Assessment of the Influence of Disturbance, Management Activities, and Environmental Factors on Carbon Stocks of U.S. National Forests

General Technical Report
RMRS-GTR-402

Appendix 4: Southern Region, Individual Forests

Office of Sustainability and Climate
National Forest System

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Abstract: This report assesses how carbon stocks at regional scales and in individual national forests are affected by factors such as timber harvesting, natural disturbances, climate variability, increasing atmospheric carbon dioxide concentrations, and nitrogen deposition. Previous baseline assessments of carbon stocks (https://www.fs.fed.us/managing-land/sc/carbon) evaluated observed trends based on forest inventory data but were limited in ability to reveal detailed causes of these trends. The expanded assessments reported here are based on an extensive disturbance and climate history for each national forest, and two forest carbon models, to estimate the relative impacts of disturbance (e.g., fires, harvests, insect outbreaks, disease) and nondisturbance factors (climate, carbon dioxide concentrations, nitrogen deposition). Results are summarized for each region of the National Forest System in the main document. A set of appendixes (available online) provides more detailed information about individual national forests within each region. Results are highly variable across the United States. Generally, carbon stocks are increasing in forests of the eastern United States as these forests continue to recover and grow older after higher historical harvesting rates and periods of nonforest land use. In contrast, carbon stocks in forests of the western United States may be either increasing or decreasing, depending on recent effects of natural disturbances and climate change. The information supports national forest units in assessing carbon stocks, quantifying carbon outcomes of broad forest management strategies and planning, and meeting carbon assessment requirements of the 2012 Planning Rule and directives. Results of these expanded assessments will provide context for project-level decisions, separated from the effects of factors that are beyond land managers' control.

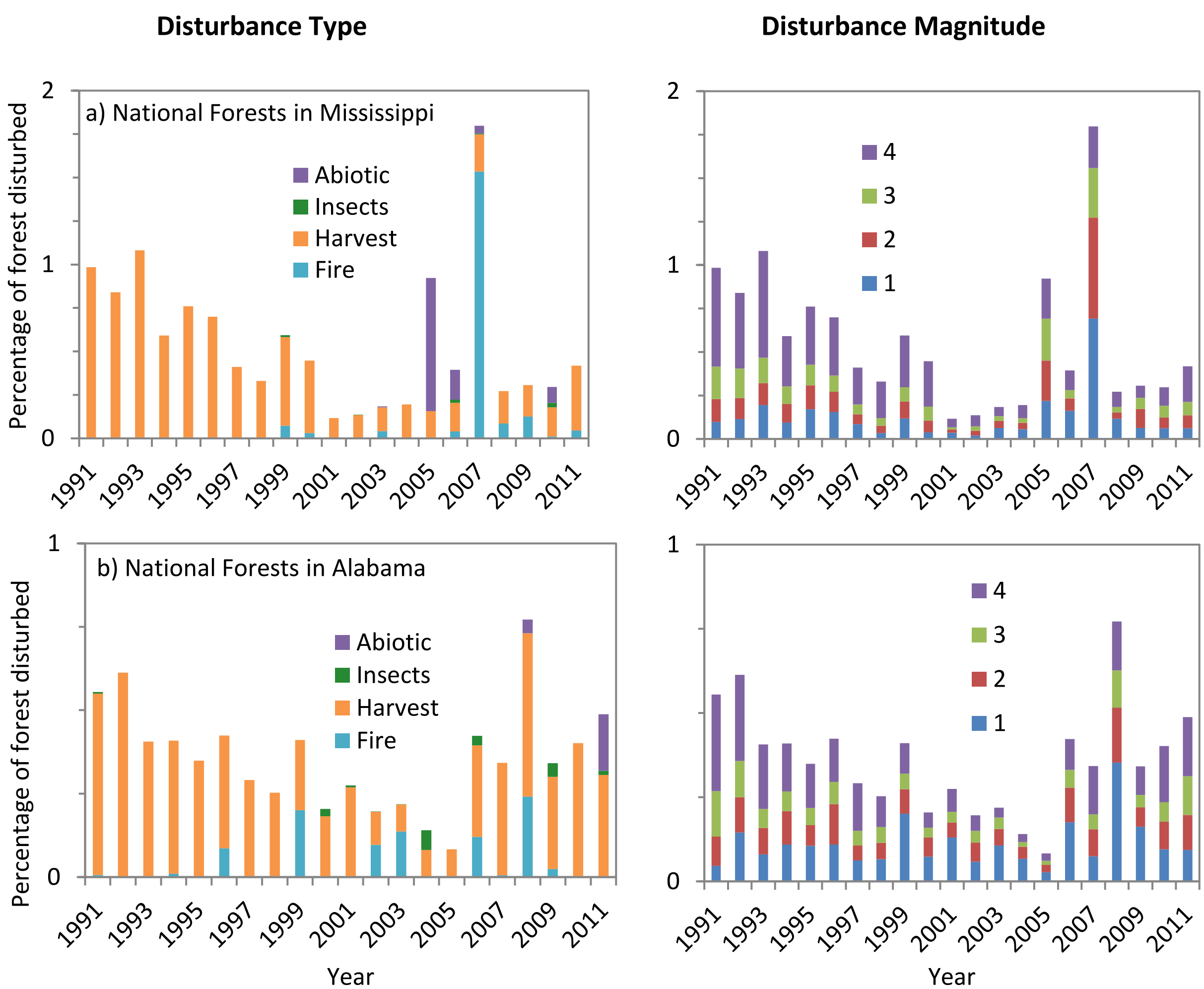
Keywords: forest carbon stock, national forest, land management, natural disturbance, climate change

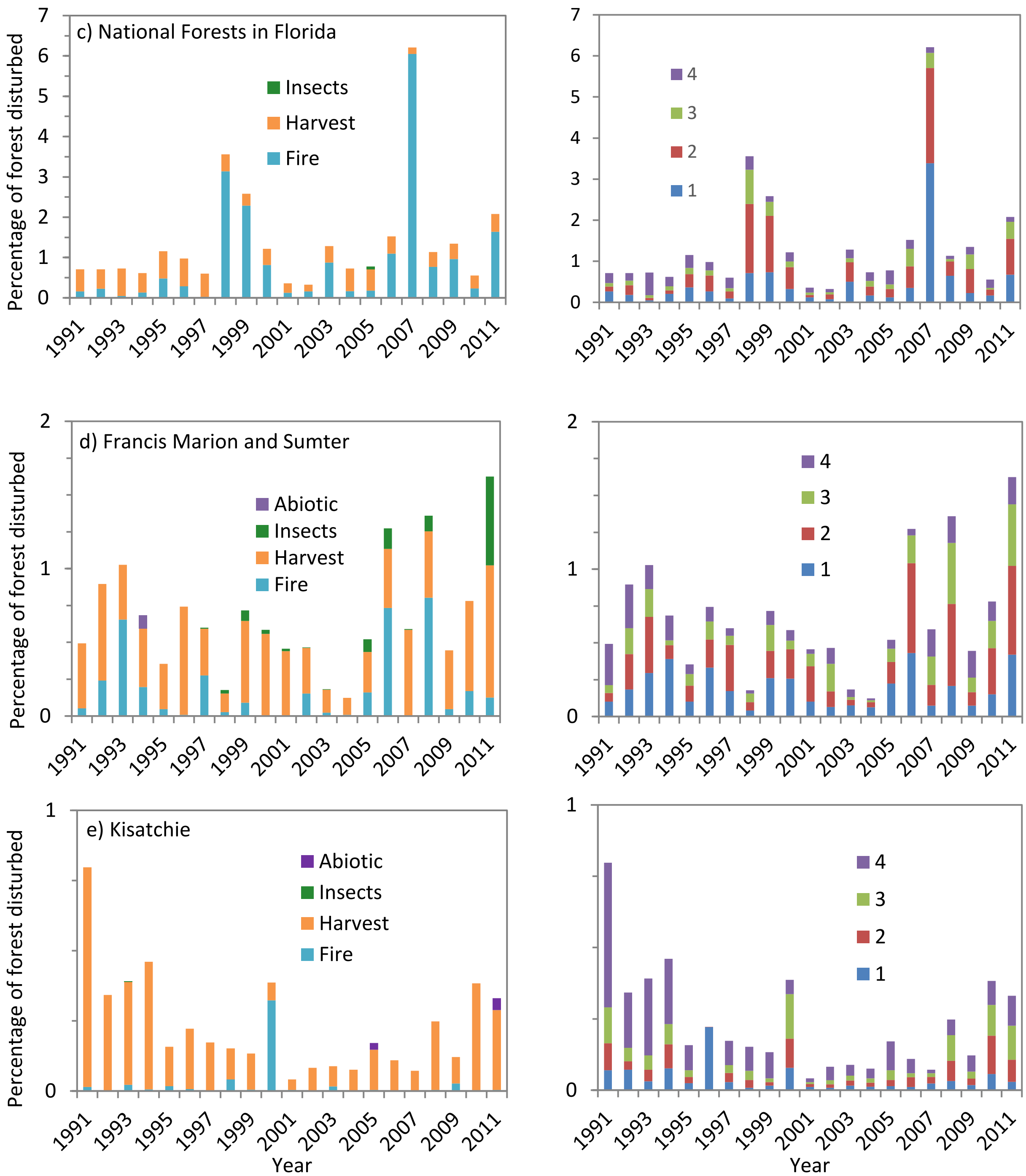
Acknowledgements: Individuals from the USDA Forest Service Washington Office provided valuable guidance and support for this research, particularly Duncan McKinley and Cindi West. The research could not have been done without substantial participation by technicians at Utah State University. The authors wish to acknowledge contributions from the staff of the Forest Service's Northern Research Station and Rocky Mountain Research Station for providing technical support and data used in this report, particularly Chris Woodall, Grant Domke, and Jim Smith. Throughout development of this report, the authors received significant input and feedback from individual national forests which helped us compile the material in a useful and understandable way. We also thank technical reviewers Grant Domke, Bill Connelly, Nadia Tase, Jim Alegria, Dave L. Peterson, Barry Bollenbacher, Elizabeth Wood, Marilyn Buford, and Leslie Brandt.

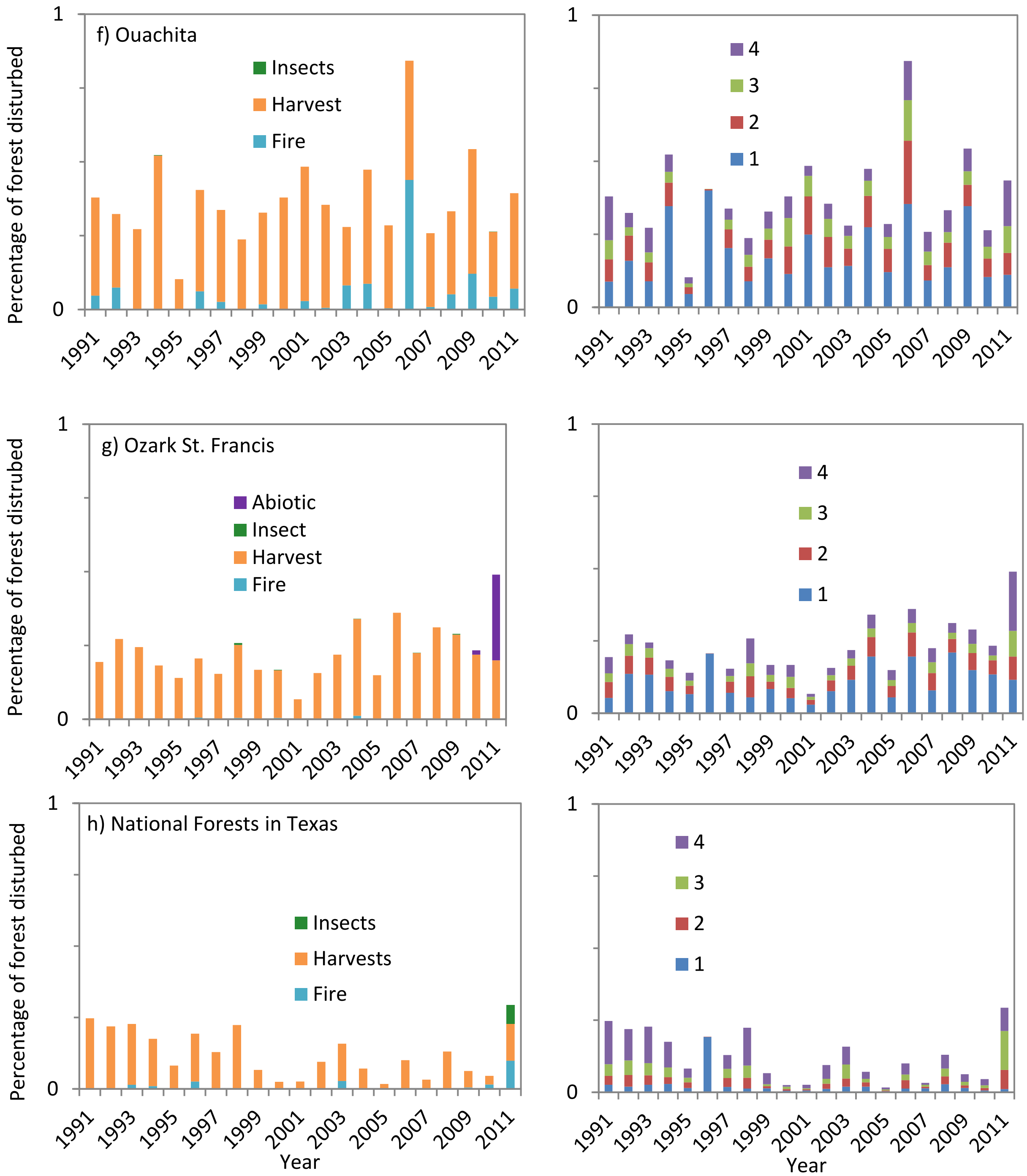
Contents

1. Disturbance trends

Disturbance records are summarized by type (fire, harvest, insects, wind) and by magnitude in Figure 1.1 a-m. In the National Forests of Mississippi (Figure 1.1a), for example, significant abiotic disturbance related to Hurricane Katrina was detected in 2005, and significant fire activity was picked up around the year 2007. Harvest in those forests affected approximately three quarters of a percent of forestland per year in the early 1990s but generally much less after 2000. Mortality due to insects was picked up only in 2011. Significant insect activity was not detected in Mississippi (Figure 1.1a), although there were periodic detected outbreaks in nearby Alabama (1.1b).




c) National Forests in Florida
Insects
Harvest
Fire
4
3
2
1
d) Francis Marion and Sumter
Abiotic
Insects
Harvest
Fire
4
3
2
1
e) Kisatchie
Abiotic
Insects
Harvest
Fire
4
3
2
1
Percentage of forest disturbed
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
Year


f) Ouachita
Insects
Harvest
Fire
Percentage of forest disturbed
1
0
1991
1993
1995
1997
1999
2001
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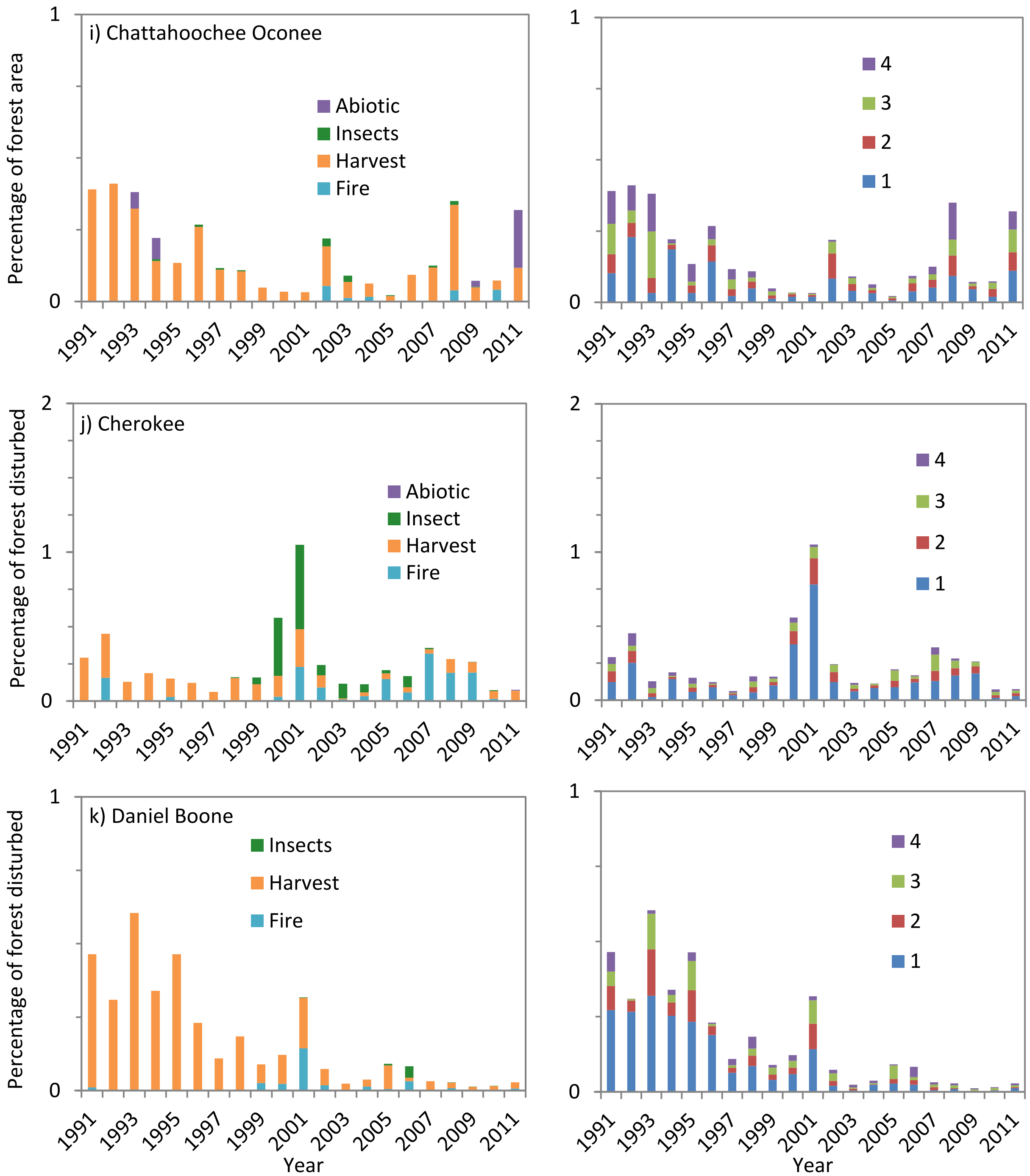
2005
2007
2009
2011
4
3
2
1
g) Ozark St. Francis
Abiotic
Insect
Harvest
Fire
Percentage of forest distrubed
h) National Forests in Texas
Insects
Harvests
Fire
Percentage of forest disturbed
Year
Year


i) Chattahoochee Oconee
Abiotic
Insects
Harvest
Fire
4
3
2
1
Percentage of forest area
j) Cherokee
Abiotic
Insect
Harvest
Fire
Percentage of forest disturbed
k) Daniel Boone
Insects
Harvest
Fire
Percentage of forest disturbed
Year
Year
1991
1993
1995
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1999
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2003
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2007
2009
2011

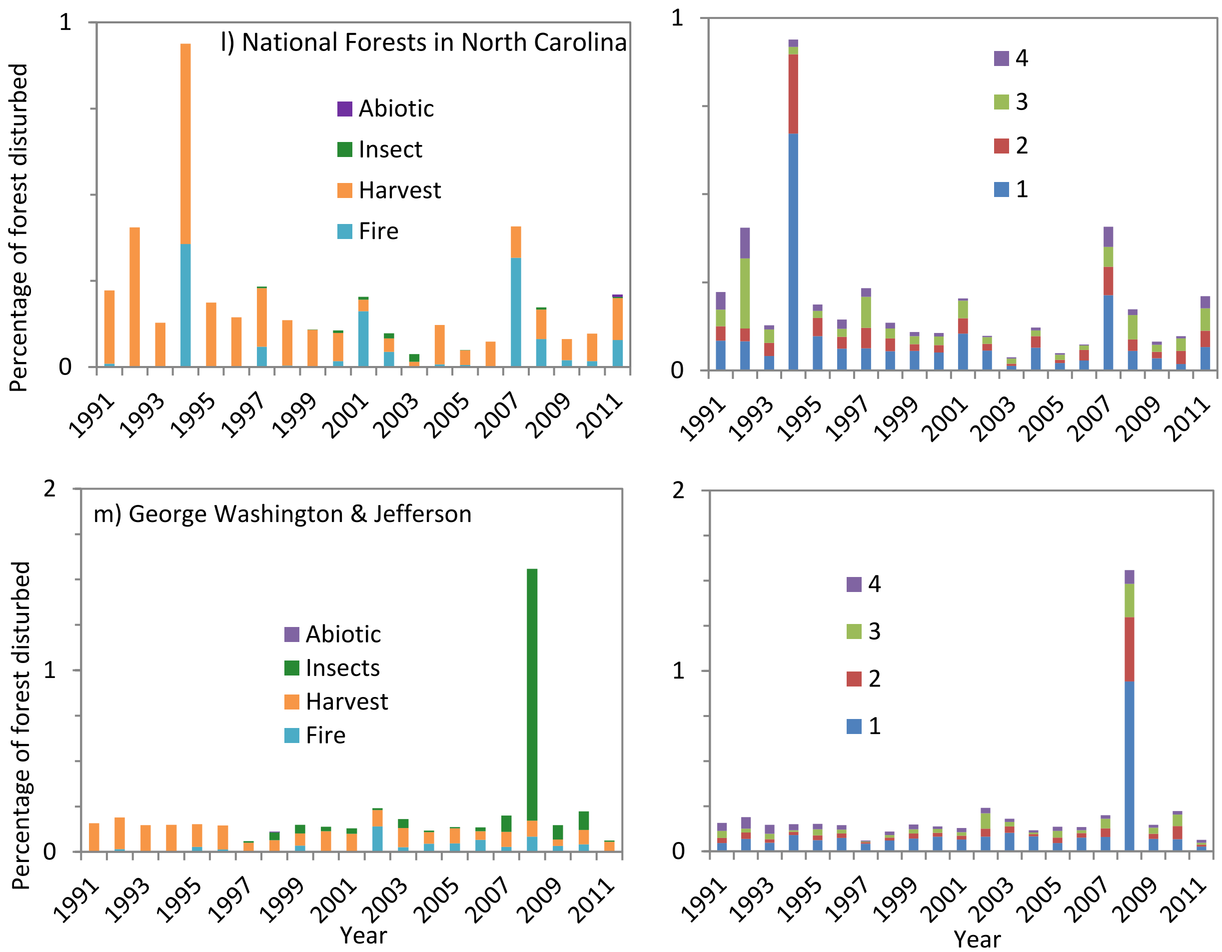


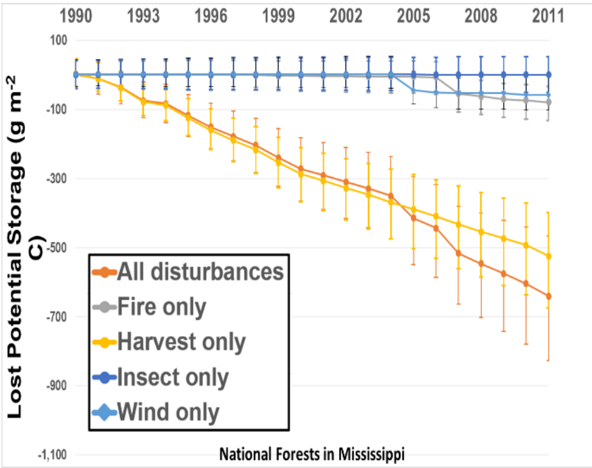
Figure 1.1. Annual rates of disturbance in the Southern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and abiotic; and b) magnitude classes, characterized by percentage change in canopy cover (CC) and categorized as follows: (1) 0 to 25 percent CC, (2) 25 to 50 percent CC, (3) 50 to 75 percent CC, and (4) 75 to 100 percent CC.

2. Effects of disturbance and management activities (ForCaMF)

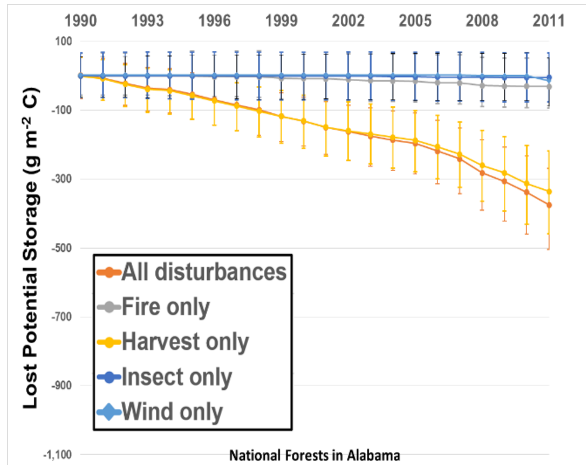
ForCaMF uses C dynamics derived from the combination of FIA plot data and FVS to interpret the consequences of recorded harvests and natural disturbances. This appendix contains ForCaMF results for each national forest in the Southern Region from 1990 to 2011. The disturbance patterns depicted in Figure 1.1a-m are clearly visible in the ForCaMF representation of C impact over time (Figure 2.1). In Mississippi (Figure 2.1a), for example, the impact of wind is not different from zero until 2005, when the effects of Katrina begin to be felt. The effect of fire diverges from zero a couple of years later with the fires depicted in Figure 1.1a. It must be emphasized that there is a residual effect for almost every disturbance because impact is being compared to what would happen to C storage if the stand had remained undisturbed. For fires, ForCaMF accounts for gradual decay of fire-killed material, so net C storage will likely continue to diverge from the undisturbed scenario for several years. This explains the fact that the effects of wind events can increase even in years when there are no storms.

Units in Figure 2.1 represent reduced C storage per square meter. Error bars around the impact of each type of disturbance represent 95% confidence intervals derived from 500 simulations of all recognized constituent uncertainties, as described earlier. Figure 2.2 summarizes the ForCaMF output shown in Figure 2.1: the pie chart represents the proportional importance of each type of disturbance as measured in 2011 (the last date in Figure 2.1). In the National Forests of Mississippi, for example, harvests occurring between 1990 and 2011 had the dominant impact on C storage, although both fire and wind did have significant effects.

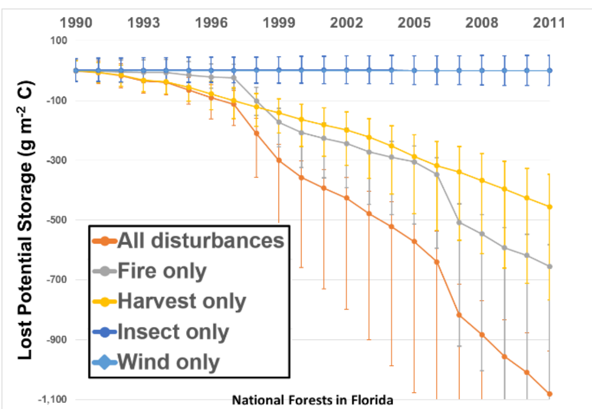
2.1a. National Forests in Mississippi



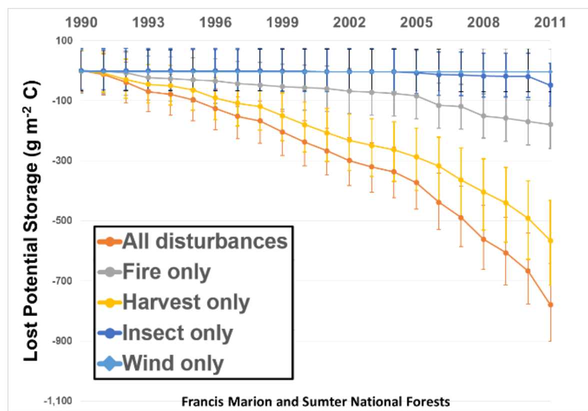
2.1b. National Forests in Alabama



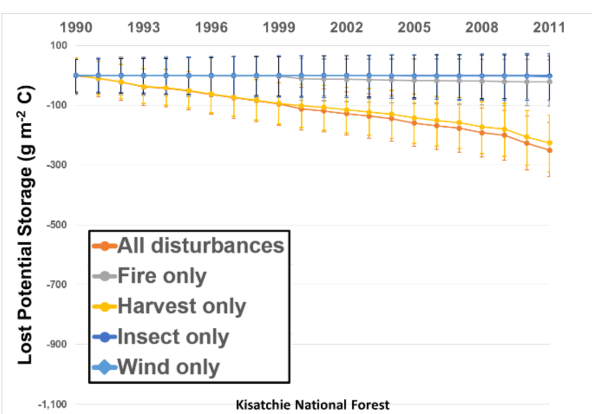
2.1c. National Forests in Florida



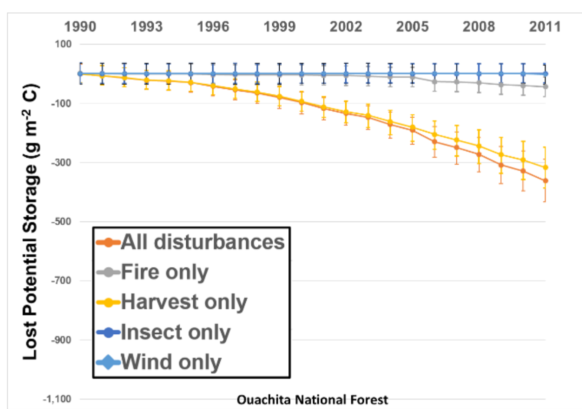
2.1d. Francis Marion and Sumter National Forests



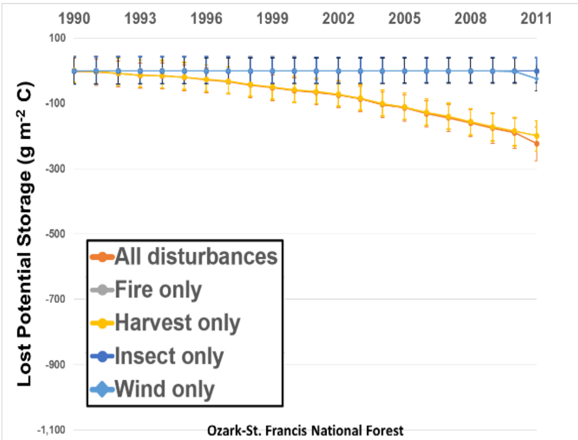
2.1e. Kisatchie National Forest



2.1f. Ouachita National Forest



2.1g. Ozark-St. Francis National Forest



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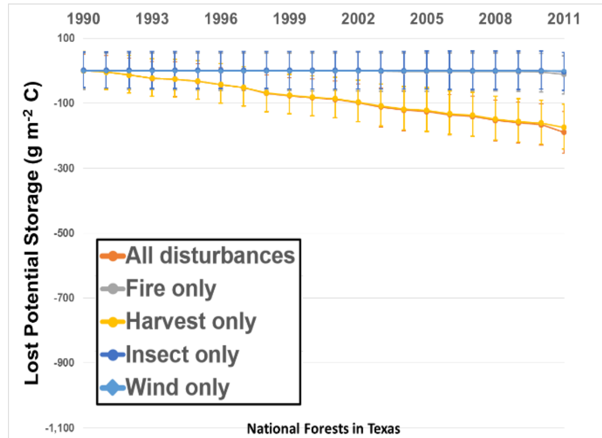
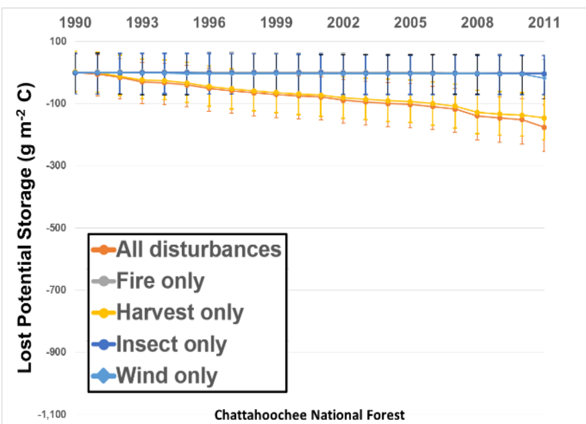
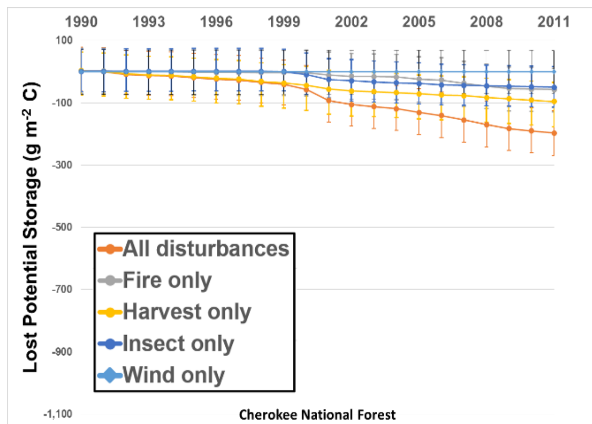


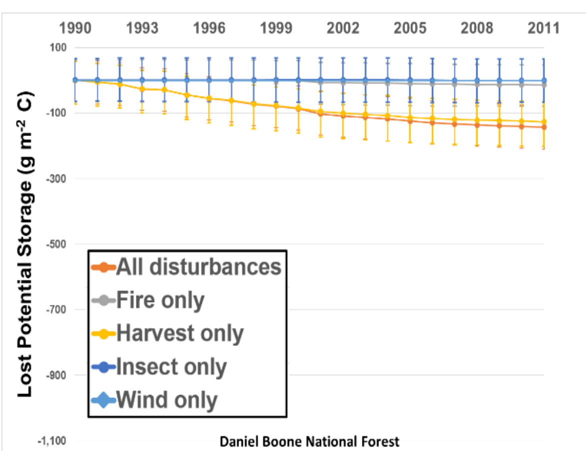
2.1i. Chattahoochee National Forest



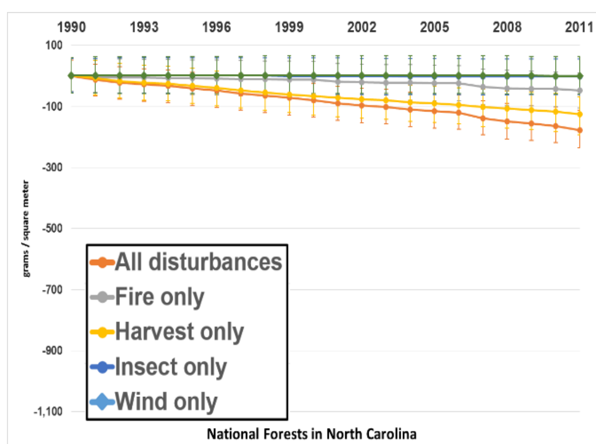
2.1j. Cherokee National Forest



2.1k. Daniel Boone National Forest



2.1l. National Forests in North Carolina



2.1m George Washington and Jefferson National Forests

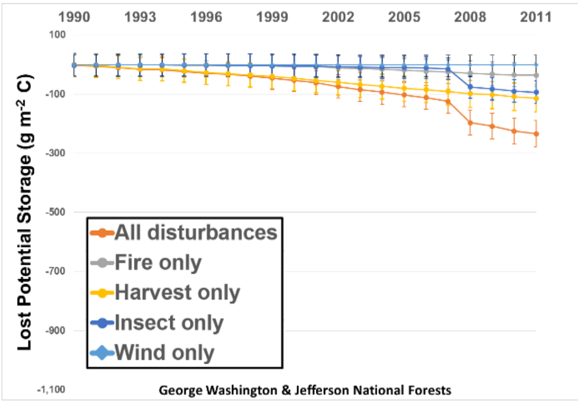
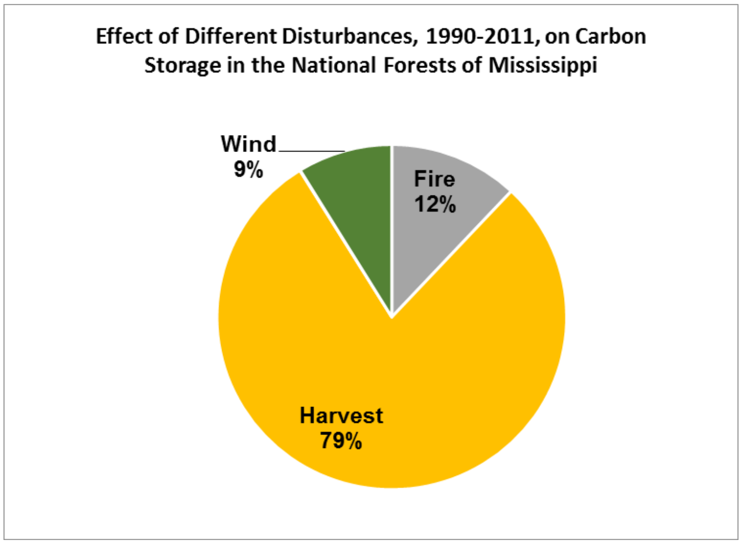
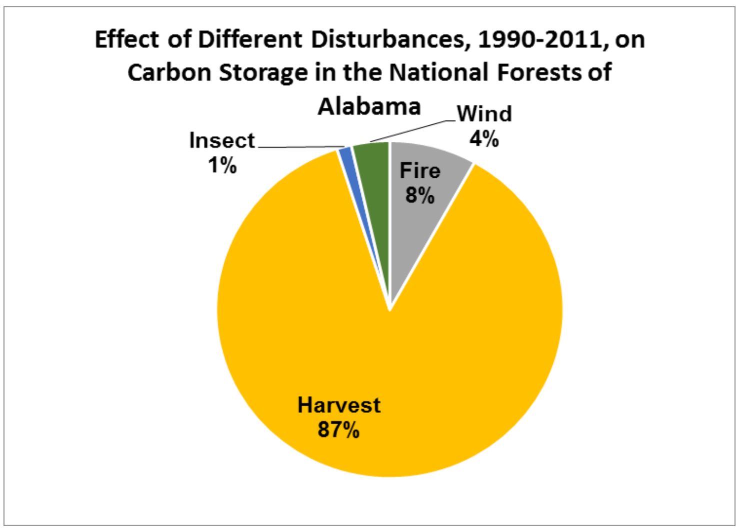
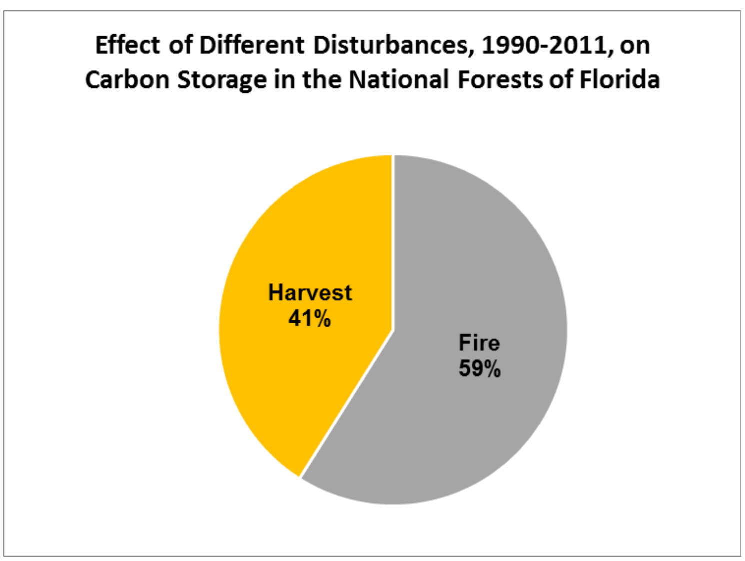
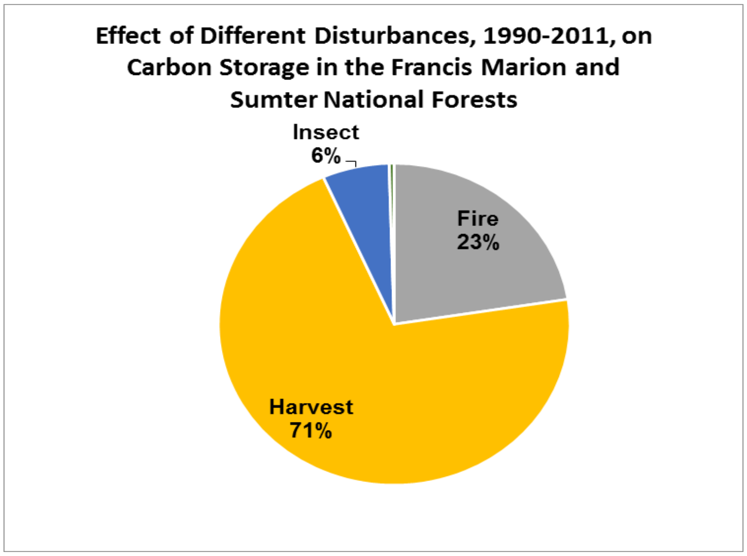


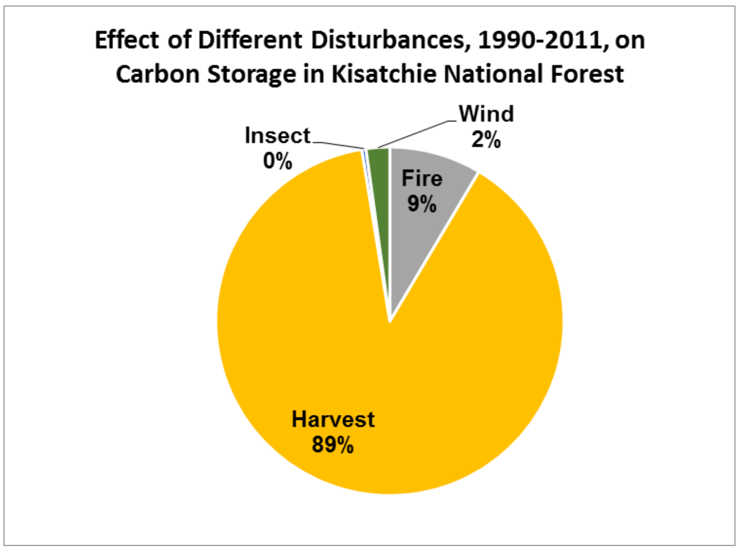
Figure 2.1 The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Southern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m2 equals 1 metric tonne (or Mg)/ha.

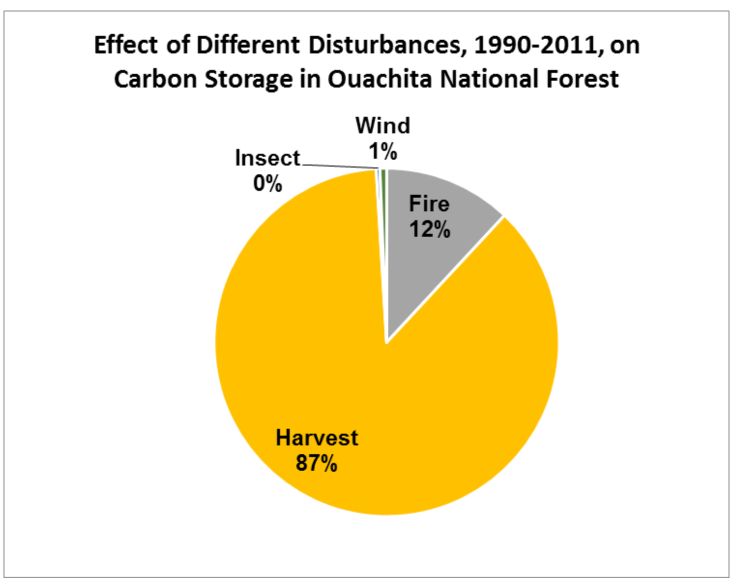

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the National Forests of Mississippi
Wind 9%
Fire 12%
Harvest 79%

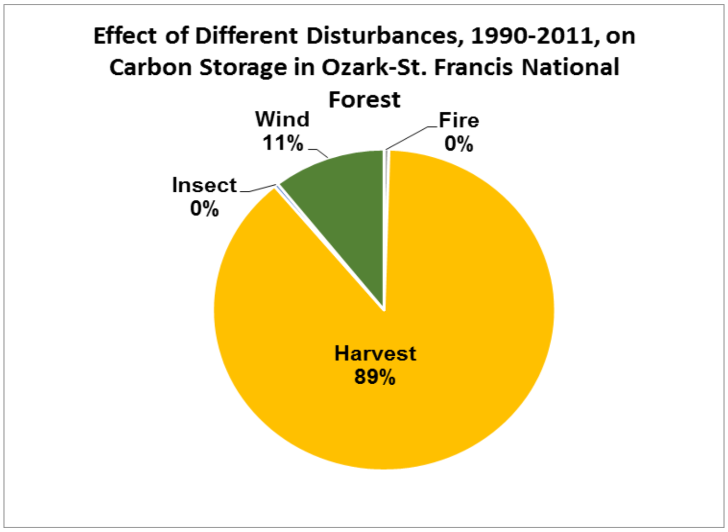

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the National Forests of Alabama
Wind 4%
Insect 1%
Fire 8%
Harvest 87%

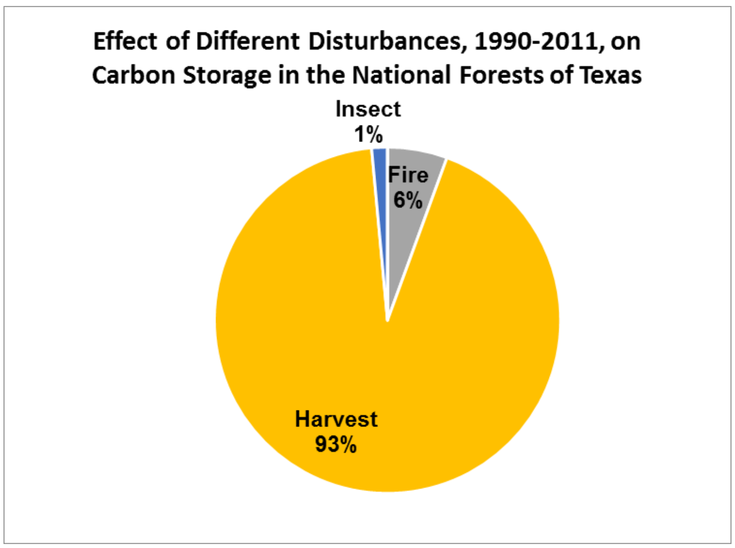

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the National Forests of Florida
Harvest 41%
Fire 59%

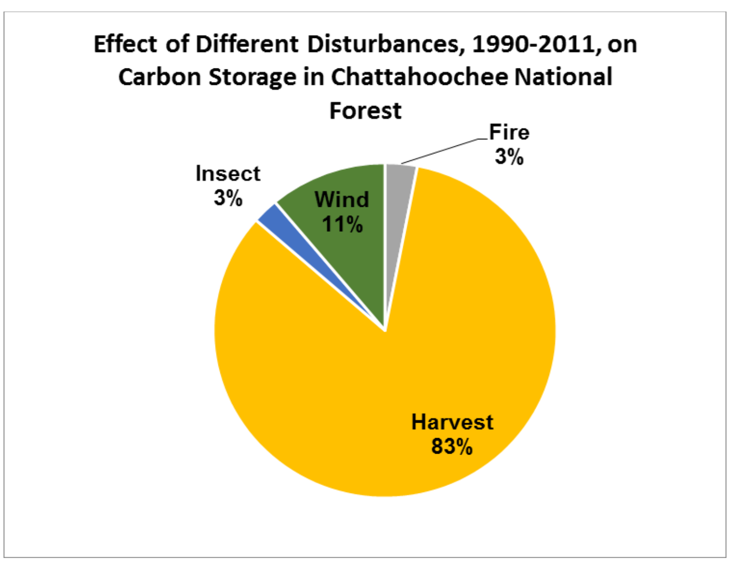

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Francis Marion and Sumter National Forests
Insect
6%
Fire
23%
Harvest
71%

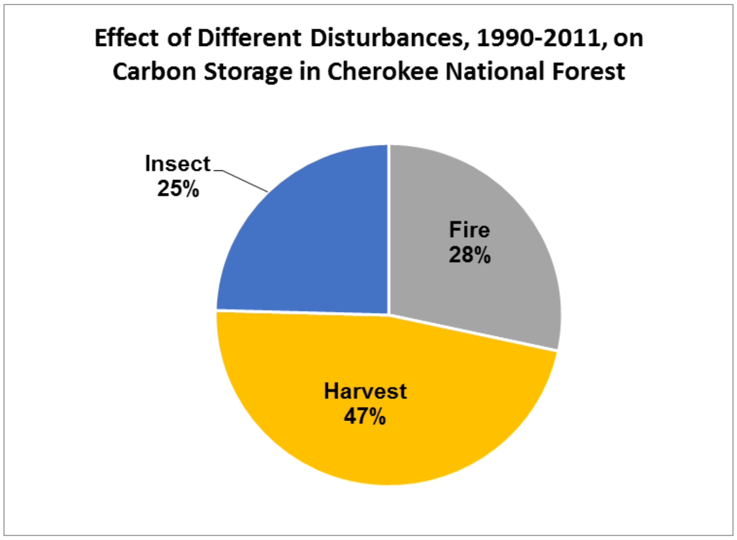

Effect of Different Disturbances, 1990-2011, on Carbon Storage in Kisatchie National Forest
Wind
2%
Insect
0%
Fire
9%
Harvest
89%

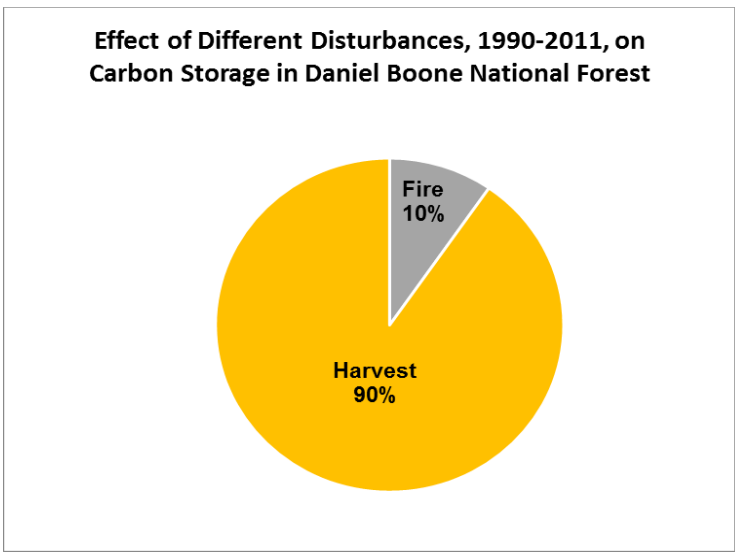

Effect of Different Disturbances, 1990-2011, on Carbon Storage in Ouachita National Forest
Wind
1%
Insect
0%
Fire
12%
Harvest
87%

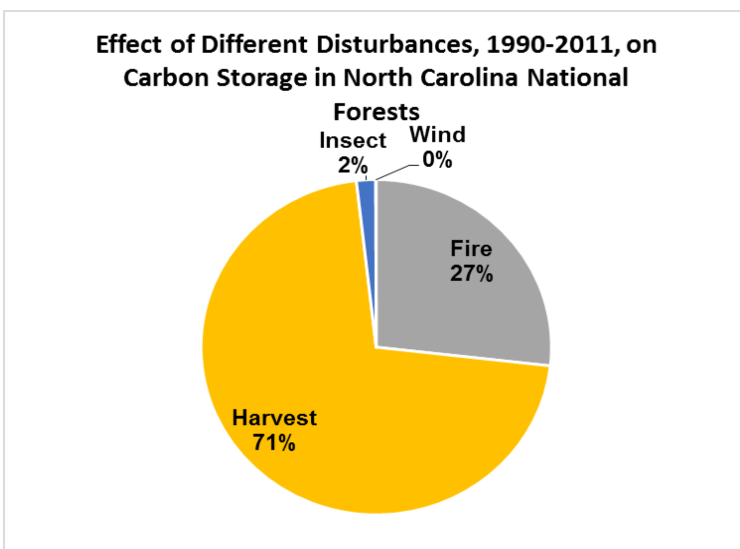

Effect of Different Disturbances, 1990-2011, on Carbon Storage in Ozark-St. Francis National Forest
Wind 11%
Fire 0%
Insect 0%
Harvest 89%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the National Forests of Texas
Insect 1%
Fire 6%
Harvest 93%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in Chattahoochee National Forest
Fire 3%
Insect 3%
Wind 11%
Harvest 83%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in Cherokee National Forest
Insect 25%
Fire 28%
Harvest 47%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in Daniel Boone National Forest
Fire 10%
Harvest 90%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in North Carolina National Forests
Insect 2%
Wind 0%
Fire 27%
Harvest 71%

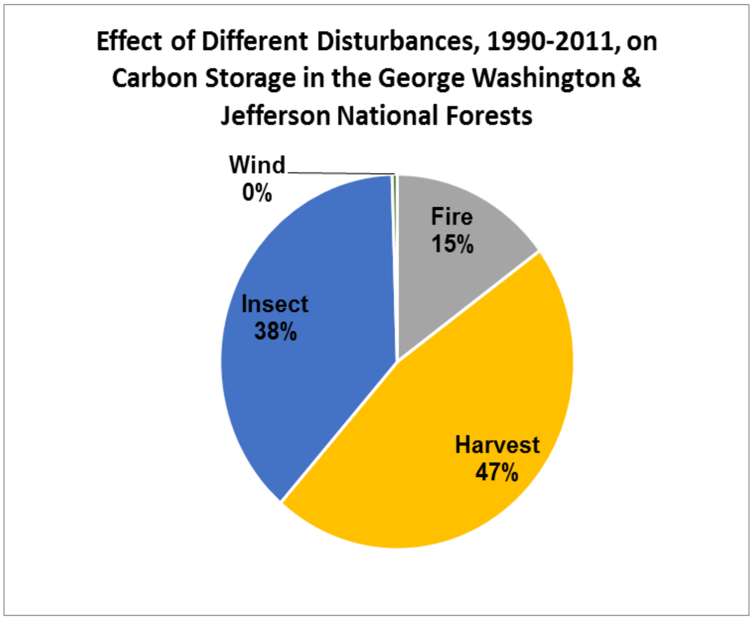


Figure 2.2. Proportional effect of different kinds of disturbance on carbon storage in eacg national forest in the Southern Region for the period 1990 through 2011.

3. Management implications of ForCaMF results

Earlier baseline assessments (http://www.fs.fed.us/climatechange/advisor/products.html) presented inventory-derived estimates of how much carbon is stored in the forests and in the harvested wood product pools of each national forest. The ForCaMF analyses here focused on how different types and intensities of disturbance have influenced those stocks in recent decades. Specifically, results given in Section 6.2 of the main report and previous sections of this appendix provide details about: 1) patterns of disturbance; 2) how disturbance impacts on C storage evolved in each forest from 1990 to 2011, and; 3) the level of uncertainty associated with assessments of each forest. In this section, we bring this information together to answer the simple questions of: "How much do disturbances really disrupt C storage?" and "which disturbance processes in each forest are the most important?"

In highlighting what information managers and planners can gain from these analyses, it is useful to remember that C storage is simply one ecological service, among many, that forests provide. That service mitigates the climate impacts of greenhouse gases emitted through the use of fossil fuels by removing carbon dioxide (CO_2) from the atmosphere. Figure 3.1 shows how much less C (by percentage) was stored in each forest in 2011 because of different types of disturbance since 1990. Disturbance patterns continue to change, but this assessment of the recent past represents the best available insight into how sensitive National Forest C storage is to fire, harvest, insects, disease, and weather events. Residual disturbance effects (*e.g.,* decaying dead C) of monitored events will depress C storage for many years after 2011, just as many pre-1990 disturbances continue to affect current stocks. In most cases, forests re-grow after disturbance and become C sinks for many decades or centuries after a relatively short period of reduced C stocks. In some regions where C stocks have reached elevated levels because of disturbance suppression, a lower level of C stock may be more sustainable compared with the recent past.

The period of this snapshot was somewhat arbitrary; however, every analysis needs sideboards, and the period used here coincides with our best monitoring data (satellite imagery, Agency activity records, FIA data). The percentages recorded in Figure 3.1 may seem relatively small, but they often represent very large amounts of climate mitigation benefit. For instance, if a national forest has half a million hectares of forestland that FIA tells us is storing 50 Mg of C per hectare, and ForCaMF tells us that there would be 2% more C without insect activity from 1990-2011, that is a difference of half a million metric tonnes (Mg) of C, or 1.835 million tonnes of CO_2 (using a 3.67 conversion ratio for C to CO_2). For perspective, this is approximately the amount of CO_2 released by burning around 200 million gallons of gasoline (US Energy Information Administration), and its offset value (amount it would be worth if its continued storage were sold on an open market at a conservative price of $10/tonne) would be almost $20 million.

There are certain ways that Figure 3.1 does not tell the complete story. The FVS model, which supplies stand dynamics within ForCaMF, does not cover soil organic C, and Figure 3.1's calculations exclude soils. Fortunately, the InTEC model presented in this assessment do provide insight into soil C dynamics. More importantly, there are some types of disturbance known to be important that were excluded. For instance, root diseases are known to be prevalent in many parts of the country, but they can be difficult to detect with satellite or aerial imagery because their effects in most years can be limited to reduced growth and suppression of regeneration. ForCaMF was used to assess the impacts of root disease in only 6 national forests, all in the Northern Region. That analysis, which was only possible because of a specialized "regional add-on" variable to core FIA measurements, showed significant root disease impacts that equaled the impacts of fire despite several large fire events in the Region (Healey et al., 2016). We know that we are missing similar processes across the country that are not well addressed by available monitoring data.

Disturbances due to climate variability were assessed with the InTEC model which includes precipitation and temperature as major factors affecting forest processes. The effects of climate variability may be positive or negative, and are often highly variable from year to year, depending on the region and how the climate variables interact to affect photosynthesis and respiration. The effects of climate also interact with other atmospheric changes particularly increasing atmospheric CO_2 concentration and nitrogen deposition, both of which typically enhance growth rates of forests.

Lastly, this assessment does not consider storage of harvested C in product pools. Conversion of forest material to durable wood products defers emissions of the associated C until decay or combustion occurs following disposal. Earlier baseline assessments and assessments by Stockmann et al. (2012) quantified C stocks in wood products that remain in use or landfills, and work is ongoing to combine ForCaMF and product C dynamics models. In the present assessment, however, harvest effects (like the effects of all disturbances) are restricted to ecosystem stocks, a limitation that overstates the emissions of CO_2 from harvest from an atmospheric point of view. The effect of substituting wood products for other materials such as concrete and aluminum are not considered in any of the assessments but are potentially significant and will be assessed in future work.

It is outside the scope of this assessment to suggest the importance of ecosystem services associated with C relative to other values such as water yield or habitat conservation. What we do provide is tangible information about how management and disturbance prevention/suppression can impact (and has impacted) the climate change mitigation a national forest generates. To the degree planners value C storage as a service, the disturbance rates published here, along with resultant C storage differences, can frame management goals moving forward.

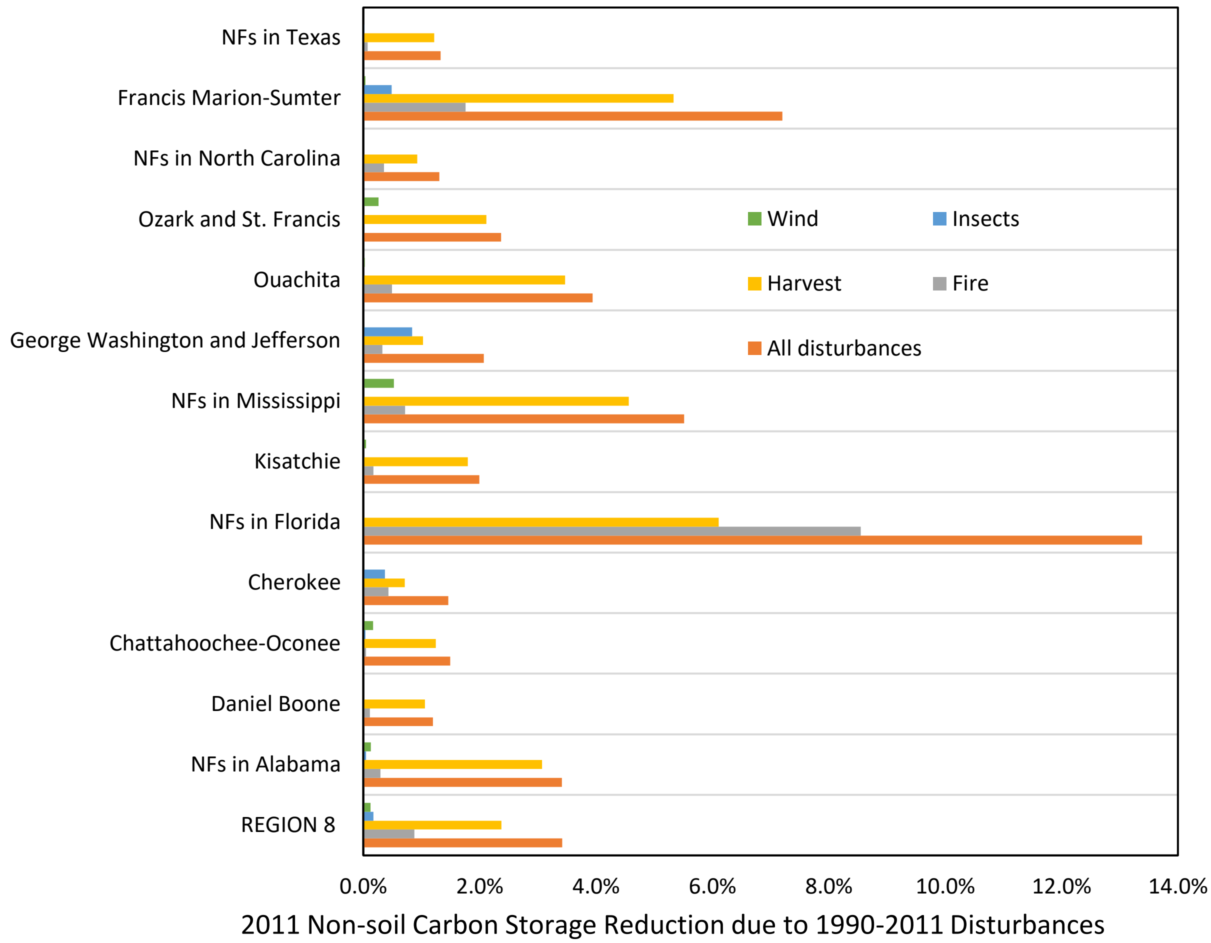


Figure 3.1. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Southern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates. “Wind” is a combination of ice and wind storms and was labelled “abiotic” in Figure 1.

4. Effects of disturbance, management, and environmental factors (InTEC)

The set of figures for each of 13 National Forests units in the Southern Region were generated from both input datasets and outputs from the InTEC model. Note that the numbering sequence of figures in this section is repeated for each National Forest. The input dataset figures presented here include stand age-forest type distributions (Figure 4.1), net primary productivity and stand age relationships (Figure 4.2), total annual precipitation (Figure 4.3a), mean annual temperature (Figure 4.3b), and total annual nitrogen (N) deposition (Figure 4.3c) from 1950-2010. A single atmospheric CO_2 dataset indicating an increasing trend from 280 ppm in 1901 to 390 ppm 2010 (Keeling et al. 2009) was used for all National Forest units across the U.S. The disturbance type and magnitude figures (Figure 1.1) are also referenced as they are useful for understanding model results. Summary figures of the input datasets have been included in these reports because they provide useful context for interpreting the model outputs. George Washington National Forest and Jefferson National Forest were modeled separately in InTEC to correspond with the Carbon Calculation Tool (CCT) model results.

Model outputs presented here include C stock changes and C accumulation due to disturbance and non-disturbance factors, and C emissions due to disturbances alone from 1950-2011. C stock change outputs show the change in C stocks over the course of a year, thus the value in a given year is the difference between total C stocks in that year and total C stocks in the previous year. C stock change is equivalent to Net Biome Production, which is the total photosynthetic uptake of C by the forest minus the loss of C due to autotrophic and heterotrophic respiration and disturbances. The change in C stocks have been attributed to the following effects: (1) individual non-disturbance factors (climate, N deposition, CO_2 concentrations) (Figure 4.4a), (2) combined disturbances factors (fire, harvests, insects, aging and regrowth) (Figure 4.4b), (3) combined non-disturbance factors (Figure 4.4b), and (4) all factors which is the sum of all non-disturbance and disturbance effects (Figure 4.4c). A positive C stock change value in a given year signifies that the factor(s) caused the forest to absorb more C from the atmosphere than it emitted, thus acting as a C sink. A negative C stock change value indicates that the factor(s) caused the forest to release more C to the atmosphere than it absorbed, thus acting as a C source.

Consecutively summing the annual C stock changes (Figure 4.4a-4.4c) yields the total accumulated ecosystem C since 1950 (Figure 4.4d). Positive values indicate accumulated effects that enhanced the total C stock, and negative values represent accumulated effects that reduced the total C stock. The total C emissions due to disturbances alone are also included (Figure 4.4e) and when added to the C stock change (NBP), yields the Net Ecosystem Productivity. The results of the InTEC model runs are numerous and include mapped outputs, C densities, and the effects of both non-disturbance and disturbance factors on individual component pools (e.g. aboveground live C, soil C), thus only summary results are presented here.

The modeled disturbance/aging effect on C stock change for several of the forests in the Southern Region, especially those in the Appalachian Mountain region during the 1960s, show higher than average inter-annual variability. The causes and validity of this high variability in model results have not yet been determined. While there may be greater uncertainty with regards to the modeled results for these particular years, their influence on longer term trends is not significant, and during this period, the disturbance/aging effects shown in the accumulated C results (Figure 4d) effectively capture the most important drivers of change.

National Forests in Mississippi

Between 1950 and 1998, forests in the National Forests in Mississippi fluctuated from a C sink to a C source, but then became a C sink again through 2010 (Fig. 4.4c). During the 1950s and 1960s, disturbance/aging effects promoted a C sink (Fig. 4.4b) and rapid increase in C accumulation (Fig. 4.4d). This trend is supported by the stand age distribution (Fig. 4.1), which shows a pulse of stands aged 70-89 years old that were establishing from 1921-1940. These stands were likely a result of restoration management after a period of intensive logging. According to the NPP-age relationships, these stands would have reached peak productivity at roughly 25-40 years of age (Fig. 4.2) or around the 1950s and 1960s, which was when forests were a C sink (Fig. 4.4c). As these forests aged and productivity declined, disturbance/aging effects shifted to promoting a C source from the 1970s through mid-late 1990s (Fig. 4.4b). Intense harvests in 1992 and 1993, abiotic disturbances in 2005, and fire in 2007 (Fig. 1.1a) all caused pulses of C emissions (Fig. 4.4e). However, these disturbances were quite small (<2% of the forested area) and did not affect stand age or changing C stocks dramatically (Fig. 4.4b).

Climate variability, mainly temperature variability, influenced changing C stocks throughout the past few decades. For instance, warmer temperatures in 1990 and 1998 (Fig. 3b) caused forests to switch to a C source (Figs. 4.4a, c). The heat wave of 1998, combined with all other factors, caused a loss of approximately 2.2 Tg C in that year alone (Fig. 4.4d). Slightly cooler temperatures and sustained precipitation in the 2000s have allowed forests to become a C sink again (Fig. 4.4a, c). Increasing CO_2 and nitrogen (N) deposition (Fig. 4.3) also had positive effects, promoting a C sink (Fig. 4.4c) and C accumulation (Fig. 4.4d). Declines in N deposition and further increases in CO_2 over the past few decades have caused the CO_2 effect to become stronger than the N deposition effect (Fig. 4.4d). Despite a period of declining C stocks from the late 1970s to the late 1990s, forests have again been accumulating C, resulting in a net increase of 17.6 Tg C between 1950 and 2010 (Fig. 4.4d).

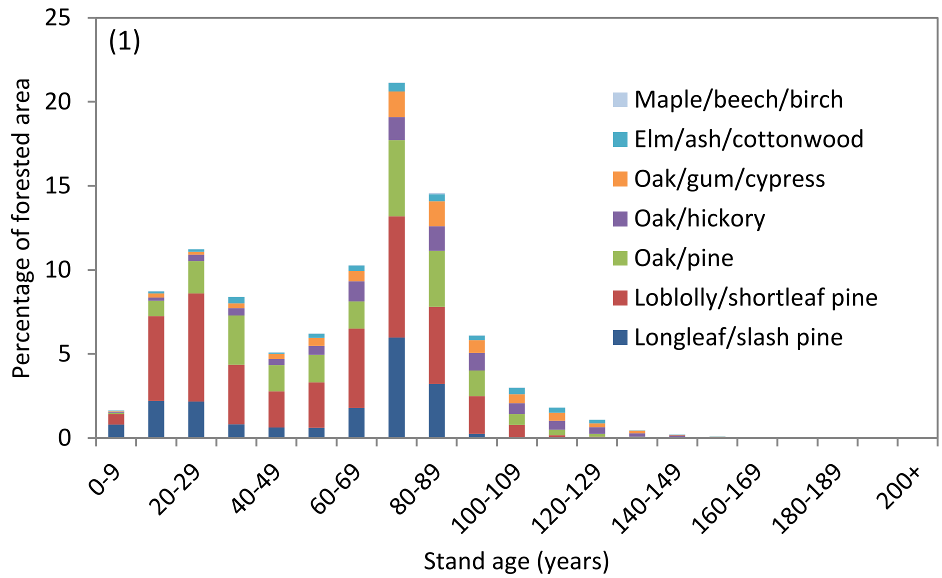


Figure 4.1. Age class distribution in 2010 in the National Forests in Mississippi displaying the percentage of forested area of each forest type group in 10-year age classes. Forest types are symbolized by stacked, colored bars that also correspond to the forest types in Figure 2 below.

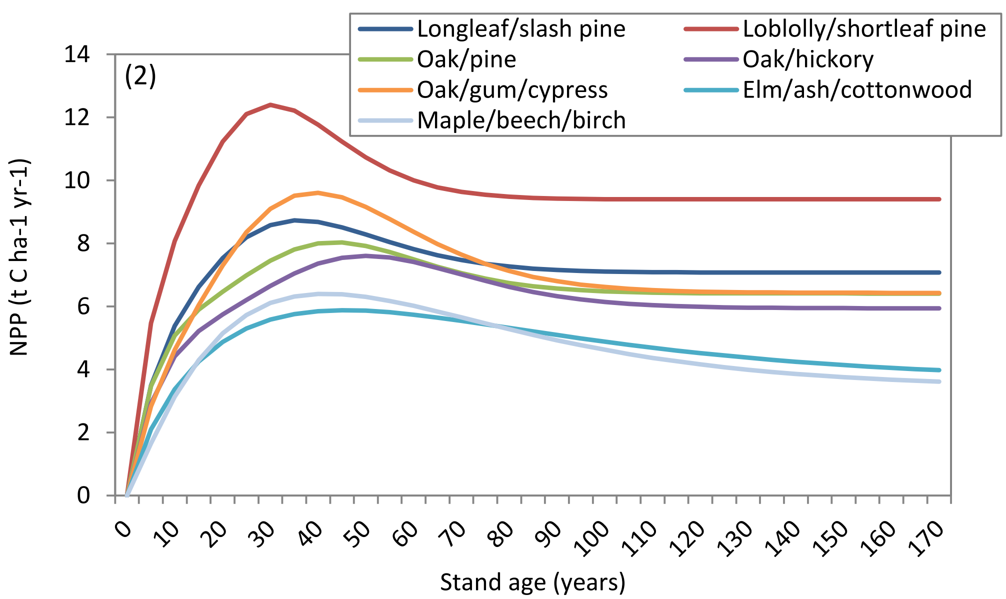


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the National Forests in Mississippi.

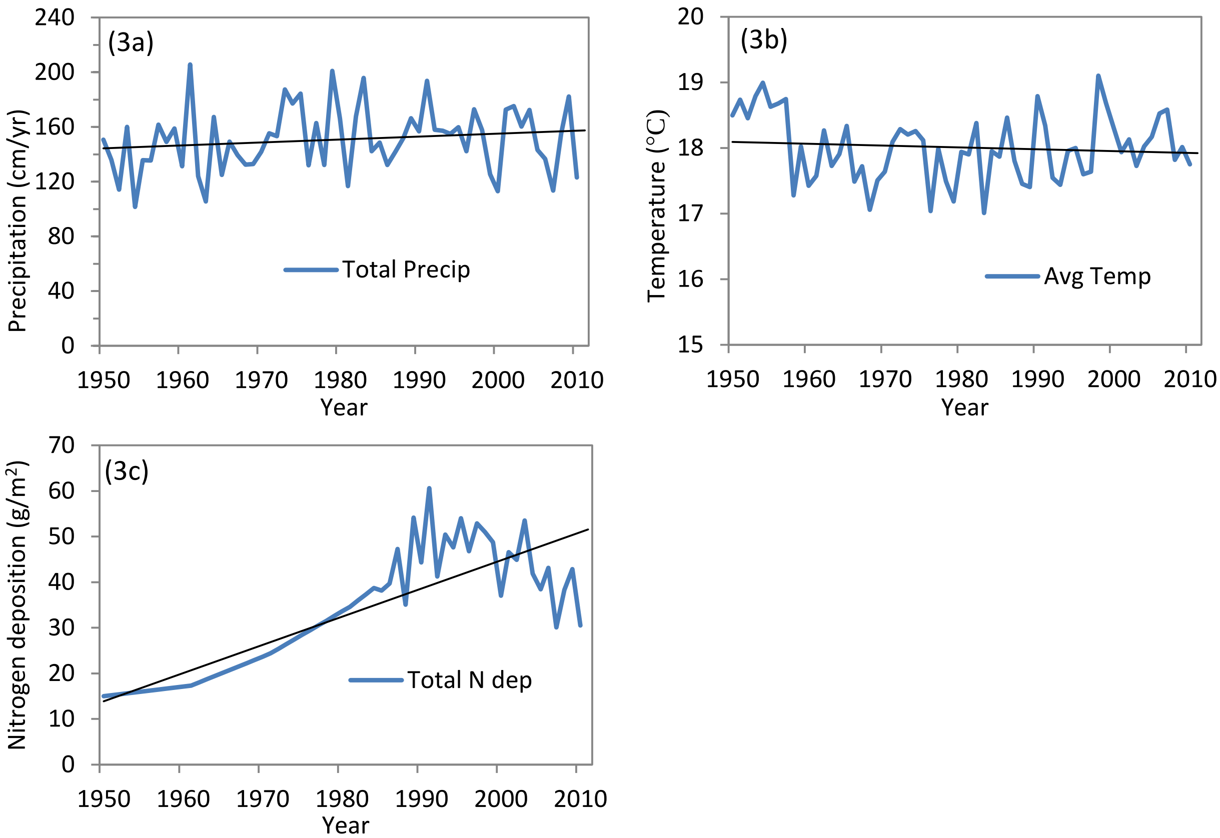


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the National Forests in Mississippi. Linear trend lines shown in black.

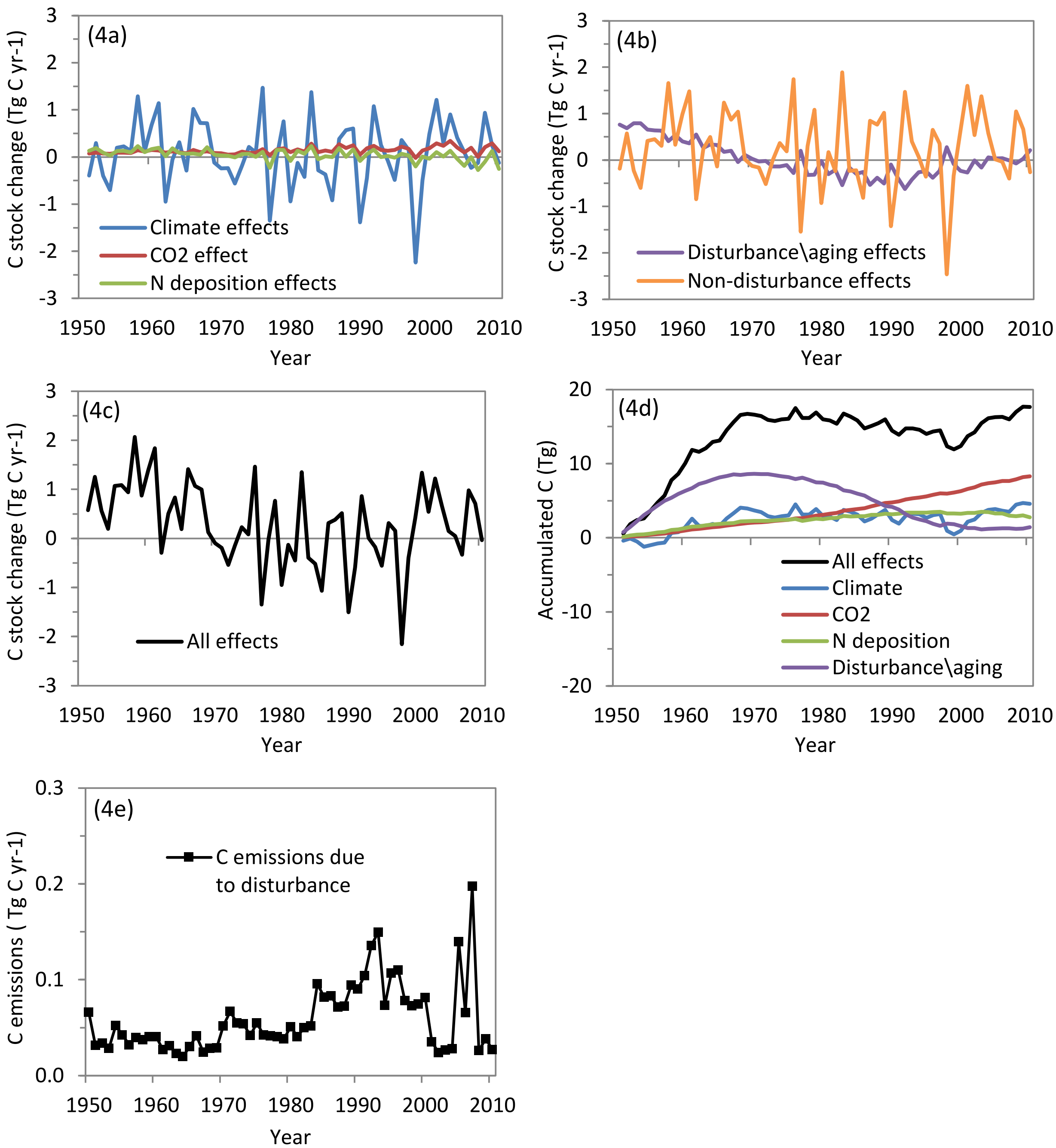


Figure 4.4. Changes in carbon stocks in the National Forests in Mississippi due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

National Forests in Alabama

Between 1950 and 1970 forests in the National Forests of Alabama were a C sink (Fig. 4.4c) and rapidly accumulating C (Fig. 4.4d). After 1970s, forests fluctuated between a C sink and C source, but overall experienced a slow decline in C stocks through 2010 (Fig. 4.4c). Fluctuations in C stocks were mostly a result of climate effects (Fig. 4.4a), but disturbance/aging also had significant effects on forest C trends (Fig. 4.4b). The stand age distribution shows that a pulse of stands established from 1921-1940 (70-89 years old) (Fig. 4.1) which was around the time the National Forests were created from mostly sub-marginal lands and extensively cleared forests. Forest rehabilitation and restoration became a priority in the 1930s, thus these heavily disturbed forests were given the opportunity to re-establish, resulting in this pulse of stand establishment. Depending on the forest type, these stands would have been most productive between roughly 30-45 years old (Fig. 4.2) or from the 1950s to the1970s, which is when disturbance/aging effects were positive (Fig. 4.4c, d). Aside from a few recent, moderate-severity disturbances, such as the harvests in 1992 and 1993 (Fig. 1.1b) which caused a slight increase in C emissions (Fig. 4.4e), recent disturbance effects have been minimal, especially in the 2000s (Fig. 4.4b) and have not altered age-structures (Fig. 4.1).

During the 1950s-1970s, climate effects were also mostly positive, further enhancing the C sink (Fig. 4.4a, c) and C accumulation (Fig. 4.4d). However, climate effects on changing C stocks fluctuated following the variability in temperature and precipitation (Figs. 4.3a-b). Generally, consecutive warmer years cause a C source, as warmer temperatures favor greater decomposition, while consecutive wetter years enhance growth and thus contribute to a C sink. Given the trend of warming temperatures (Fig. 4b), these positive climate effects have subtly declined since 2000 (Fig. 4.4d). Since the 1950s nitrogen (N) deposition and CO_2 fertilization had slight positive effects on changing C stocks (Fig. 4a) and aided in the accumulation of C (Fig. 4.4d) but were generally overshadowed by the stronger climate and disturbance/aging effects. However, without N deposition and CO_2 fertilization, by 2010 forests would have experienced a net loss of C, but instead saw a net gain of roughly 5.8 Tg C since 1950 (Fig. 4.4d).

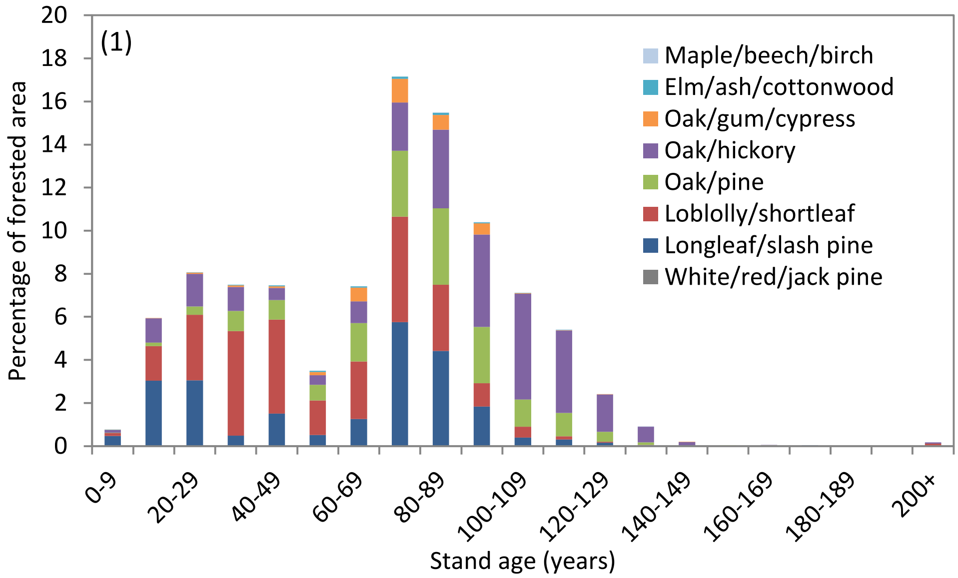


Figure 4.1. Age class distribution in 2010 in the National Forests of Alabama displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

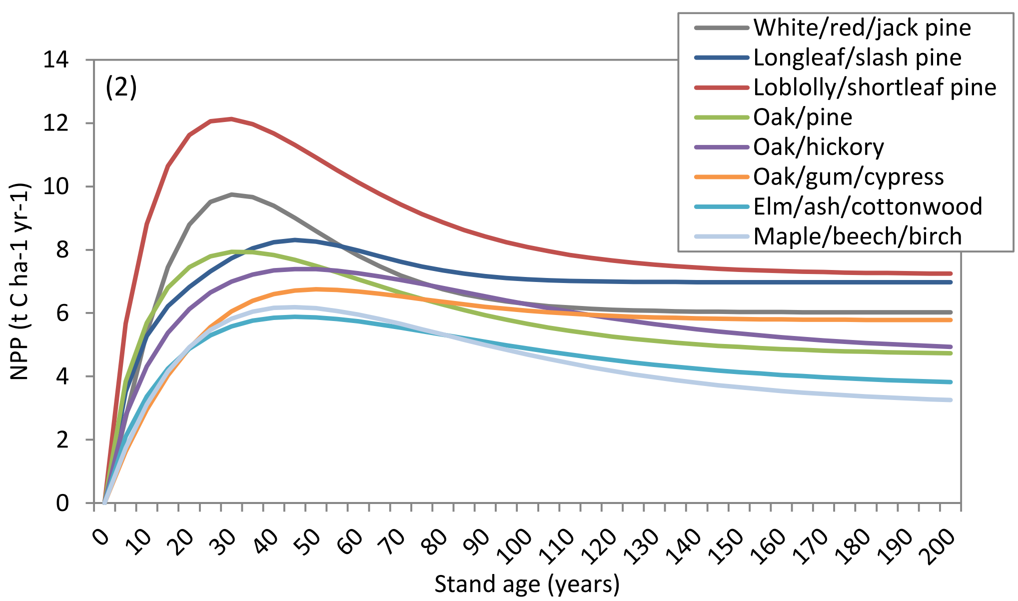


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the National Forests of Alabama. Due to the small number of Spruce/fir stands and similar growth and yields as White/red/jack pine stands, these forest type groups were combined for NPP-age modeling.

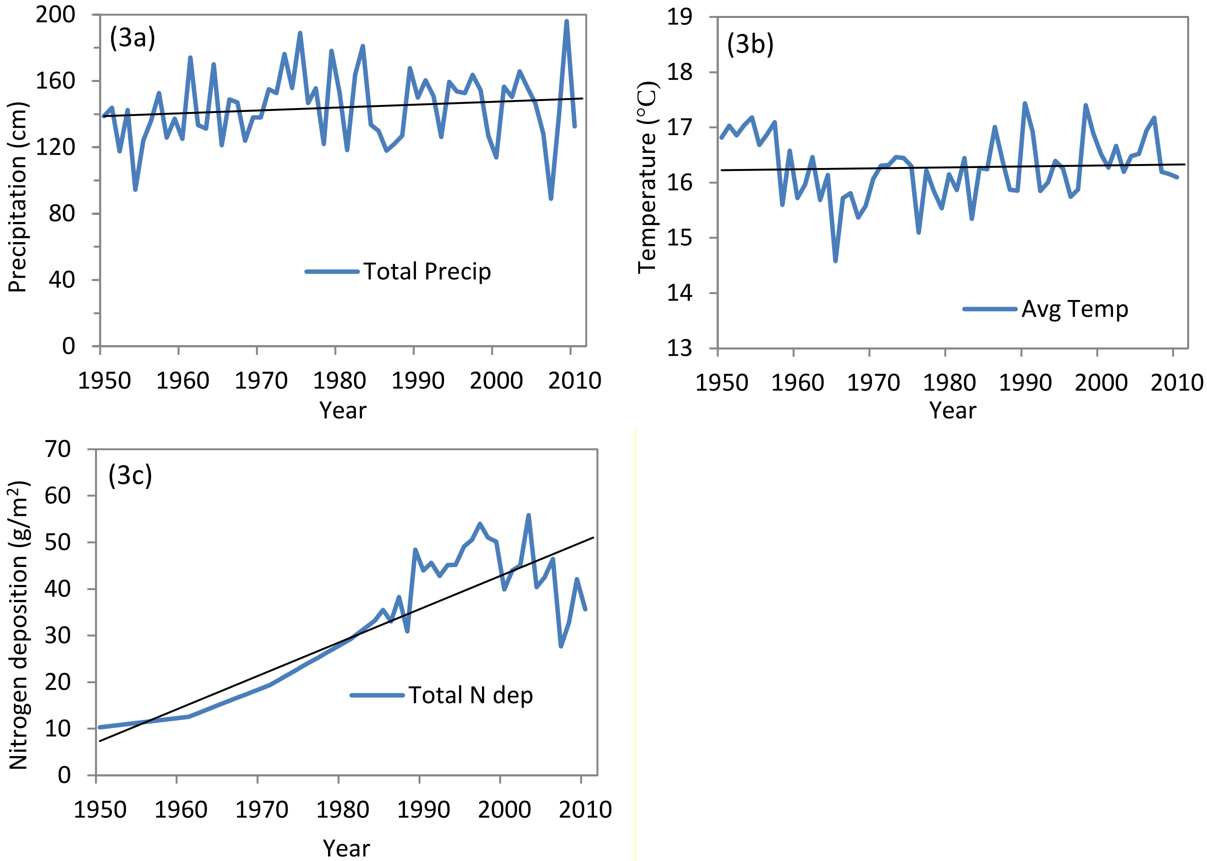


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the National Forests of Alabama. Linear trend lines shown in black.

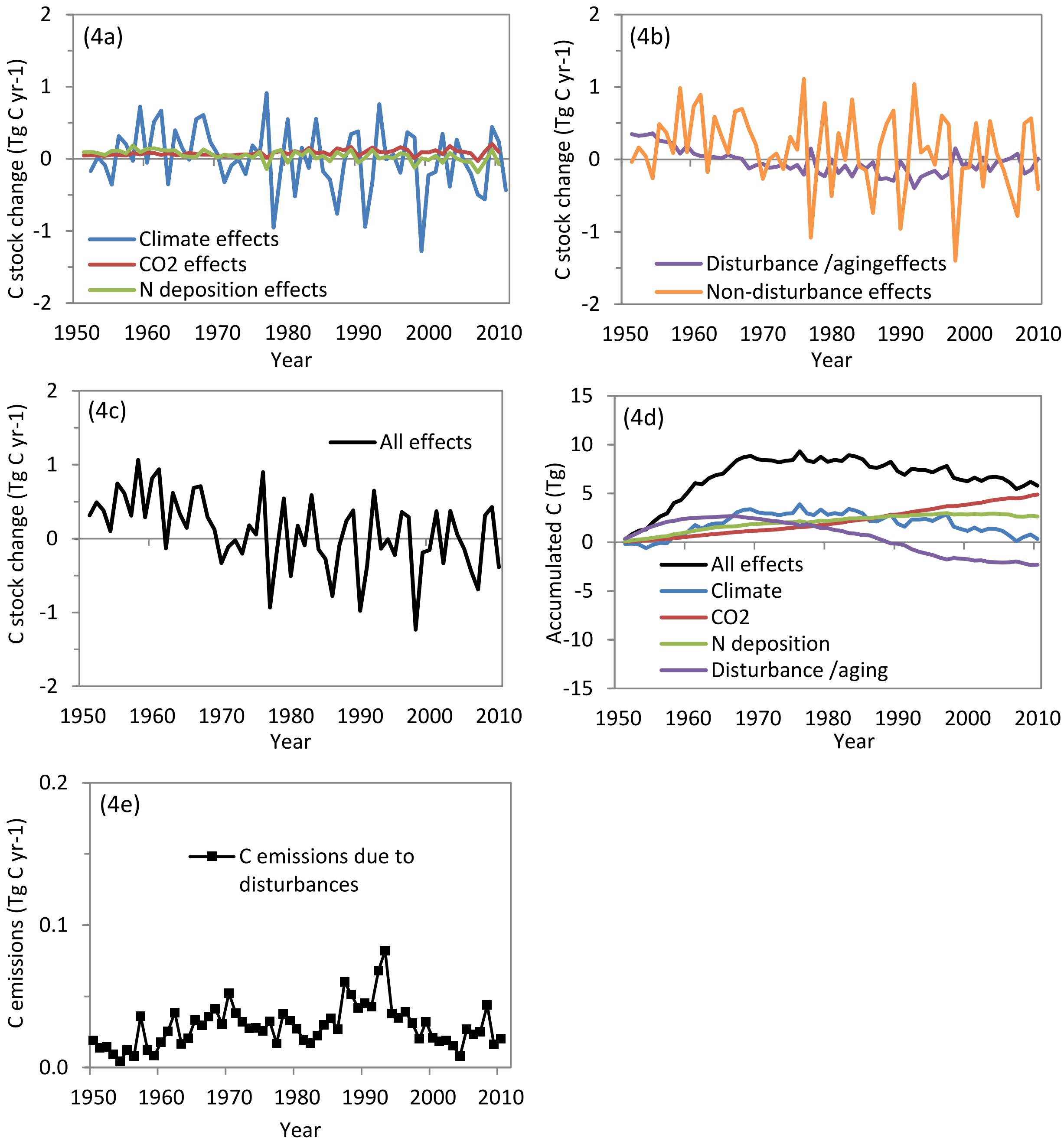


Figure 4.4. Changes in carbon stocks in the National Forests of Alabama due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

National Forests in Florida

Forests in the National Forests of Florida maintained a C sink from 1950-1971 (Fig. 4.4c) mostly following disturbance and aging effects (Fig. 4.4b), but then fluctuated between a C sink and C source through 2010 as a result of climate effects and variability (Fig. 4.4a). The stand age distribution shows a pulse of stands 70-89 years old that were establishing in 1921-1940 (Fig. 4.1), likely due to substantial regrowth following the acquisition of these heavily cut-over, waste lands from private owners in 1911. This pulse of mostly longleaf-pine/slash pine and oak/pine stands (Fig. 4.1), would have reached peak productivity at 30-55 years old, or 1950s-80s (Fig. 4.2). As a result, during this period, forests were a C sink, accumulating C stocks due to disturbance/aging effects (Figs. 4.4b-d). Despite some larger fires in 1998 and 2007, these were mostly low-moderate severity (Fig. 1.1b), causing initial increases in C emissions (Fig. 4e), but did not result in enough mortality to alter age structures (Fig. 4.1) or strongly impact disturbance/aging effects on C stocks (Fig. 4.4b).

Changing C stocks after the early 1970s closely follow climate variability, such that coolers years, like 1976, 1992, and 1996 caused a C sink, while warmer years like 1990 and 1998 promoted a C source (Figs 4.3a-b, 4.4a). Warmer temperatures increase decomposition rates and subsequently soil respiration rates. By the late 1980s, climate effects were more often promoting a C source (Fig. 4.4a). For the most part, nitrogen deposition and CO_2 concentrations had slight positive effects on changing C stocks (Fig. 4.4a) and promoted C accumulation (Fig. 4.4d). Overall, between 1950-2010, forests in the National Forests of Florida saw a net gain of approximately 14.5 Tg C (Fig. 4.4d).

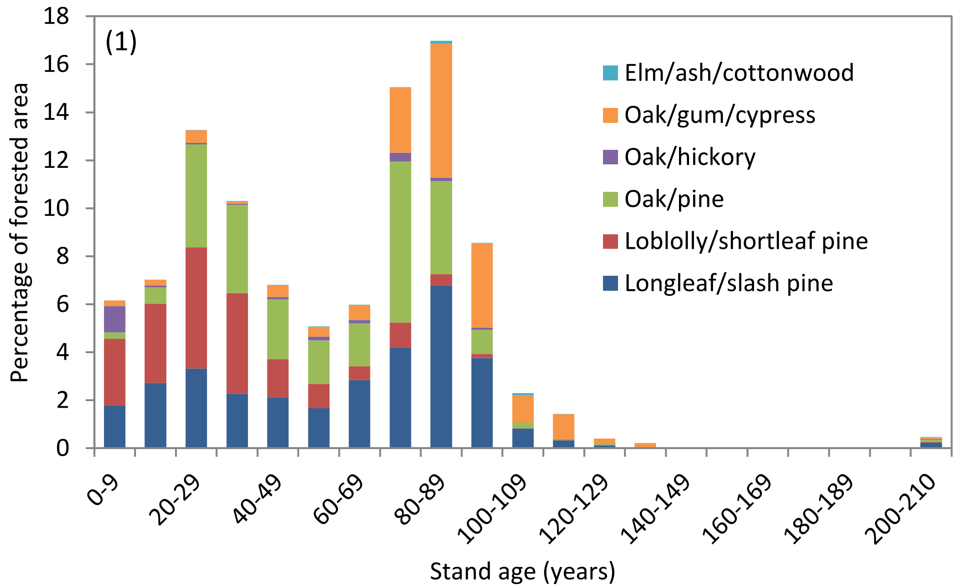


Figure 4.1. Age class distribution in 2010 in the National Forests of Florida displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

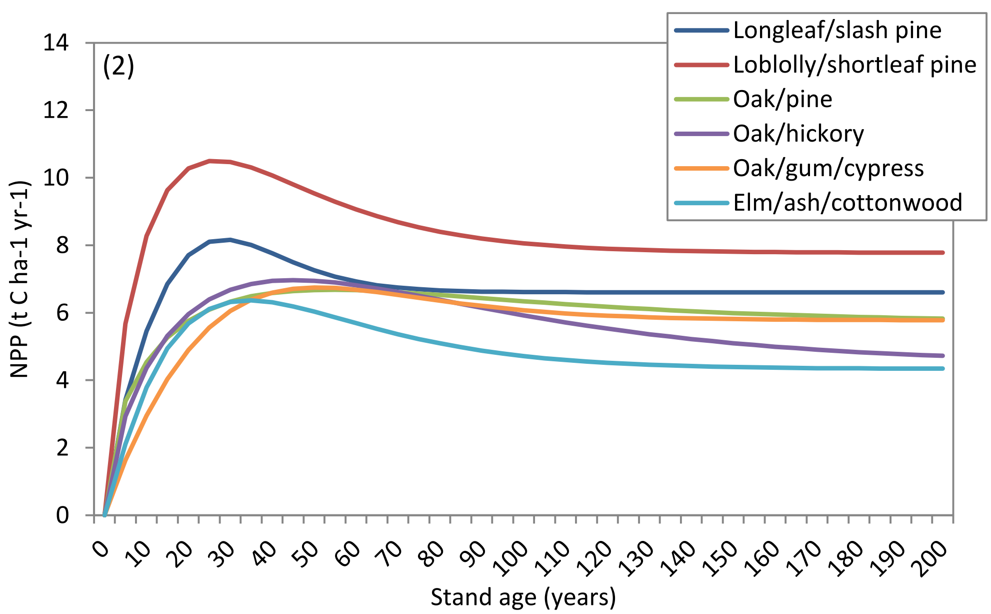


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the National Forests of Florida.

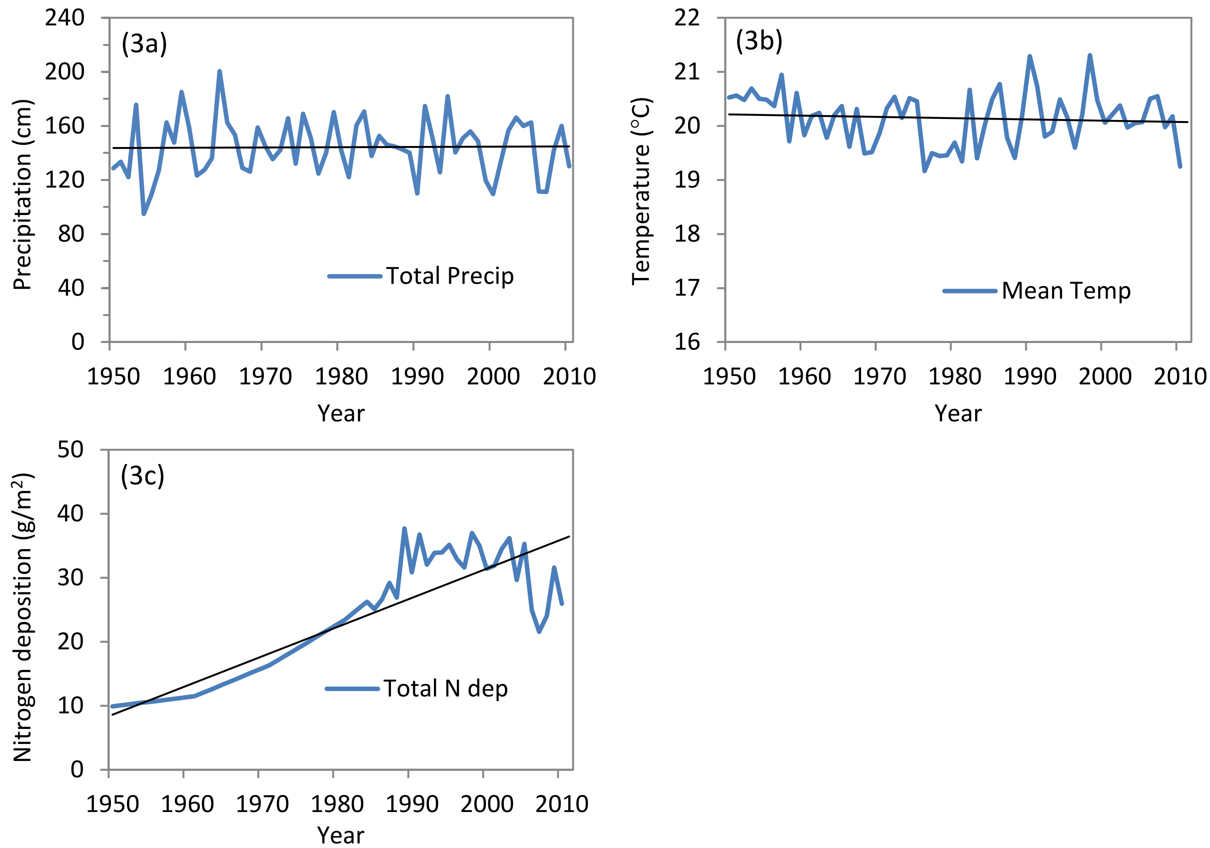


Figure 4.3. Average annual (a) precipitation (cm), (b) temperature (°C), and (c) nitrogen deposition (g/m^2) from 1950-2010 in the National Forests of Florida. Linear trend lines shown in black.

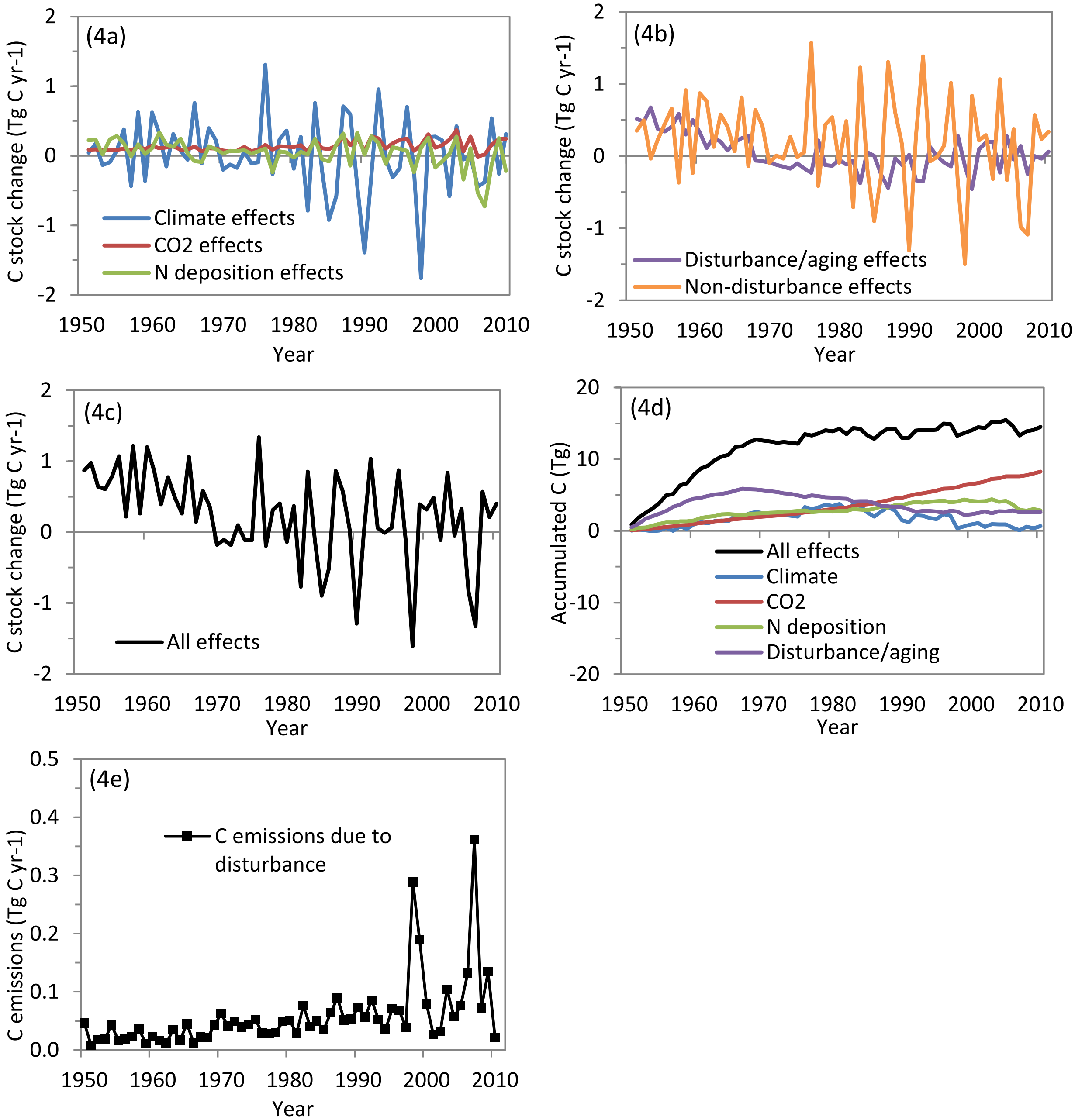


Figure 4.4. Changes in carbon stocks in the National Forests of Florida due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Francis Marion & Sumter National Forests

Between 1950 and 1970 forests in the Francis Marion and Sumter National Forests maintained a C sink (Fig. 4.4c) and were rapidly accumulating C (Fig. 4.4d), but fluctuated between a C sink and source thereafter. Due to the variable nature of climate, changing C stocks were generally driven by fluctuations in climate variables (Figs. 4.4a-c), although disturbance/aging effects also had a significant impact on longer term forest C trends (Fig. 4.4b). The stand age distribution shows a pulse of stands 70-89 years old (Fig. 4.1) which were establishing from 1921-1940. By the 1920s, these forests were depleted of timber and restoration became a management goal, which explains the large peak of establishment ~80 year ago. The mostly Loblolly/shortleaf pine stands in this pulse would have been most productive when they were around 25 years old or from 1950-1970 (Fig. 4.2), which corresponds with when disturbance/aging effects were positive.

Another pulse of stands 20-29 years old (Fig. 4.1) is likely a result of regeneration after Hurricane Hugo, a category 4 storm, which devastated about 4.45 million acres of forests in the Francis Marion NF in 1989. In addition to widespread mortality prompting the regeneration pulse, the hurricane also caused a significant increase in C emissions (Fig. 4.4e) and a slight decline in changing C stocks (Fig. 4.4d). However, as the forests began to recover in 1990s and 2000s, disturbance/aging affects again promoted a C sink and C accumulation (Figs. 4.4c-d). Aside from larger fires in 2006 and 2008, disturbances have been relatively small and low-magnitude (Fig. 1.1d), thus there has been lower levels of stand establishment in recent years (Fig. 4.1).

Climate effects on changing stocks were also positive between the mid-1950s and 1970 further enhancing the C sink and amplifying C accumulation (Figs. 4.4a-d). However years with notably warmer average temperatures, such as 1990 and 1998 (Fig. 4.3b), correspond with declines in climate effects on C flux (Fig. 4.4a) with forests switching to C sources during those years (Fig. 4.4c). Warmer temperatures both increase soil respiration as well as constrain productivity given increased evapotranspiration and subsequent water stress. Consistently positive CO_2 fertilization and nitrogen deposition effects helped forests to achieve a net gain of approximately 5.2 Tg C between 1950 and 2010 (Fig. 4.4d).

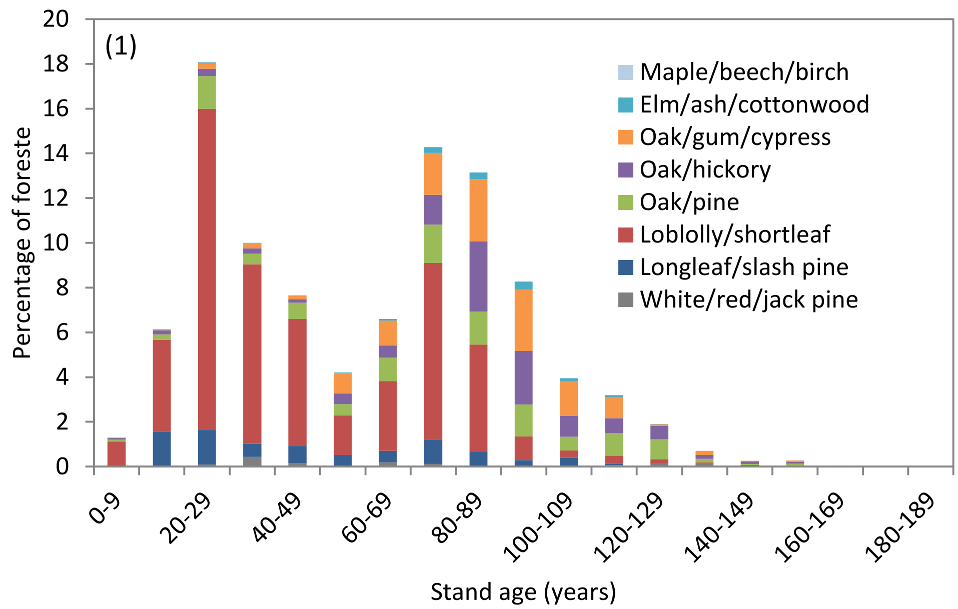


Figure 4.1. Age-class distribution in 2010 in the Francis Marion and Sumter National Forests displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

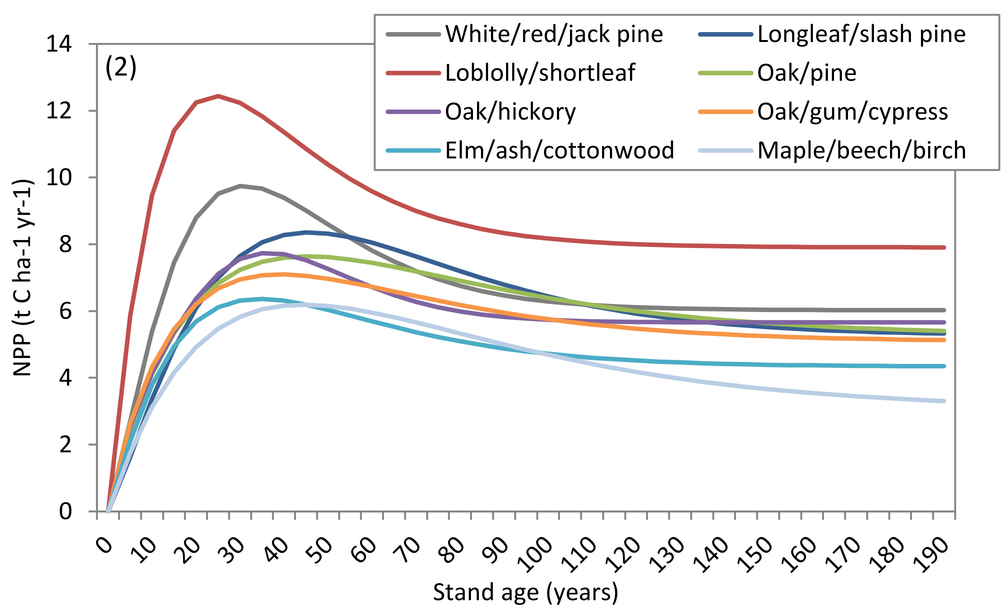


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Francis Marion and Sumter National Forests.

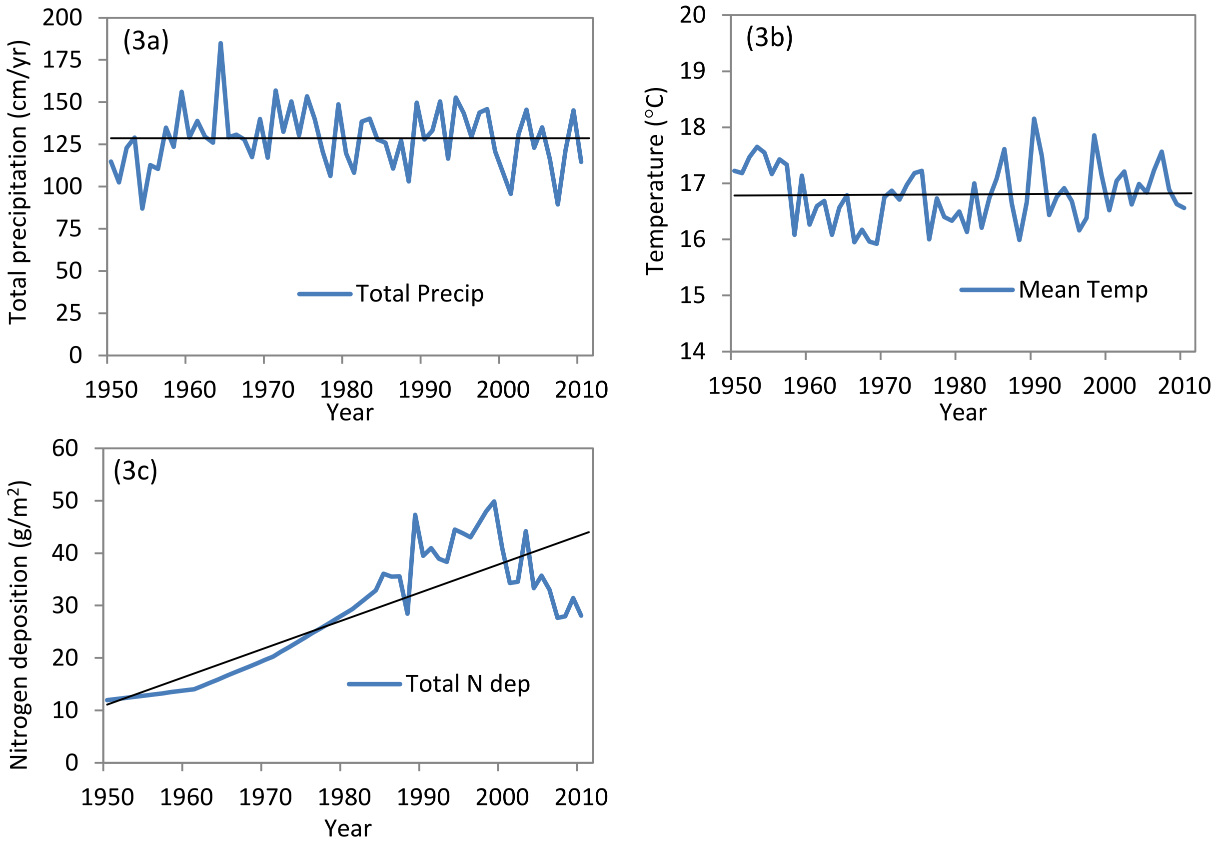


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Francis Marion and Sumter National Forests. Trend lines shown in black.

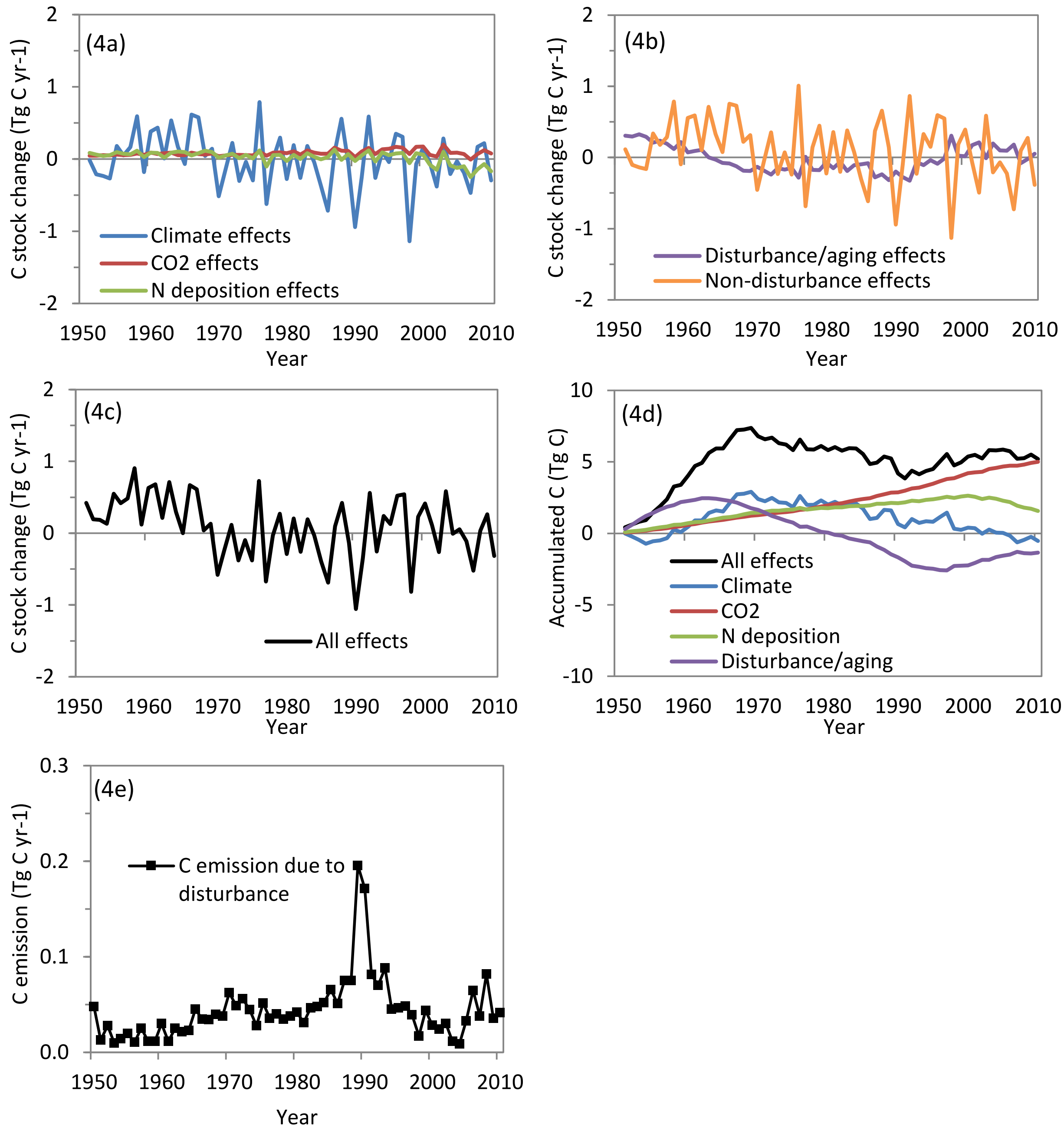


Figure 4.4. Changes in carbon stocks in the Francis Marion and Sumter National Forests due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Kisatchie National Forest

After maintaining a C sink for roughly two decades, forests in the Kisatchie National Forest switched from a C sink to a C source in the late 1970s (Fig. 4.4c). Changing C stocks were influenced primarily by climate effects (Fig. 4.4a), although disturbance/aging effects played an important role enhancing the C sink in the 1950s-1960s (Fig. 4.4b). The stand age distribution shows a period of elevated stand establishment 70-79 years old (1930s) when the National Forest was first designated. Though the Kisatchie NF was created from submarginal lands and extensively logged forests, restoration and rehabilitation were encouraged in the 1930s, likely fostering this pulse in stand establishment (Fig. 1.1e). The predominately loblolly/shortleaf pine stands (Fig. 4.1) would have been most productive around age 25 or in the 1950s and 60s (Fig. 4.2), corresponding to the positive disturbance/aging effects during this time period. There is a second, though more minor, pulse of stands which established 20-29 years ago or in the 1980s (Fig. 1.1e). This period of elevated establishment rates, the decline in C stock change due to disturbance/aging effects in the late 1980s (Fig. 4b), and the pulse of in C emissions in 1987 (Fig. 4.4e) were likely the result of the 1987 Kisatchie Hills Wilderness Fire that destroyed some 7000 acres.

Climate effects on changing C stocks fluctuated annually, though have become more negative over the past few decades. Warmer than average temperatures in 1990 and 1998 (Fig. 4.4b) caused forests to switch to a C source (Figs. 4.4a, c), as warmer temperatures favor increased decomposition and soil respiration. The notably warmer temperatures of the 1998 “heat wave” caused a loss of approximately 1.2 Tg C from the previous year (Fig. 4.4d). Increasing nitrogen (N) deposition (Fig. 4.3c) and atmospheric CO_2 concentrations had a small positive effect on C stocks, helping forests to accumulate additional C. However, due to declines in the amount of N deposition (Fig. 4.3c), the positive N deposition effect has also been declining in recent years (Fig. 4.4a, d). Overall, Kisatchie National Forest saw a net increase of approximately 8 Tg C between 1950 and 2010 (Figs. 4.4d).

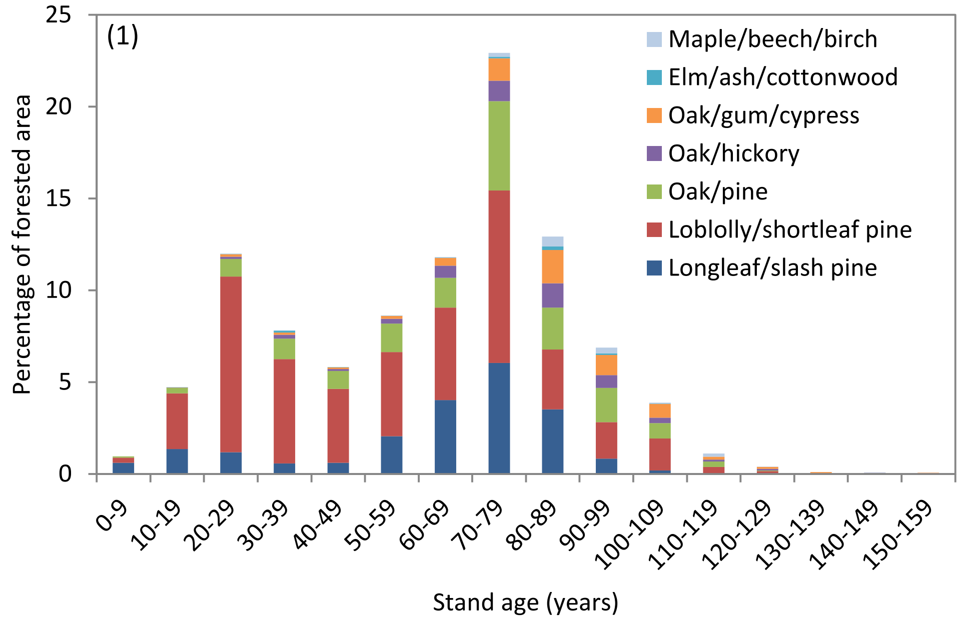


Figure 4.1. Age class distribution in 2010 in the Kisatchie National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

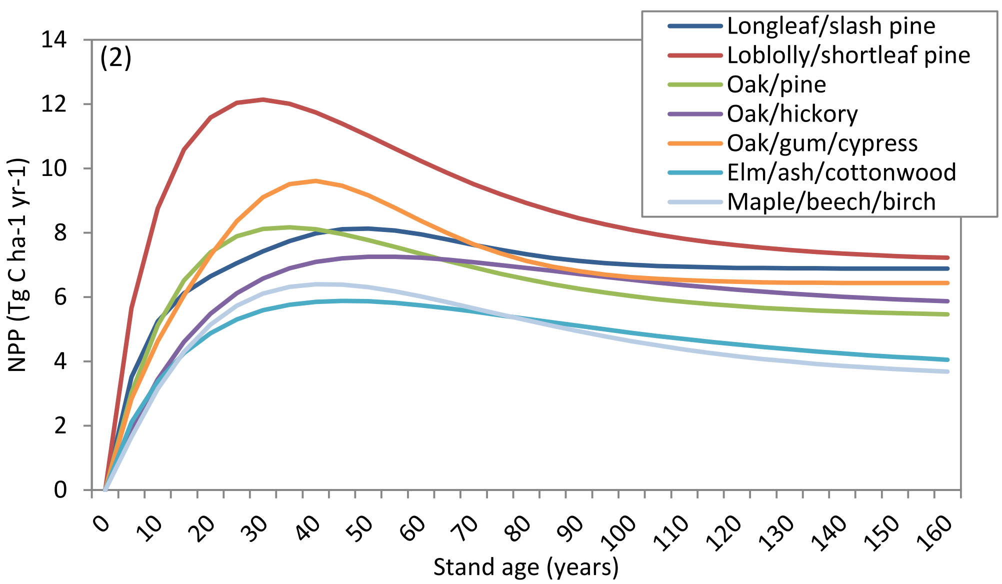


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Kisatchie National Forest.

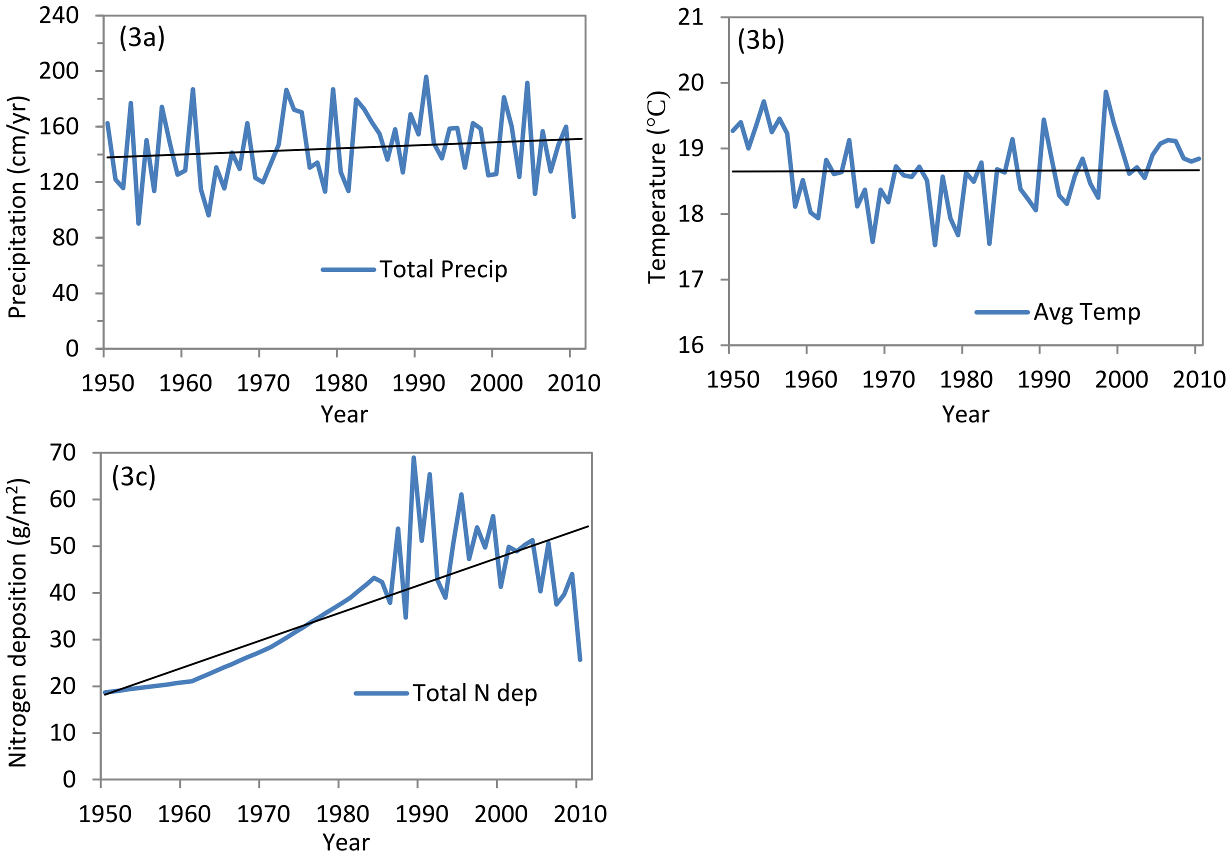


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Kisatchie National Forest. Linear trend lines shown in black.

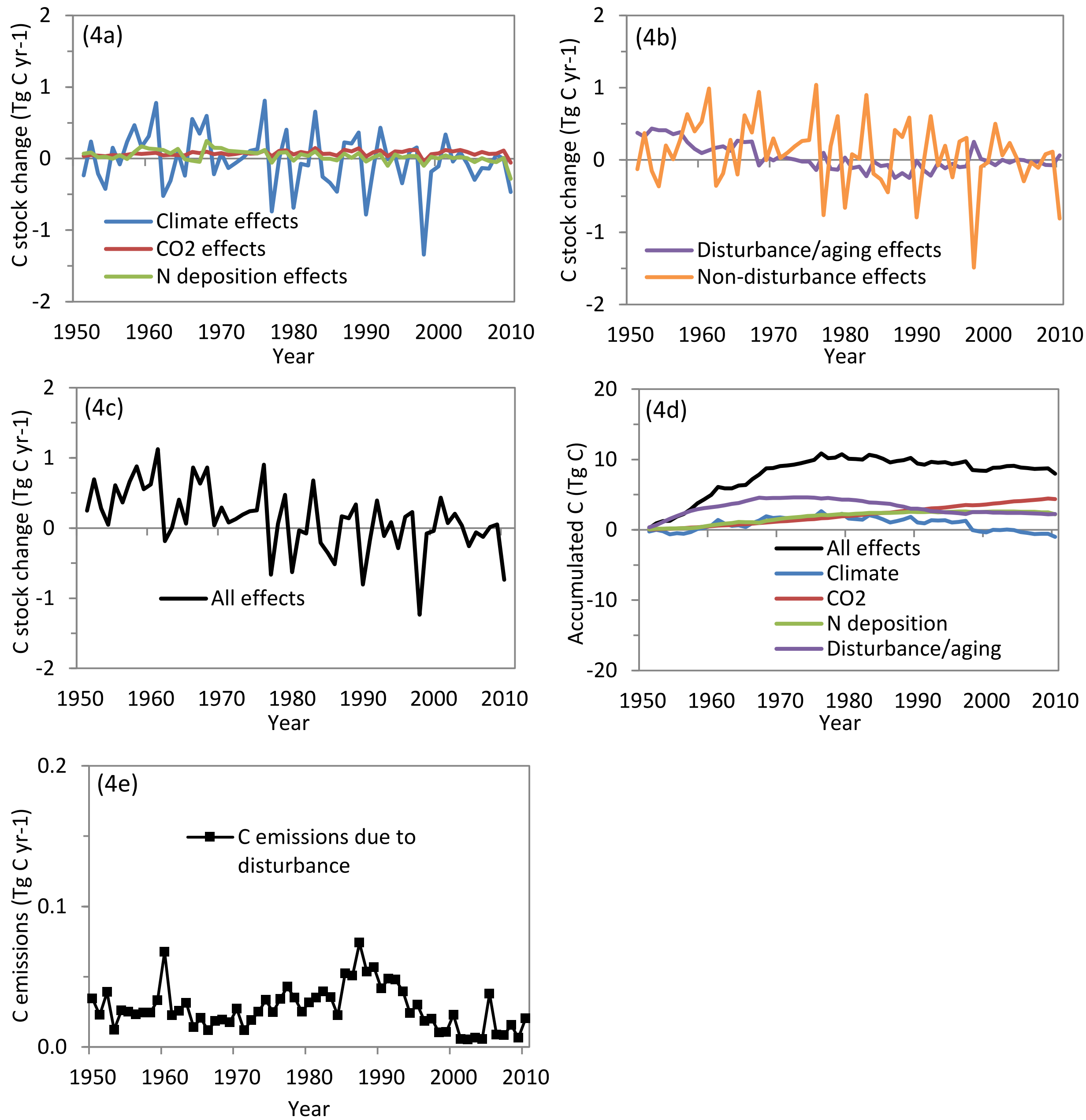


Figure 4.4. Changes in carbon stocks in the Kisatchie National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Ouachita National Forest

Forests in the Ouachita National Forest maintained a C sink from 1950 through the mid-1970s (Fig. 4.4c) due to positive disturbance/aging and climate effects (Figs. 4.4a-b). Forests then switched to mostly a C source through 2010 due to negative disturbance/aging effects (Fig. 4.4b). The stand age distribution indicates a period of elevated stand establishment 70-99 years ago (1911 to 1940) (Fig. 4.1f). This pulse of stand establishment is likely the result of restoration and recovery after extensive logging operations in the region. The predominately loblolly/shortleaf pine stands making up this pulse would have reached peak productivity around 35 years old (Fig. 4.2) or from the 1940s to 1970s, which is generally when disturbance/aging effects were positive (Fig. 4.4b) and forests were accumulating C (Fig. 4.4d). The stand age distribution shows a smaller pulse of stands 20-29 years old (Fig. 4.1), establishing during the 1980s. This pulse likely reflects regrowth after a disturbance event in 1984, as it also corresponds to a large decline in changing C stocks due to disturbance/aging and a pulse of C emissions (Figs. 4.4b, e). Despite maintaining a C source through 2010, forests have been able to slowly recover as more recent disturbances have been smaller (< 1% annually) and mostly low-moderate in severity (Fig. 1.1f).

Climate effects on changing C stocks have fluctuated with variability in temperature and precipitation. Changing C stocks generally decline when temperatures are warmer than usual such as in 1954 and 1998 (Figs. 4.3b, 4.4a), as warmer temperatures can increase soil respiration and decomposition. Specifically, the prominent heat wave of 1998 (Fig. 3b) caused the most significant C source over these few decades (Fig. 4.4a) and the forest lost approximately 2 Tg C during that year alone (Fig. 4.4d). Increasing nitrogen deposition and atmospheric CO_2 concentrations consistently promoted a C sink and helped forest to accumulate C despite losses due to disturbance/aging and climate effects (Fig. 4.4d). Between 1950 and 2010, forests in Ouachita National Forest experienced a net C gain of approximately 10.4 Tg C (Fig. 4.4d).

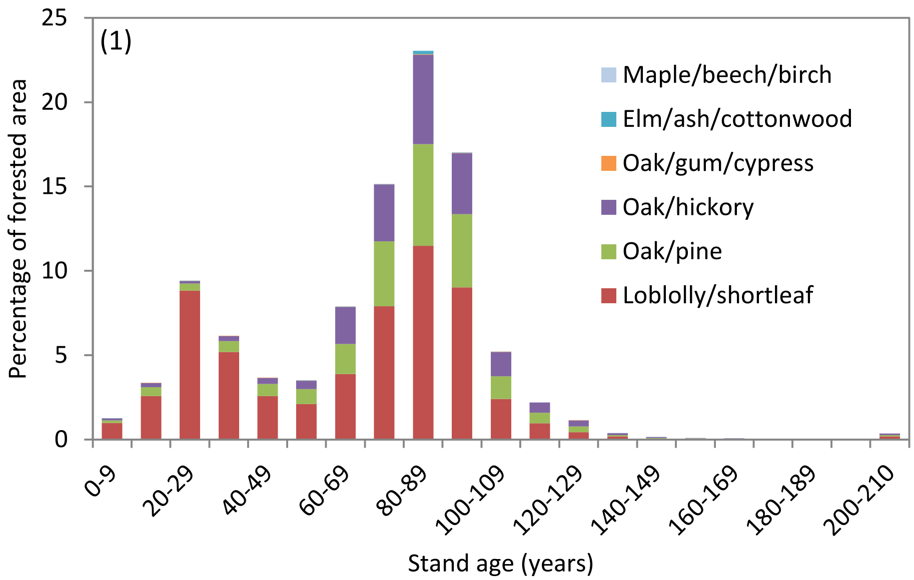


Figure 4.1. Age class distribution in 2010 in the Ouachita National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

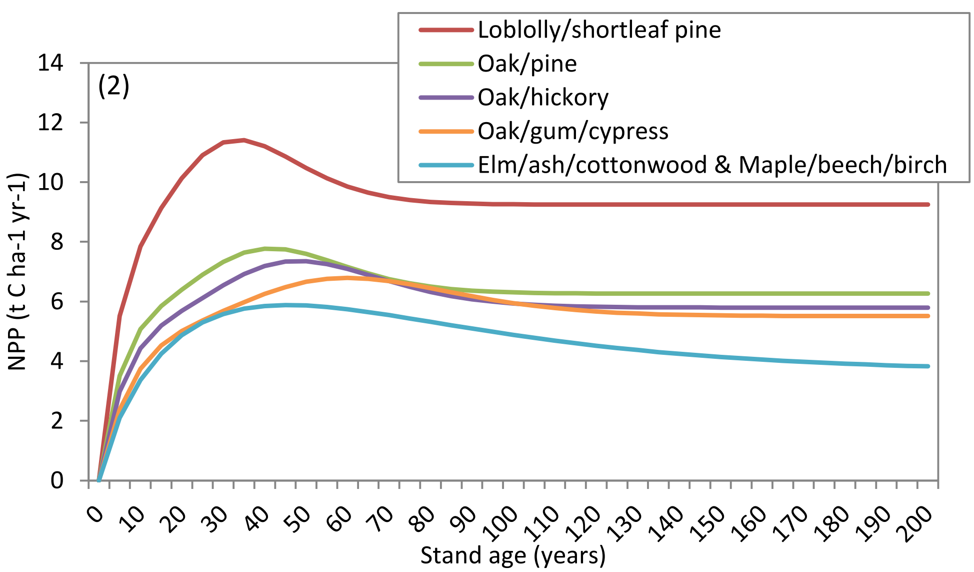


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Ouachita National Forest. Due to a small sample size and similar growth and yields, Maple/beech/birch stands were combined with Elm/ash/cottonwood stands for NPP-stand age modeling.

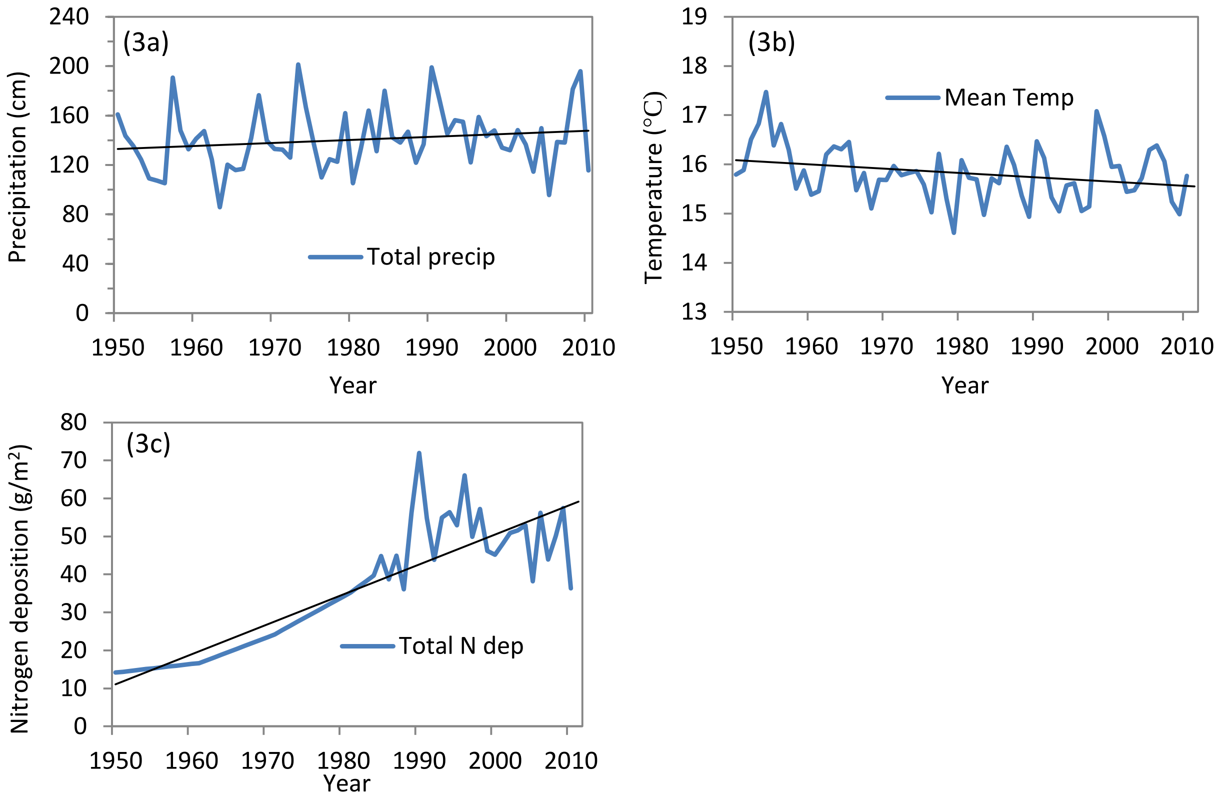


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Ouachita National Forest. Linear trend lines shown in black.

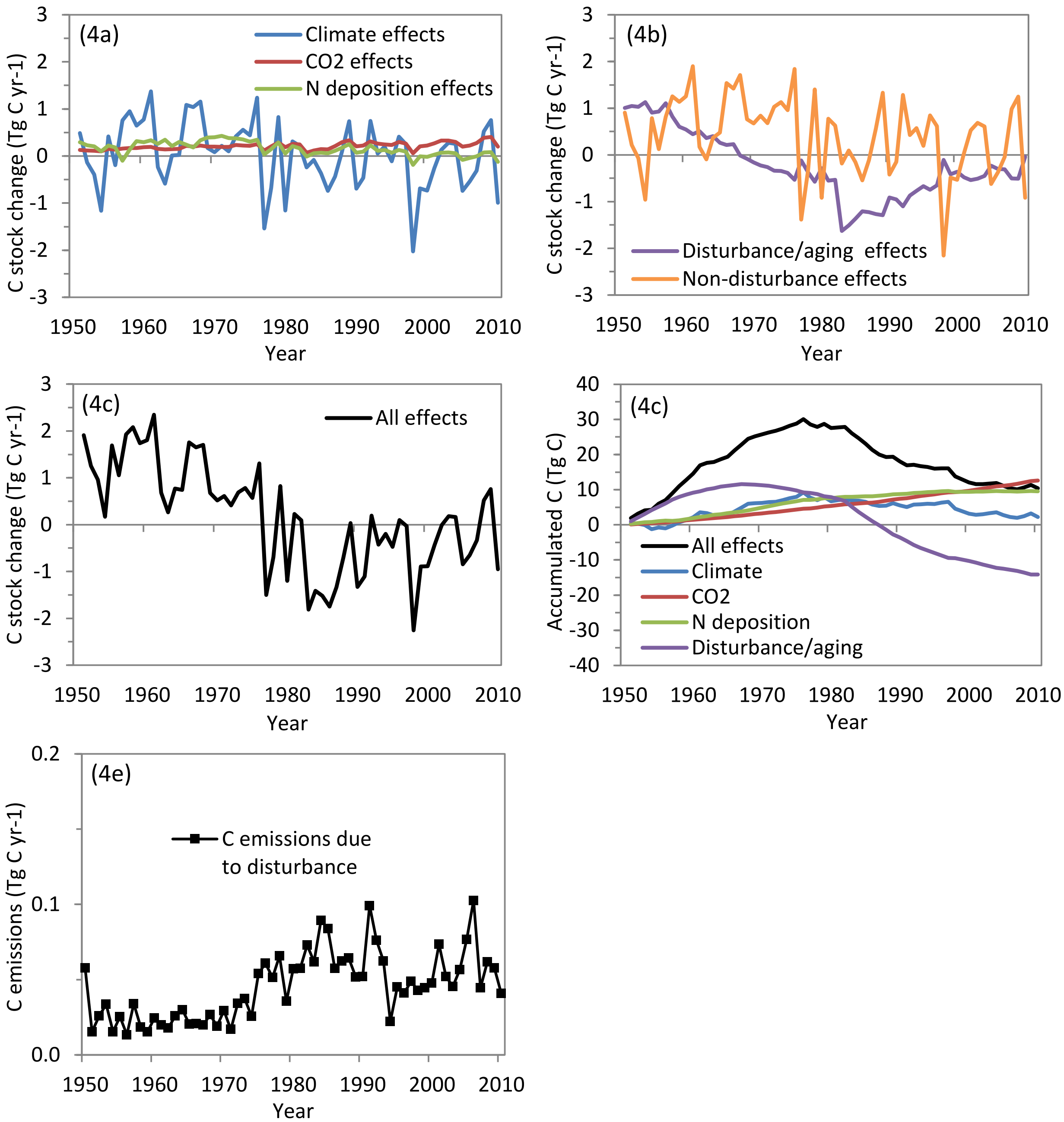


Figure 4.4. Changes in carbon stocks in the Ouachita National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Ozark-St. Francis National Forests

Forests in the Ozark-St. Francis National Forests fluctuated between a C sink and a C source, though were mostly a C source, especially since the 1970s (Fig. 4.4c). From the 1950-1960 disturbances/aging had positive effects on C flux, enhancing the forest C sink, but after 1960 effects were consistently negative, adding to the C source (Fig. 4.4b). This decline is due to a strong aging effect as the significant pulse of mostly Oak/hickory stands establishing 80-99 years ago (Fig. 4.1) during the 1910s-1930 have aged beyond their maximum productivity (Fig. 4.2). Ozark St. Francis National Forest experienced mostly small (< 0.5% of forest annually), low-moderate severity harvests from 1991-2010 (Fig. 1.1g), which had a minimal effect on C emissions (Fig. 4.4e). Though disturbance/aging effects remained negative through 2010, the lack of large and severe disturbances in recent decades may have allowed the forest to recover and C stock change due to disturbance/aging effects to approach zero (Fig. 4.4b).

Climate effects on changing C stocks fluctuated annually between positive and negative. Very warm years such as 1954 and 1998 had negative effects on C stocks, causing forests to be a source, whereas cooler years, with average to above average precipitation (ex. 1958, 1979, 2008) had positive effects, enhancing the C sink (Figs. 4.3a-b, 4.4a). Warmer temperatures can increase decomposition rates and subsequently soil respiration. Increases in nitrogen (N) deposition and atmospheric CO_2 concentrations had a positive effect on changing C stocks (Fig. 4.4a) and C accumulation (Fig. 4.4d). However due to C losses associated with an aging forest, by 2010 the forest experienced a net loss of 3.2 Tg C as compared to 1950 levels. C losses would have been much more significant if it was not for the C gains due to N deposition, CO_2 fertilization, and to a lesser extent climate (Fig. 4.4d).

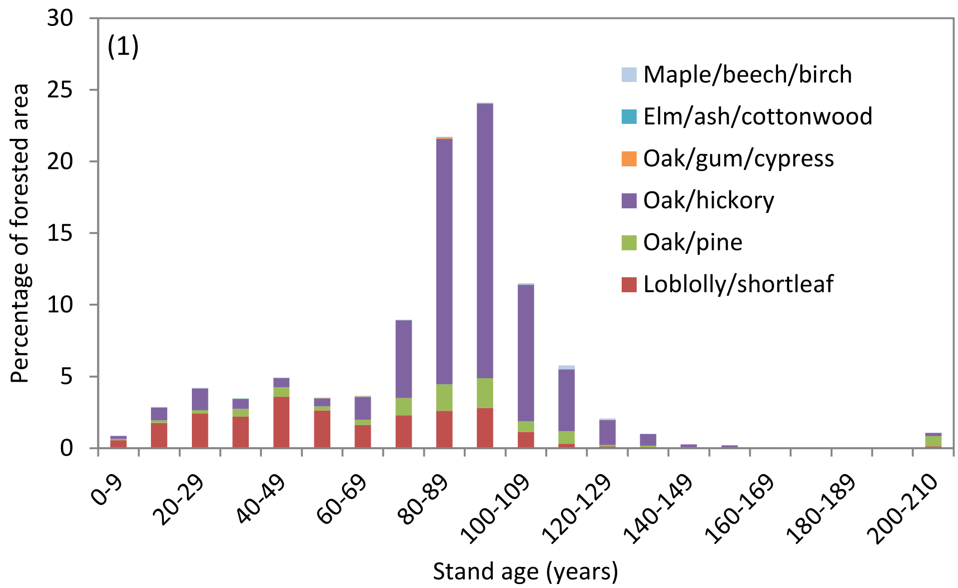


Figure 4.1. Age class distribution in 2010 in the Ozark-St. Francis National Forests displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

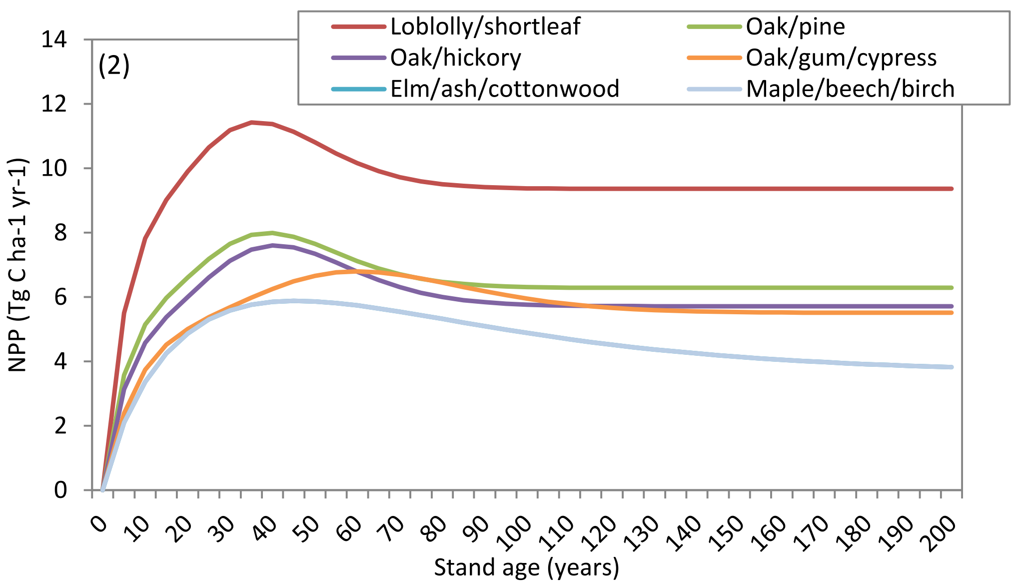


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type in the Ozark-St. Francis National Forests.

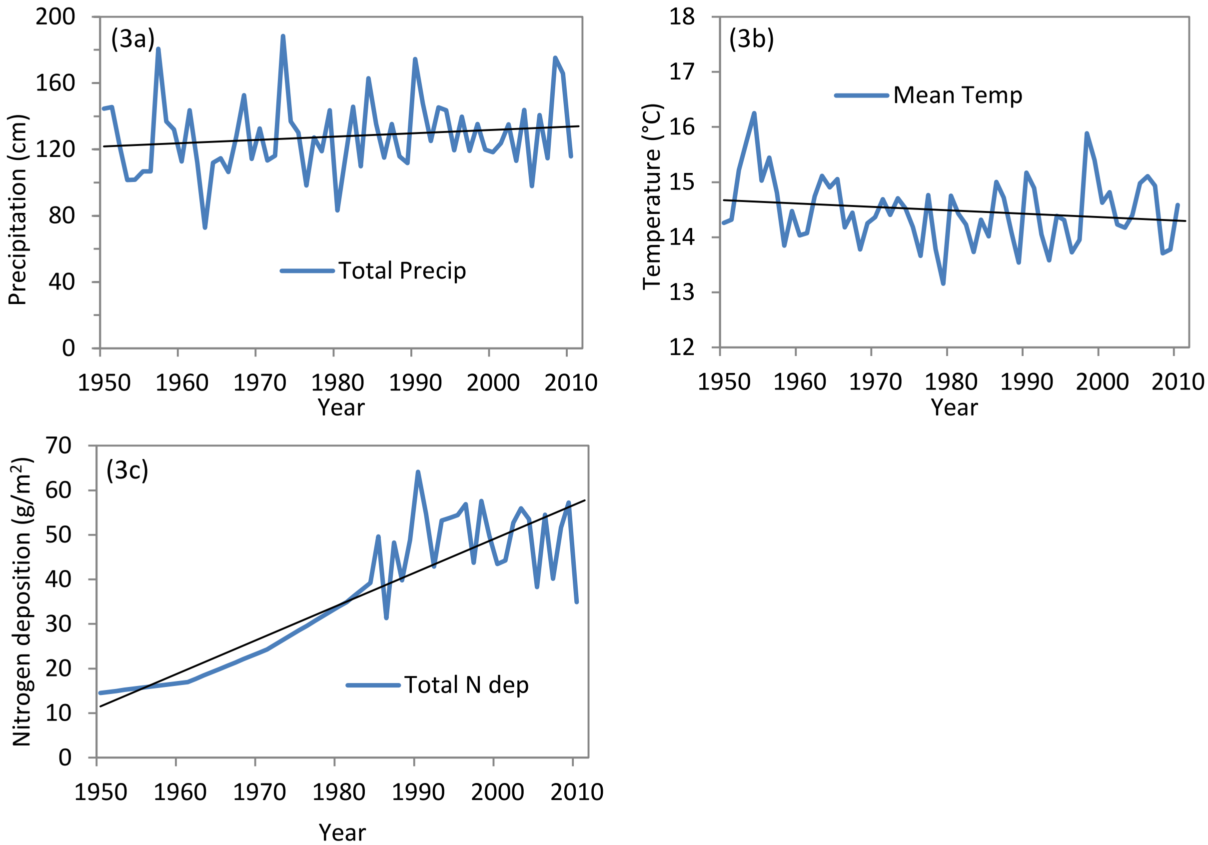


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Ozark-St. Francis National Forests. Linear trend lines shown in black.

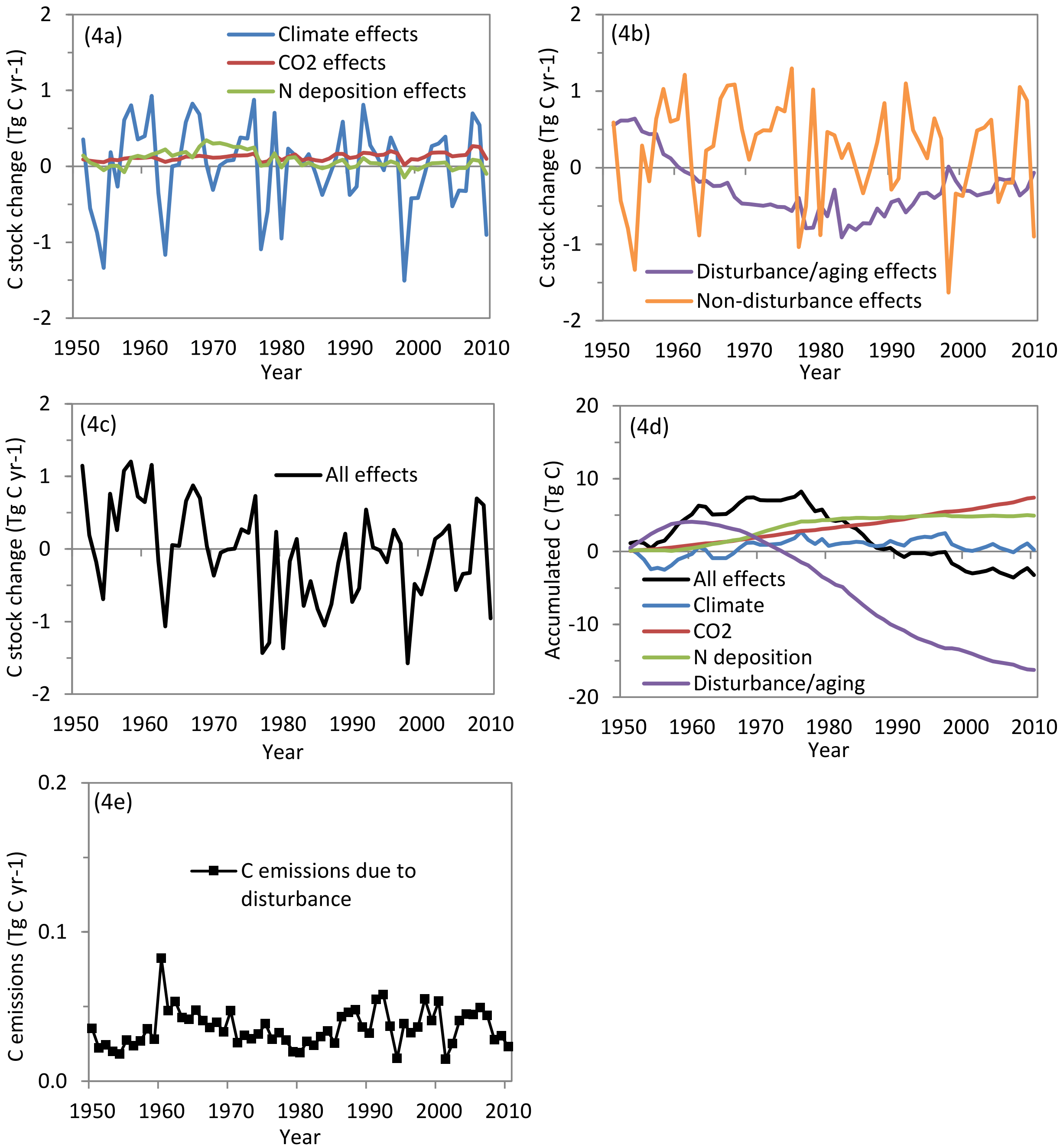


Figure 4.4. Changes in carbon stocks in the Ozark-St. Francis National Forests due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1951-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects

National Forests in Texas

Forests in the National Forests of Texas generally maintained a C sink in the 1950s and 1960s (Fig. 4.4c), but thereafter C accumulation slowly declined (Fig. 4.4d) and the forests fluctuated between a C sink and source through 2010 (Fig. 4.4c). Disturbance/aging effects promoted the C sink during the 1950s, as stands that regenerated after intensive harvesting in the 1920s were at their most productive ages (Fig. 4.2). The stand age distribution shows a pulse of predominantly loblolly/shortleaf pine stands aged 70-99, which were establishing between 1911 and 1940 (Fig. 4.1). These stands would have reached peak productivity at age 25 (Fig. 4.2) or between the mid-1930s-1960s, when forests were accumulating C due to disturbance/aging (Fig. 4.4d). By the mid-to-late 1960s, forests had aged beyond this maximum productivity and disturbance/aging effect declined and became negative for several decades. A smaller pulse of stands aged 20-39 years old were establishing between 1971 and 1990 (Fig. 4.1) and reached peak productivity in the mid-1990s, when aging/disturbance effects started to increase C again (Fig. 4.4b, d). Recent disturbances were mostly moderate-high intensity harvests, but were very small (Fig. 1.1h) thus did not greatly influence C emissions (Fig. 4.4e), C flux, or the forest age structure.

Climate effects on changing C stocks fluctuated with inter-annual variability in temperatures and precipitation (Fig. 4.4a). For instance, cooler temperatures in the late-1950s to early-1960s promoted a C sink as cooler temperatures can reduce soil respiration and decomposition rates. On the other hand, warmer than usual temperatures such as the heat wave in 1998, and the generally warmer temperatures of the past decade (Fig. 4.3b) increased the rates of respiration and decomposition, thus climate has more recently promoted a C source (Fig. 4.4c) and declines in C accumulation (Fig. 4.4d). Sustained positive effects of both nitrogen (N) deposition and atmospheric CO_2 promoted a C sink and helped forest to accumulate more C, but their effects were overshadowed by the stronger, slightly negative effects of climate and disturbance/aging since the late 1998s. Between 1950 and 2010 the forest experienced a small net loss of approximately 1.8 Tg C (Fig. 4.4d).

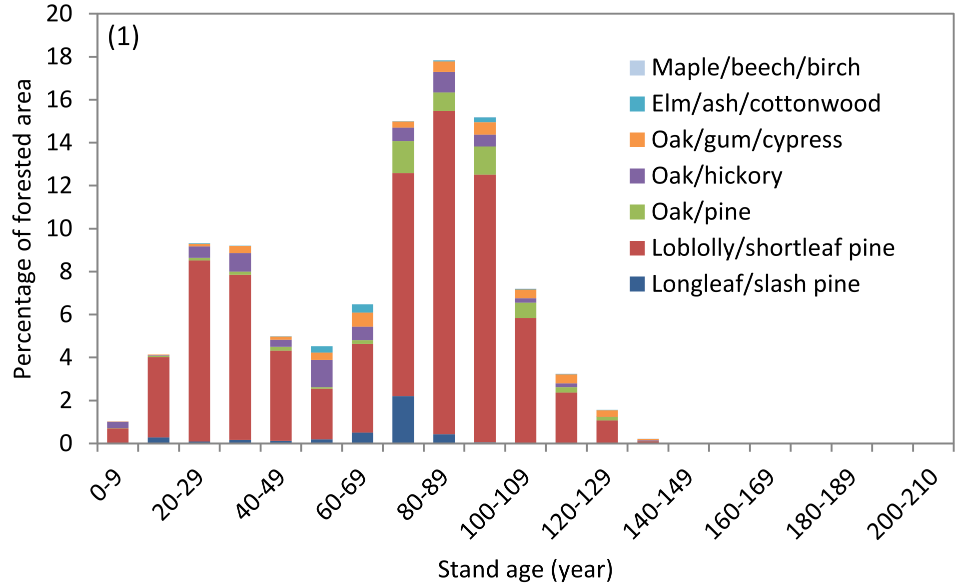


Figure 4.1. Age class distribution in 2010 in the National Forests of Texas displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

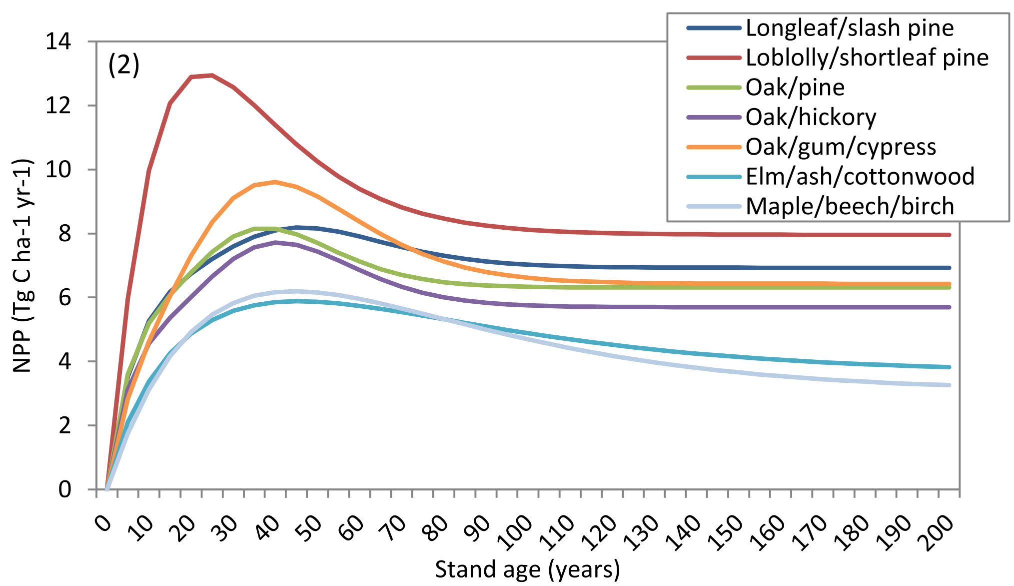


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the National Forests of Texas.

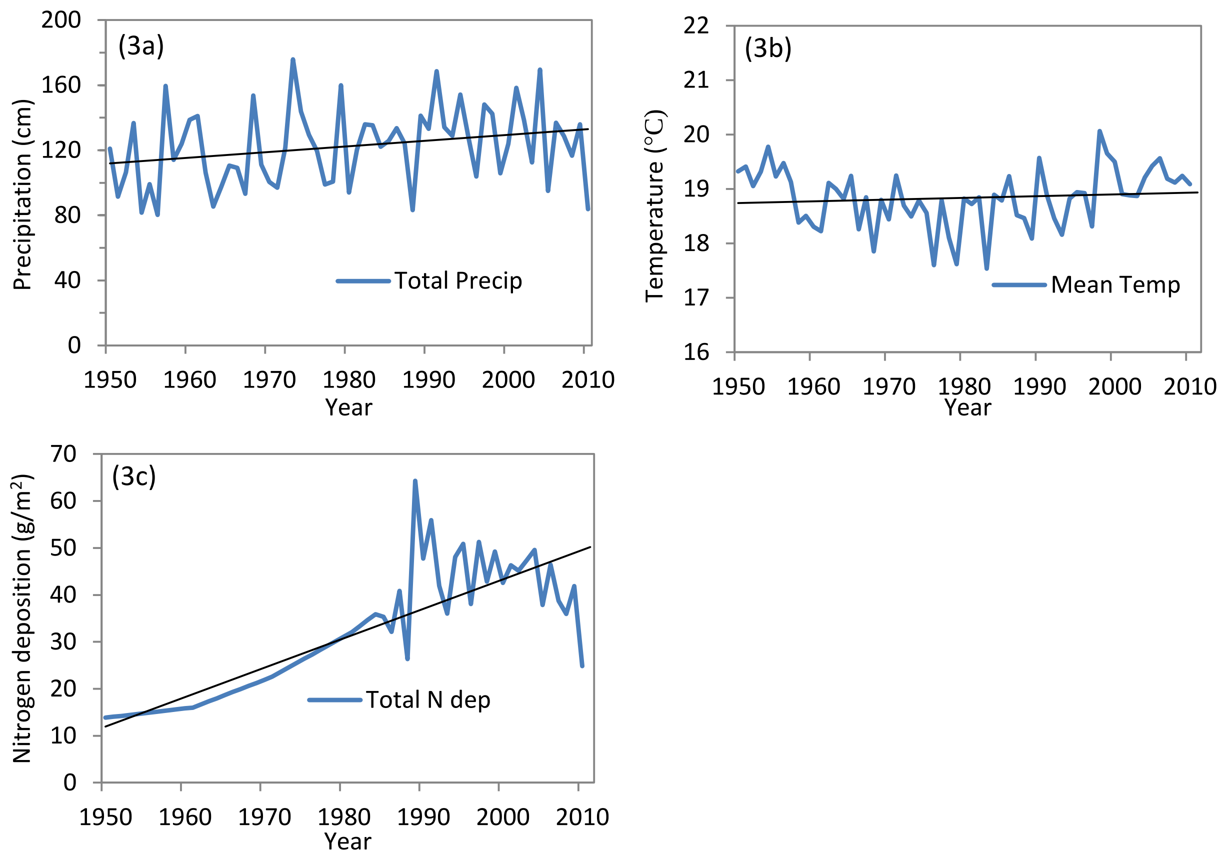


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the National Forests of Texas. Linear trend lines shown in black.

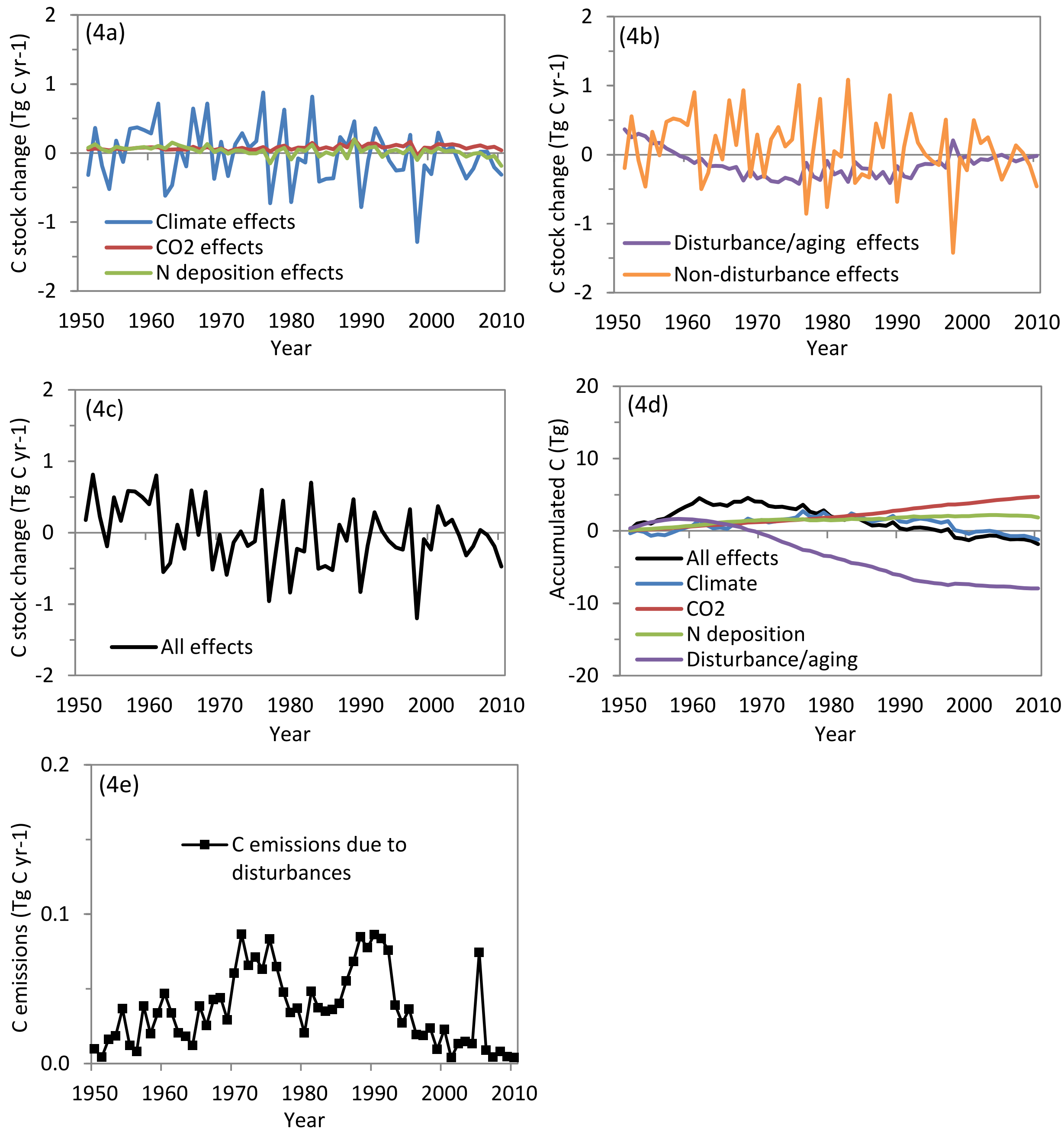


Figure 4.4. Changes in carbon stocks in the National Forests of Texas due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Chattahoochee-Oconee National Forest

Forests in the Chattahoochee National Forest switched from a C sink to a C source in the early 1960s and have remained a C source through 2010 (Fig. 4.4c). Disturbance and aging effects have been largely responsible for the declining C stocks, while non-disturbance effects have had lesser but generally positive effects (Fig. 4.4b). This decline in C is primarily due to a strong aging effect as ~73% of the forest is > 70 years old (Fig. 4.1), thus their rates of productivity have declined (Fig. 4.2). The stand age distribution shows a pulse of stands that established from 1900-1940 (70-109 years old) (Fig. 4.1), which likely represents regeneration of the forests which were originally denuded for hydraulic mining and lumber in the late 1800s and early 1900s, then replanted by the Civilian Conservation Corp in the 1930s. These stands which consist of predominantly Oak/Hickory forests would have been most productive from ages 25-30 (Fig. 4.2) or between roughly 1930 and 1970. Although recent disturbances generally been small harvests (Fig. 1.1i), there may have been several large and/or more severe disturbances such as in 1978, 1983, and 1992, that caused increases in C emissions (Fig. 4.4e), and further negative disturbance/aging effects (Fig. 4.4b).

Climate effects were initially negative, promoting a C source in the early 1950s (Fig. 4.4c) due to warmer temperatures (Fig. 4.4b) which increase soil respiration and decomposition rates. While climate effects have been quite variable, following variability in temperature and precipitation, when combined with nitrogen deposition and CO_2, the combined non-disturbance effect has generally been positive. Although these non-disturbance effects promoted a C sink (Fig. 4.4b) and caused positive C accumulation (Fig. 4.4d), non-disturbance effects were greatly overshadowed by the stronger, negative disturbance and aging effects, resulting in a net loss of roughly 12.1 Tg C between 1950 and 2010 (Fig. 4.4d).

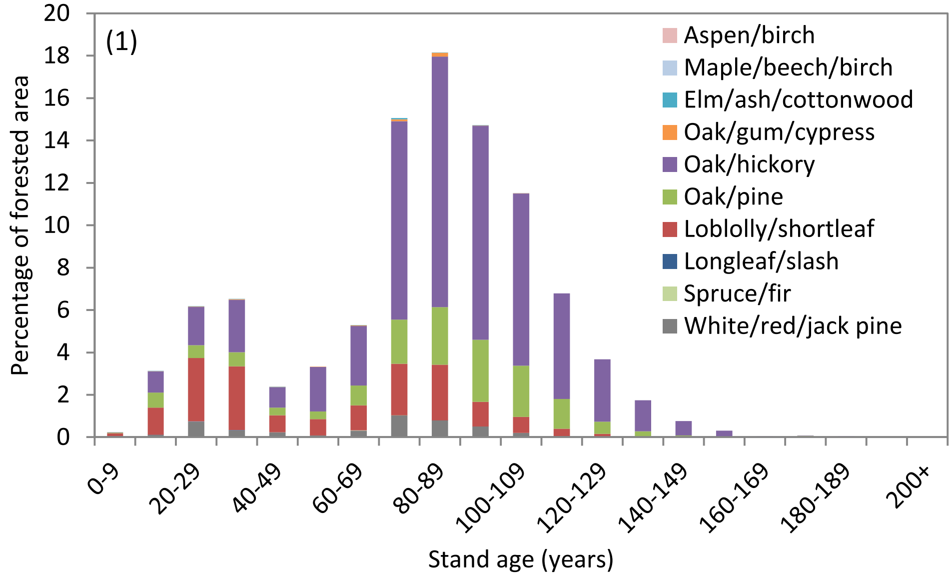


Figure 4.1. Age class distribution in 2010 in the Chattahoochee National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

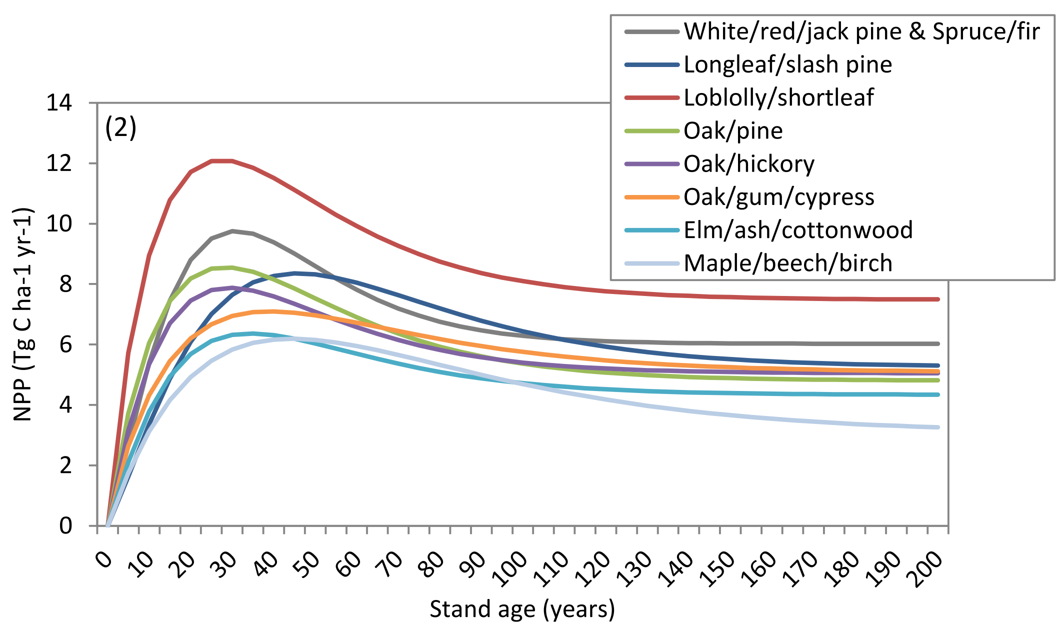


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Chattahoochee National Forest. Due to a small sample size Spruce/fir stands were combined with White/red/jack pine stands for modeling NPP-age relationships, given their similar growth and yield trends.

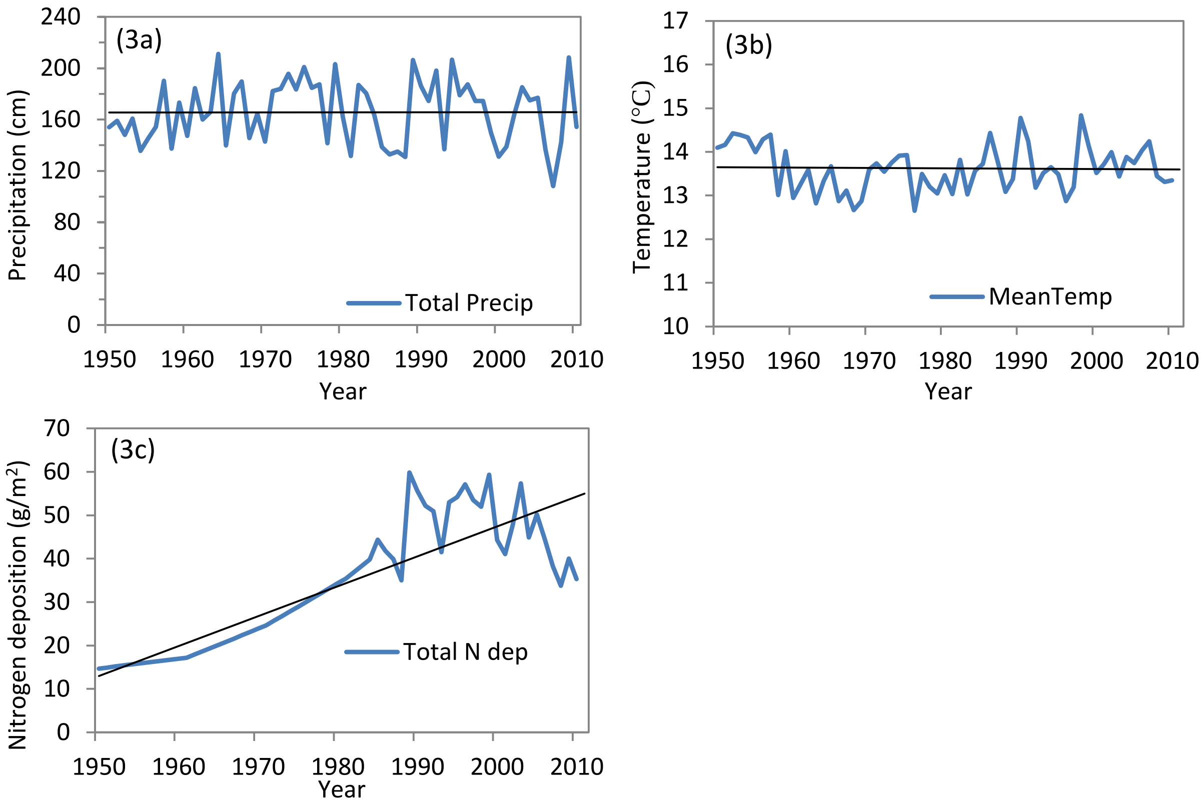


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Chattahoochee National Forest. Linear trend lines shown in black.

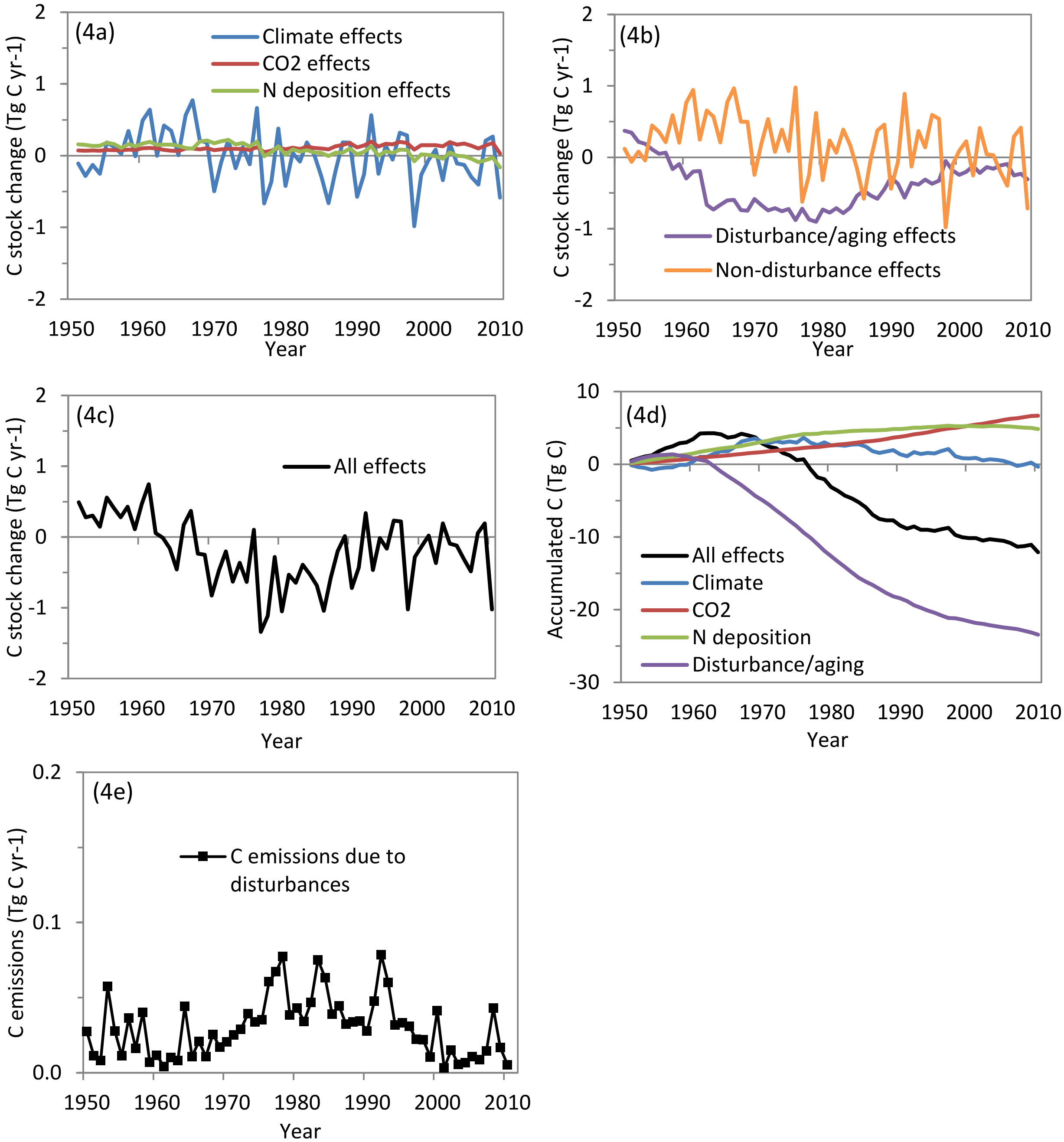


Figure 4.4. Changes in carbon stocks in the Chattahoochee National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Cherokee National Forest

Forests in the Cherokee National Forest maintained a small C sink in the 1950s, then switched to a C source in the early-mid 1960s and remained a source through 2010 (Fig. 4.4c). Disturbance and aging effects have been largely responsible for the declining C stocks, while non-disturbance effects have had lesser but generally positive effects (Fig. 4.4b). This negative disturbance/aging effect is primarily due to the forest aging and declining in productivity, as roughly 77% of the stands are > 70 years old (Fig. 1.1j), thus have aged past their maximum productivity (Fig. 2). The stand age distribution shows a pulse of stands that were establishing from 1910-1930 (80-100 years old) (Fig. 4.1j), which likely represents regeneration after forests were heavily harvested for timber or cleared for agriculture and development in the late 1800s and early 1900s. These stands which consist of predominantly Oak/Hickory forests would have been at most productive at age 35 (Fig. 4.2) or between roughly 1945 and 1965, which is when forests were still a C sink (Fig. 4.4c). As stands continued to age, productivity declined to the point where C losses due to decomposition and decay were greater than gains, causing the forest to remain a C source. Recent disturbances have generally been small and low-severity (Fig. 1.1j), thus did not increase C emissions, alter stand age, or affect C stocks greatly.

While climate effects have been quite variable (Fig. 4.4a), following variability in temperature and precipitation (Figs. 4.3a-b), cumulatively climate did not significantly affect C accumulation from 1950-2010 (Fig. 4.4d). However, in the late 1990s and 2000s, climate effects were mostly negative due to warming temperatures which increase soil respiration and C loss. Nitrogen deposition and atmospheric CO_2 effects mostly promoted a C sink and C accumulation (Fig. 4.4a, d). However, these positive non-disturbance effects were greatly overshadowed by the stronger, negative disturbance/aging effects, resulting in a net loss of roughly 13.6 Tg C between 1950 and 2010 (Fig. 4.4d).

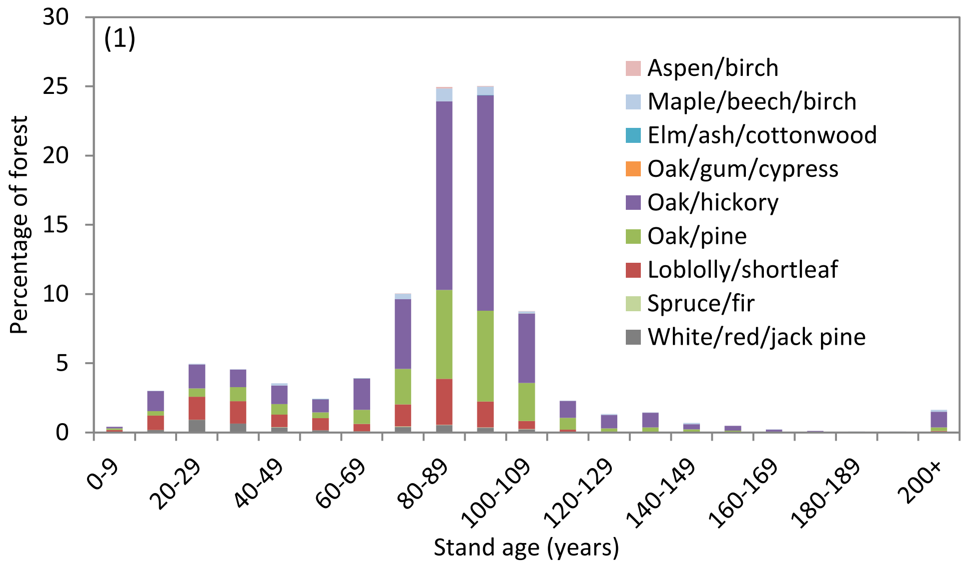


Figure 4.1. Age class distribution in 2010 in the Cherokee National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

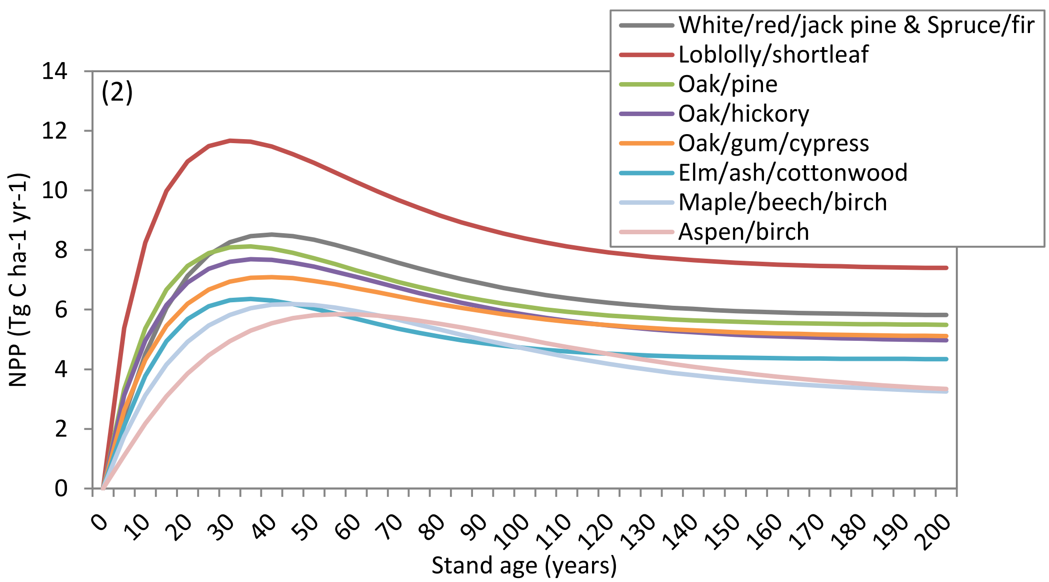


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Cherokee National Forest. Due to the low number of Spruce/fir stands and similar growth and yields, they were combined with White/red/jack pine stands for modeling NPP-age relationships.

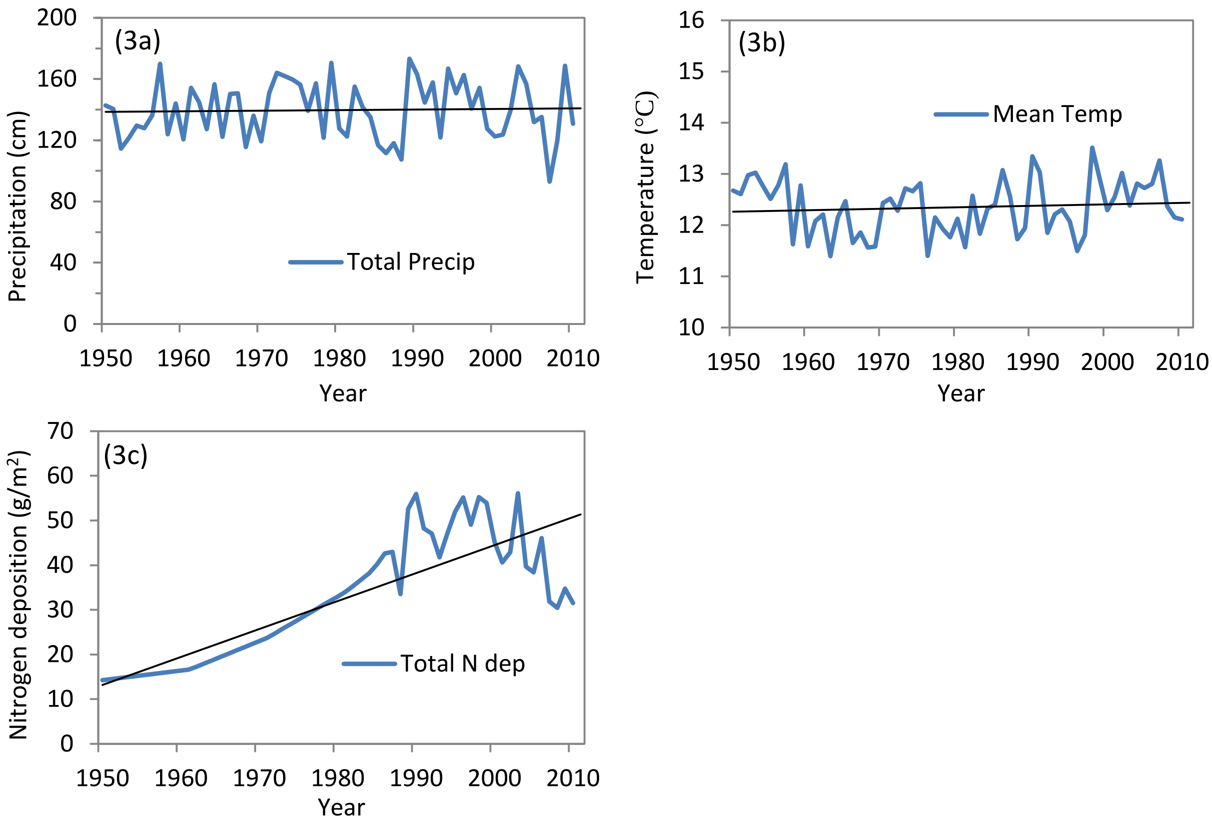


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Cherokee National Forest. Linear trend lines shown in black.

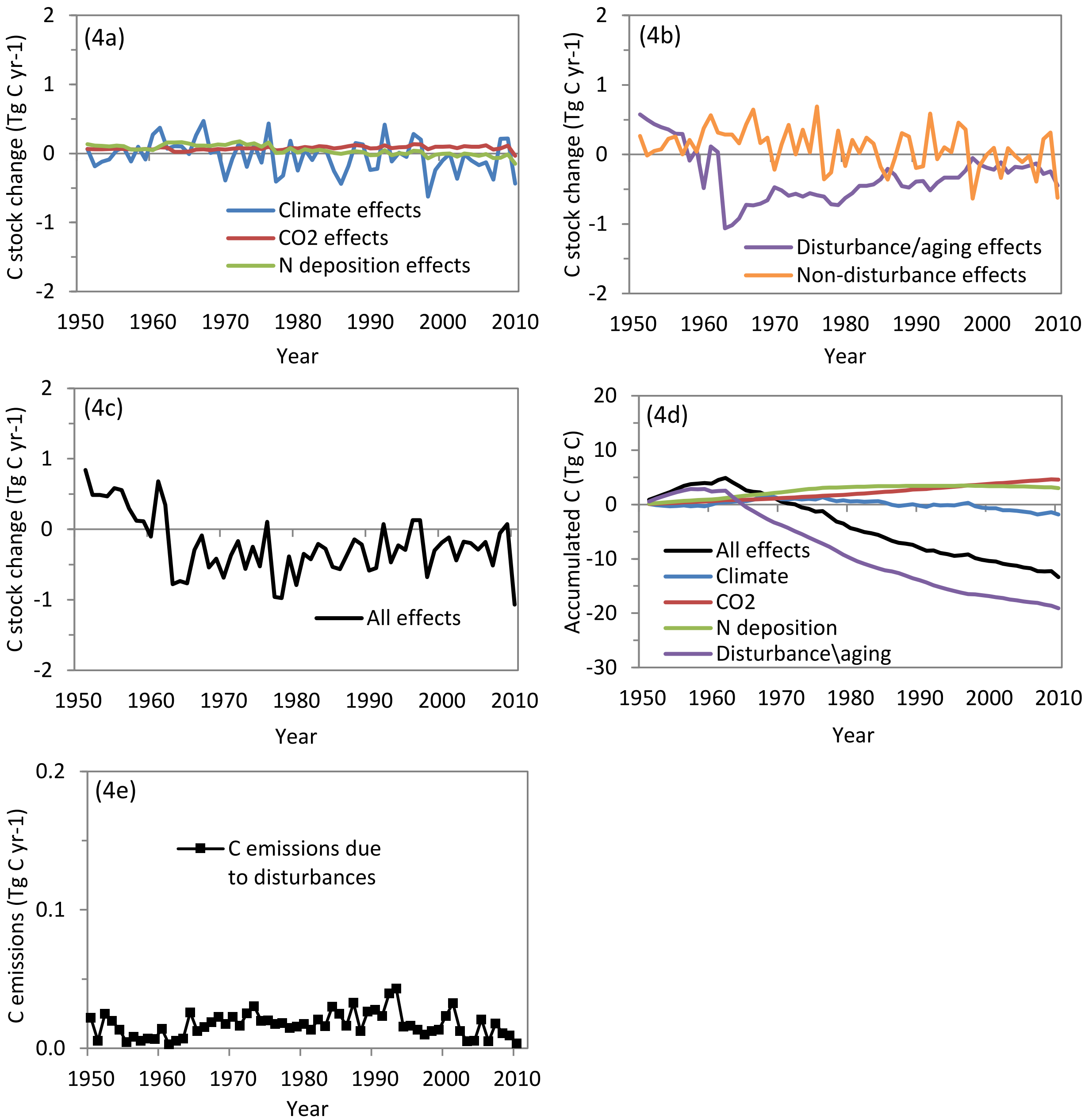


Figure 4.4. Changes in carbon stocks in the Cherokee National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

Daniel Boone National Forest

Forests in the Daniel Boone National Forest fluctuated between a small C sink and source, but were mostly a C sink from 1950 into the mid-1970s and more often a C source through 2010 (Fig. 4.4c). A combination of negative disturbance and aging effects and mostly positive non-disturbance factors were responsible for fluctuating C stocks (Fig. 4.4b). The stand age distribution shows that a pulse of stands, largely consisting of oak/hickory, were establishing roughly 80-109 years ago (1901-1930). These stands would have been most productive around 35 years old (Fig. 4.2) or 1935-1965. This period corresponds to when disturbance/aging effects were promoting a C sink (Fig. 4.4b) and the forests were accumulating C (Fig. 4.4d). Small disturbances in the 1960s, likely timber harvests, again caused a greater release of C (Fig. 4.4e) and enhanced the C source, but were often counteracted by the positive climate effects, such that the forest remained a C sink. Recent disturbances have been relatively small, less severe, and have declined since the 1990s (Fig. 1.1k) resulting in low rates of stand establishment in recent years (Fig. 4.1).

From the 1950s through the 1970s, climate effects fluctuated between positive and negative following variability in temperature and precipitation. Generally cooler years like 1976 had a positive effect on C stocks while warmer years like 1998 had a negative effect (Fig. 4.3b, 4.4a), as warmer temperatures increase decomposition rates and soil respiration. Nitrogen deposition and atmospheric CO_2 concentrations consistently promoted a small C sink and C accumulation (Fig. 4.4a, d). After the short period of C accumulation due the positive disturbance and non-disturbance effects, C accumulation declined slightly in the late 1970s-early 1980s due to negative climate and disturbance/aging effects. From the 1980s through 2010, C accumulation remained relatively stable, around zero, due to the balance of the positive non-disturbance effects and more negative disturbance/aging effects (Fig. 4.4d).

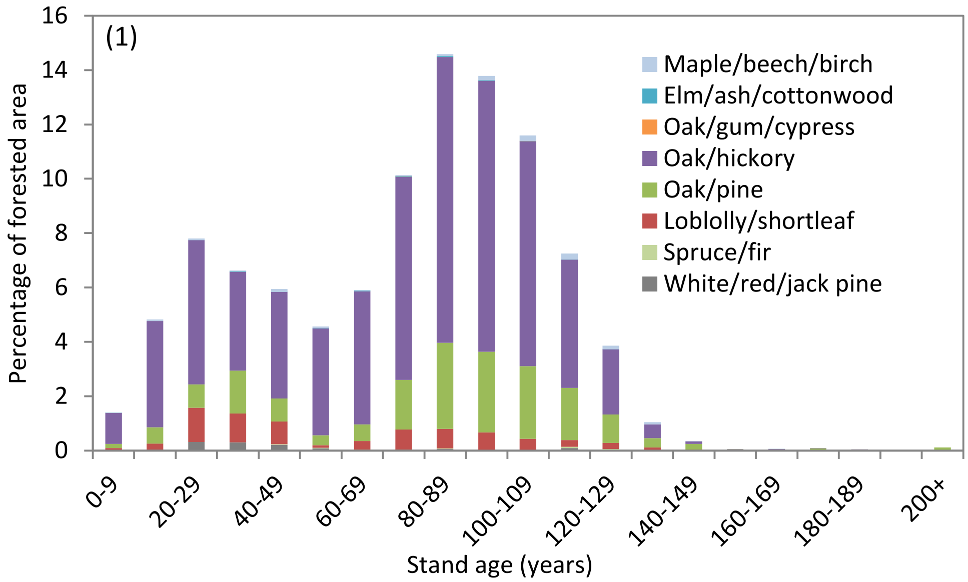


Figure 4.1. Age class distribution in 2010 in the Daniel Boone National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

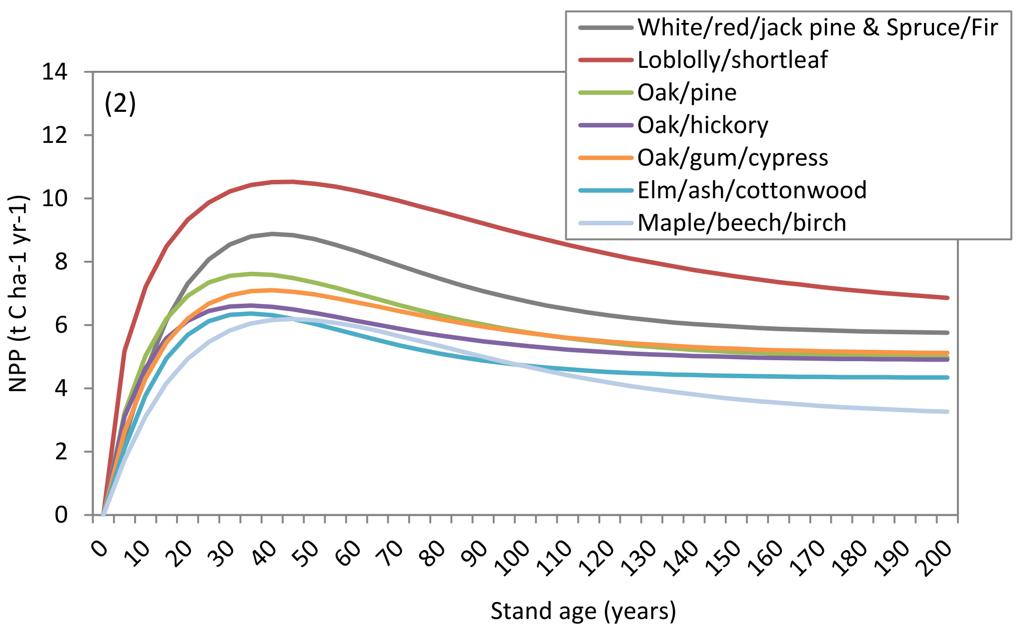


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Daniel Boone National Forest. Due to the low number of Spruce/fir stands and similar growth and yields, they were combined with White/red/jack pine stands for modeling NPP-age relationships.

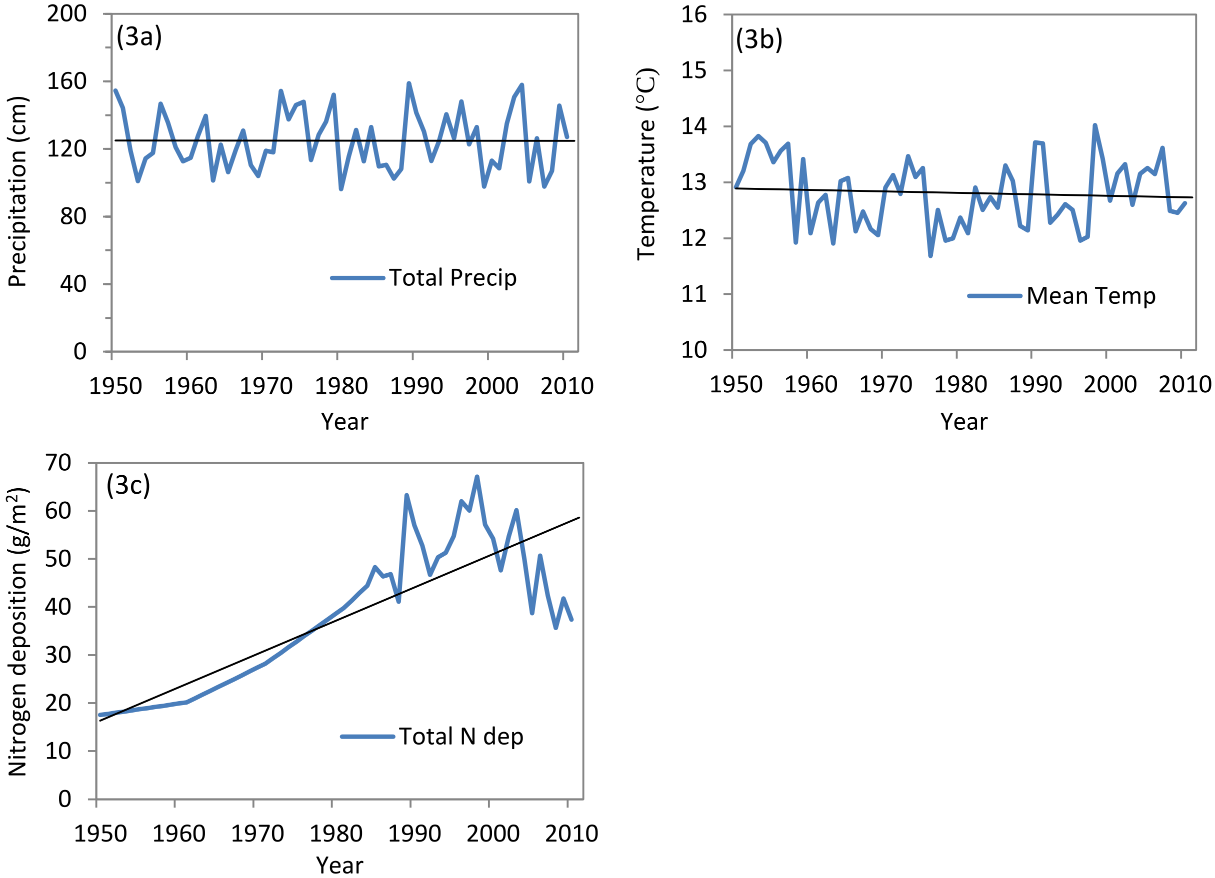


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Daniel Boone National Forest. Linear trend lines shown in black.

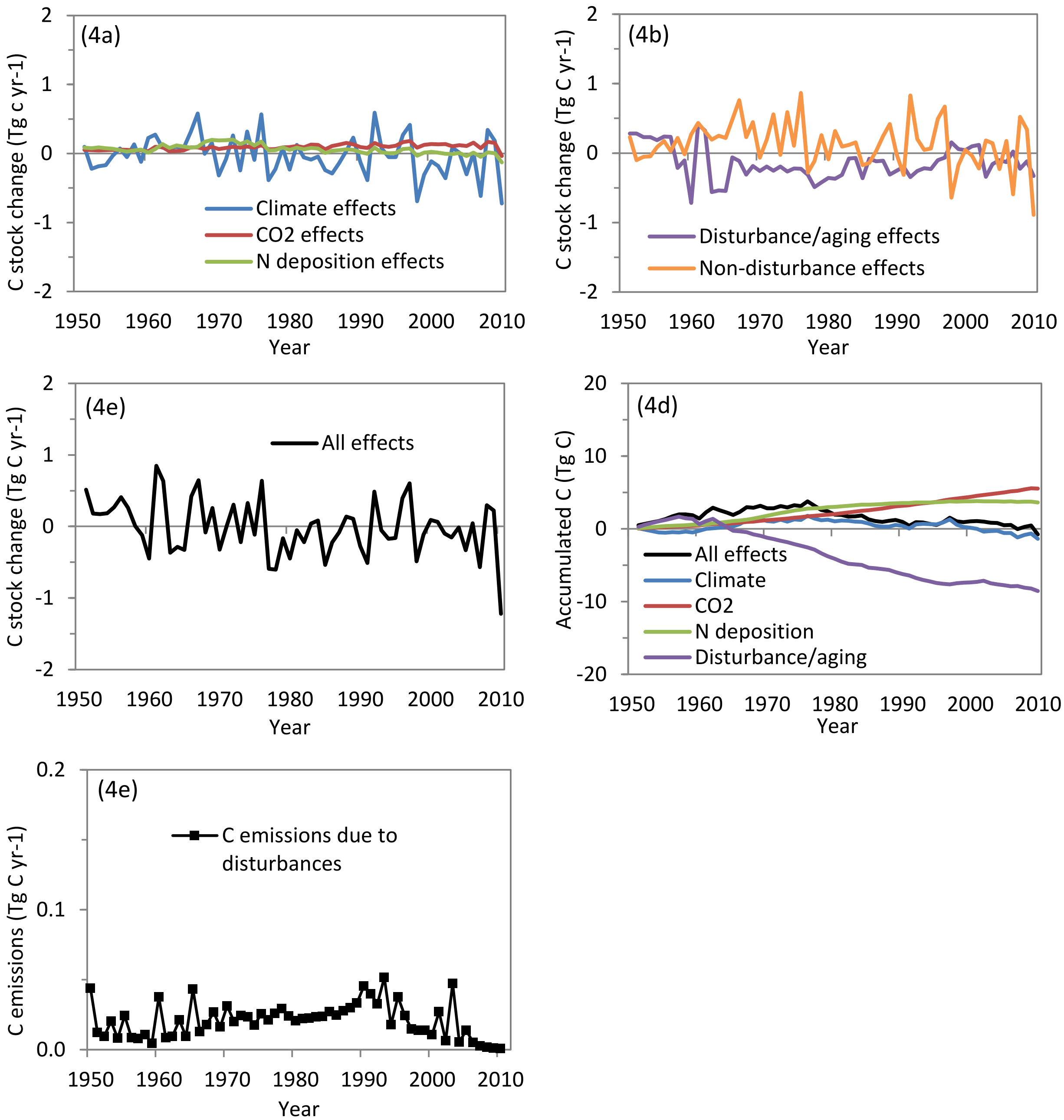


Figure 4.4. Changes in carbon stocks in the Daniel Boone National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

National Forests in North Carolina

Between 1951 and the 1960s, forests in the National Forests in North Carolina maintained a C sink then shifted to mostly a C source through 2010 (Fig. 4.4b). During the 1950s and 1960s, disturbance/aging effects promoted a C sink (Fig. 4.4b) and rapid increase in C accumulation (Fig. 4.4d). This trend is supported by the stand age distribution (Fig. 4.1), which shows a pulse of stands aged 70-99 years old that were establishing from 1911-1940. These stands were likely a result of restoration management after a period of intensive logging and land use in the late 1800s and early 1900s. According to the NPP-age relationships, these stands mostly consisting of Oak/hickory, Loblolly/shortleaf pine, and Oak/pine would have been most productive at roughly 30-45 years of age (Fig. 4.2) or through much of the mid-1900s when forests were a C sink (Fig. 4.4c). As these forests further aged and productivity declined, C losses due to decomposition and decay exceeded C gains causing the C source (Fig. 4.4b). Despite relatively large disturbances in the early 1990s (fires and harvests) (Fig. 1.1l), recent disturbances have been quite small (<1% of the forested area) and less severe, thus did not affect stand age, C emissions (Fig. 4.4e) or changing C stocks dramatically (Fig. 4.4b).

Climate variability, mainly temperature variability, influenced changing C stocks throughout the past few decades. For instance, warmer temperatures in 1990 and 1998 (Fig. 4.3b) caused a greater C source (Figs. 4.4a, c). Warmer temperatures increase evaporative demands and soil respiration causing a loss of C. Though highly variable, overall climate did not affect C accumulation greatly (Fig. 4.4d). Increasing CO_2 and nitrogen (N) deposition (Fig. 4.3c) had mostly positive effects, promoting a C sink (Fig. 4.4a) and C accumulation (Fig. 4.4d). Declines in N deposition and further increases in CO_2 over the past few decades have caused the CO_2 effect to become stronger than that of N deposition (Fig. 4.4d). The C gains due to the CO_2 and N deposition effects were not significant enough to offset the C losses due to disturbance/aging, therefore, the forest experienced a net C loss of 6.6 Tg C from 1950-2010 (Fig. 4.4d).

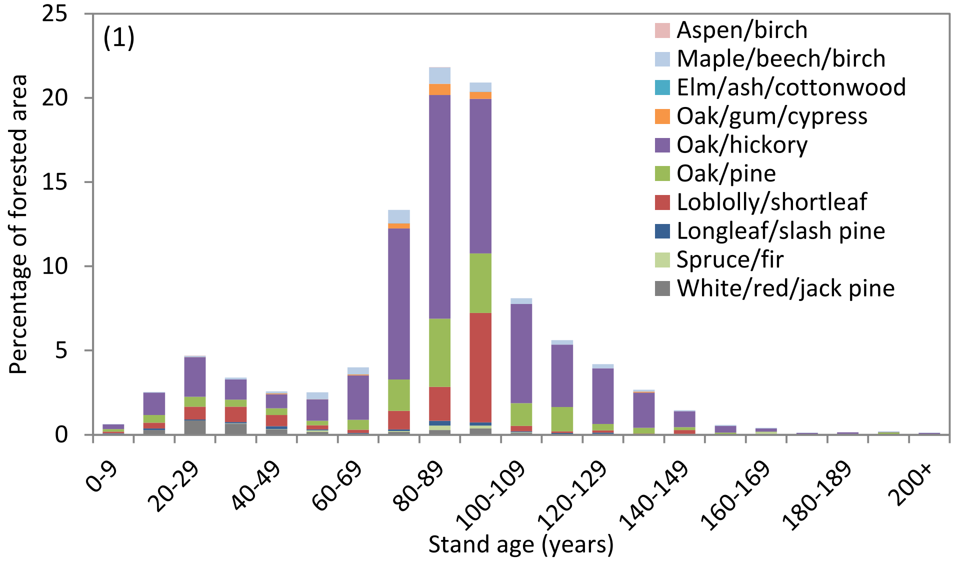


Figure 4.1. Age class distribution in 2010 in the National Forests in North Carolina displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

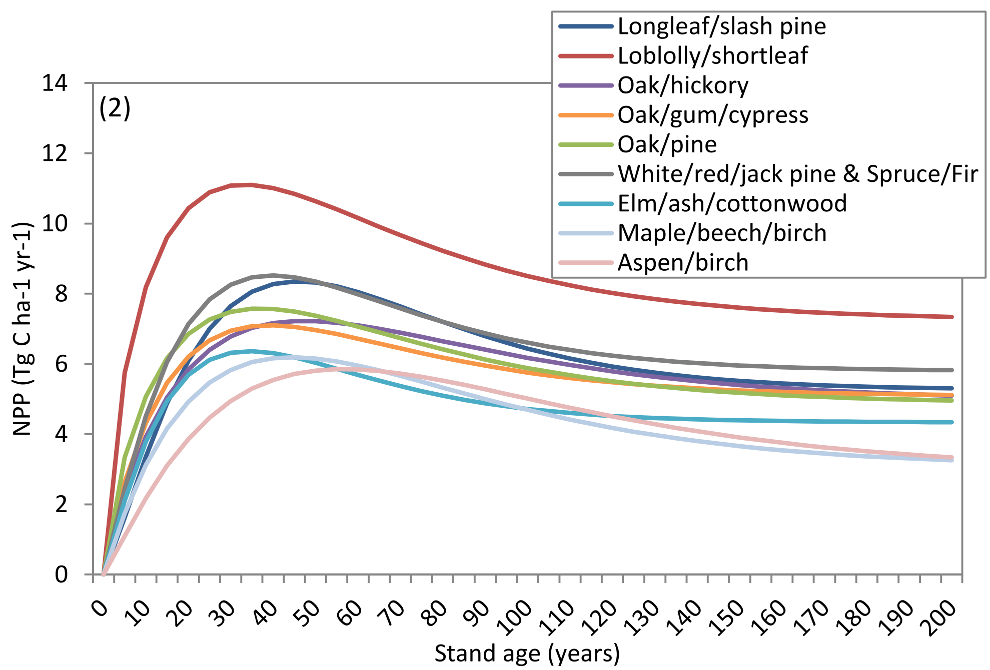


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the National Forests in North Carolina. Due to the small number of Spruce/fir stands and similar growth and yields as White/red/jack pine stands, these forest type groups were combined for modeling NPP-age relationships.

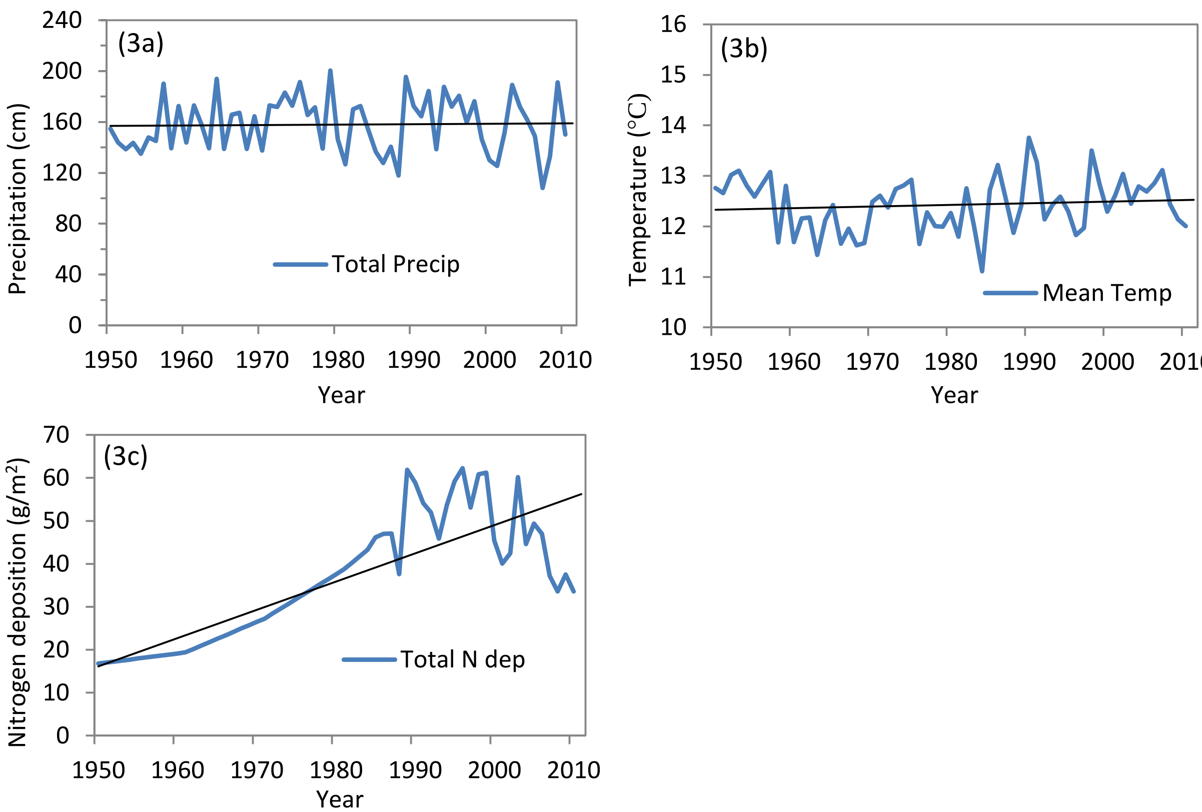


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the National Forests in North Carolina. Linear trend lines shown in black.

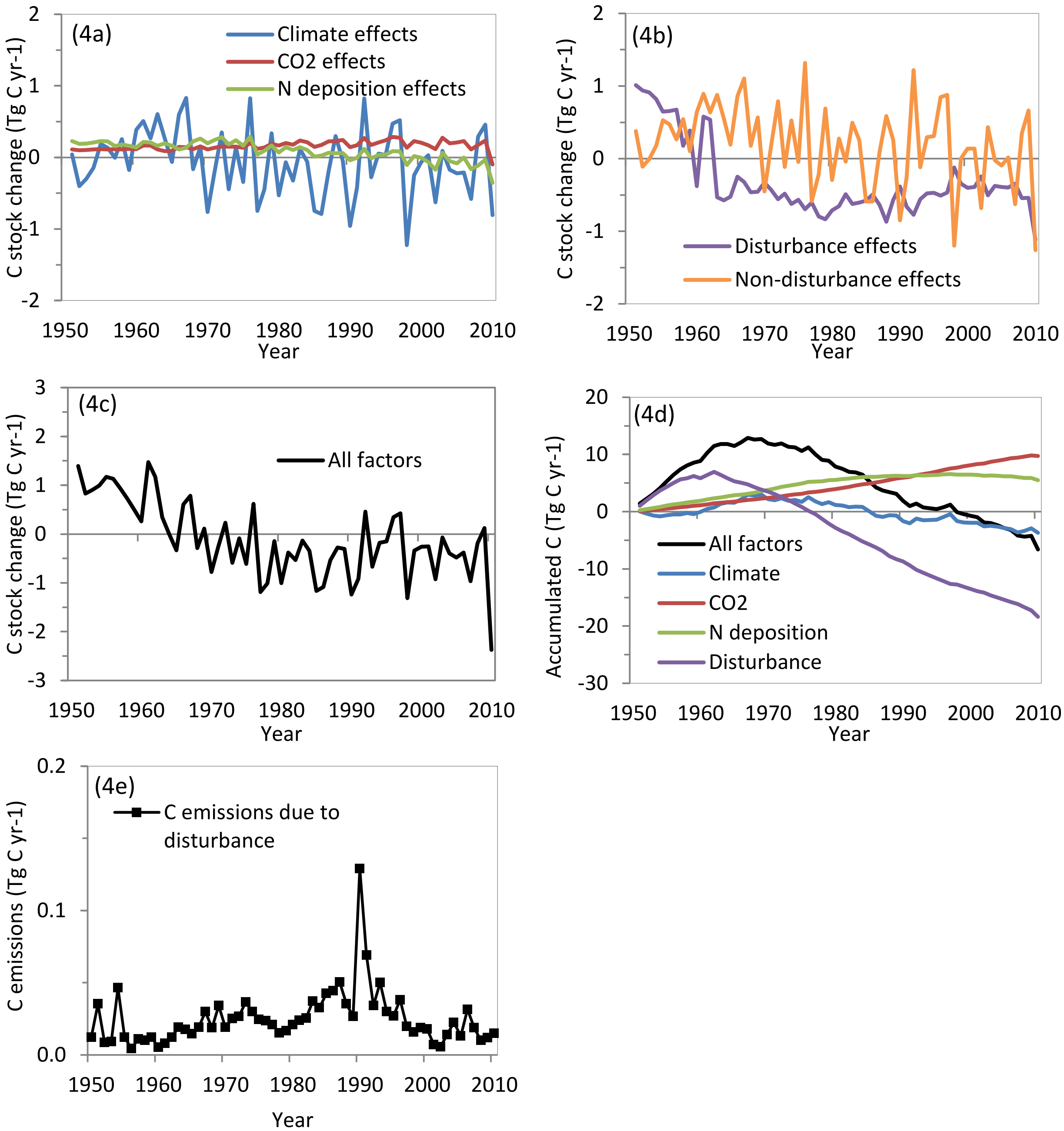


Figure 4.4. Changes in carbon stocks in the National Forests in North Carolina due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

George Washington National Forest

Between 1950 and 2010 forests in the George Washington National Forest have mostly been a C source due to negative disturbance/aging effects (Figs. 4.4b, c). The stand age distribution shows a period of elevated stand establishment from 90 to109 years ago (1901-1920) (Fig. 4.1). These stands were likely a result of restoration management after a period of intensive logging and land use in the late 1800s and early 1900s. Consisting of mostly Oak/hickory forests, these stands would have been most productive in the mid-20th century (Fig. 4.2). As these forests further aged and productivity declined, C losses due to decomposition and decay exceeded C gains causing the C source over the past few decades (Fig 4.4b-c). Aside from an increase in insect disturbances in 2008, recent disturbances have been very small and low-severity (Fig. 1.1m), resulting in low-levels of stand establishment and the stand age structure to remain relatively older (Fig 4.1).

Climate effects on changing C stocks have been quite variable following interannual variability in temperature and precipitation. Warmer temperatures, such as those in 1990 and 1998 (Fig. 4.3b), can cause an increase in decomposition and soil respiration rates thus promoting a C source (Fig. 4.4a). On the other hand, very cool and dry conditions such as those in 1963 (Fig. 4.3a-b) can impede growth and productivity (Fig. 4.4a). Overall the cumulative climate effects have been small but mostly negative since the 1950s (Fig. 4.4d). In contrast, increases in CO_2 and nitrogen (N) deposition had mostly positive effects, increasing forest productivity and causing a C sink (Fig. 4.4a). However, the gains from CO_2 fertilization and N deposition were greatly overshadowed by negative disturbance/aging effects causing the forest to experience a net loss of approximately 14 Tg C from 1950 to 2010 (Fig. 4.4d).

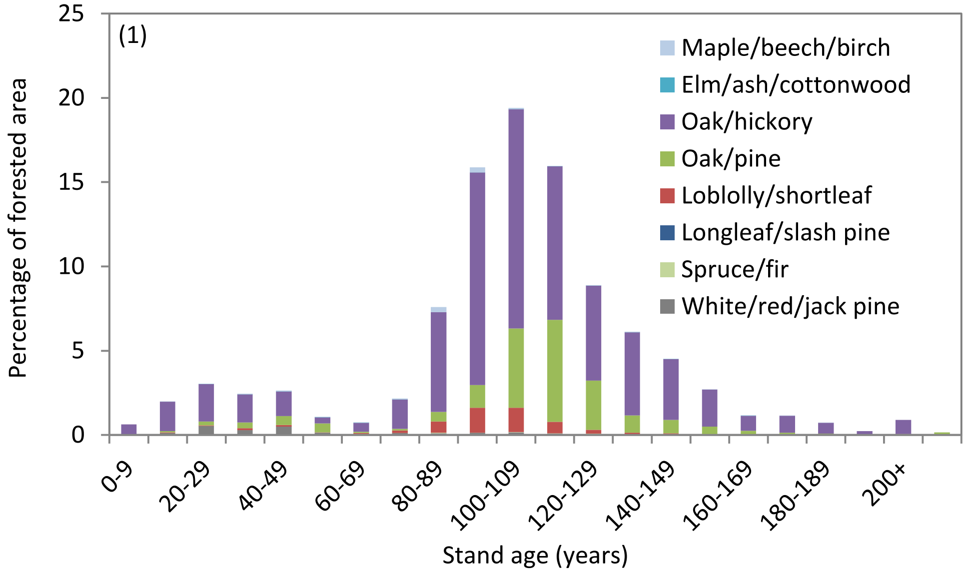


Figure 4.1. Age class distribution in 2010 in the George Washington National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 2 below.

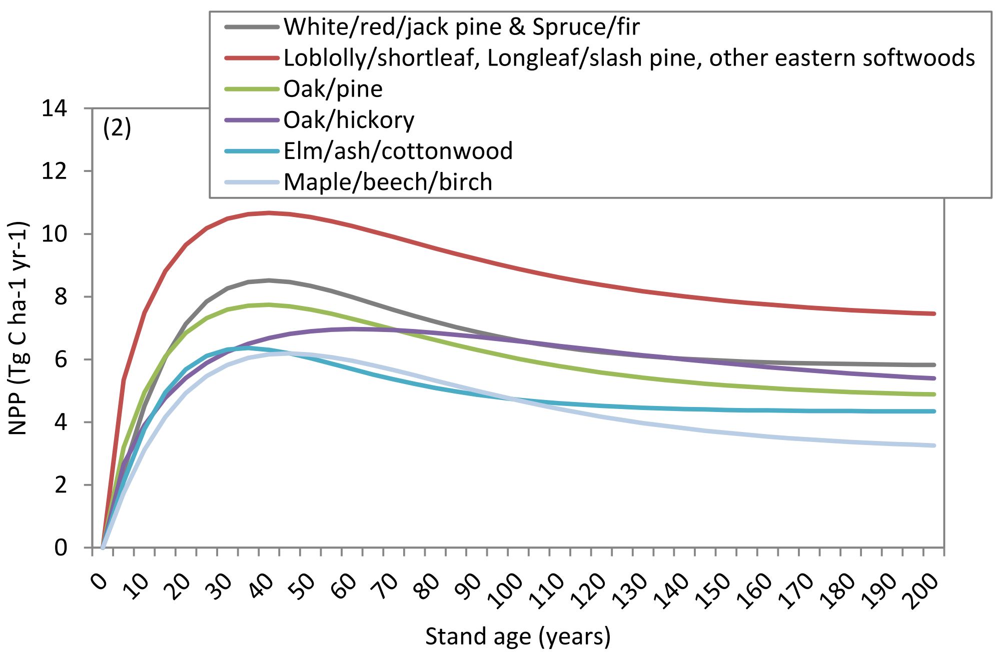


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the George Washington National Forest. Due to the small number of Spruce/fir stands and similar growth and yields as White/red/jack pine stands, these forest type groups were combined for modeling NPP-age relationships. Loblolly/shortleaf pine, longleaf/slash pine, and other eastern pines were also combined.

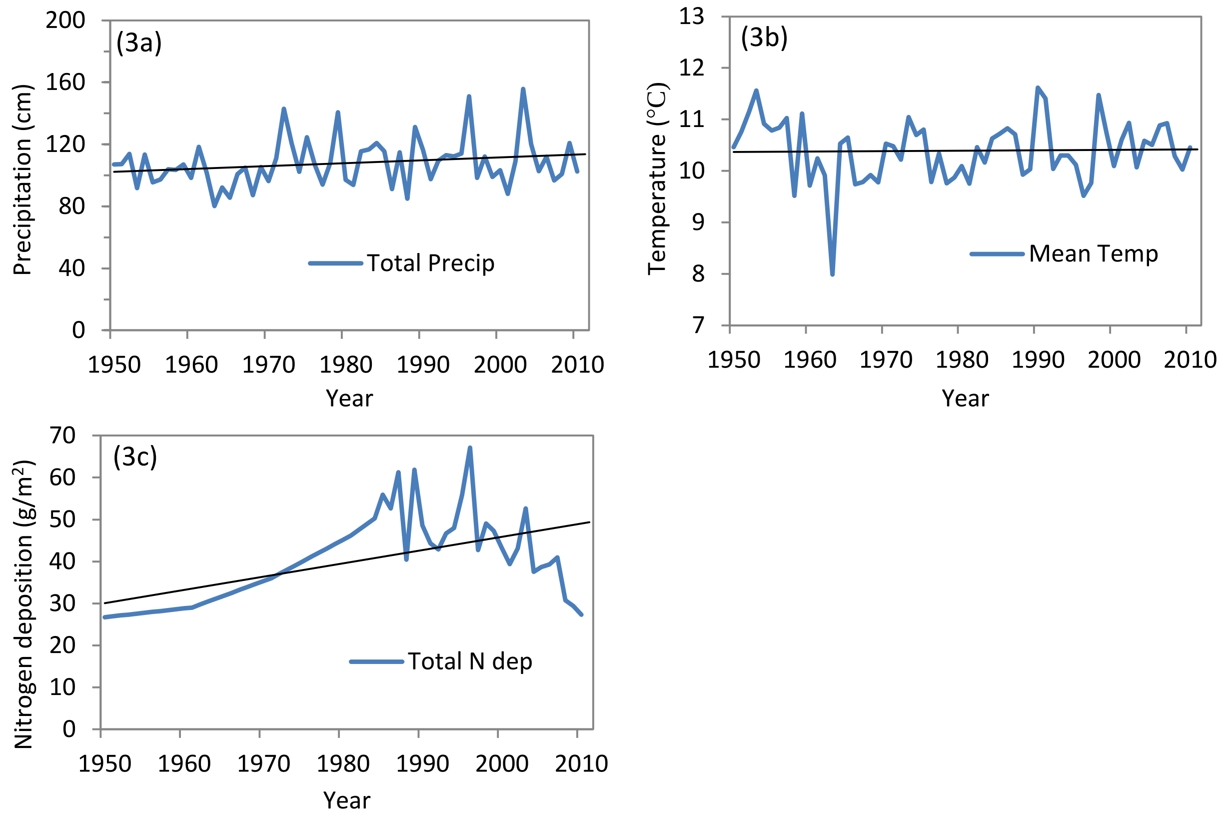


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the George Washington National Forest. Linear trend lines shown in black.

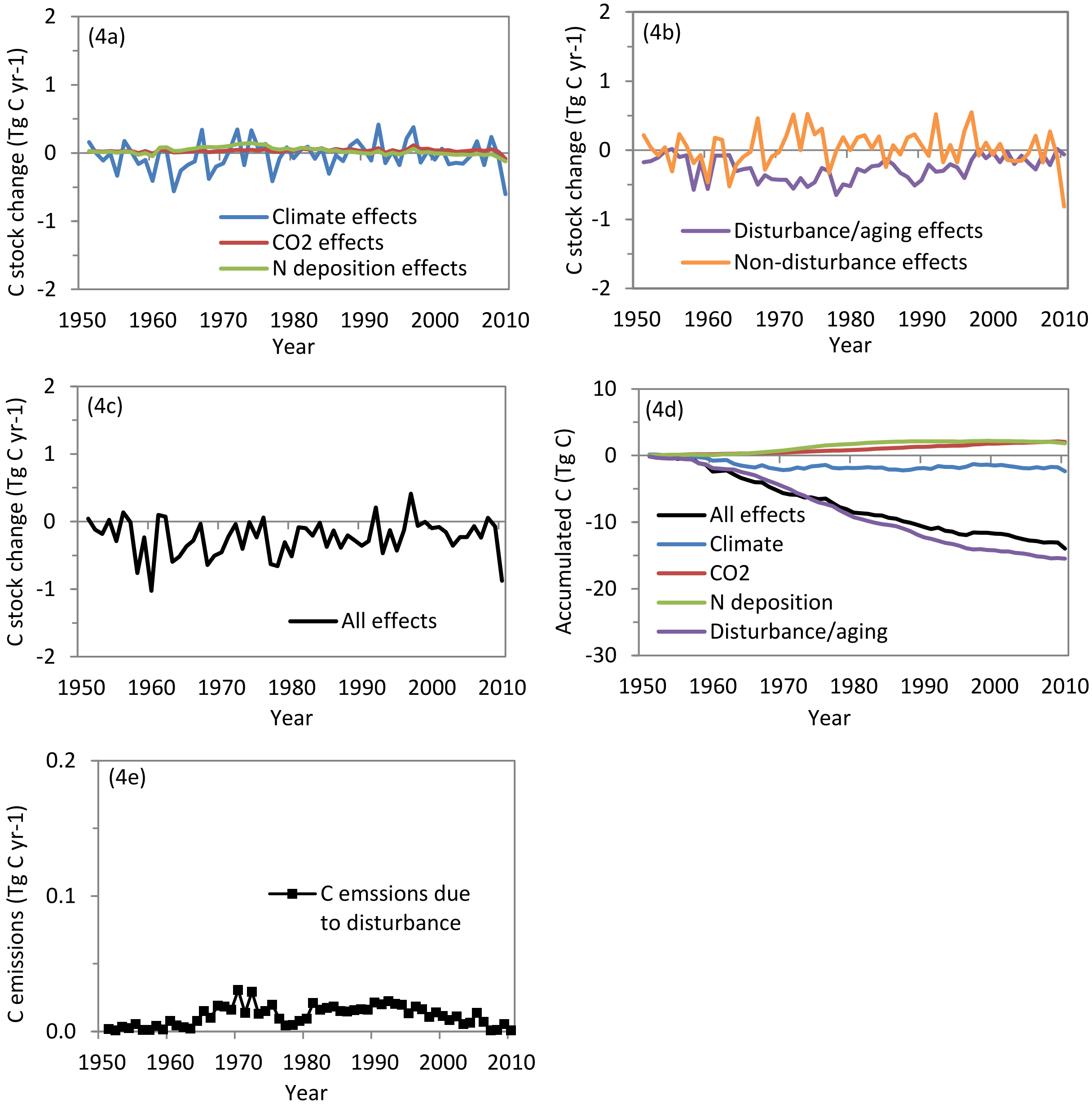


Figure 4.4. Changes in carbon stocks in the George Washington National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.14 Jefferson National Forest

From the 1950s through the 1970s, forests in the Jefferson National Forest were mostly a C sink, but later transitioned to a C source due to disturbance/aging effects (Fig. 4.4b-c). The stand age distribution indicates a period of elevated establishment of mostly Oak/hickory and Oak/pine stands from 80 to 99 years ago (1910-1930) (Fig. 4.1). This coincided with the promotion of forest restoration and recovery after a period of intensive logging and land use in the late 1800s and early 1900s. These stands would have reached maximum productivity at around 50 years old or during the mid-20th century (Fig. 4.2). As these forests further aged and productivity declined, C losses due to decomposition and decay exceeded C gains, causing the forest to shift to a C source over the past few decades (Fig 4b-c). Aside from an increase in insect disturbances in 2008, recent disturbances have been very small and low-severity (Fig. 1.1m), resulting in low-levels of stand establishment and the prevalence of this predominately older forest structure (Fig 4.1).

Climate effects on changing C stocks have been quite variable following interannual variability in temperature and precipitation. Warmer temperatures, such as those in 1990 and 1998 (Fig. 3b), can cause an increase in soil respiration and decomposition rates thus promoting a C source (Fig. 4a). On the other hand, wetter and cooler conditions such as those in 1996 (Fig. 3a-b) can decrease forest productivity causing a C sink (Fig. 4a). Overall the cumulative climate effects have been negligible but have resulted in a small C loss over more recent decades (Fig. 4d). In contrast, increases in CO_2 and nitrogen (N) deposition had mostly positive effects, helping to offset C losses due to disturbance/aging and climate (Fig. 4a). Despite the C sink and C accumulation during the mid-20th century, between 1950 and 2010 the forest saw a net loss of roughly 2.8 Tg C (Fig. 4d).

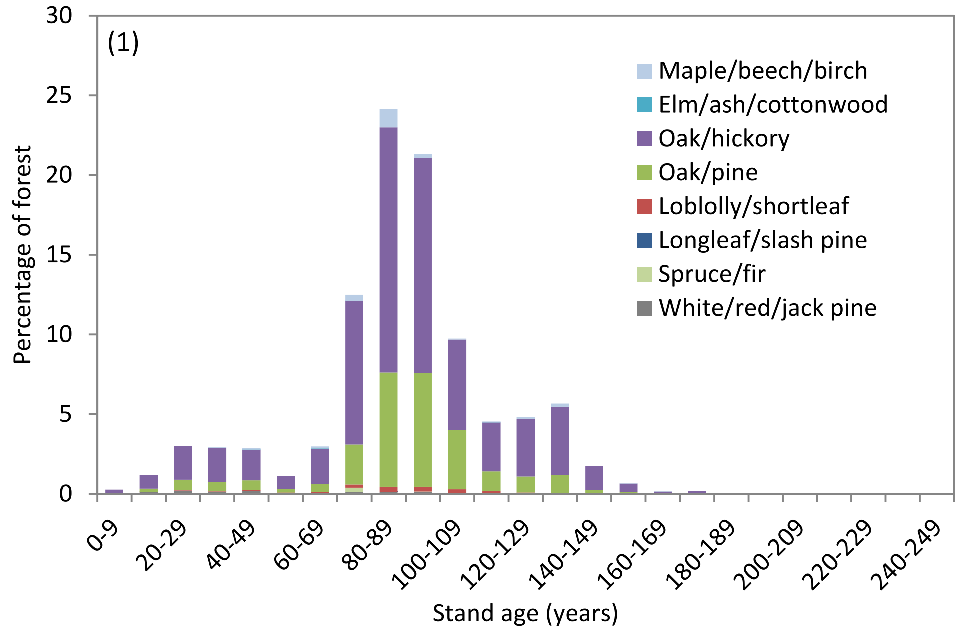


Figure 4.1. Age class distribution in 2010 in the Jefferson National Forest displaying the percentage of forested area of each forest type group in 10-year age classes. Forest type groups are symbolized by stacked, colored bars that also correspond to the forest type groups in Fig. 3 below.

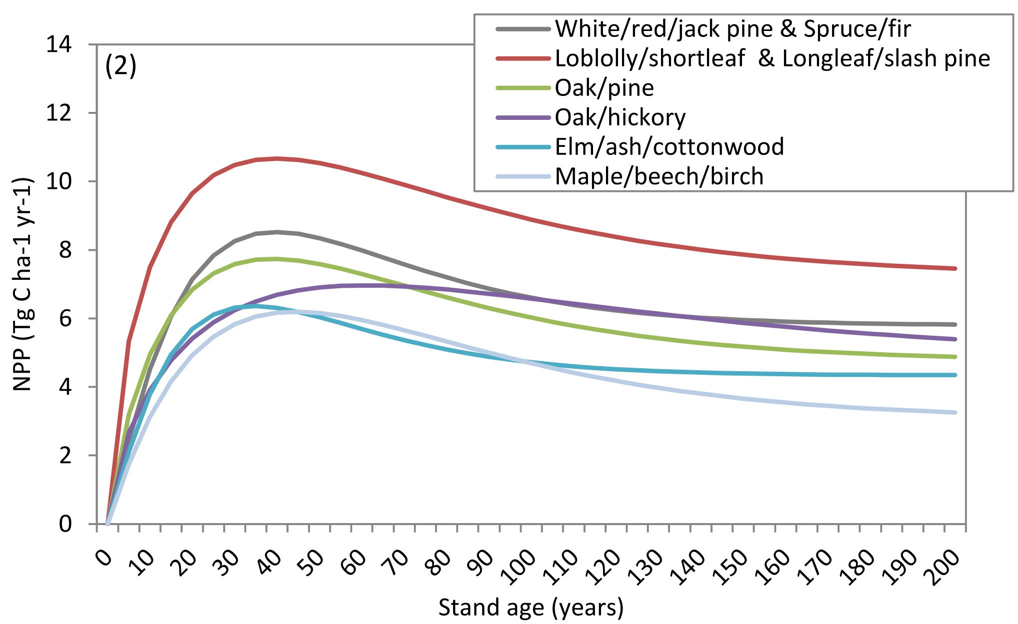


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest type group in the Jefferson National Forest. Due to small sample sizes and similar growth and yield trends, Spruce/fir stands were combined with White/red/jack pine stands and Loblolly/shortleaf pine and Longleaf/slash pine stands were combined.

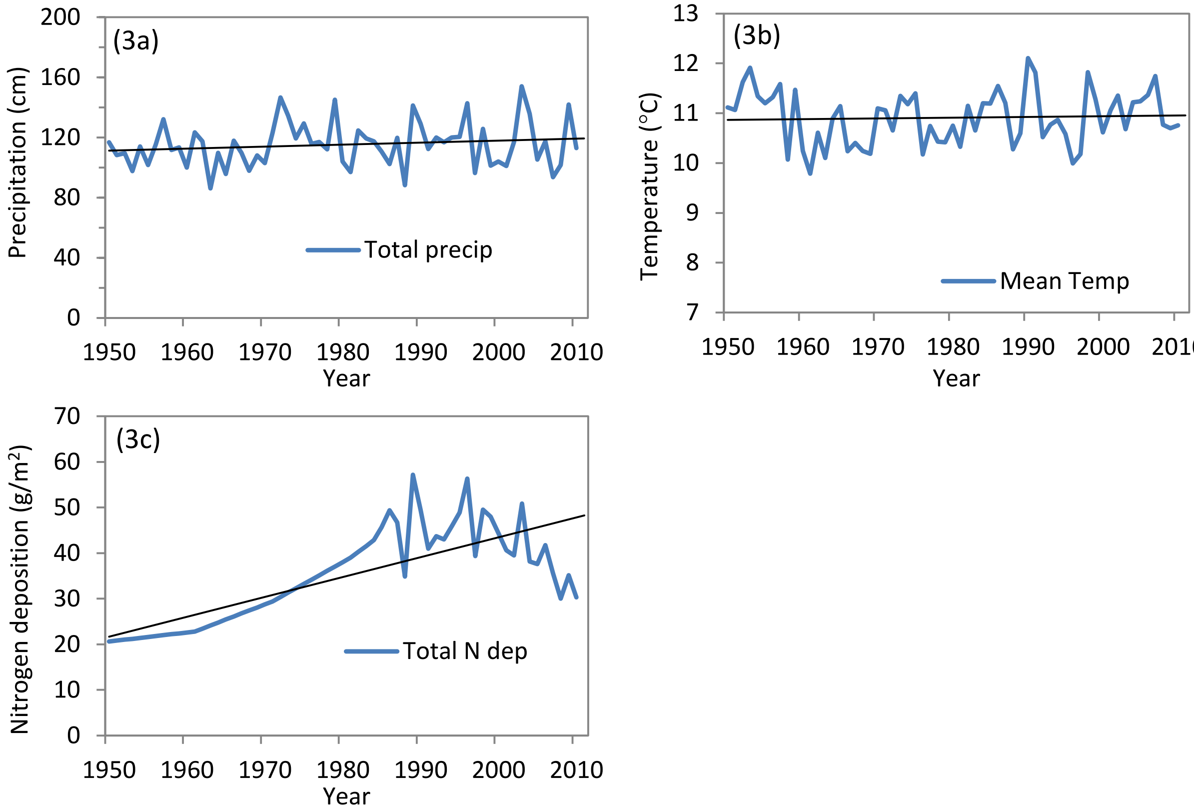


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Jefferson National Forest. Linear trend lines shown in black.

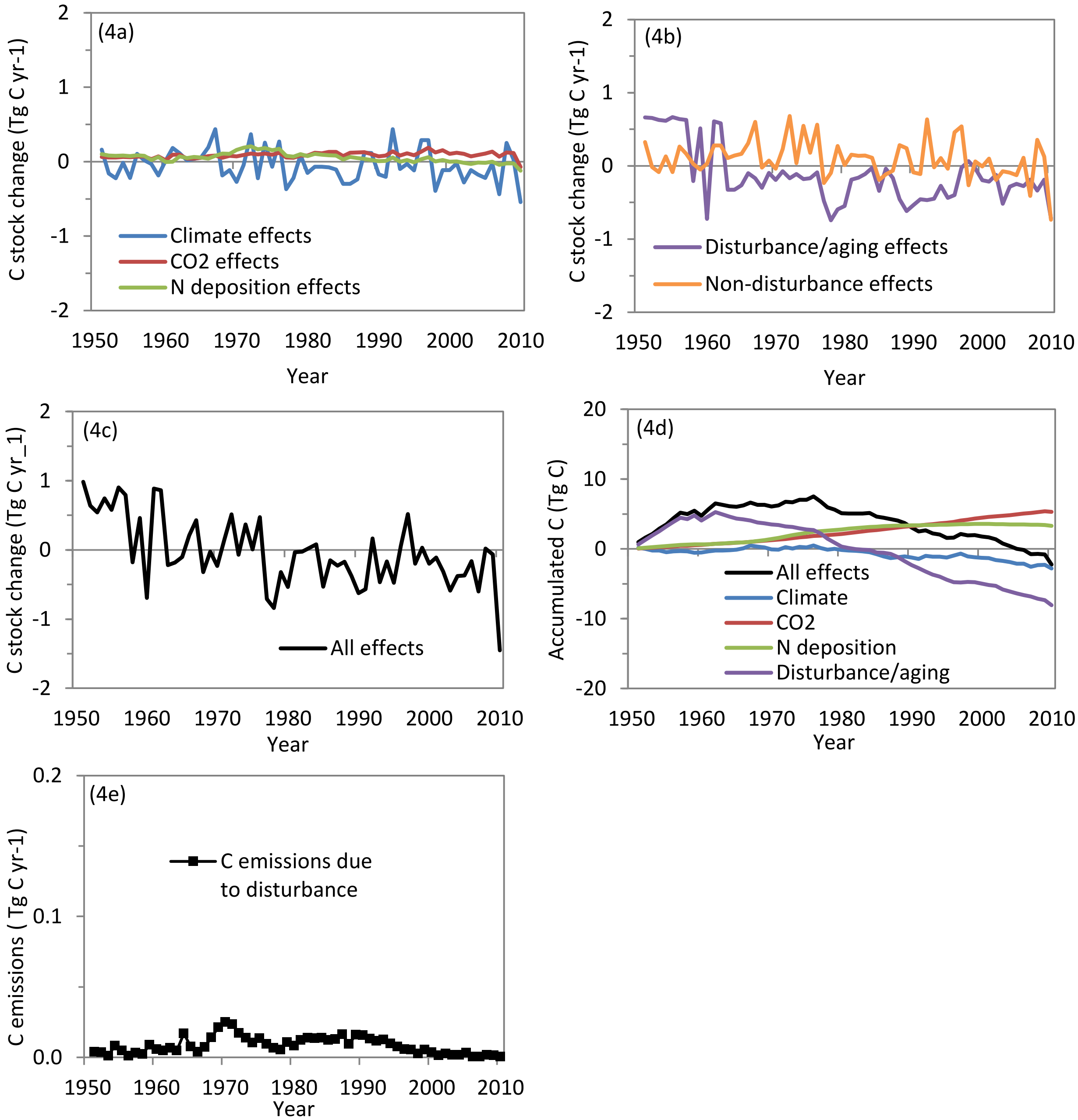


Figure 4.4. Changes in carbon stocks in the Jefferson National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figure 4.4 a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effect.