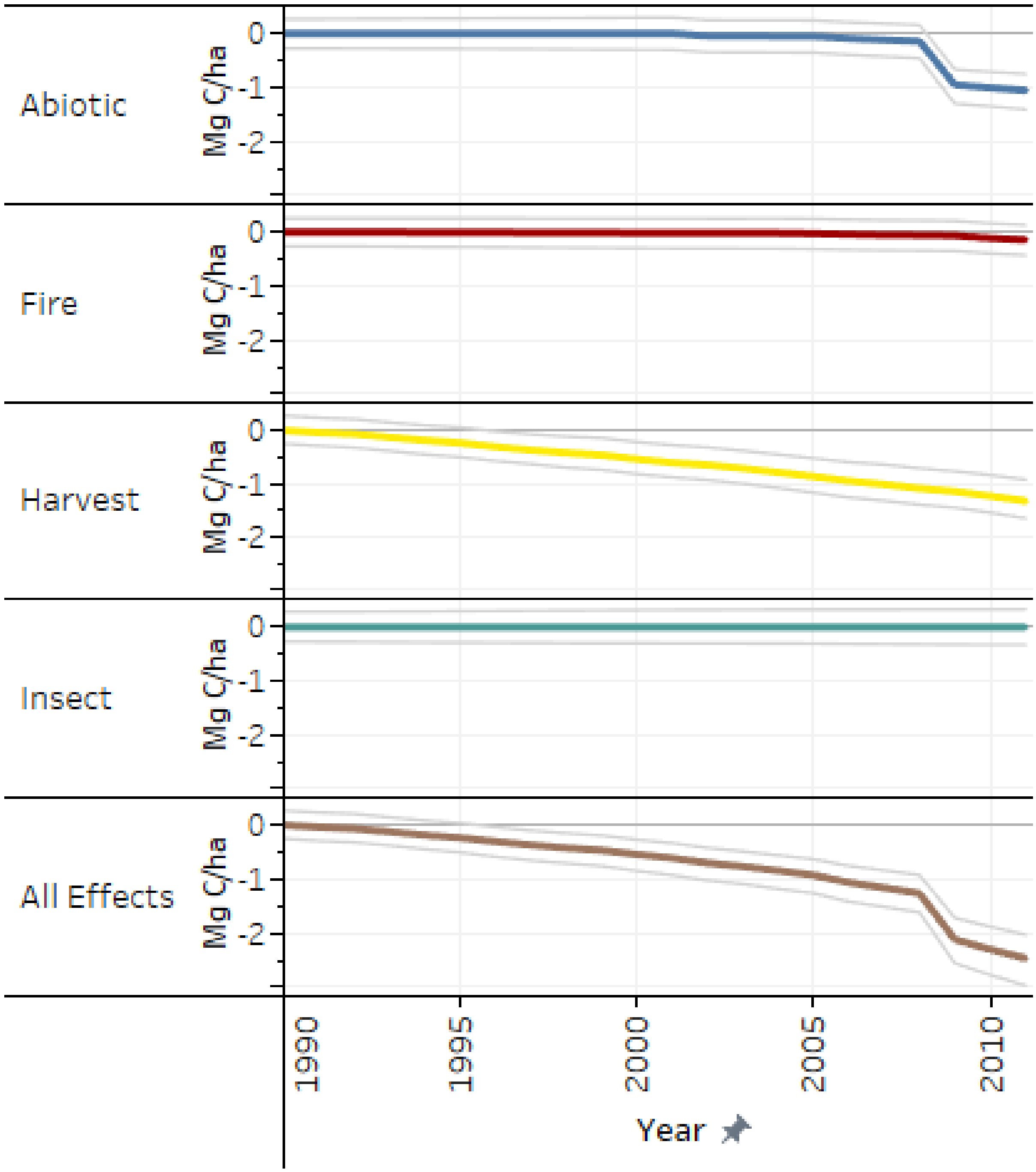


Figure 8. *Lost potential storage of carbon (Mg/ha) because of disturbance for the period 1990 to 2011 in Mark Twain National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95 percent confidence intervals. Estimated using the Forest Carbon Management Framework model.*

Timber harvesting on the Mark Twain National Forest was the primary disturbance influencing carbon stocks from 1990 to 2011. The Forest Carbon Management Framework model indicates that, by 2011, Mark Twain National Forest contained 1.3 Megagrams of carbon per hectare less non-soil carbon (that is vegetation and associated pools) due to harvests since 1990, as compared to a hypothetical undisturbed scenario (fig. 8). As a result, non-soil carbon stocks in the Mark Twain National Forest would have been approximately 1.5 percent higher in 2011 if harvests had not occurred since 1990 (fig. 9). Similarly, carbon stocks would have likely been 1 Megagram of carbon per hectare higher if the 2009 derecho had not occurred.

Figure 9 displays the percent reduction in non-soil carbon stocks in 2011 due to disturbances that occurred from 1990 to 2011 for national forests in the Eastern Region. Across all national forests in the Eastern Region, harvest has been the most significant disturbance affecting carbon storage. The reductions for harvest generally range from about 0.5 to 2.7 percent across the various forests.

The Mark Twain National Forest exhibits about 1.5 percent reduction from harvest and an additional 0.5 percent from fire. These values are about mid-range as compared to the other forests in the region. Note that the reductions on the Mark Twain National Forest due to the derecho are very apparent at about 1.3 percent for abiotic reduction and is far greater than the abiotic reductions of other national forests in the Eastern Region.

Across national forests in the Eastern Region, by 2011, abiotic factors (like wind and ice storms) accounted for the loss of 0.2 percent of non-soil carbon stocks, fire was 0.17 percent, and insects were 0.01 percent.

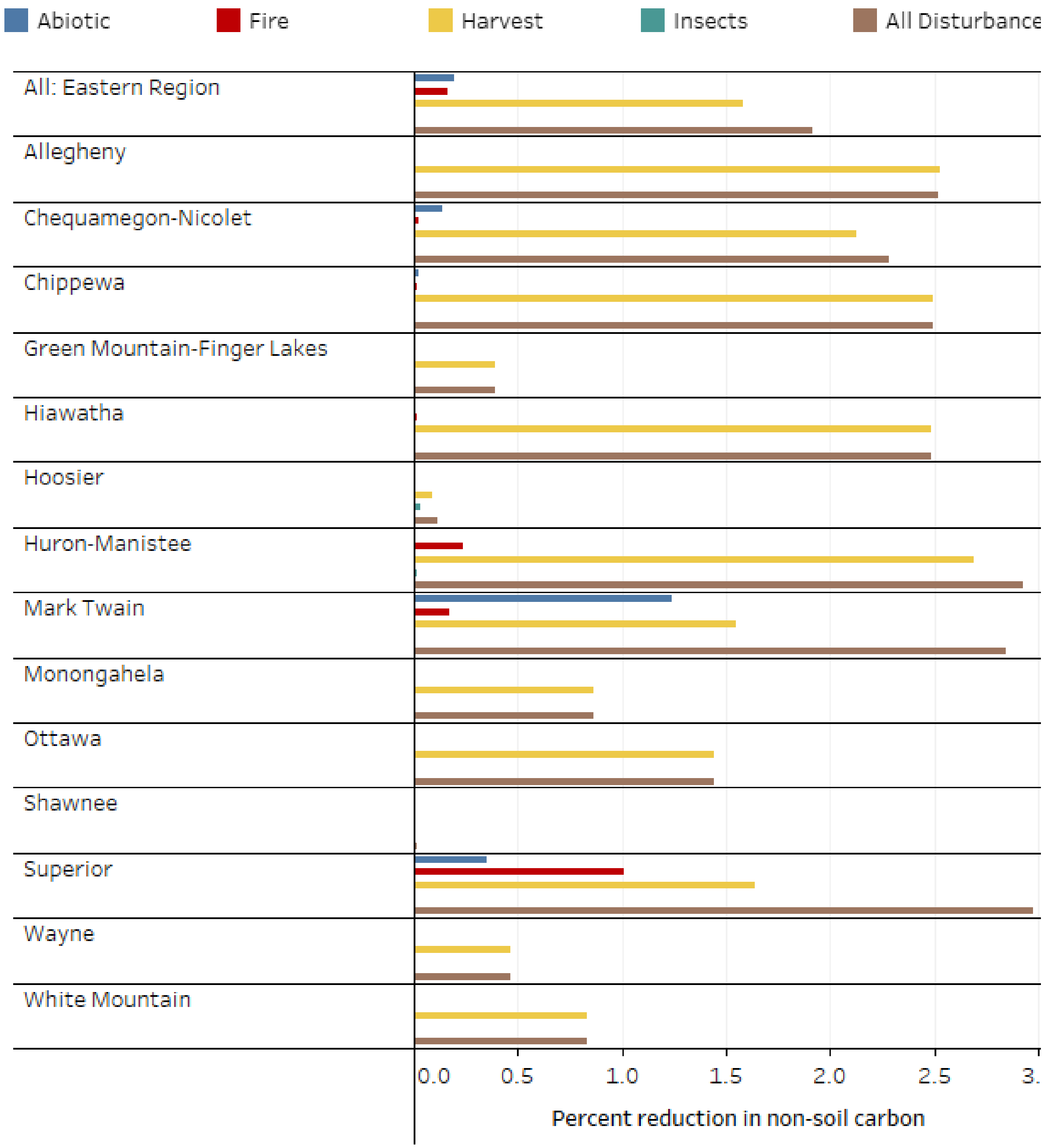


Figure 9. *The degrees to which 2011 carbon storage on each national forest in the Eastern Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The brown line indicates the effect of all disturbance types combined. Estimated using disturbance effects from Forest Carbon Management Framework and non-soil carbon stock estimates from the Carbon Calculation Tool.*

The Forest Carbon Management Framework model 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. Several decades may be needed to recover the carbon removed. The time needed to recover carbon depends on the type of the harvest (for example clear-cut versus partial cut), and the conditions prior the harvest (like forest type and amount of carbon) (Raymond et al. 2015).

The Forest Carbon Management Framework model 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 greenhouse gases to the atmosphere than if the forest was not managed. These lower net contributions of greenhouse gases are apparent when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Dugan et al. 2018, Lippke et al. 2011, McKinley et al. 2011, Skog et al. 2014). Consistently, the Intergovernmental Panel on Climate Change recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC 2000).

The Forest Carbon Management Framework model 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 Integrated Terrestrial Ecosystem Carbon model was to reconcile recent disturbance impacts with these other factors.

3.2 Effects of Forest Aging

The Integrated Terrestrial Ecosystem Carbon 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. 7), 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. 2011b). 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.

Figure 10a displays the stand age class and species for the Mark Twain National Forest as estimated in 2011. Figure 10b displays the net primary productivity-stand age and species for the Mark Twain National Forest as estimated in 2011.

Stand-age distribution data indicates elevated stand establishment on the Mark Twain National Forest during the period of approximately 1911 through 1941 (fig. 10a). 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.

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 (He et al. 2012, Pregitzer & Euskirchen 2004), as indicated by the net primary productivity-age curves shown in figure 10b. Productivity stabilizes and declines as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees.

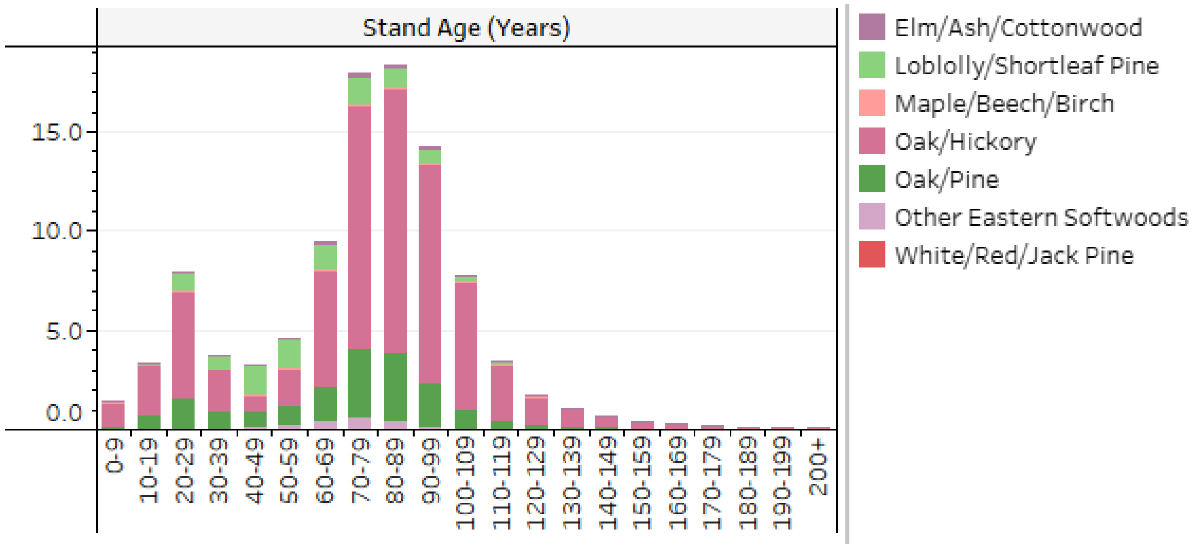


Figure 10. *(a) Stand age distribution in 2011 by forest type group in Mark Twain National Forest. Derived from forest inventory data.*

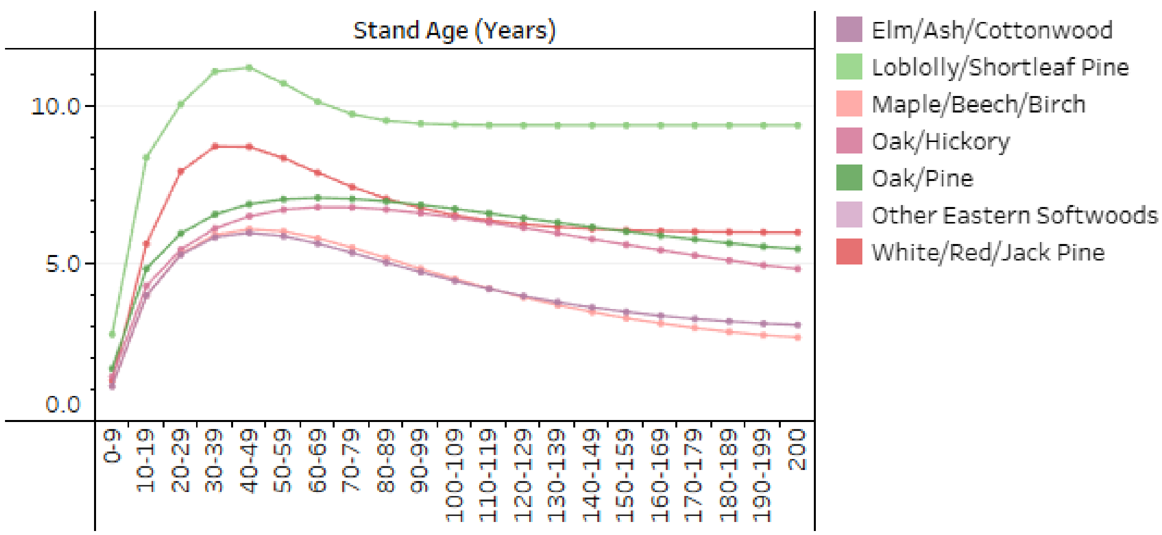


Figure 10. *(b) Net primary productivity-stand age curves by forest type group in Mark Twain National Forest. Derived from forest inventory data and He et al. 2012.*

The Integrated Terrestrial Ecosystem Carbon model results show that Mark Twain National Forest was accumulating carbon steadily at the start of the analysis in the 1950s through 2011 (fig. 11) (positive slope of the orange line). This accumulation of carbon was a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (20-60 years old) (fig. 10b). The rate of carbon accumulation has decreased through time as forests reach their peak in productivity.

Across forest types, the net primary productivity on the Mark Twain National Forest increases rapidly across age classes from age 0 until about 20 years of age. The rates of net primary productivity then exhibit an increasing, but slightly lesser rate of increase to generally about 40 years of age. Some species generally level off for a few years and then decline as the species stand continues to age.

Note that the general net primary productivity curves are generally similar in shape across species on the Mark Twain National Forest. Although a smaller portion of the overall acreage, shortleaf pine exhibits the highest level of net primary productivity as a forest type. Oak-hickory is the most prominent forest type in the Mark Twain National Forest, and exhibits mid-level net primary productivity.

3.3 Effects of Climate and Environment

The Integrated Terrestrial Ecosystem Carbon model isolates the effects of climate (temperature and precipitation), atmospheric carbon dioxide 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 positive effect on carbon stocks in the Mark Twain National Forest (fig. 11).

Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju et al. 2007, Melillo et al. 2017). 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 carbon dioxide 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 carbon dioxide and nitrogen emissions (Chen et al. 2000, Keeling et al. 2009, Zhang et al. 2012). According to the Integrated Terrestrial Ecosystem Carbon model, higher carbon dioxide has consistently had a positive effect on carbon stocks in Mark Twain National Forest, tracking an increase in atmospheric carbon dioxide concentrations worldwide (fig. 11).

However, a precise quantification of the magnitude of this carbon dioxide 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 carbon dioxide 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 carbon dioxide on forest growth and biomass accumulation, thus warranting additional study (Körner et al. 2005, Norby et al. 2010, Zhu et al.

2016).

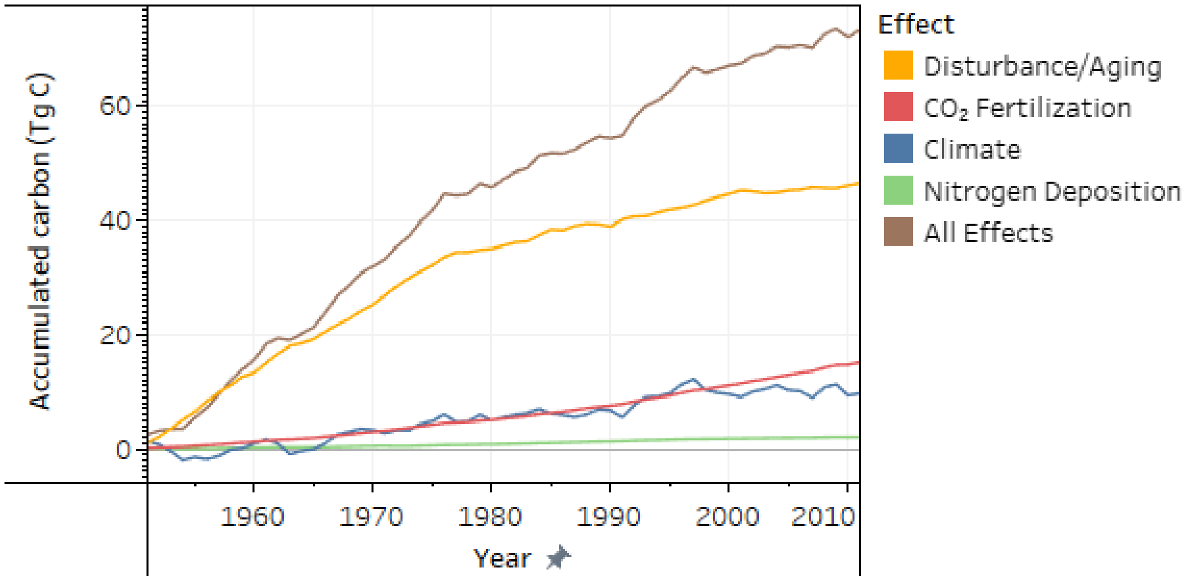


Figure 11. *Accumulated carbon in Mark Twain National Forest due to disturbance or aging, climate, nitrogen deposition, carbon dioxide fertilization, and all factors combined (shown in brown line) for1950 to 2011, excluding carbon accumulated pre-1950 Estimated using the Integrated Terrestrial Ecosystem Carbon model.*

Modeled estimates suggest that overall nitrogen deposition had a slightly positive effect on carbon accumulation in the Mark Twain National Forest (fig. 11). Like carbon dioxide, the actual magnitude of this effect remains uncertain.

Overall, the Integrated Terrestrial Ecosystem Carbon model suggests that climate, carbon dioxide fertilization, and historical disturbance, aging, and regrowth have all contributed to the positive effects on carbon accumulation in the Mark Twain National Forest.

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 Forest Carbon Management Framework and the Integrated Terrestrial Ecosystem Carbon models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods.

The Forest Carbon Management Framework model results may also incorporate errors from the inventory data and the Forest Vegetation Simulator-derived carbon accumulation functions (Raymond et al. 2015). To quantify uncertainties, the Forest Carbon Management Framework 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 the Integrated Terrestrial Ecosystem Carbon model, 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). The Integrated Terrestrial Ecosystem Carbon model is highly calibrated to Forest Inventory and Analysis data and remotely sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the Integrated Terrestrial Ecosystem Carbon model estimates.

National-scale sensitivity analyses of the Integrated Terrestrial Ecosystem Carbon model 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 (displayed fig. 11 “all effects”). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (like national forest scale) are likely to be considerably higher.

Results from the Forest Carbon Management Framework and the Integrated Terrestrial Ecosystem Carbon models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Dugan et al. 2017, Zhang et al. 2012). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas Forest Carbon Management Framework and the Integrated Terrestrial Ecosystem Carbon models 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 Mark Twain National Forest are mostly middle-aged to mature (60 to 110 years old) (fig. 10a). If the forest continues this aging trajectory, more stands will reach a slower growth stage in coming years and decades (fig. 10b). A slower growth stage could potentially cause the rate of carbon accumulation to decline and the forest may eventually transition to a steady state in the future.

Yield curves indicate that biomass carbon stocks may be approaching maximum levels (fig. 10b). However, 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. Potential changes in management activities or disturbances could affect future stand age and forest growth rates (Davis et al. 2009, Keyser & Zarnoch 2012).

The Resource Planning Act assessment provides regional projections of forest carbon trends across forestland ownerships in the United States based on a new approach. The new approach uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (USDA Forest Service 2016, Woodall et al. 2015). The Resource Planning Act 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.

For Resource Planning Act's North Region (equivalent to Forest Service's Eastern Region boundary, which includes the Mark Twain National Forest, but includes all land ownerships).

Projections indicate that the rate of carbon sequestration may rapidly decline in the 2020s and 2030s and then stabilize towards the middle of the century. This projected decline in carbon sequestration is mostly due to the loss of forestland (land-use transfer), and to a lesser extent through forest growth, aging, and disturbances (net sequestration) (fig. 12).

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 (Houghton et al. 2012, Pan et al. 2011a). 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 Mark Twain National Forest in the future. Therefore, on National Forest System lands, the projected carbon trends may closely resemble the net sequestration trend in figure 12. This trend 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.

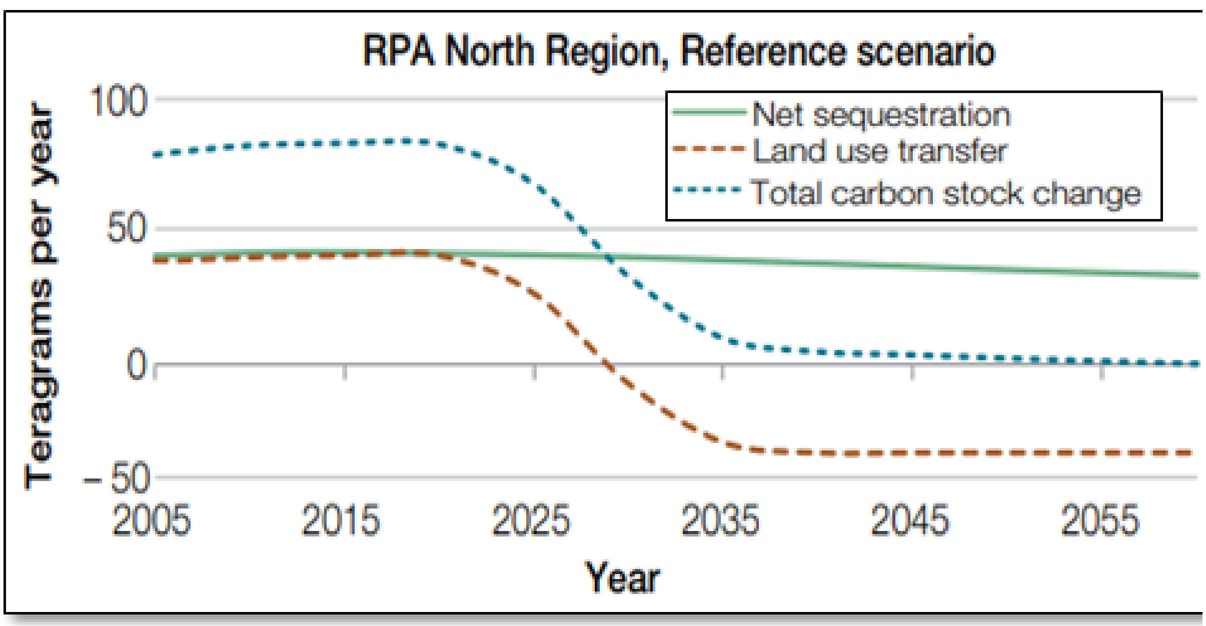


Figure 12. *Projections of forest carbon stock changes in the North Region (equivalent to the boundaries of Eastern Region, but includes all land tenures) for the Resource Planning Act reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

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. This pattern is occurring in the Mark Twain National Forest and elsewhere across the region.

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.

The climate change vulnerability assessment for the Central Hardwoods Region (Brandt et al. 2014), which encompasses the Mark Twain National Forest, indicates that climate change is expected to cause temperatures to continue to rise in all seasons, increasing mean temperatures as well as the frequency of heat waves. Growing season length is expected to increase by several weeks under various climate scenarios, and a longer growing season may enhance forest growth and carbon sequestration, where water supply is adequate, and temperatures do not exceed biological thresholds (Brandt et al. 2014, McMahon et al. 2010). However, 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 Integrated Terrestrial Ecosystem Carbon model indicate that elevated temperatures have generally had a negative effect on carbon uptake in the Mark Twain National Forest (fig. 11).

All global climate models project that temperatures will increase in the Central Hardwoods Region over the next century (IPCC 2013, Kunkel et al. 2013). The downscaled climate projections examined in the vulnerability assessment suggest an increase in temperature over the next century across all seasons by 2 to 7 degrees Fahrenheit in the Missouri Ozarks.

Precipitation is projected to increase in winter and spring by 2 to 5 inches for the two seasons combined by the end of the century. There is a difference in model projections for later in the growing season, but evidence seems to indicate there may be a decrease in precipitation in either summer or fall, depending on scenario. Even if the total annual amount of precipitation does not change substantially, some models suggest it may occur as heavier rain events interspersed among relatively drier periods (Kunkel et al. 2013). More winter precipitation and more intense rain events are projected to lead to increased streamflow and increased risk for severe flooding in Missouri by mid-century (Qiao, Pan, Herrmann, and Hong 2013).

These changes are also related to projected changes in extreme weather, hydrological changes, and changes in growing season length (Brandt et al, 2014). The potential for reduced soil moisture and drought is also predicted to increase, especially later in the growing season as increased temperatures drive evapotranspiration (Berg et al. 2017, Campbell et al. 2009, Zhao & Dai 2017). Although a longer growing season may increase annual biomass accumulation, droughts could offset these potential growth enhancements and increase the potential for other forest stressors. Drought-stressed trees may also be more susceptible to insects and pathogens (Dukes et al. 2009), which can significantly reduce carbon uptake (D'Amato et al. 2011, Kurz et al. 2008).

The assessment (Brandt et al. 2014) examined the vulnerability of different natural community types to climate change, based on the impacts of climate change on dominant species, stressors, and system drivers and the capacity of those systems to adapt to these changes. Of nine community types assessed, mesic upland forests were the most vulnerable due to negative impacts on dominant species and a limited capacity to adapt to disturbances such as fire, flooding, and drought. Dry-mesic forests were considered moderately vulnerable but were expected to be more vulnerable at the western extent of their range where conditions are drier. Fire-adapted communities such as woodlands, savannas, and glades were considered less vulnerable because they have more drought and heat-adapted species and are better able to withstand large-scale disturbances. Bottomland forests had slightly higher vulnerability due to the possibility of shifts in flood dynamics. These determinations of vulnerability are general across the entire Central Hardwoods region, and will be influenced by local conditions, forest management, and land use.

Changes in climate are also expected to drive changes in forests establishment and composition through the next century (Brandt et al. 2014). The vulnerability assessment summarized projected climate-induced impacts over the next century on selected tree species or species groups based on three forest impact models: Tree Atlas (Iverson, Prasad, Matthews, and Peters 2008, Landscape Change Research Group 2014), Linkages v. 2.2 (Wullschleger et al. 2003), and Landis Pro (Wang et al. 2013). All models used the same two downscaled model-scenario combinations as climate inputs. Under both climate change scenarios, all three forest impact models used in the assessment project an increase in habitat suitability and establishment probability for shortleaf pine in the Missouri Ozarks over the next century.

Projections for oak species are more mixed. For example, the Tree Atlas model projects decreases in habitat suitability for scarlet oak under both scenarios, and a decrease in habitat suitability for black oak under the warmer, drier scenario. In areas where scarlet oak is lost, it would possibly be replaced by pine. The other two models project a decrease in red oak group species under the drier, warmer scenario and an increase under the wetter scenario.

Model results for some species are available from the Tree Atlas model only. Suitable habitat for woody understory species such as eastern redbud and dogwood is projected to remain stable under the range of climate scenarios examined. As with oaks, projections for hickory species are also mixed, with suitable habitat for some species projected to remain stable, some increase, and some decline in habitat suitability.

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 or spread into the region (like pine), there is greater uncertainty about how well these species will be able to take advantage of new niches that may become available (Brandt et al. 2014, 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 Integrated Terrestrial Ecosystem Carbon model (fig. 11), project greater increases in forest productivity when the carbon dioxide 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 carbon dioxide on forest productivity is transient and can be limited by the availability of nitrogen and other nutrients (Norby et al. 2010). Productivity increases under elevated carbon dioxide could 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 carbon dioxide 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

The Mark Twain National Forest is maintaining a carbon sink. Forest carbon stocks increased by about 18.6 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 Mark Twain National 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 Mark Twain National Forest, resulting in a loss of about 1.5 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 harvested wood products 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 in the Mark Twain National Forest is the legacy of intensive timber harvesting and land clearing for agriculture during the 19th century (Birdsey et al. 2006, Nelson, 2005). A period of forest recovery and more sustainable forest management began in the early to mid-20th century, which continues to promote a carbon sink today (Birdsey et al. 2006). Stands on the Mark Twain National Forest are mostly middle aged to mature now due to the mid-20th century reforestation and conservation actions.

Many of the middle-aged to mature forest stands on the Mark Twain National Forest may be expected to begin losing carbon. The rate of carbon uptake and sequestration generally decline as forests age. Accordingly, projections from the Resource Planning Act assessment indicate a potential age-related decline in forest carbon stocks in the Eastern Region (all land ownerships) beginning in the 2020s.

Climate and environmental factors, including elevated atmospheric carbon dioxide, have also influenced carbon accumulation on the Mark Twain National Forest. 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 carbon dioxide may have enhanced growth rates in some species and helped to counteract ecosystem carbon losses from disturbances, aging, and climate.

The effects of future climate conditions are complex and remain uncertain. However, under changing climate and environmental conditions, forests in the Mark Twain National Forest may be increasingly vulnerable to a variety of stressors. These potentially negative effects might be balanced somewhat by the positive effects of a longer growing season, greater precipitation, and elevated atmospheric carbon dioxide concentrations (Brandt et al. 2014). However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the Mark Twain National Forest.

Forested area on the Mark Twain National Forest 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 (Shifley & Moser 2016) and this activity can cause substantial carbon losses (FAOSTAT 2013, USDA Forest Service 2016). The Mark Twain National Forest will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

6.0 REFERENCES

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.

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

Birdsey, R., Dugan, A.J., Healey, S., Dante-Wood, K., Zhang, F., Mo, G., Chen, J., Hernandez, A., Raymond, C., McCarter, J. *In press*. 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-xxx.

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.

Brandt, L., He, H., Iverson, L., Thompson, F., III, Butler, P., Handler, S., et al. (2014, February). Central hardwoods ecosystem vulnerability assessment and synthesis: a report from the central hardwoods climate change response framework project. Gen. Tech. Rep. NRS-124. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. Retrieved February 12, 2014, from http://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs124.pdf.

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

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

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

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.

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.

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.

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

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

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

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

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.

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

Halpern, J. A. (2012, Fall) A general history of the Mark Twain National Forest. Available from Mark Twain National Forest at https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3807474.pdf

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.

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.

Iverson, L.R.; Prasad, A.M.; Matthews, S.N.; Peters, M. (2008). Estimating potential habitat for 134 eastern U.S. tree species under six climate scenarios. Forest Ecology and Management. 254(3): 390-406.

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.

Jones, A.G., Scullion, J., Ostle, N., Levy, P.E. & Gwynn-Jones, D. (2014) Completing the FACE of elevated CO_2 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 CO_2. *Journal of Environmental Management*, **85**, 538-562.

Keeling, R., Piper, S., Bollenbacher, A. & Walker, S. (2009) Atmospheric CO_2 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 CO_2. *Science*, **309**, 1360-1362.

Kunkel, K.E.; Stevens L.E.; Stevens, S.E.; Sun, L.; Janssen, E.; Wuebbles, D.; Hilber, S.D.; Timlin, M.S.; Stoecker, L.; Westcott, N.E.; Dobson, J.G. (2013). Regional climate trends and scenarios for the U.S. National Climate Asssessment. Part 3. Climate of the Midwest. U.S. NOAA Technical Report NESDIS 142-3. Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. 103 p.

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.

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

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

Nelson, P. W. (2005). The terrestrial natural communities of Missouri. Jefferson City, MO: Missouri Natural Areas Committee.

Norby, R.J., Warren, J.M., Iversen, C.M., Medlyn, B.E. & McMurtrie, R.E. (2010) CO_2 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences*, **107**, 19368-19373.

Ollinger, S., Goodale, C., Hayhoe, K. & Jenkins, J. (2008) Potential effects of climate change and rising CO_2 on ecosystem processes in northeastern U.S. forests. *Mitigation and Adaptation Strategies for Global Change*, **13**, 467-485.

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

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

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

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.

Qiao, L., Pan, Z., Herrmann, R.B., and Hong, Y., (2013). Hydrological Variability and Uncertainty of Lower Missouri River Basin Under Changing Climate. Journal of the American Water Resources Association (JAWRA) 1-15. DOI: 10.1111/jawr.12126.

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 CO_2 on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 436-441.

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.

Spencer, John S. Jr.; Roussopoulos, Sue M.; Messengale, Robert A. (1992). Missouri''s forest resource, 1989: an analysis. Resource Bulletin NC-139. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station.

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.

U.S. Department of Agriculture, Forest Service (2005). Mark Twain National Forest, Final Environmental Impact Statement. https://www.fs.usda.gov/detail/mtnf/landmanagement/?cid=fsm8_045643.

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

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

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

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

Wang, W.J.; He, H.S.; Spetich, M.A.; Shifley, S.R.; Thompson, F.R., III; Larson, D.R.; Fraser, J.S. (2013). A large-scale forest landscape model incorporating multi-scale processes and utilizing forest inventory data. Ecosphere. 4(9): art106.

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.

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.

Wullschleger, S.D.; Gunderson, C.A.; Tharp, M.L.; Post, W.M.; West, D.C. (2003). Simulated patterns of forest succession and productivity as a consequence of altered precipitation. In: Hanson, P.J.; Wullschleger, S.D., eds. North American temperate deciduous forest responses to changing precipitation regimes. New York: Springer-Verlag: 433-446.

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)

Yatskievych, G. (1999). Steyermark's Flora of Missouri, Volume 1. Revised edition. Missouri Department of Conservation in cooperation with the Missouri Botanical Garden Press, St. Louis, Missouri.

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

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

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

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

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

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD3027, found online at How to File a Program Discrimination Complaint and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.