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 5: Northern Region, Individual Forests

Office of Sustainability and Climate
National Forest System

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Forest Service

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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

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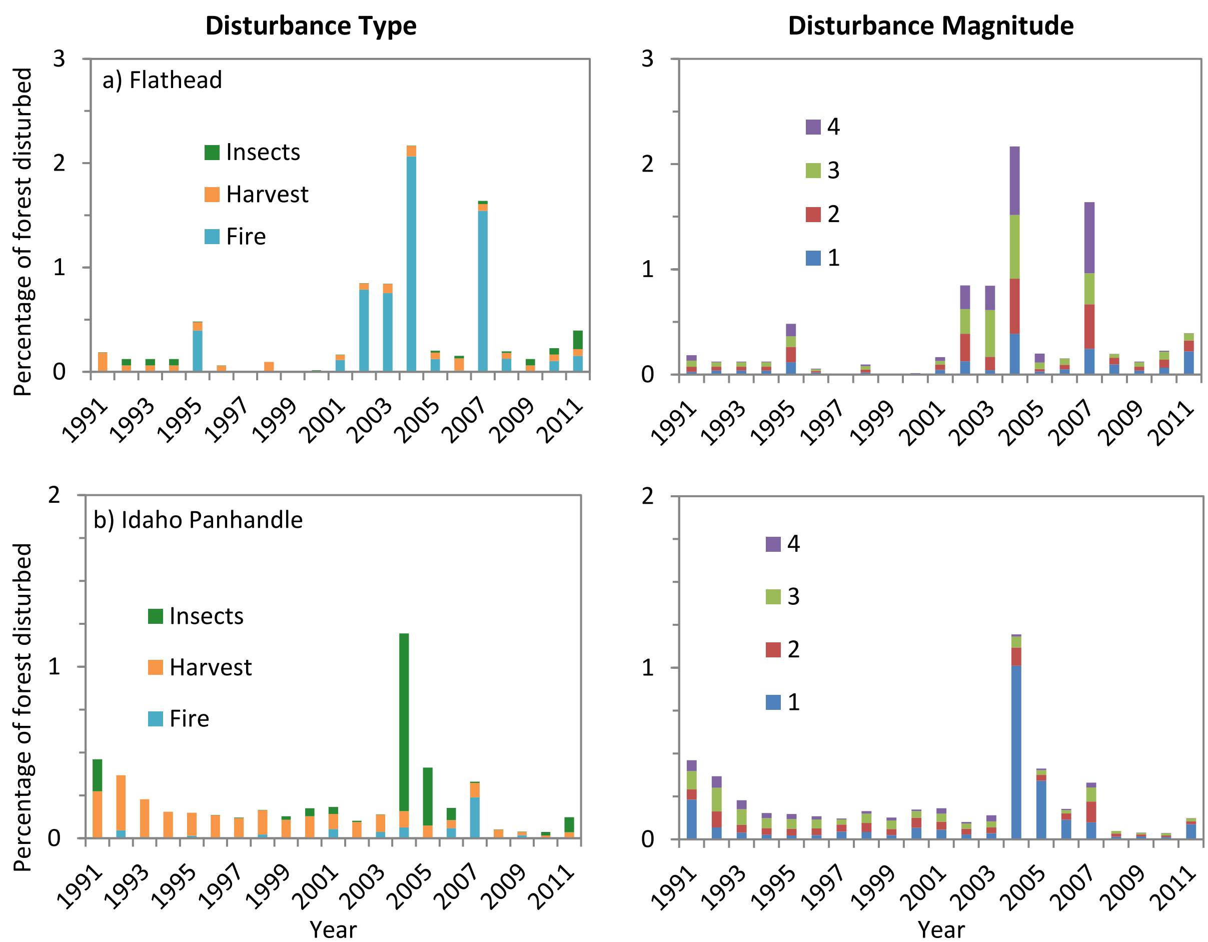
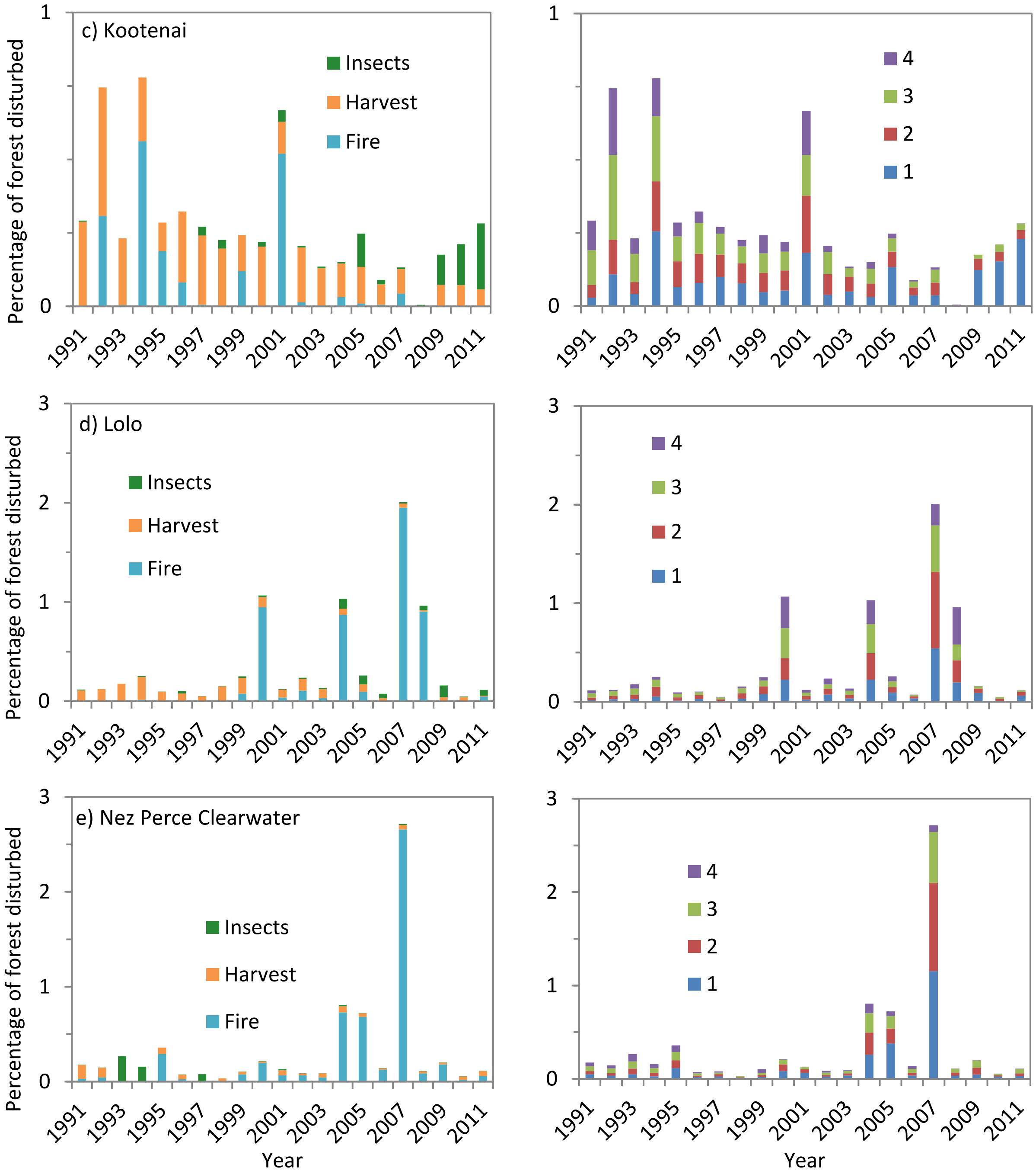
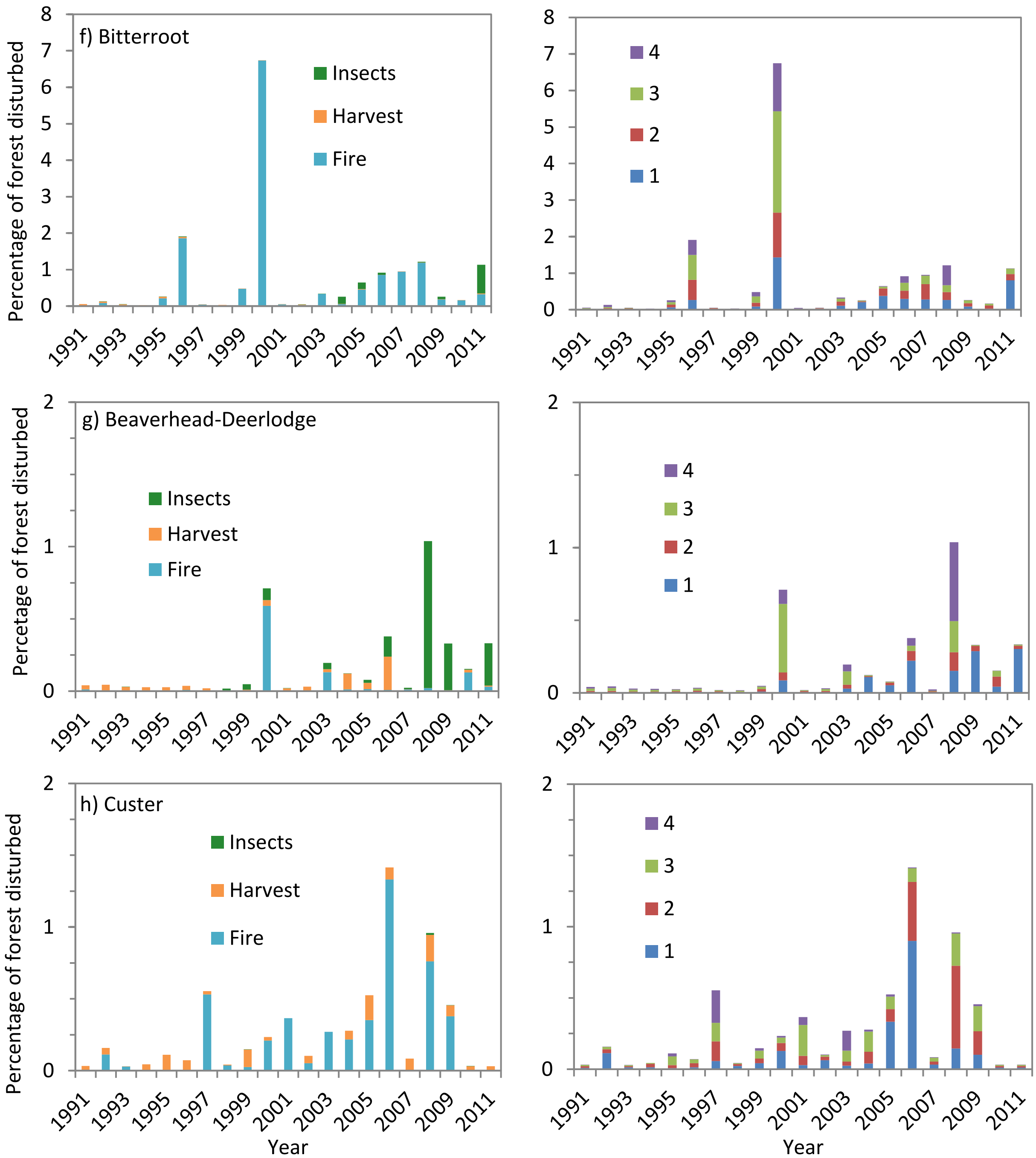
Contents

1. Disturbance trends

Disturbance records are summarized by type (fire, harvest, insects, disease) and by magnitude in Figure 1.1 a-k. In the Flathead National Forest (Figure 1.1a), for example, there were significant fire events affecting more than 1% of all forestland in 2002-2004 and 2007. Harvest in that forest affected approximately one-quarter percent of forestland in the early 1990s and generally declined throughout the monitoring period. Mortality due to insects was picked up only in 2011. Not shown in Figure 1.1 is the rate of infection due to root disease, which was not mapped over time but was instead estimated from the FIA root disease severity variable.




c) Kootenai
d) Lolo
e) Nez Perce Clearwater
Insects
Harvest
Fire
1
2
3
4
Percentage of forest disturbed
Year
0
1
2
3
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011


f) Bitterroot
Percentage of forest disturbed
Insects
Harvest
Fire
4
3
2
1
g) Beaverhead-Deerlodge
Percetage of forest disturbed
Insects
Harvest
Fire
4
3
2
1
h) Custer
Percentage of forest disturbed
Insects
Harvest
Fire
4
3
2
1
Year
Year
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011

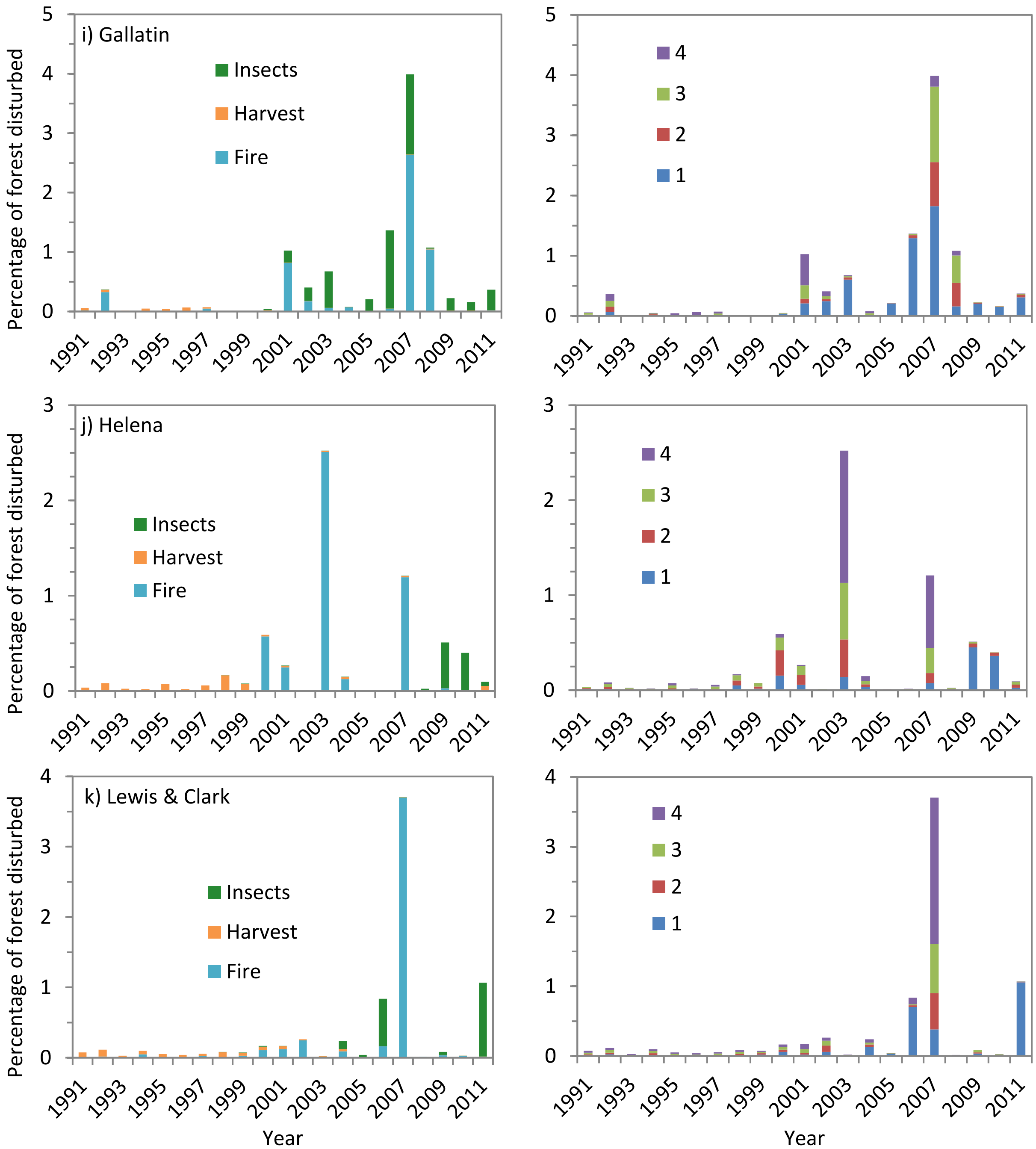


Figure 1.1. Annual rates of disturbance in the Northern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and abiotic; and b) magnitude 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

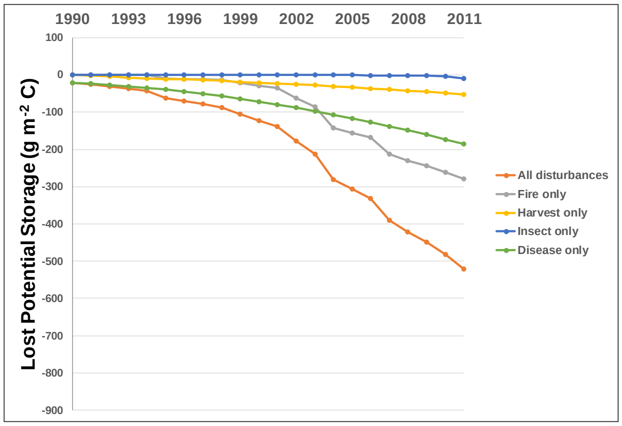
2. Effects of disturbance and management activities (ForCaMF)

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 Northern Region from 1990 to 2011.

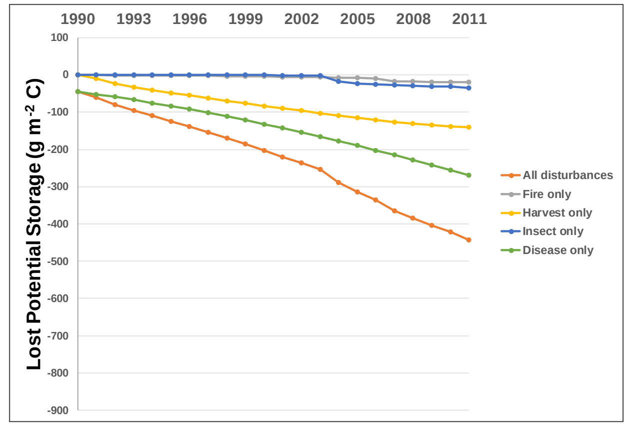
The disturbance patterns depicted in Figure 1.1 a-k are clearly visible in the ForCaMF representation of C impact over time (Figure 2.1). In the Flathead, for example, the impact of fire significantly increased in the years corresponding to major fires. It must be emphasized that there is a residual 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 there is still an impact of harvest in the Flathead in 2011 despite low recent harvest rates; most stands harvested in the early 1990s have not yet reached the storage levels they would have attained if they had not been harvested.

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 in the main document. Figure 2.2 summarizes the ForCaMF output shown in Figure 2.1: the pie charts represent the proportional importance of each type of disturbance as measured in 2011 (the last date in Figure 2.1). In the Flathead illustration, wildfire and root disease affected carbon storage from 1990 to 2011 much more than harvest and insect activity.

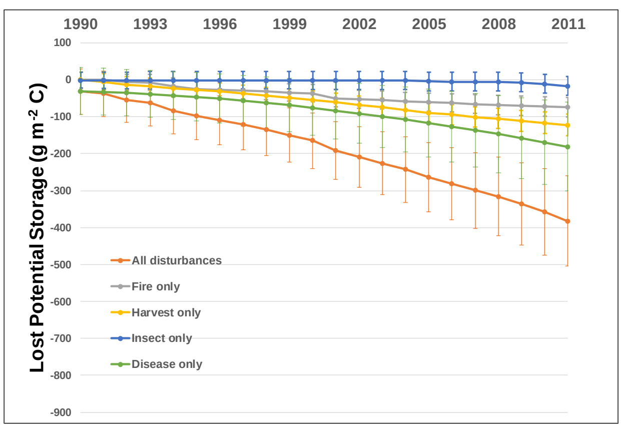
2.1a) Flathead National Forest



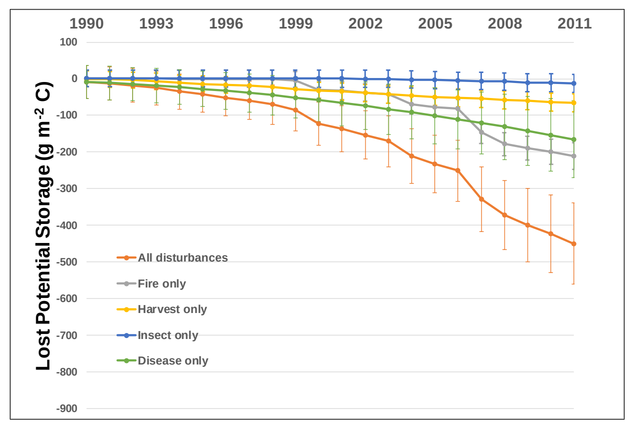
2.1b) Idaho-Panhandle National Forest



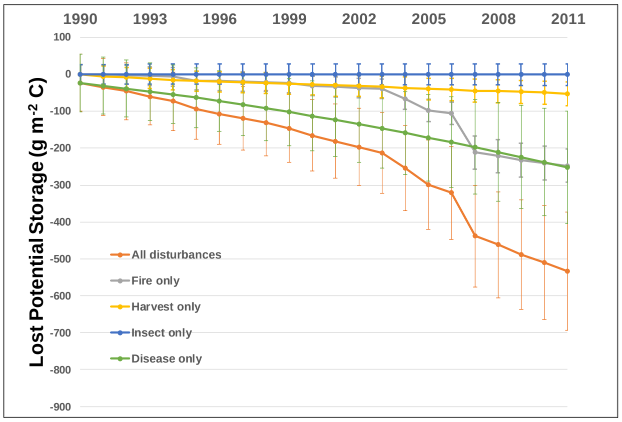
2.1c) Kootenai National Forest



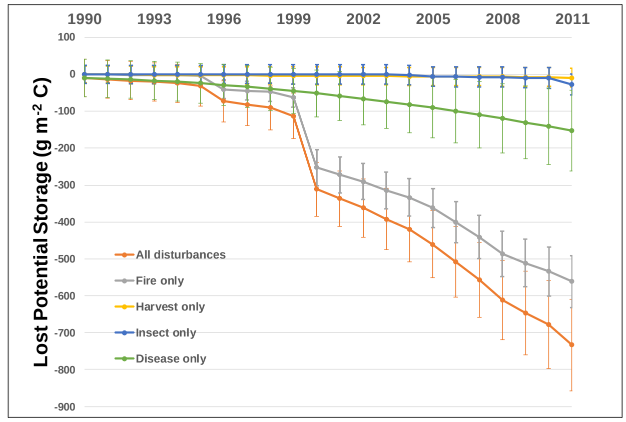
2.1d) Lolo National Forest



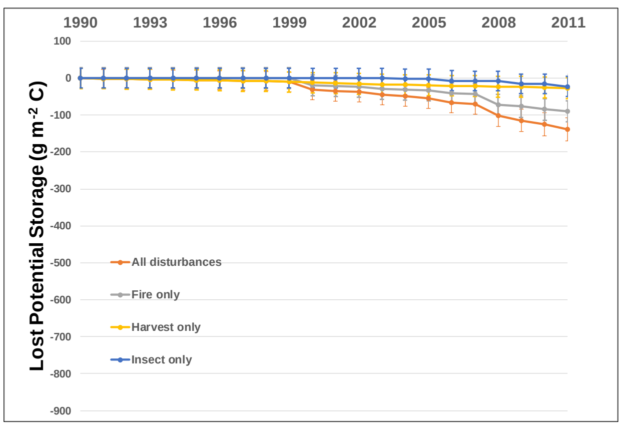
2.1e) Nez Perce-Clearwater National Forest



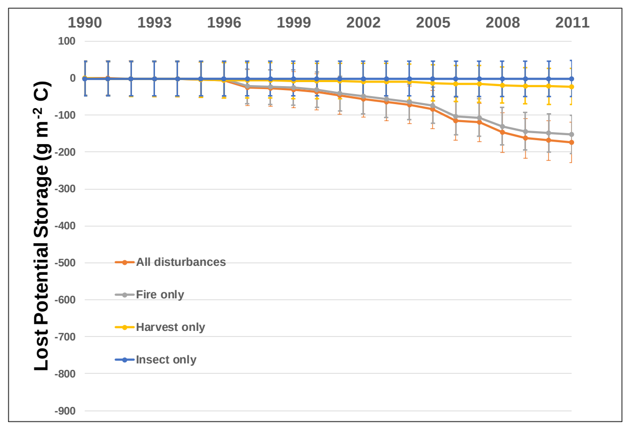
2.1f) Bitterroot National



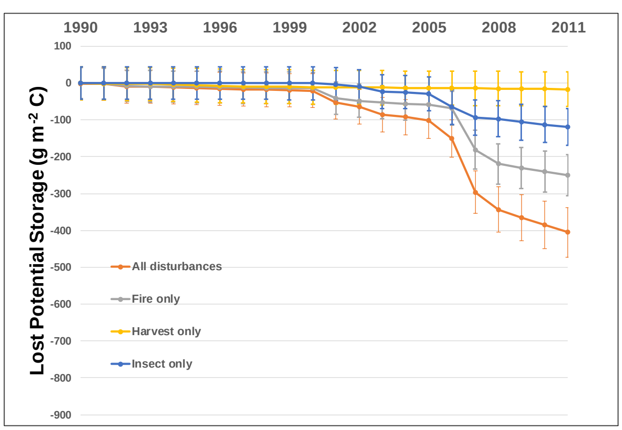
2.1g) Beaverhead-Deerlodge National



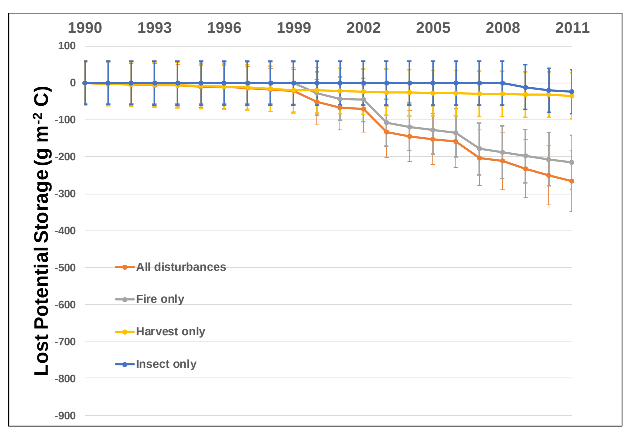
2.1h) Custer National Forest



2.1i) Gallatin National Forest



2.1j) Helena National Forest



2.1k) Lewis and Clark National Forest

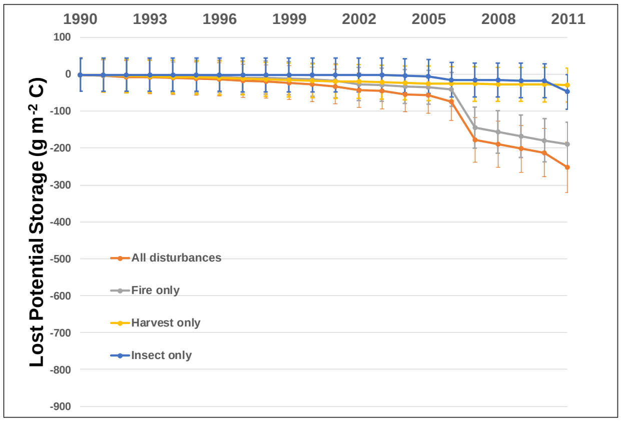
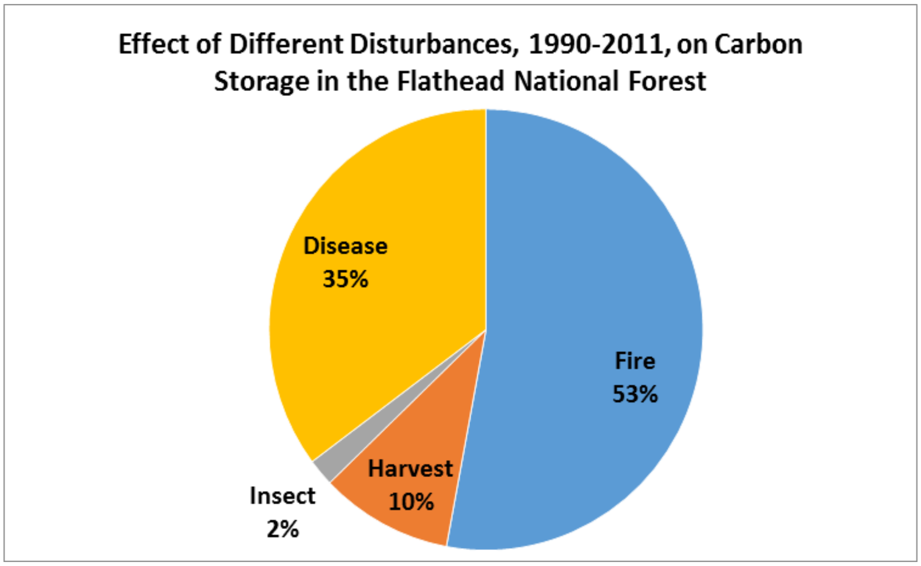
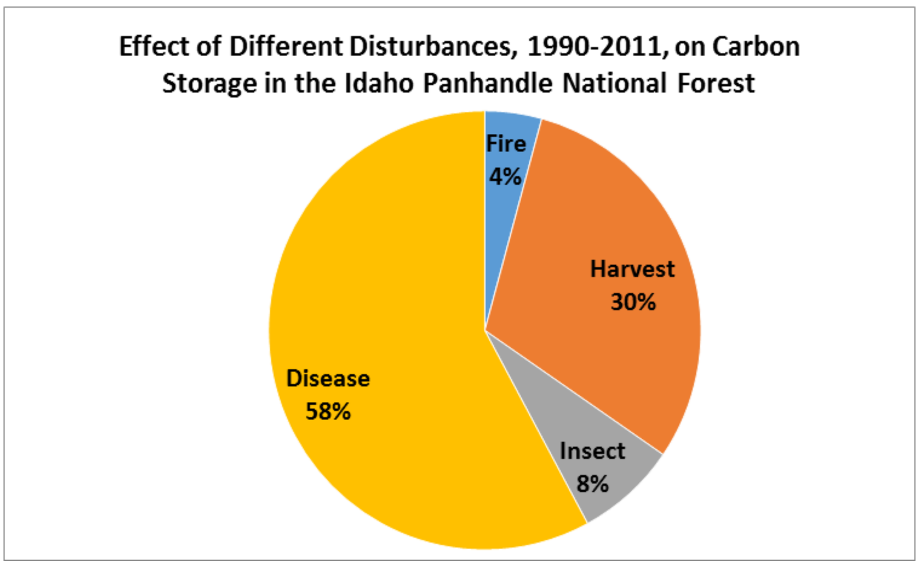
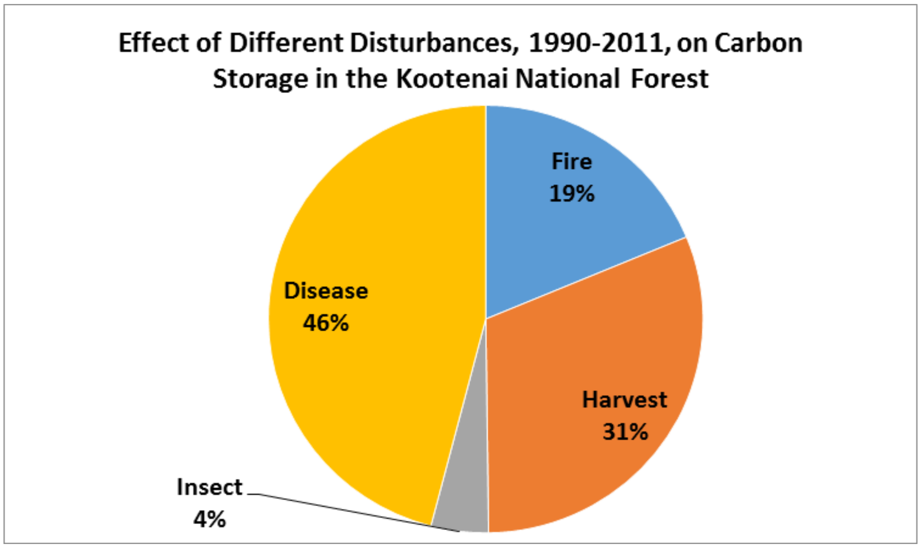
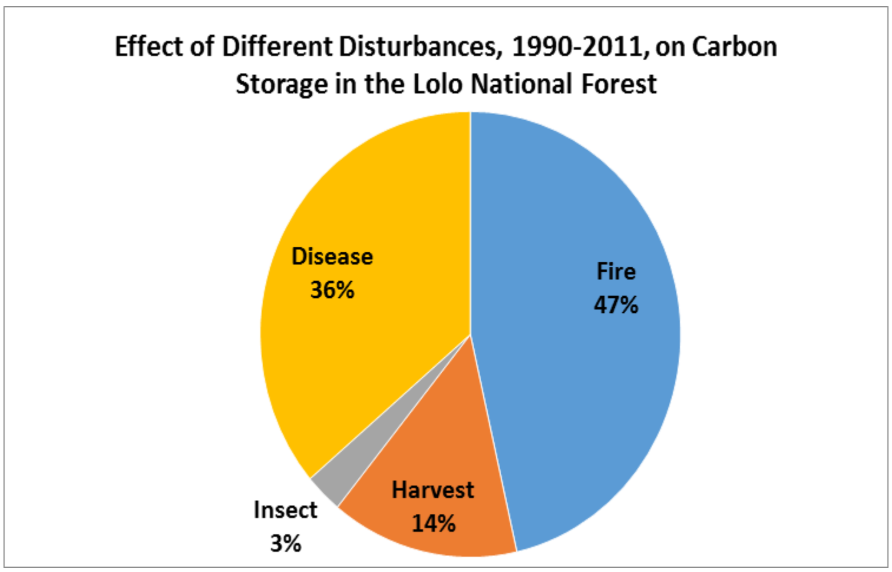


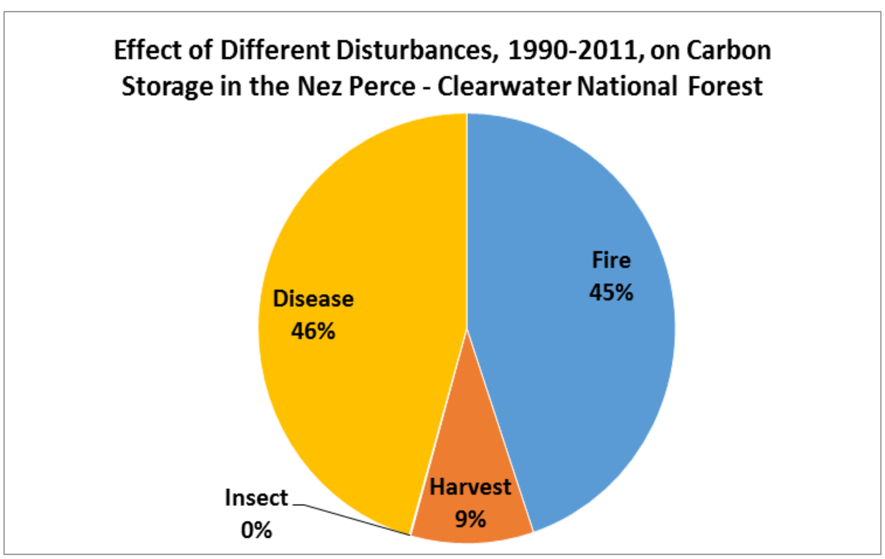
Figure 2.1. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Northern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

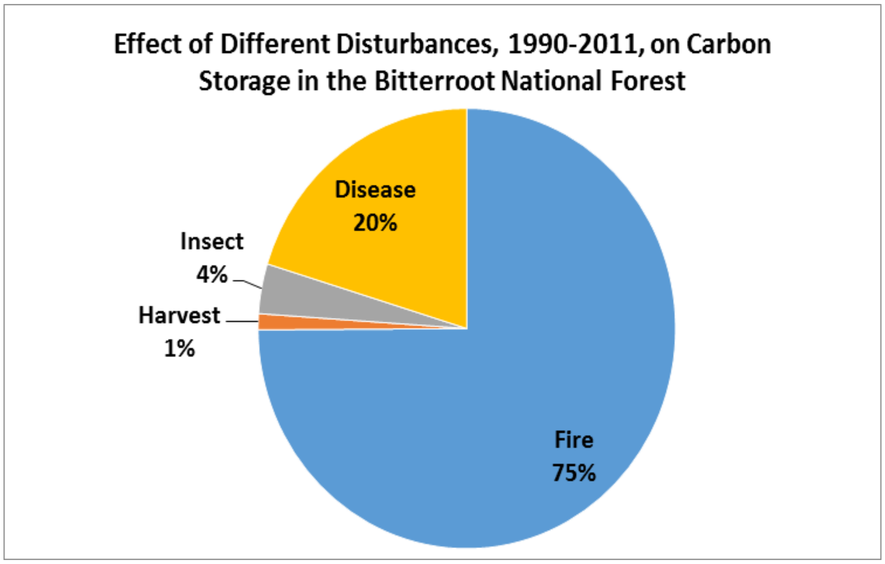

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Flathead National Forest
Disease
35%
Fire
53%
Harvest
10%
Insect
2%

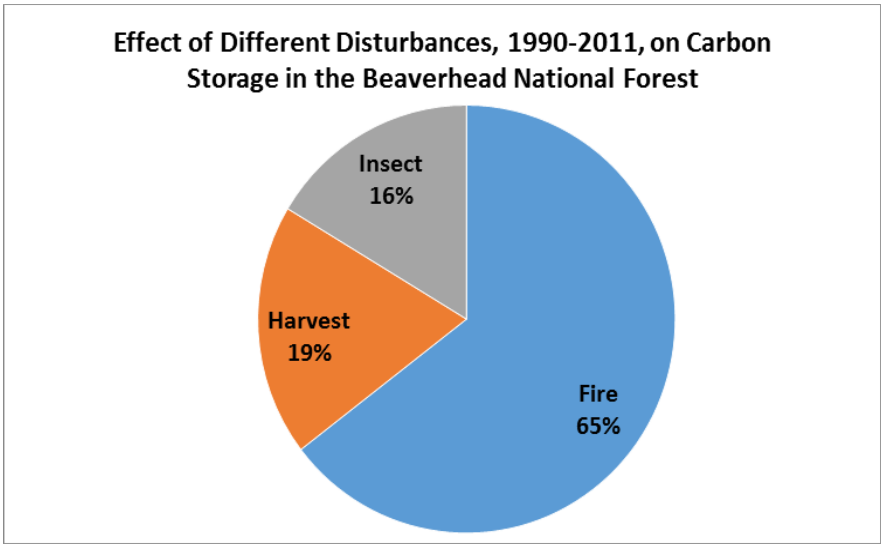

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Idaho Panhandle National Forest
Fire
4%
Harvest
30%
Disease
58%
Insect
8%

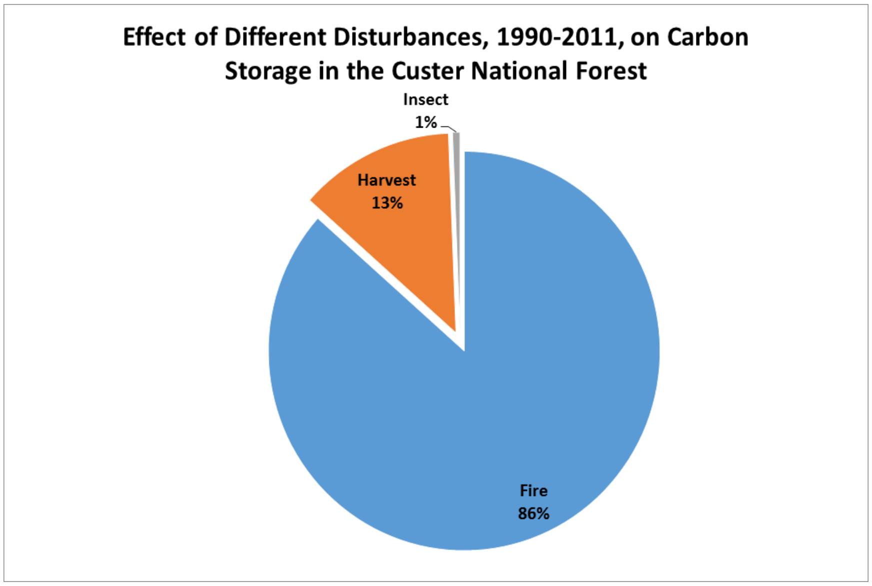

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Kootenai National Forest
Fire 19%
Harvest 31%
Insect 4%
Disease 46%

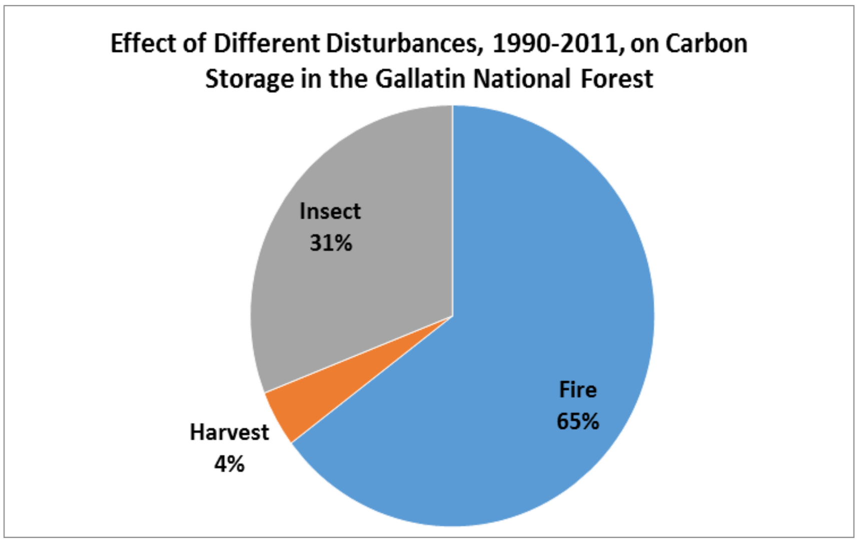

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Lolo National Forest
Fire 47%
Harvest 14%
Insect 3%
Disease 36%

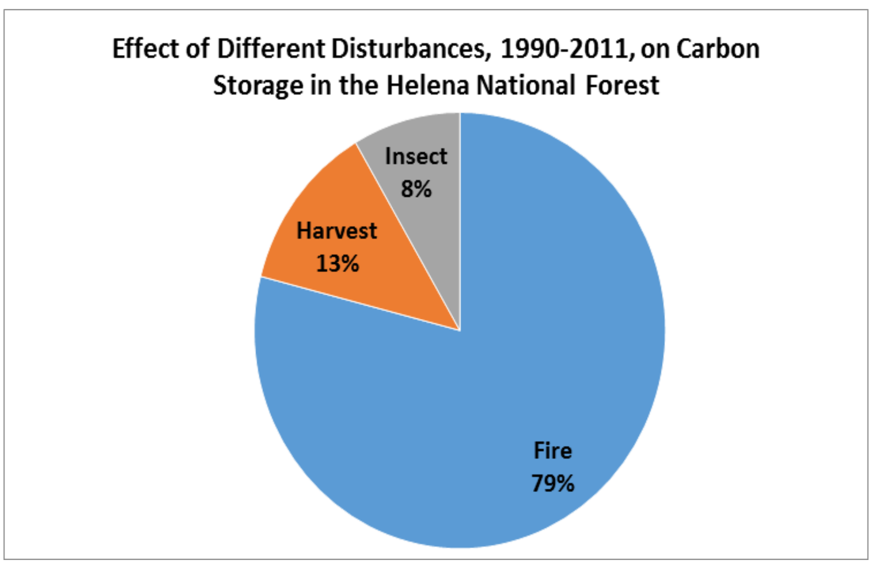

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Nez Perce - Clearwater National Forest
Fire 45%
Harvest 9%
Insect 0%
Disease 46%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Bitterroot National Forest
Disease 20%
Insect 4%
Harvest 1%
Fire 75%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Beaverhead National Forest
Insect 16%
Harvest 19%
Fire 65%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Custer National Forest
Insect
1%
Harvest
13%
Fire
86%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Gallatin National Forest
Insect
31%
Harvest
4%
Fire
65%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Helena National Forest
Insect
8%
Harvest
13%
Fire
79%

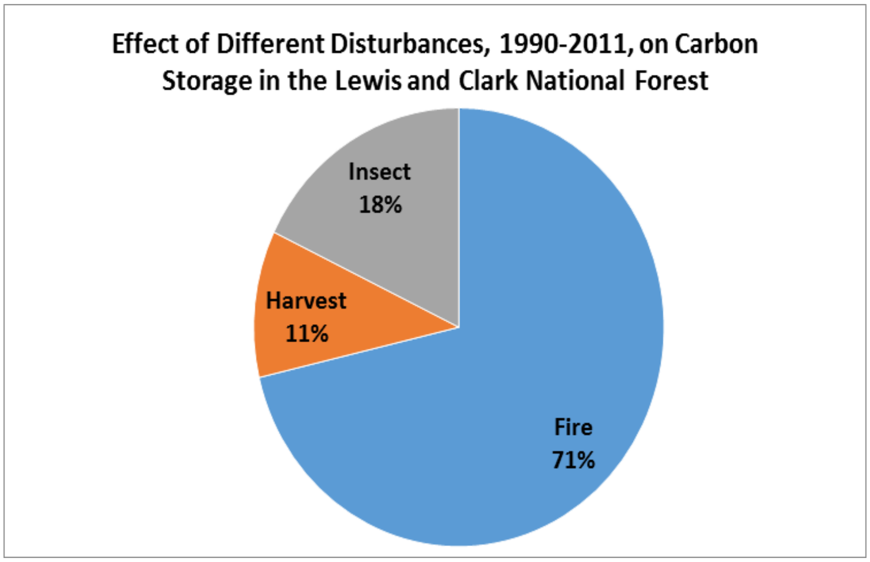


Figure 2.2. Proportional effect of different kinds of disturbance on carbon storage in each national forest in the Northern Region for the period 1990 through 2011.

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 6.3 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.

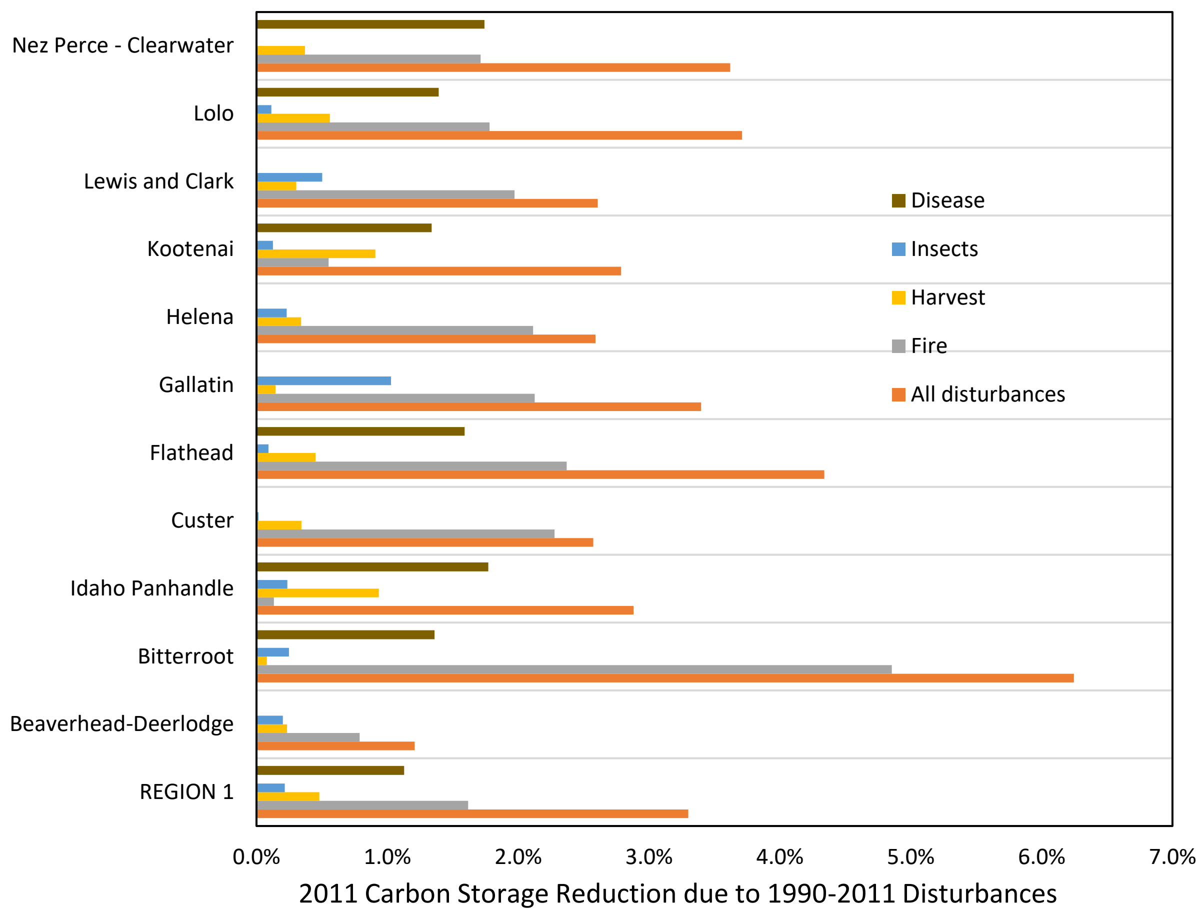


Figure 3.1. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Northern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

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

The set of figures for each of 11 National Forests units in the Northern 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.

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.

For further examples of how to interpret the figures in this section, see Section 6.3 of the main report which provides explanation of the regional InTEC results.

Beaverhead-Deerlodge National Forest - Montana

Between 1950 and 2010 forests in the Beaverhead-Deerlodge National Forest transitioned from a C sink to predominantly a C source (Figure 4.4c). Disturbances/aging has had mostly negative effects on changing C stocks over the past few decades (Figure 4.4b). This trend is primarily due to an aging effect as more than 75% of the stands are >80 years old (Figure 4.1) and have aged past their peaks in productivity (Figure 4.2). The stand age distribution shows a pulse of stands establishing 120-129 years old ago (1881-1890), likely a result of re-establishment following disturbances such as large wildfires or land use change associated with EuroAmerican settlement in the region. Another important factor during the re-growth phase has been fire suppression, which allowed the stands to continue re-growing rather than being disturbed at a more typical historical rate. Depending on the forest type, this establishment pulse would have reached peak productivity around 1930-1950 (Figure 4.2), which explains the transition from a C sink to a C source in the 1950s (Figure 4.4b), as losses from decomposition and decay exceeded C gains. As forests recovers from the small, but higher-severity disturbances in 2000 and 2008 (Figure 1.1g) and reach peak productivity in several decades, they may transition to a C sink again. However, there have been only low-levels of establishment of young stands (Figure 4.1) and forests have remained a C source (Figure 4.4b-c).

Of non-disturbance factors, climate has had the strongest effect on changing C stocks, with effects being mostly negative since the late 1990s (Figure 4.4a). The overall increasing trend in mean temperatures (Figure 4.3a) may have increased soil respiration and water stress, negatively affecting total C stocks, but not to the extent of disturbance/aging effects (Figure 4.4d). The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 concentrations enhanced the C sink (Figure 4.4a), causing an increase in accumulated C since 1950 (Figure 4.4d), but were not enough to offset the C losses due to disturbances, aging, and climate. Overall, Beaverhead-Deerlodge National Forest experienced a net loss of approximately 25.2 Tg C from 1950-2010 (Figure 4.4d), mostly due to disturbances and aging stands, followed by negative climate effects (Figure 4.4d).

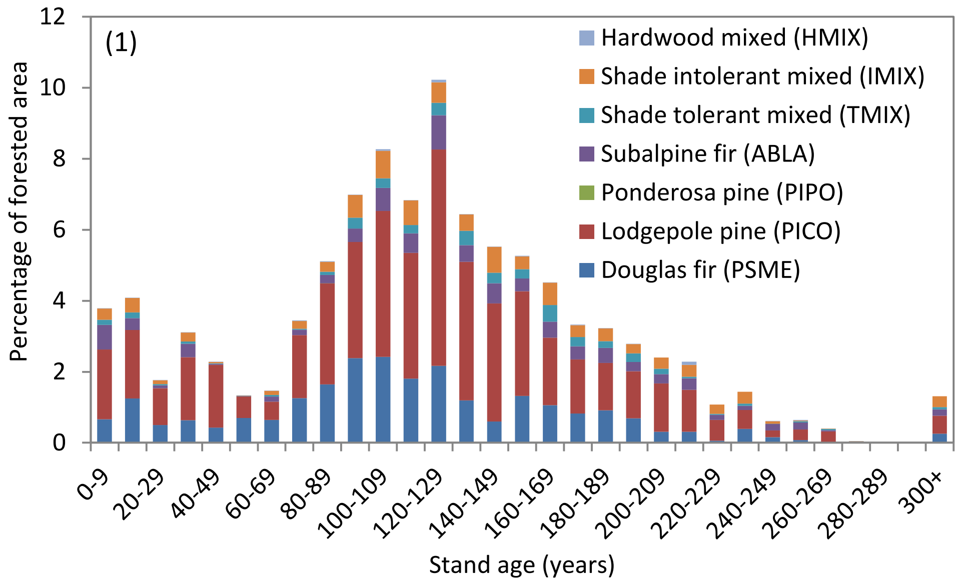


Figure 4.1. Age class distribution in 2010 in the Beaverhead-Deerlodge National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

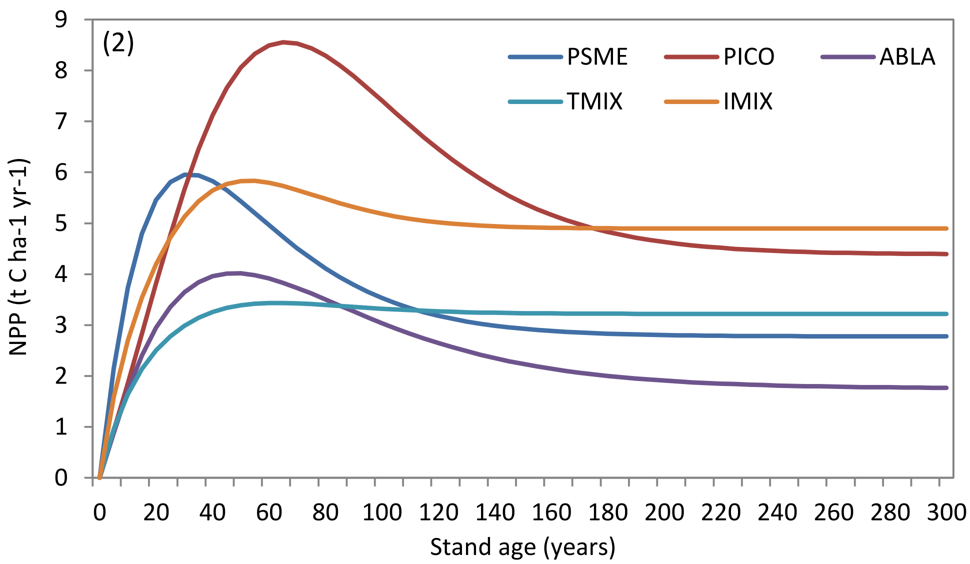


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Beaverhead-Deerlodge National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) or hardwood mixed (HMIX) plots to derive NPP-age curves, thus the IMIX curve was used for the few PIPO and HMIX stands.

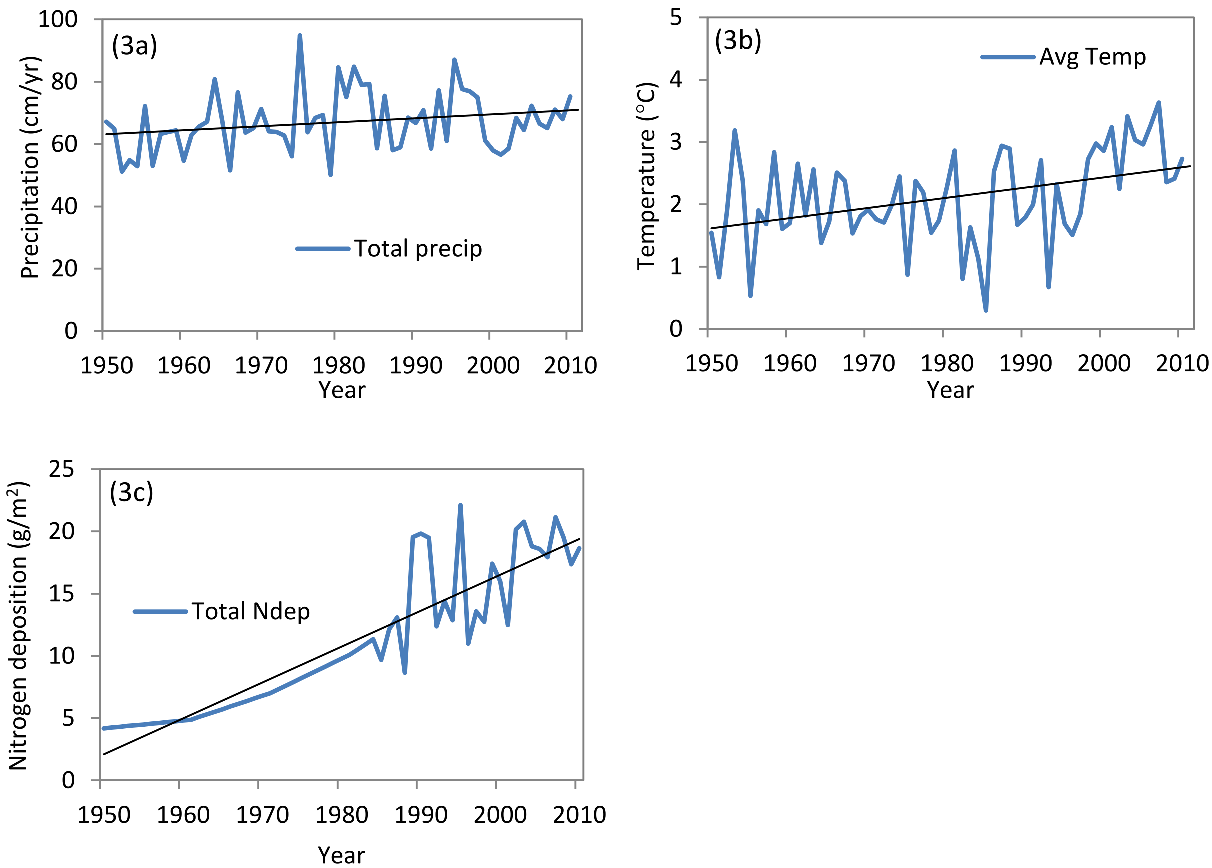


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Beaverhead-Deerlodge National Forest. Linear trend lines shown in black.

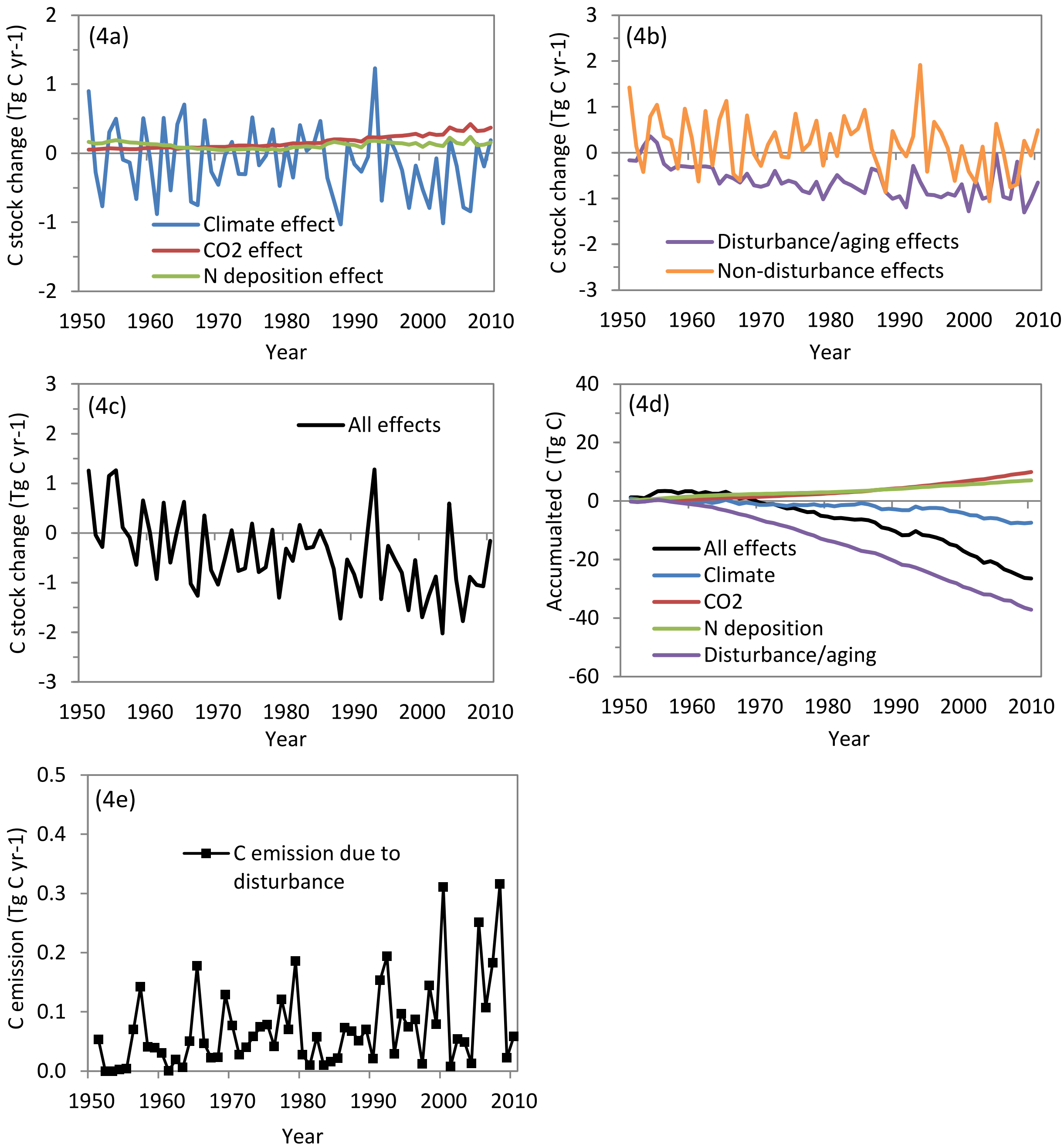


Figure 4.4. Changes in carbon stocks in the Beaverhead-Deerlodge National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth 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 Figures 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.

Bitterroot National Forest - Montana & Idaho

Between 1950 and 2010, forests in the Bitterroot National Forest transitioned from a C sink to mostly a C source (Figure 4.4c). Disturbance/aging has had a negative effect on C stocks, enhancing the C source since 1950 (Figure 4.4b). This is primarily due to aging forests, as roughly 65% of the stands are >80 years old (Figure 4.1) and have aged past their peak productivity (Figure 4.2). The pulse of stand establishment occurring 90-99 years ago (1911-1920), consisting of primarily Douglas-fir, would have reached maximum productivity in the 1940s (Figure 4.2), which supports the transition from a C sink to a source thereafter in the 1950s (Figure 4.4b), as C losses from decomposition and decay became greater than C gains. This pulse may be a result of recovery after major fires and/or increased disturbances associated with settlement activities, as well as fire suppression which allowed more young trees to survive than if normal disturbance rates continued. High severity fires in 2000, which affected > 10% of the forest (Figure. 1.1f), caused the emission of 1.2 Tg C (Figure 4.4e), and the forests to become a significant C source (Figure 4.4b-c). Bitterroot NF is starting to recover from this fire, evidenced by the significant pulse of young tree which established between 2000 and 2010 (Figure 4.1). The ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1f). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source since 1990 than the InTEC results indicate.

Climate has also had a negative effect on changing C stocks (Figure 4.4c) and C accumulation (Figure 4.4d), due to warmer temperatures (Figure 4.3b) and a decrease in precipitation (Figure 4.3a). Warmer temperatures increase respiration while drought conditions cause water stress and constrain growth. The increases in nitrogen deposition (Figure 4.3c) and atmospheric CO_2 enhanced the C sink, but were overshadowed by the C losses due to disturbances, aging, and climate. Overall the Bitterroot NF experienced a net loss of approximately 16.2 Tg C since 1950 (Figure 4.4d), mostly due to negative disturbance/aging and climatic effects (Figure 4.3d). When taking into account potential C losses due to recent disease impacts (Figure 2.1f), Bitterroot NF likely experienced a larger net loss in total C stocks.

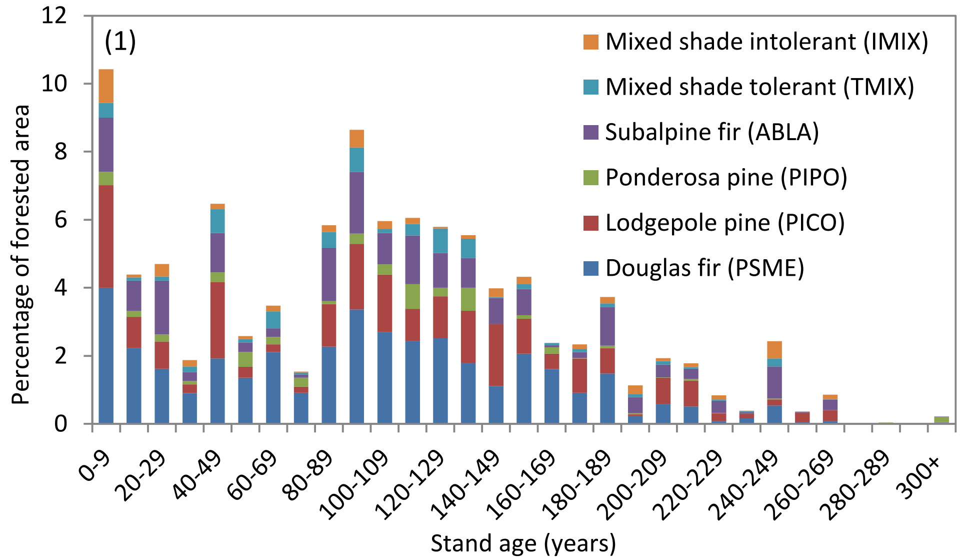


Figure 4.1. Age class distribution in 2010 in the Bitterroot National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

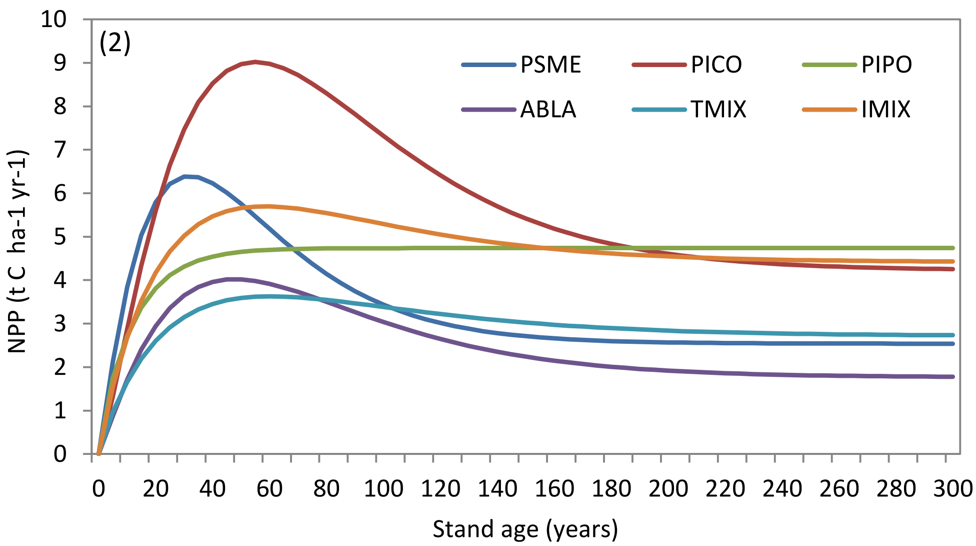


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Bitterroot National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

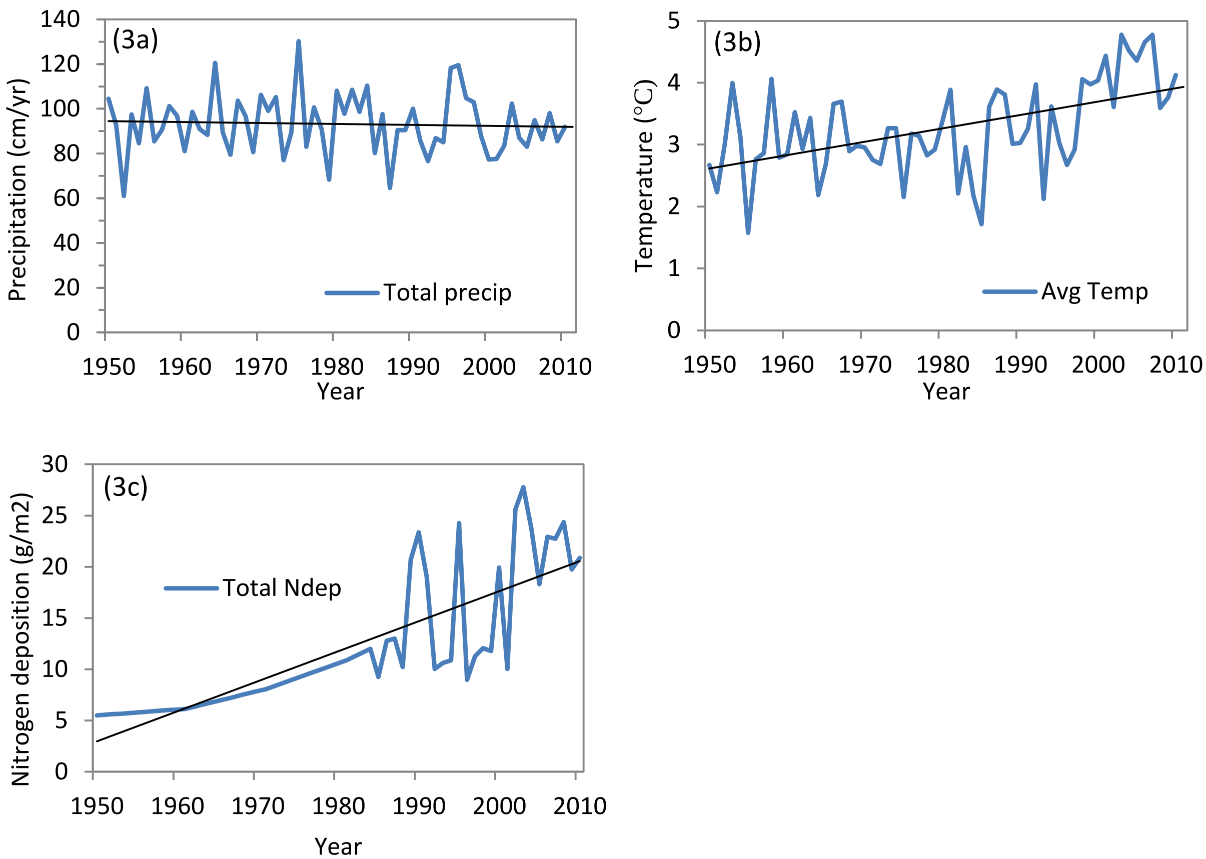


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Bitterroot National Forest. Linear trend lines shown in black.

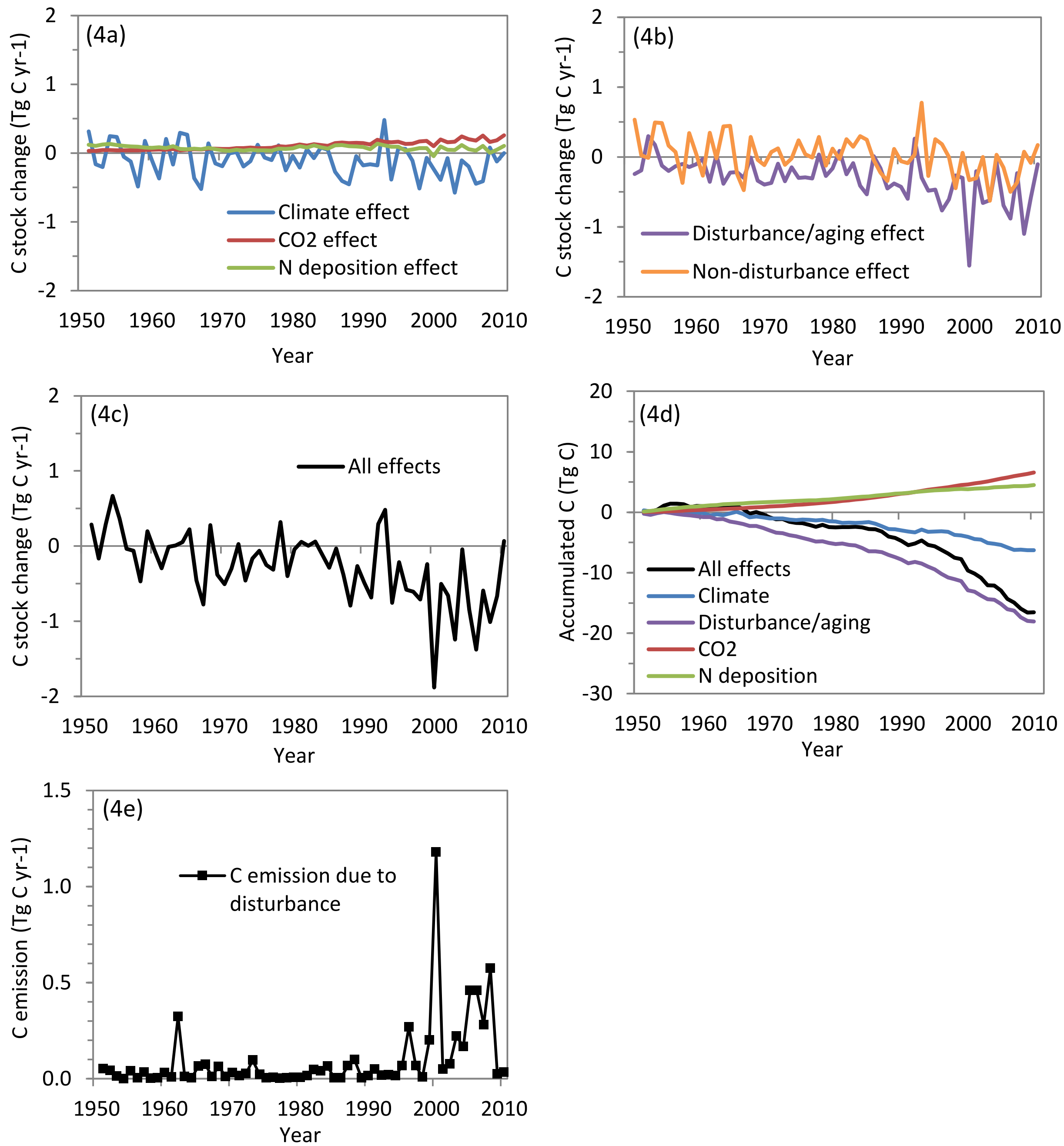


Figure 4.4. Changes in carbon stocks in the Bitterroot National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Custer National Forest - Montana, South Dakota & North Dakota

From 1950-1993, forests in the Custer National Forest maintained a small carbon (C) sink, but then switched to mostly a C source due to recent disturbances (Figure 4.4.4 a-c). Roughly 22% of the forests in Custer NF are young (<10 year old), reflecting establishment and regrowth after significant fire and harvest disturbances in 2006, 2008, and 2009 (Figure 1.1h). As the predominantly young, Ponderosa pine stands (Figure 1) approach middle-age (~35 years old) they will be growing at peak productivity suggesting C stocks may accumulate most rapidly in approximately two decades (Figure 4.2), and forests have the potential to switch to a C sink again. The negative influence of disturbances in the 2000s (Figure 4.4b) suggests that the forests have not yet recovered C from these recent disturbances.

Climate variability caused the forest to fluctuate between a C sink and source over this period. However, over the past two decades climate effects on changing C stocks have been mostly negative (Figure 4.4a), likely due to warming temperatures (Figure 4.3b) causing increased soil respiration and water stress. The increases in nitrogen deposition (Figure 4.3c) and atmospheric CO_2 concentrations enhanced the C sink, helping forests to accumulate C since 1950 (Figure 4.4d). Despite recent C losses due to disturbances and climate, CO_2 fertilization and nitrogen deposition partially offset these losses and ultimately enabled the forest to achieve a net gain of approximately 6.4 Tg C from 1950-2010 (Figure 4.4d).

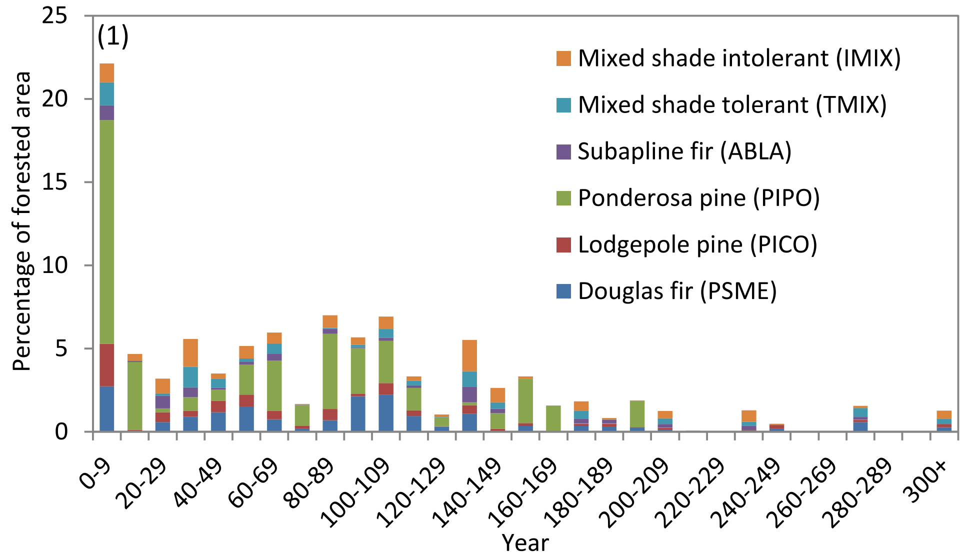


Figure 4.1. Age class distribution in 2010 in the Custer National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

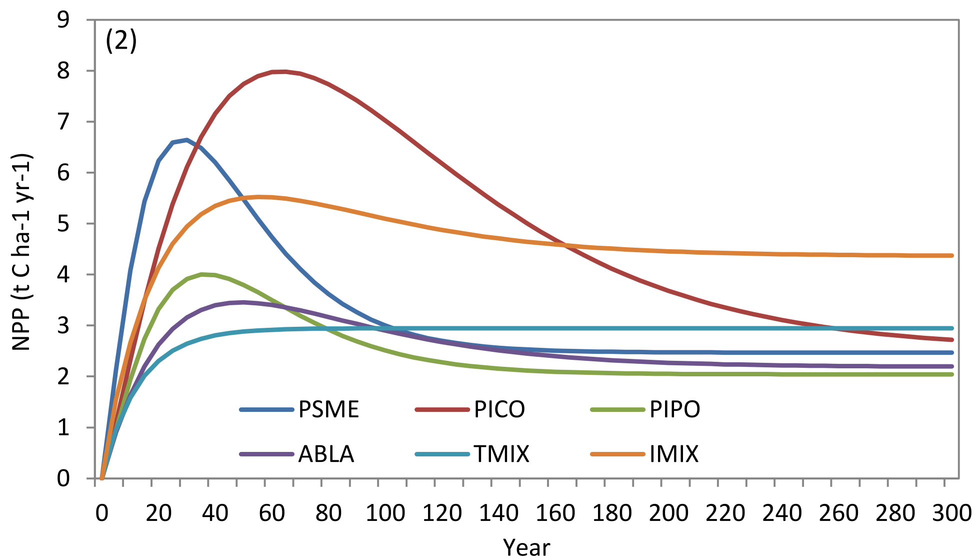


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Custer National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

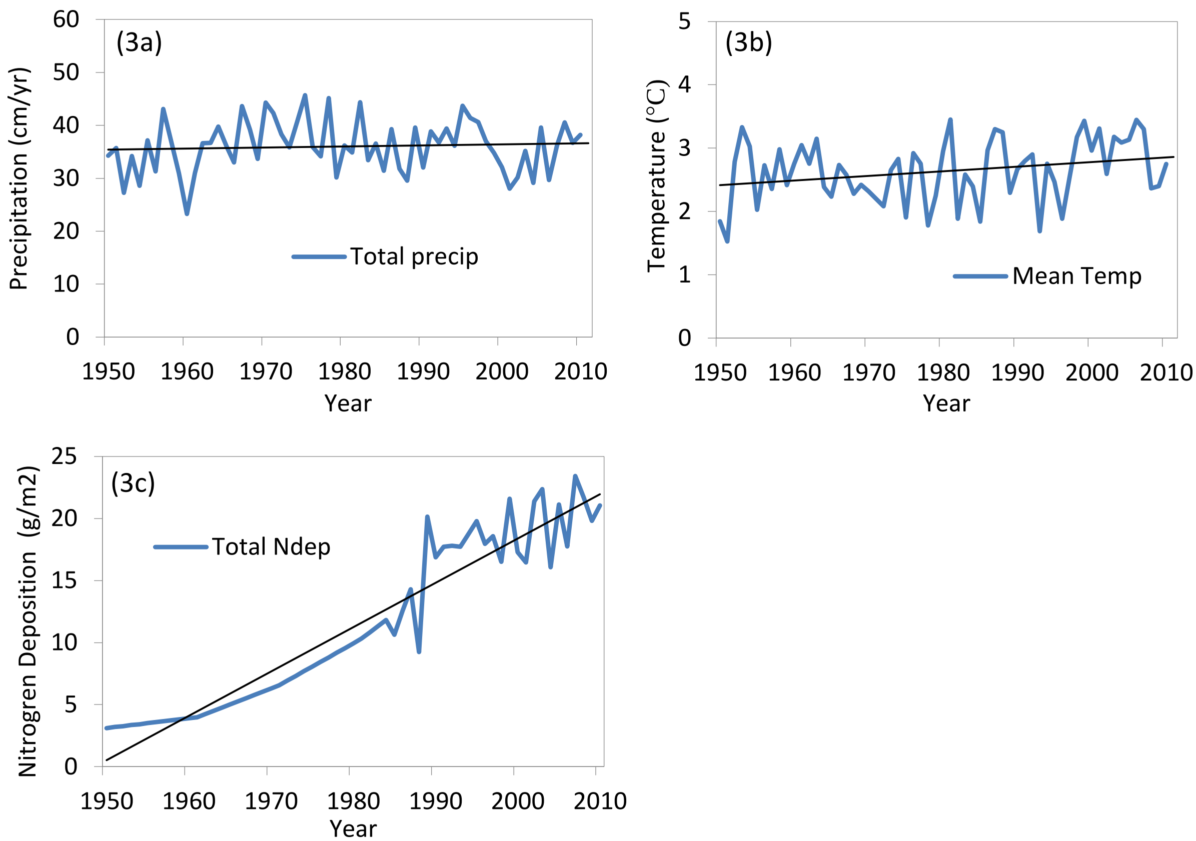


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Custer National Forest. Linear trend lines shown in black.

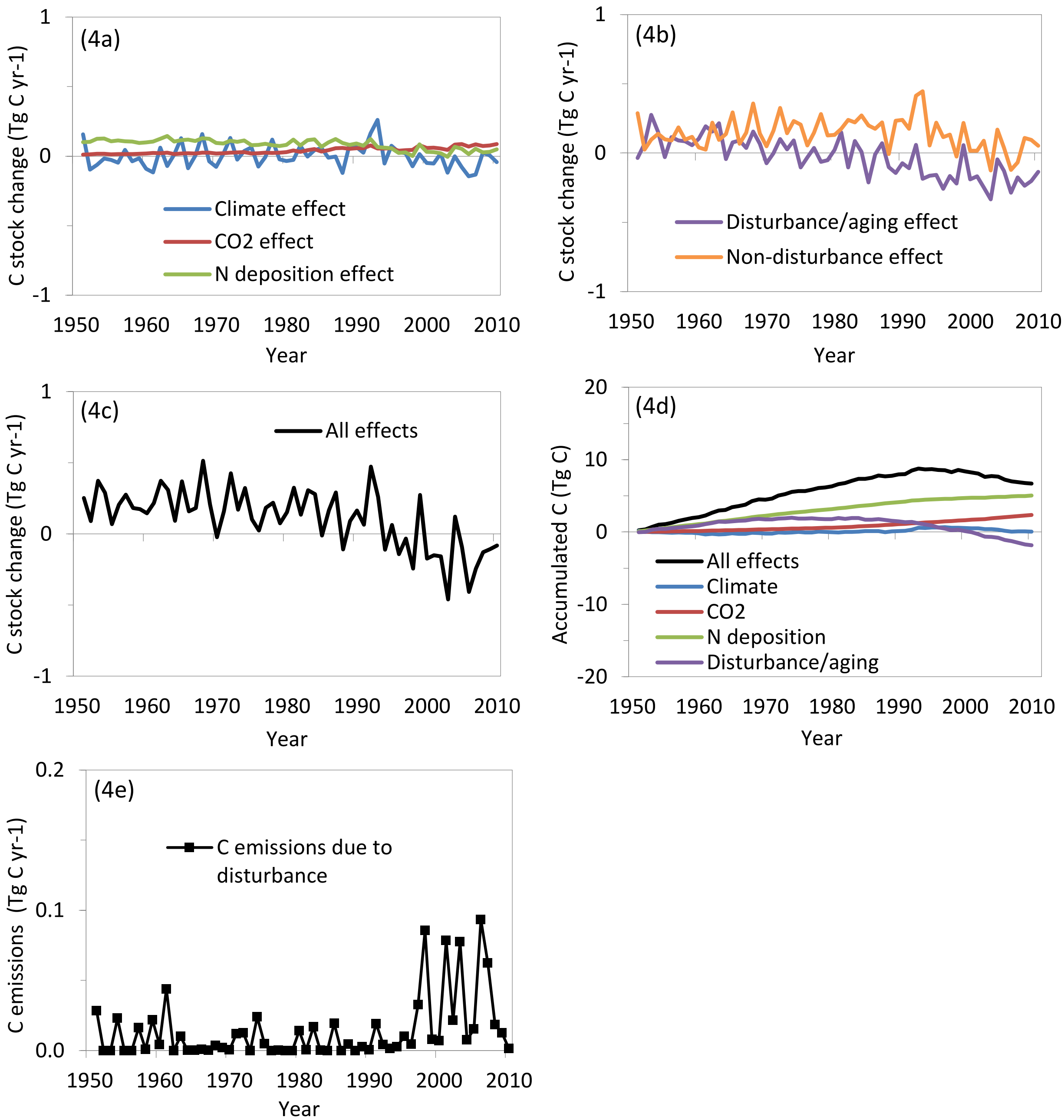


Figure 4.4. Changes in carbon stocks in the Custer National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Flathead National Forest - Montana

Despite periodic C sink years, forests in the Flathead National Forest have more often been a C source (Figure 4.4c), experiencing an overall decline in C stocks between 1950 and 2010, due to negative disturbance/aging and climatic effects (Figure 4.4d). In the 1950s and 1960s disturbance/aging effects enhanced the C sink (Figure 4.4b), likely due to recovery from early 20th century disturbances, evidenced by the pulse of stand establishment 80-90 years ago (Figure 4.1). Also, fire suppression during this period allowed stands to survive and continue to re-grow, rather than being disturbed at a more typical historical rate. These mostly Subalpine fir and Douglas fir stands (Figure 4.1) would have reached maximum productivity when they were middle-aged, approximately 35-60 years old (Figure 4.2) or in the mid-1900s , corresponding to the C sink years (Figure 4.4b) and period of positive C accumulation (Figure 4.4c).

From 2000-2009 disturbance/aging effects caused Flathead NF to be C source (Fig 4.4b), as C emissions also dramatically increased (Figure 4.4e) due to moderate-to high-severity disturbances throughout much of the 2000s—the largest of which were in 2004 and 2007 (Figure 1.1a). The ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1a). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source than the InTEC results indicate. These recent disturbances are also reflected in the pulse of young stands (<10 years old) (Figure 4.1), causing the forest to become a C sink again in 2010. The newly established stands will soon reach their maximum productivity (Figure 4.2), thus there is the potential for an increase in C accumulation in coming decades.

Of the non-disturbance factors, climate has had a predominantly negative effect on C stocks since the late 1950s, due to increasing temperatures and decreasing precipitation (Figs. 4.3a-b), which result in greater soil respiration and water stress, constraining growth. Nitrogen deposition and atmospheric CO_2 concentrations have had increasingly positive impacts (Figs. 4.4a, d), though these were overshadowed by the negative disturbance/aging and climate effects, resulting in a net decline of approximately 13.5 Tg C since 1950 (Figure 4.4d). When taking into account potential C losses due to recent disease impacts (Figure 2.1a), Flathead NF likely experienced a larger net loss in total C stocks.

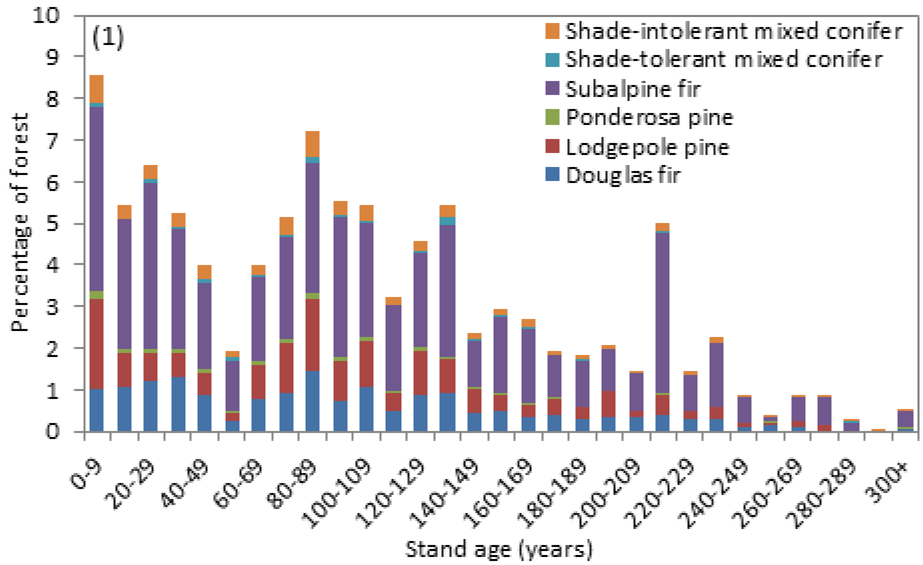


Figure 4.1. Age class distribution in 2010 in the Flathead National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

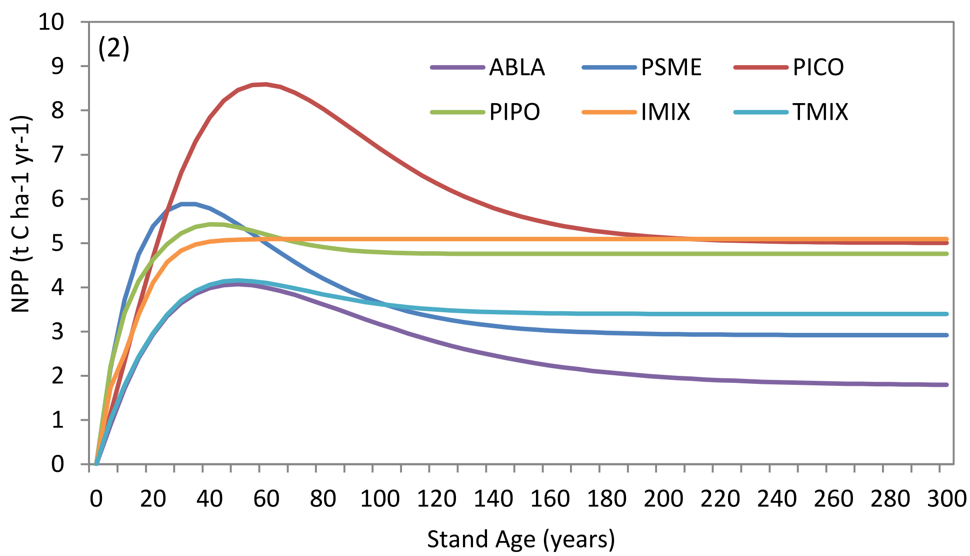


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Flathead National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

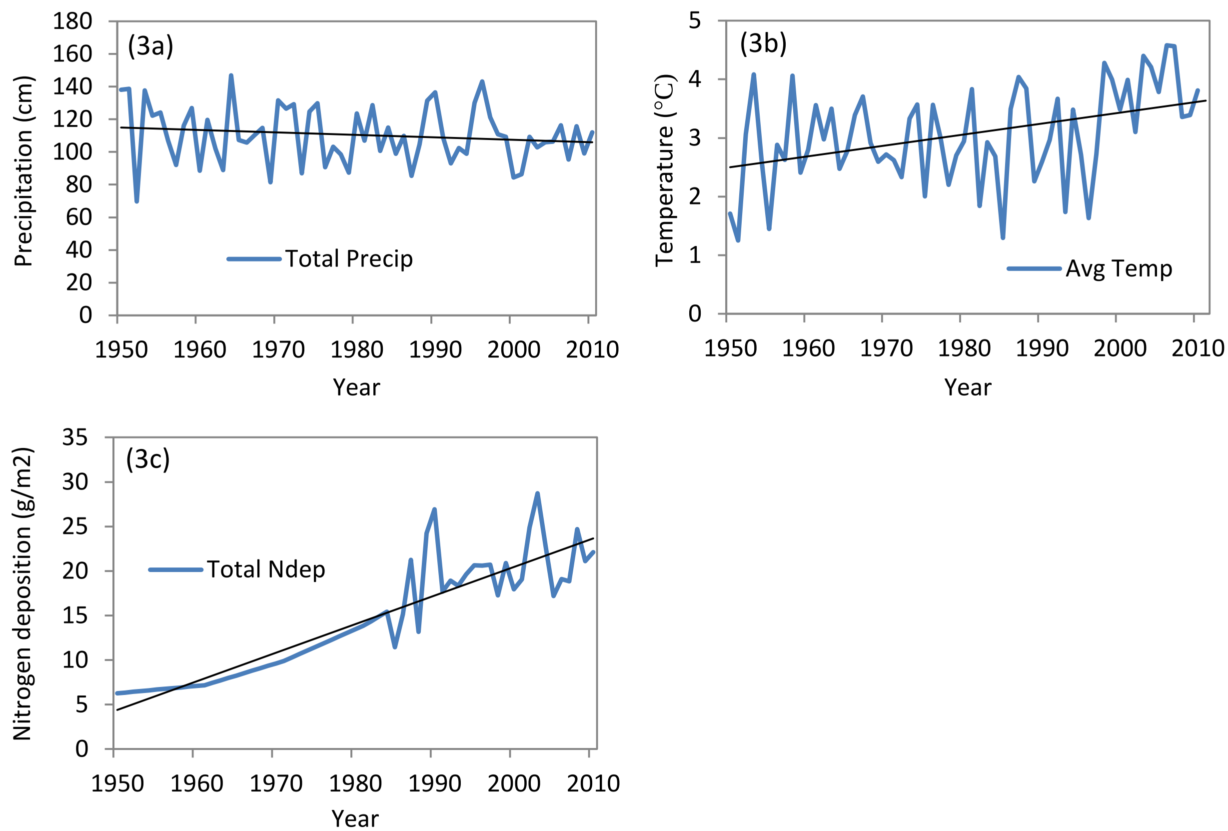


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Flathead National Forest. Linear trend lines shown in black.

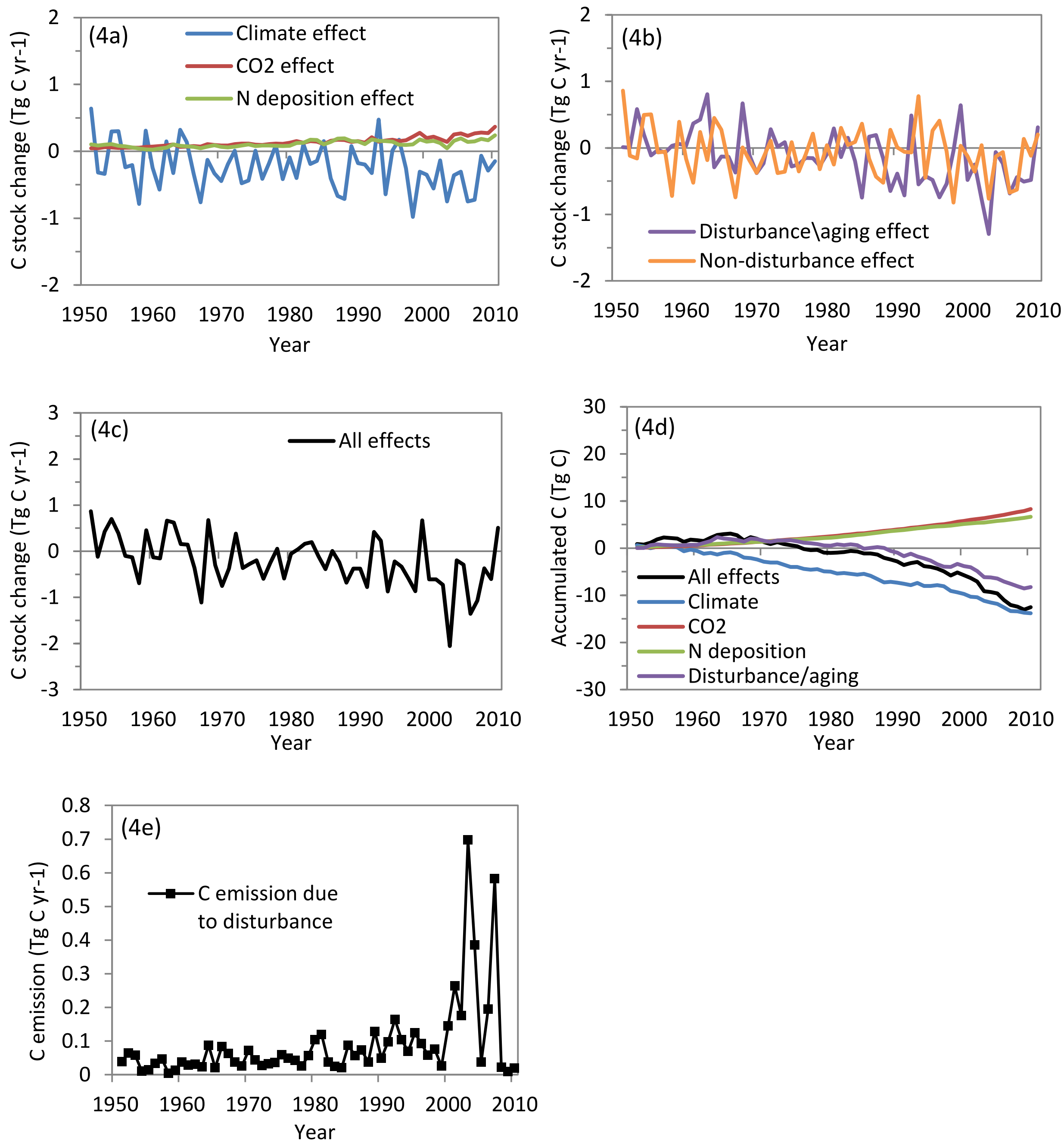


Figure 4.4. Changes in carbon stocks in the Flathead National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Gallatin National Forest - Montana

Between 1950 and 2010, forests in the Gallatin National Forest maintained a small carbon (C) source, and experienced a downward trend in changing C stocks (Figure 4.4c), mostly due to negative disturbance/aging effects (Figure 4.4b). The stand age distribution indicates that approximately 66% of the stands are >90 years old, with a subtle pulse of stands establishing about 110-139 years ago (1871-1900) (Figure 4.1), likely as a result of major fires or land-use change associated with Euro-American settlement in the region. Fire suppression activities beginning in the early 20^{th} century then enabled stands to survive and continue re-growing rather than being disturbed at a more typical historical rate. These middle-older aged stands have aged past their peak in NPP and have been declining in productivity (Figure 4.2) contributing to the decline in forest C from 1950-2010 (Figure 4.4d), as C losses from decomposition and decay were greater than C gains. About 17% of the stands consist of young forests, <20 years old (Figure 4.1), indicative of establishment and recovery after recent, large disturbances, especially the fires and insect outbreaks in 2001 and 2006-2008 (Figure 1.1i). Although these recent disturbances caused an immediate loss of C through direct emissions to the atmosphere (Figure 4.4e), this pulse of young stands indicates that forests are recovering and have the potential to become a C sink within a few decades, especially as they age to maximum productivity (Figure 4.2).

Increases in atmospheric CO_2 concentrations and nitrogen (N) deposition (Figure 4.3c) have had positive effects on C stocks, while climate effects fluctuated between positive and negative following the inter-annual variability in climatic variables (Figure 4.3a-b). From 1994-2010, climate effects were consistently negative, as a result of warming temperatures which can increase soil respiration and water stress, hampering growth. Despite C accumulation from CO_2 fertilization and N deposition, forests in Gallatin NF experienced a net loss of approximately 14 Tg C from 1950-2010, due to negative disturbance/aging and climate effects (Fig. 4.4d).

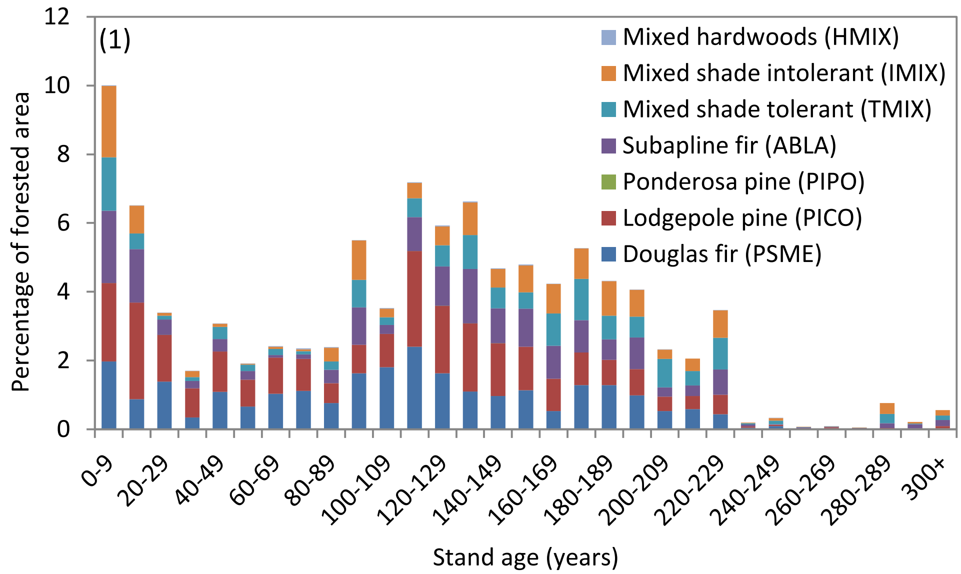


Figure 4.1. Age class distribution in 2010 in the Gallatin National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

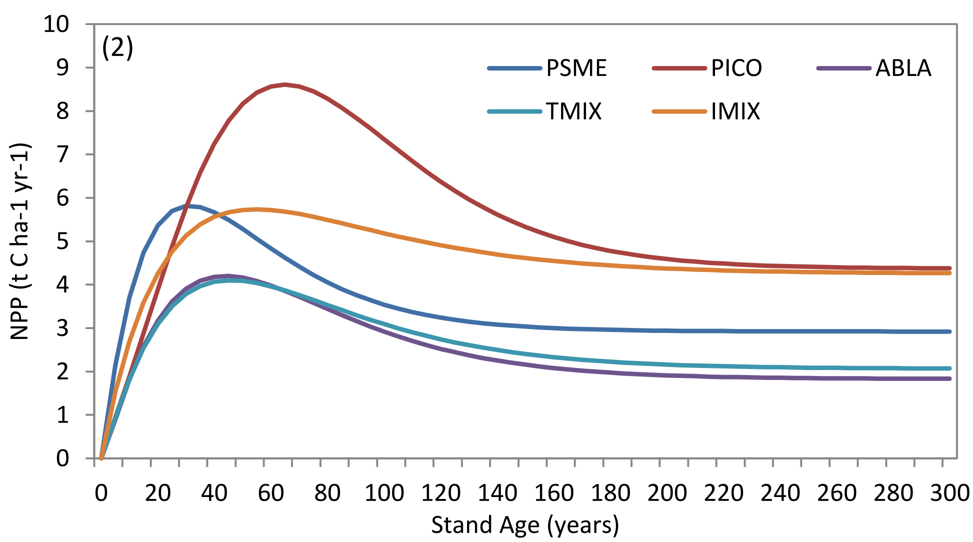


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Gallatin National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) or mixed hardwoods (HMIX) plots to derive NPP-age curves, thus the IMIX curve was used for any PIPO and HMIX stands.

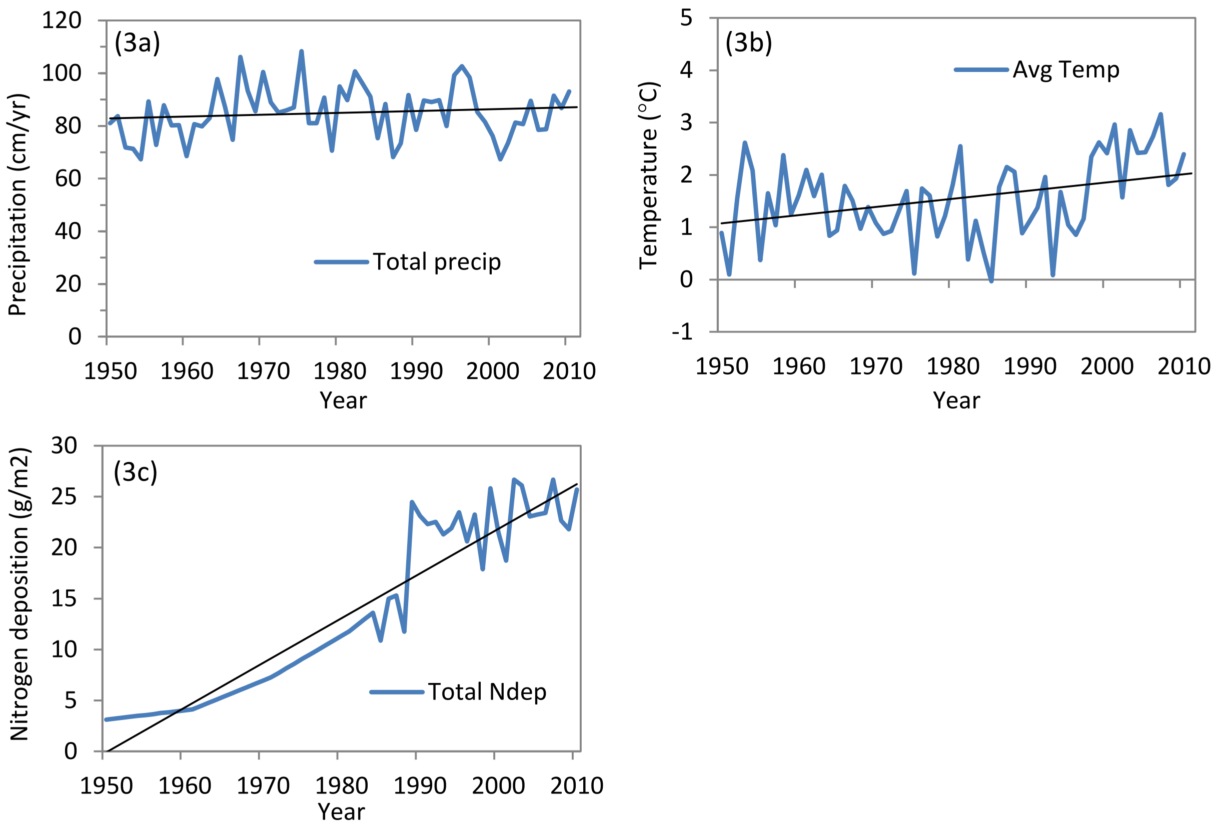


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Gallatin National Forest. Linear trend lines shown in black.

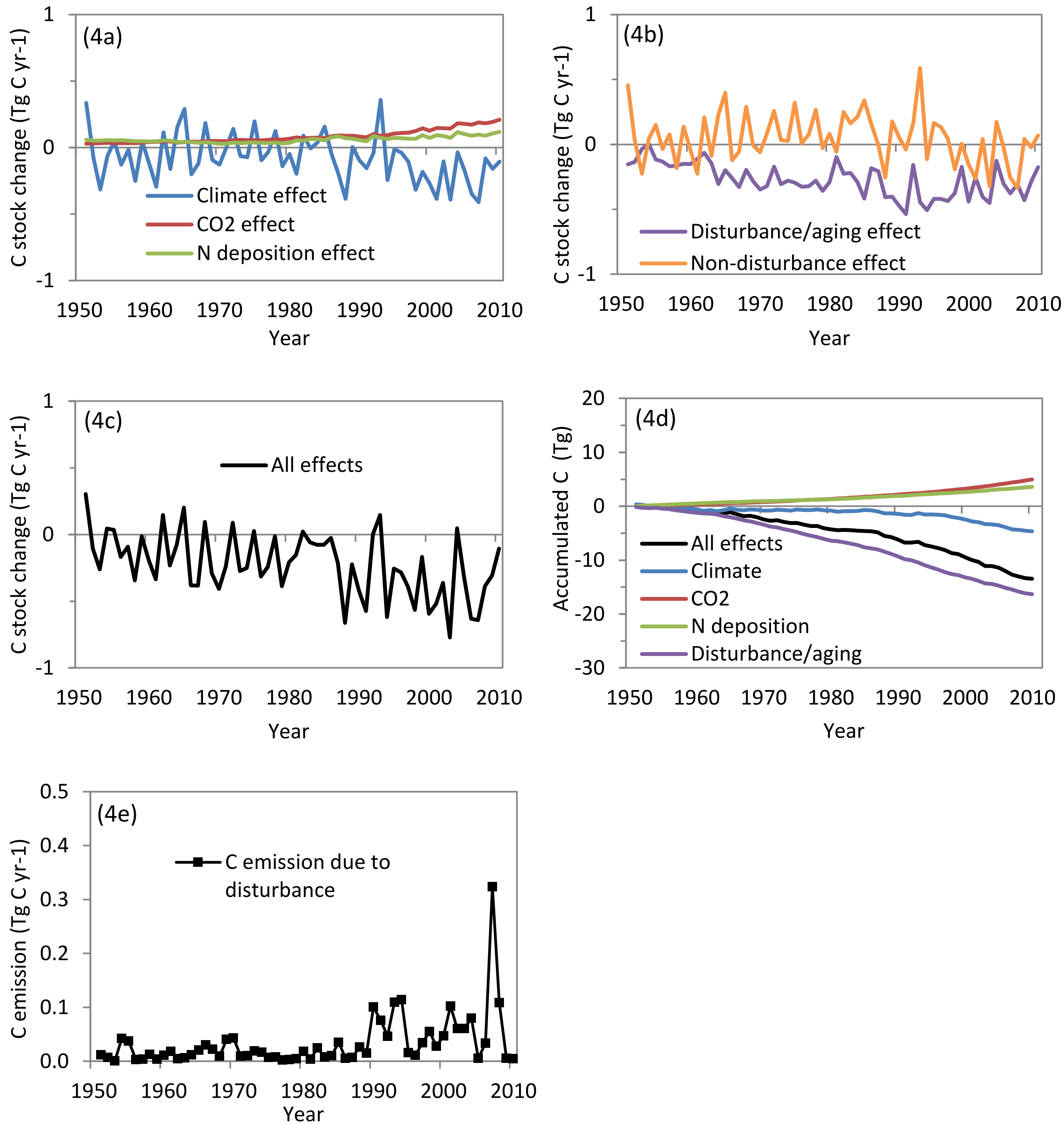


Figure 4.4. Changes in carbon stocks in the Gallatin National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Helena National Forest - Montana

Forests in the Helena National Forest were a carbon (C) sink from 1950-1993 then switched to a C source through 2010 (Figure 4.4c). This shift from a C sink to a source corresponds to the increased negative effects of disturbances and aging (Figure 4.4b), as well as negative climate effects (Figure 4.4a). The disturbance and aging effects are supported by the stand age distribution which shows a distinct pulse of stand establishment occurring 80-120 years ago (1890-1930), likely due to recovery from the last major fires and/or disturbances associated with Euro-American settlement in the late 1800s (Figure 4.1). Fire suppression activities beginning in the early 20th century would have also enabled these stands to continue re-growing rather than being disturbed at a more typical historical rate. This pulse of predominantly Douglas-fir and Lodgepole pine stands (Figure 4.1) would have been growing at peak productivity between ages 30-65 (Figure 4.2), which corresponds to the increasing C accumulation and the C sink during much of the mid-1900s (Figure 4.4b, d). Another establishment pulse consists of young stands, <20 years old (Figure 4.1), resulting in part from the large high-severity fires in 2003 and 2007 (Figure 1.1j). As these young stands reach middle-age in coming decades, the rate of productivity and subsequent C accumulation will likely increase (Figure 4.2), thus the Forest has the potential to become a C sink again.

Climate has had a slight negative effect on changing C stocks and accumulation since the late 1960s (Figure 4.4a, d). Warmer temperatures (Figure 4.3b) and a slight decrease in precipitation (Figure 4.3a) caused a greater decrease in C during the 21st century (Figure 4.4d) than previous decades. Warmer temperatures increase respiration while droughts limit growth. Nitrogen deposition and atmospheric CO_2, which both increased over the past few decades (Figure 4.3c), had positive effects on changing C stocks and C accumulation (Figure 4.4a, d). C gains from N deposition and CO_2 fertilization offset C losses due to climate and disturbances, causing total C stocks in 2010 to be about equal to those in 1950.

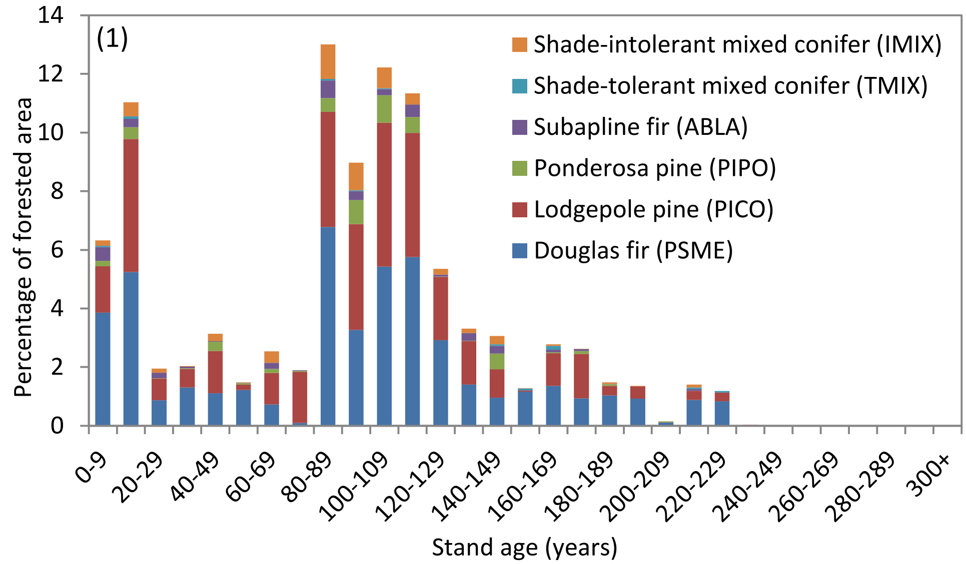


Figure 4.1. Age class distribution in 2010 in the Helena National Forest displaying the number of forested pixels of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

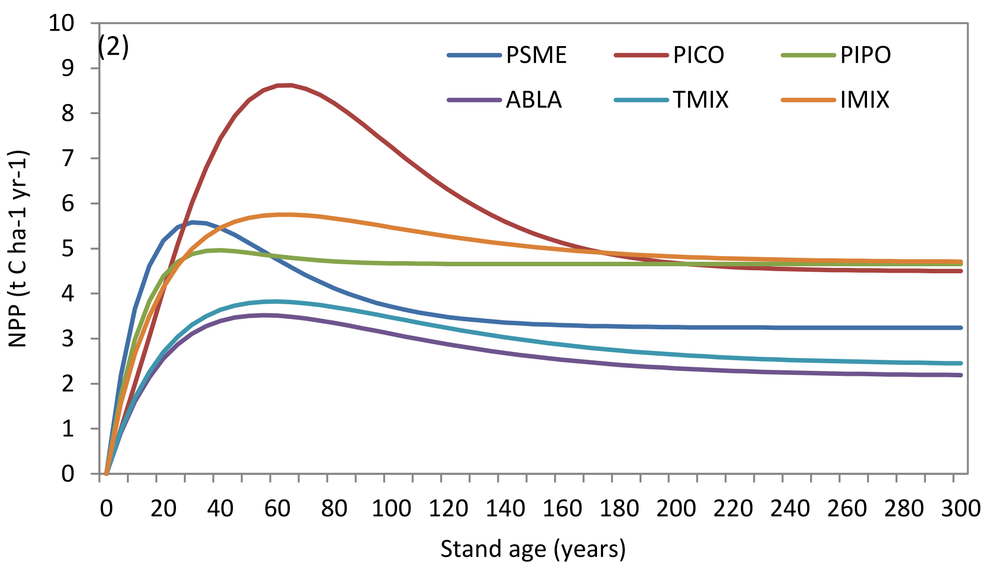


Figure 4.2. Net primary productivity (NPP)-stand age relationships for each forest dominance type in the Helena National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

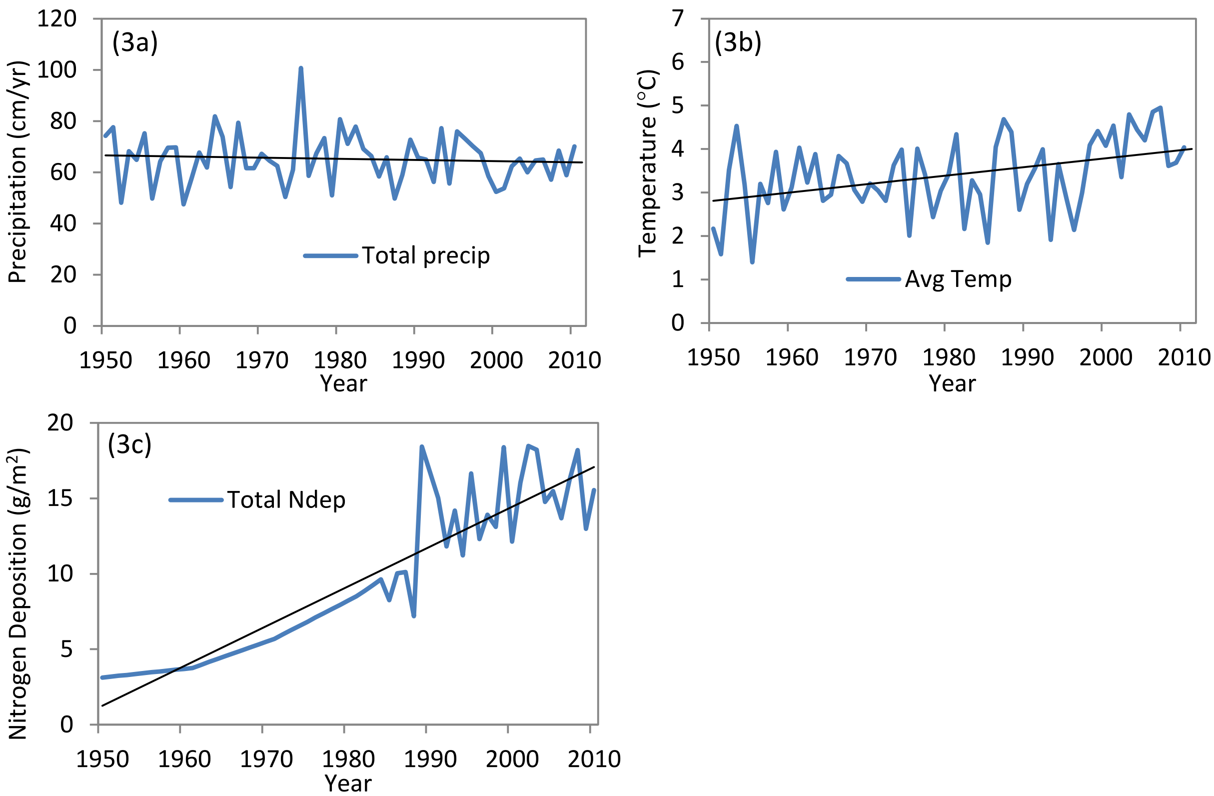


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition (g/m^2) from 1950-2010 in the Helena National Forest. Linear trend line shown in black.

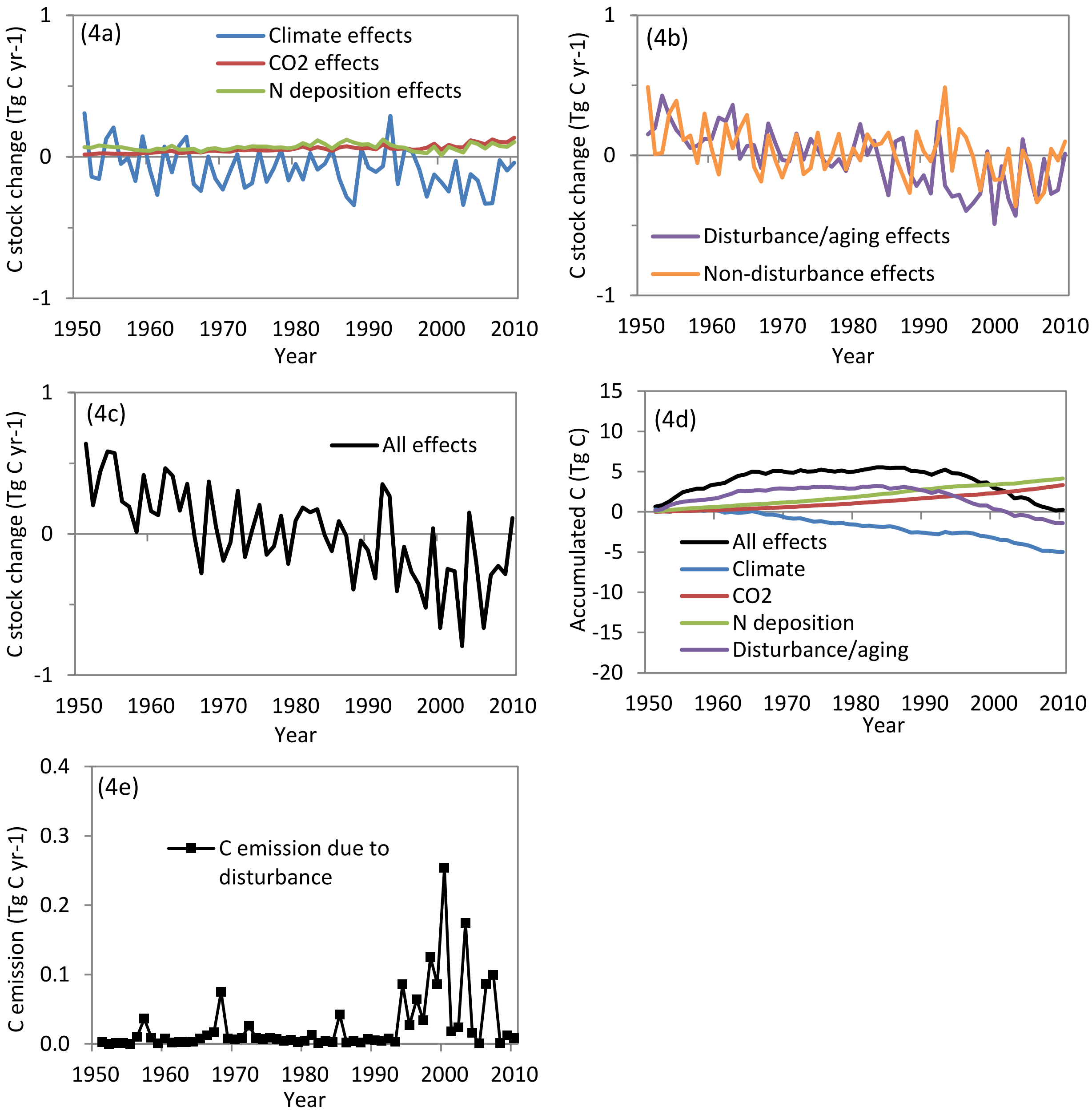


Figure 4.4. Changes in carbon stocks in the Helena National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Idaho Panhandle National Forest - Idaho

Forests in the Idaho Panhandle National Forest generally show a decreasing trend in changing carbon (C) stocks and a shift from a C sink to a source in the mid-1980s (Figure 4.4c) mostly following the effects of disturbances and aging (Figure 4.4b, d). The stand age distribution shows the forest is mostly older, with a distinct peak in establishment 70-110 years ago (1900-1940), likely due to recovery after the last major fires before the onset of fire suppression and/or disturbances associated with Euro-American settlement in the region. Fire suppression also allowed the stands to continue re-growing rather than being disturbed by fires through much of the 20th century. Through the 1950s and 1960s, many of these stands were still growing at their peak productivity (Figure 4.2), thus contributing to the C sink, but have since aged and productivity has declined, causing forests to switch to a C source (Figure 4.4b-c) as decay and decomposition losses were greater than C gains. Recent fires, insects, and harvests were quite small or low-severity (Figure 1.1b) thus did not greatly affect the age structure or disturbance/aging effects, or cause significant, immediate C emissions (Figure 4.4b, e). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1b). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused greater C emissions and a stronger C source than the InTEC results indicate. Overall, disturbance/aging had the greatest positive impact on C accumulation from 1950-2010, but this rate of accumulation has been steadily declining since the mid-1980s (Figure 4.4d).

Of the non-disturbance factors, climate has had a mostly negative effect on C stocks since the late 1950s, while increased nitrogen (N) deposition (Figure 4.3c) and atmospheric CO_2 concentrations show positive effects (Figure 4.4a, d). The negative climate effects and positive CO_2 and N deposition effects mostly offset each other such that total accumulated C since 1950 is almost entirely a function of disturbance and aging effects (Figure 4.4d). Idaho Panhandle NF experienced a net gain of approximately 4.4 Tg C in C stocks from 1950 to 2010 (Figure 4d). When taking into account potential C losses due to recent disease impacts (Figure 2.1b), Idaho Panhandle NF may have experienced a small net loss in total C stocks.

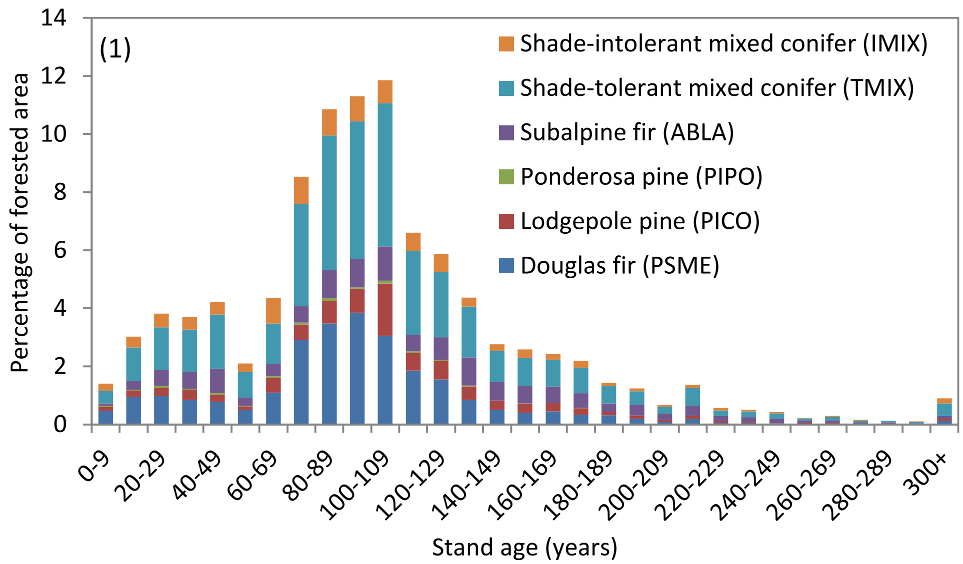


Figure 4.1. Age class distribution in 2010 in the Idaho Panhandle National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

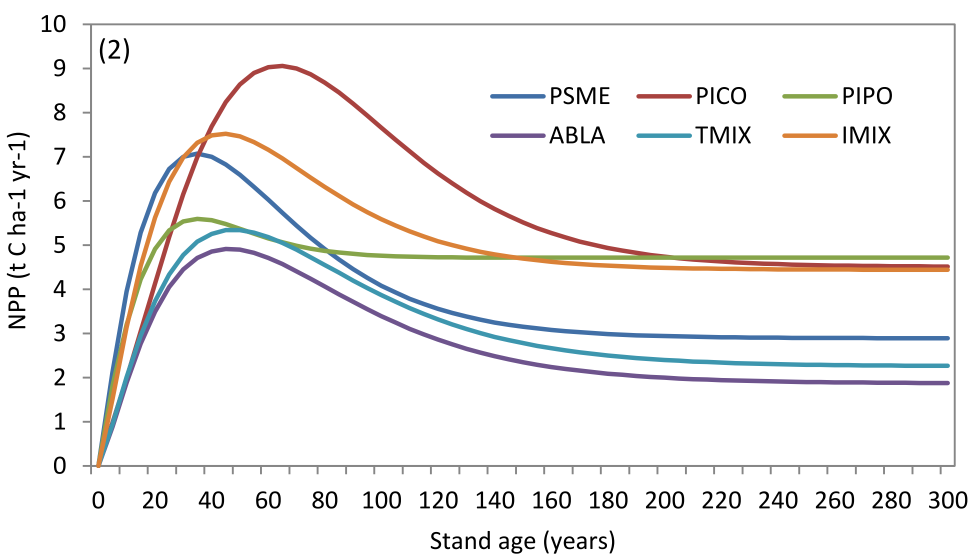


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Idaho Panhandle National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

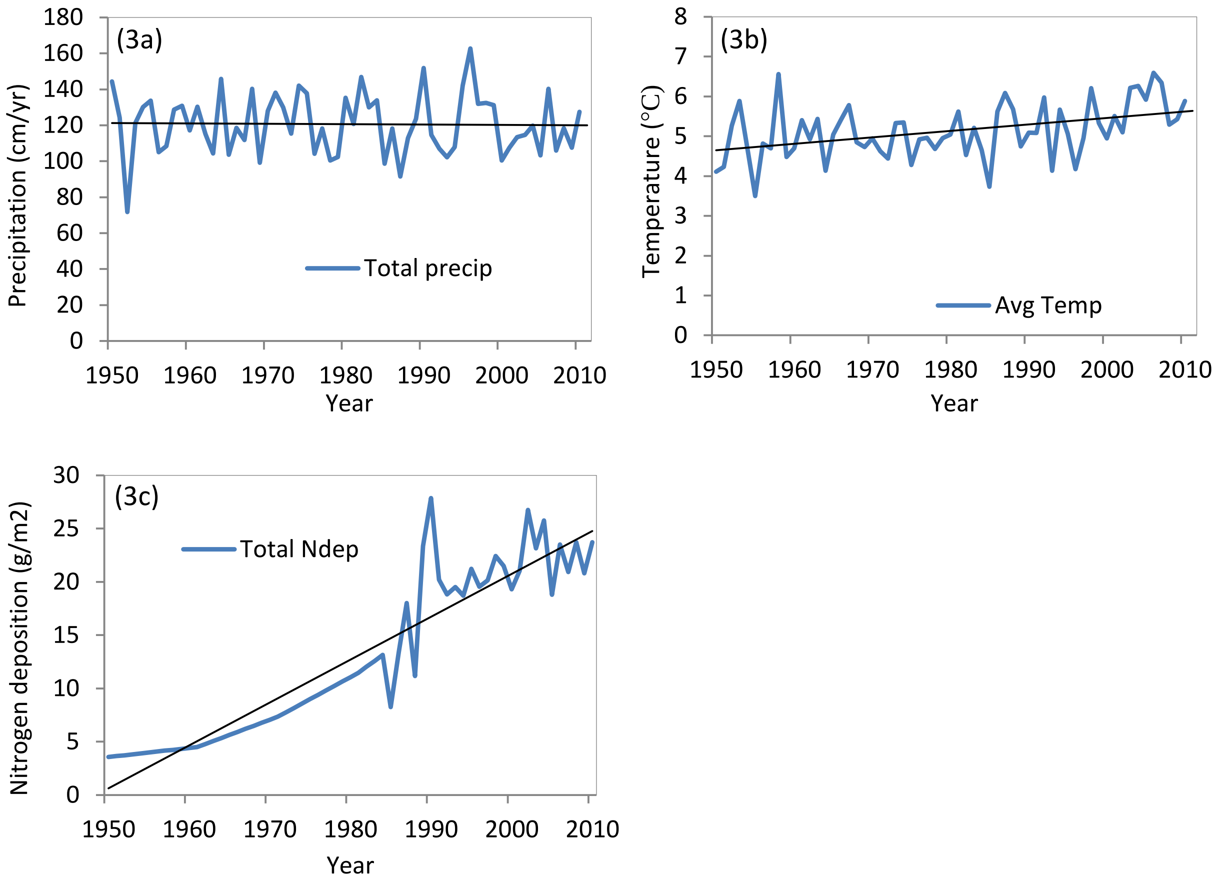


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Idaho Panhandle National Forest. Linear trend lines shown in black.

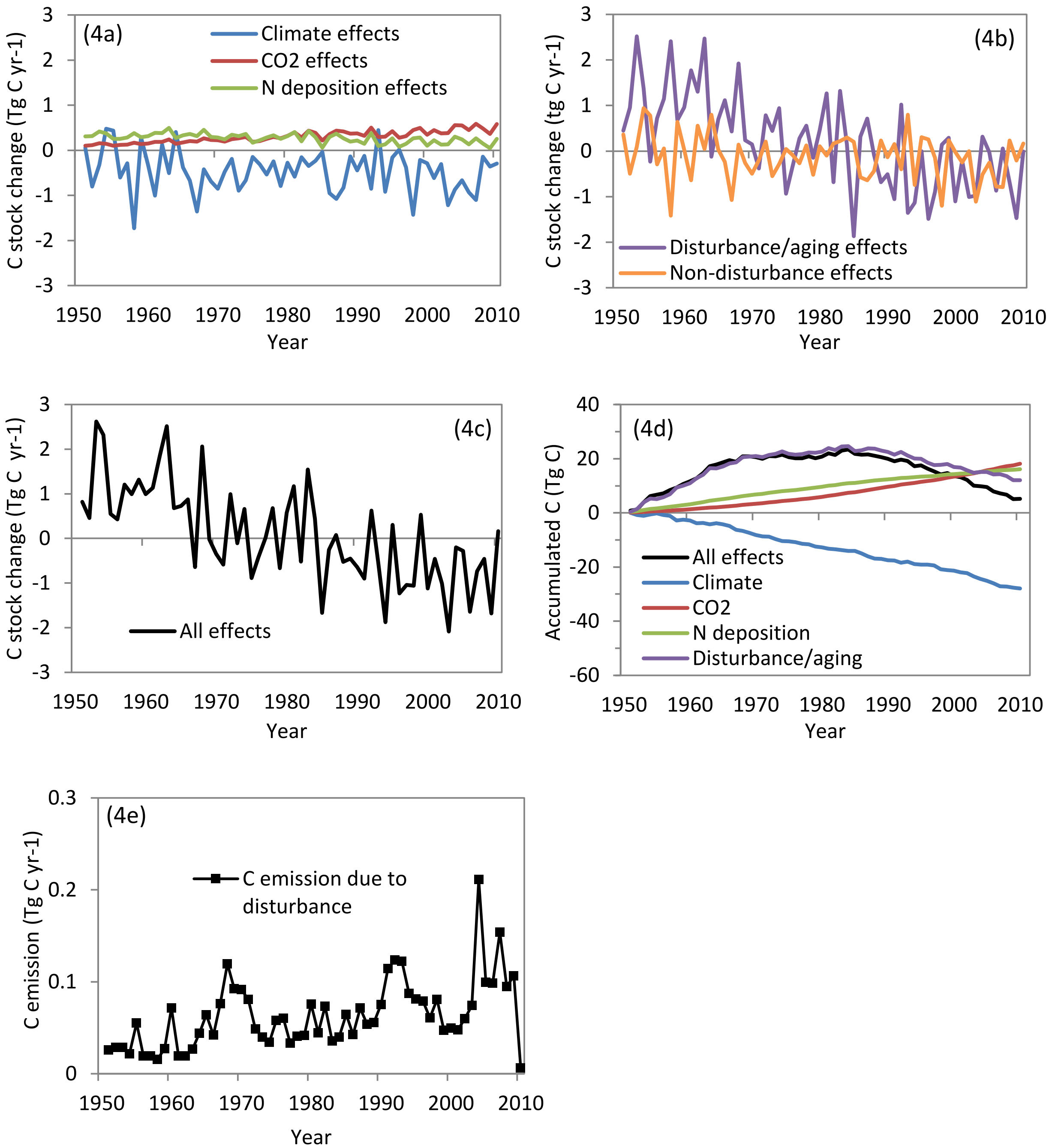


Figure 4.4. Changes in carbon stocks in the Idaho Panhandle National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth 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 Figures 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.

Kootenai National Forest – Montana & Idaho

Forests in the Kootenai National Forest fluctuated between a carbon (C) sink and a source from 1950-2010, but generally show a decline due to disturbance/aging and climate effects (Figure 4.4a-d). The stand age distribution shows a large pulse of stands that were establishing 100-109 years old (1900-1910) (Figure 4.1), likely due to recovery after the last major fires preceding fire suppression and/or disturbances soon after Euro-American settlement in the region. Fire suppression, beginning in the early 1900s would have also allowed these young stands to survive and continue to re-grow in the absence of fire. This pulse of mostly Douglas fir and Shade-tolerant mixed conifer stands would have reached peak productivity at about 30-55 years old (1930-1955)(Figure 4.2), explaining the C sink and positive C accumulation due to disturbances/aging through the 1950s and 1960s (Figure 4.4b, d). Despite the several moderate to severe disturbances, mostly harvests and fires, over the past few decades (Figure 1.1c), there has been minimal re-establishment (Figure 4.1), likely because these disturbances were quite small, affecting less than 1% of the forested area. The most significant disturbance years were 1992, 1994, and 2000 (Figure 1.1c) which caused increased direct C emissions (Figure 4e) contributing to the C source (Figure 4.4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1c). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source than the InTEC results indicate.

Climate has had a mostly negative effect on C stocks since the late 1950s with a few years of positive influence (Figure 4.4a, d). The trend of warmer temperatures (Figure 4.3b) and decreased precipitation (Figure 3a), cause increased soil respiration and constrained growth. The increases in nitrogen deposition (Figure 4.3c) and atmospheric CO_2 enhanced the C sink causing an accumulation of C (Figure 4.4a, d), but were overshadowed by the C losses due to disturbances/aging and climate. Overall, Kootenai NF experienced a net loss of approximately 24.5 Tg C from 1950-2010 (Figure 4.4d). When taking into account potential C losses due to recent disease impacts (Figure 2.1c), Kootenai NF likely experienced a larger net loss in total C stocks.

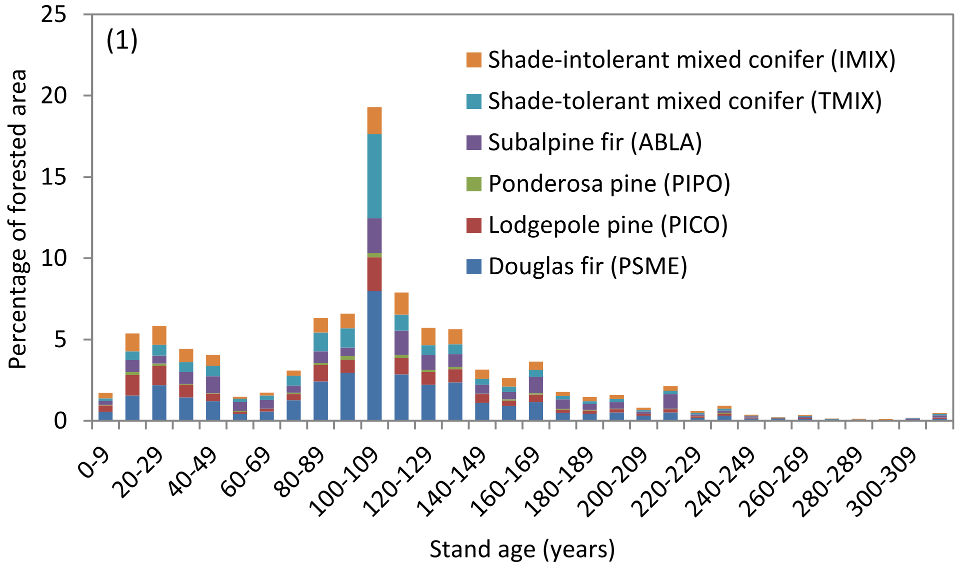


Figure 4.1. Age class distribution in 2010 in the Kootenai National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

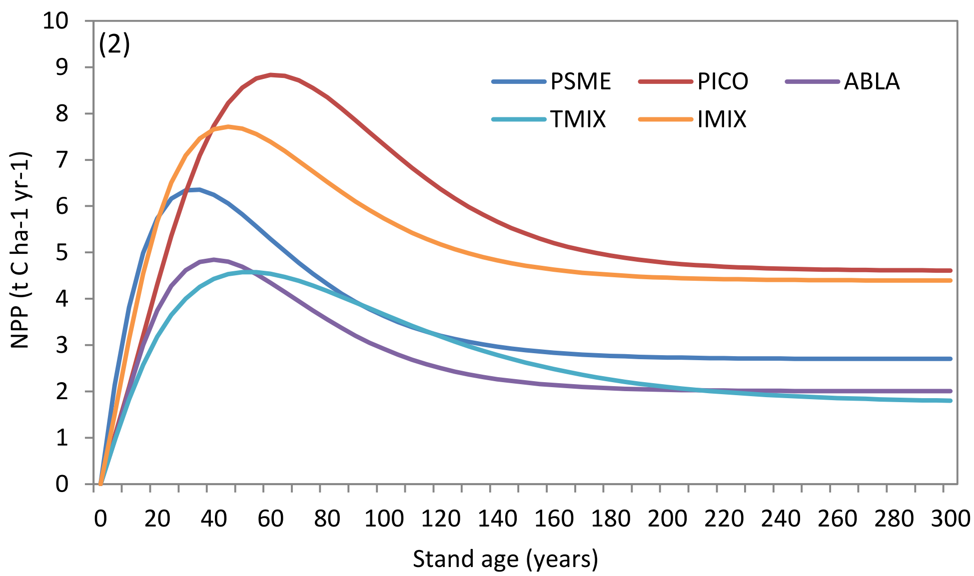


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Kootenai National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) plots to derive NPP-age curves, thus the IMIX curve was used for any PIPO stands.

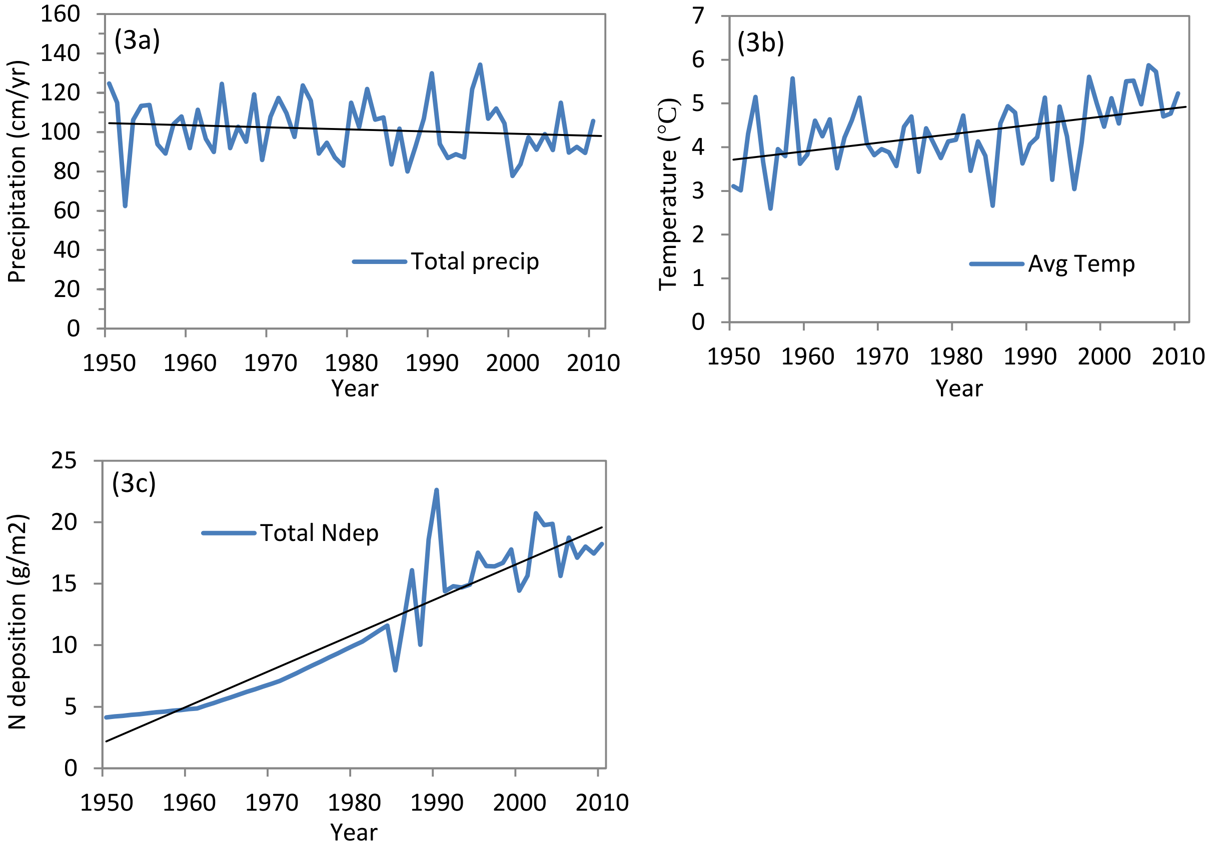


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Kootenai National Forest. Linear trend lines shown in black.

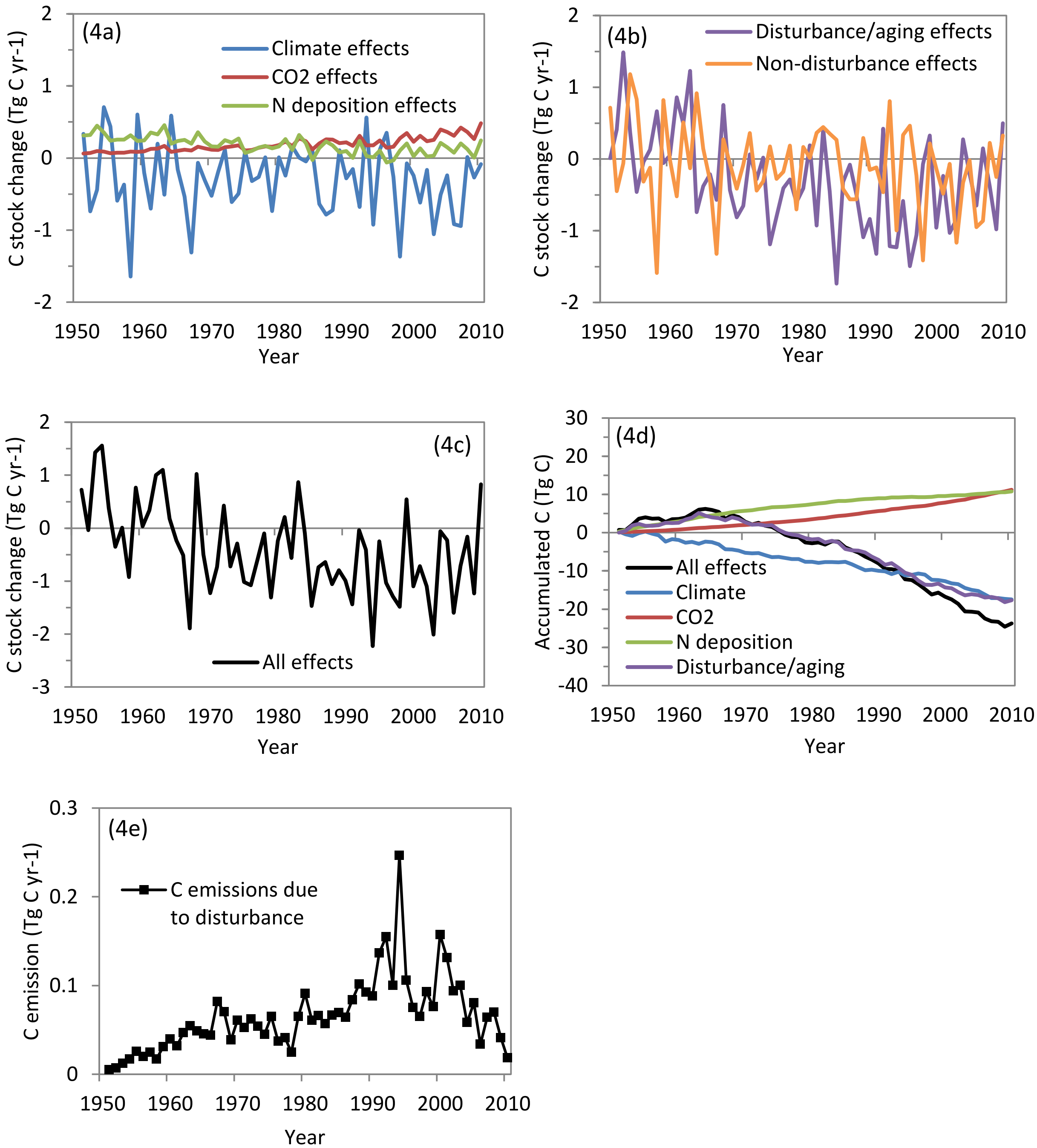


Figure 4.4. Changes in carbon stocks in the Kootenai National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging 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 Figures 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.

Lewis and Clark National Forest - Montana

Forest in the Lewis and Clark National Forest switched from mostly a carbon (C) sink to a source in the 1970s (Figure 4.4c) and C stocks have continued to decline through 2010 (Figure 4.4d). Increased disturbance and aging effects were responsible for this shift, though unfavorable climate conditions also played a role (Figure 4.4c). The stand age distribution shows that most stands are middle-older age, with a pulse of stands establishing 80-109 years ago (1901-1930) (Figure 4.1), likely as a result regrowth following the last major fires preceding the onset of fire suppression and/or disturbances associated with Euro-American settlement in the region. Fire suppression may have then allowed these stands to survive and continue to regrow, rather than being disturbed by fire. This pulse of mostly Douglas-fir forests would have reached maximum productivity (Figure 4.2) between the 1930s and 1960, which corresponds to period when forests were still a C sink (Figure 4.4b-c), and C stocks increasing (Figure 4.4d). Though most forests are older with declining rates of productivity, a large pulse of young stands <20 years old (Figure 4.1) have the potential to cause greater C accumulation and productivity in coming decades as they reach middle ages (Figure 4.2). These young stands are a result of post-disturbance recovery from major disturbances like the large high-severity fire in 2007 (Figure 1.1k), which also caused an immediate pulse of C emissions (Figure 4.4e).

Climate has generally had a negative effect on C stocks since the late 1950s (Figure 4.4a, d). A trend of warmer temperatures (Figure 4.3b) and decreased precipitation (Figure 4.3a) enhanced the negative climate effect, especially during the early-mid 2000s. Warmer temperatures increase soil respiration while droughts cause water stress, limiting growth. The increases in nitrogen deposition (Figure 4.3c) and atmospheric CO_2 enhanced the C sink (Figure 4.4a), but were not able to offset the C losses due to disturbances/aging, and climate. Forests in the Lewis and Clark NF experienced a net loss of approximately 16 Tg C from 1950-2010 (Figure 4.4d).

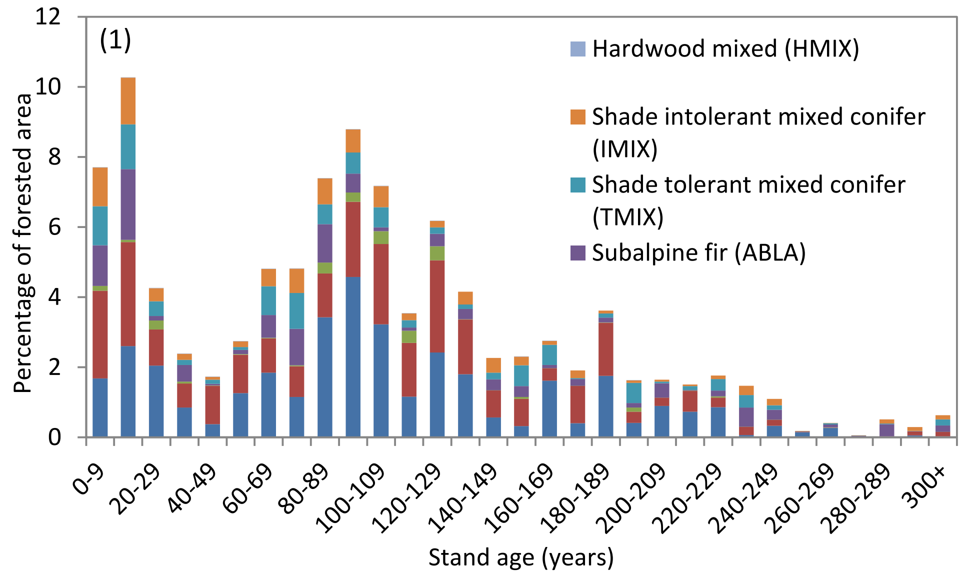


Figure 4.1. Age class distribution in 2010 in the Lewis and Clark National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

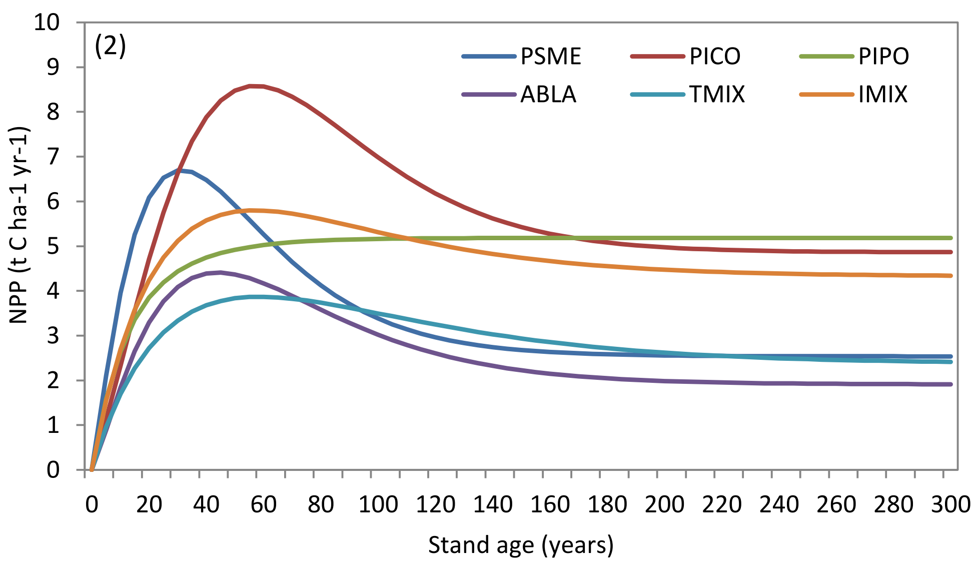


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Lewis and Clark National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

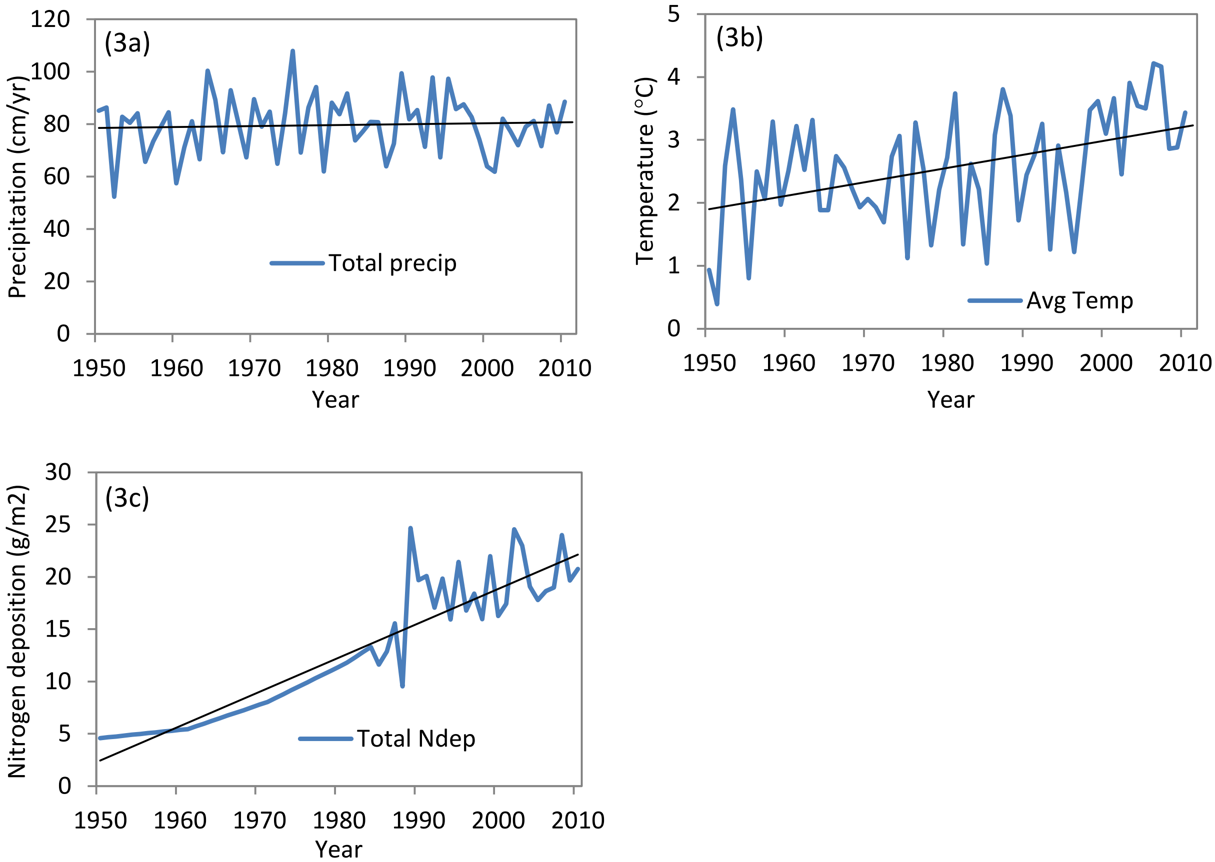


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Lewis and Clark National Forest. Linear trend lines shown in black.

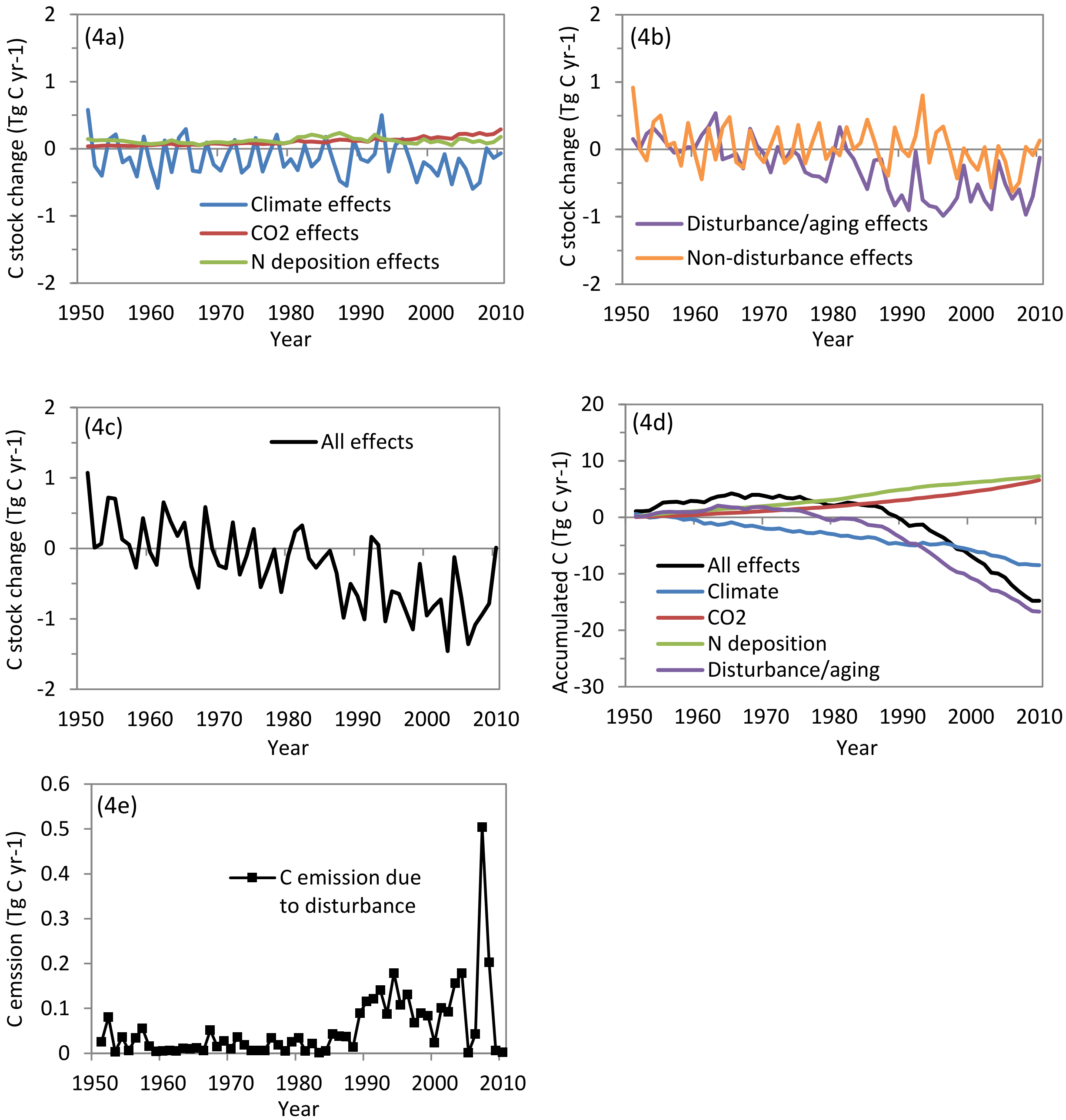


Figure 4.4. Changes in carbon stocks in the Lewis and Clark National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth 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 Figures 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.

Lolo National Forest - Montana

Forests in the Lolo National Forest fluctuated between a carbon (C) sink and a source from 1950-2010, but generally show a decline in changing C stocks due to negative disturbance/aging and climate effects (Figure 4.4a-d). The negative disturbance and aging effect is supported by the stand age distribution, which shows a pulse of stands 90-109 years old that were establishing from 1901-1920 (Figure 4.1), likely as a result of recovery from the last major fires before fire suppression began and/or early settlement disturbances. Fire suppression may have also allowed these stands to survive and continue growing in the absence of subsequent fire disturbances. These mostly Douglas fir stands would have reached their highest rates of productivity when they were 30 years old or around 1930 through 1960, which corresponds to when disturbances/aging supported the C sink (Figure 4.4b) and when C stocks were increasing (Figure 4.4d). There is also a pulse of young stands 0-20 years old, which established after recent moderate to high severity disturbances, such as larger fires in 2000, 2004, 2007, and 2008 (Figure 1.1d). As these young stands enter middle-age, they will be most productive (Figure 4.2), and forests may continue to experience a C sink as happened in 2010 (Figure 4.4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1d). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger or more consistent C source since 1990 than the InTEC results indicate.

Climate has had more of a negative effect on C trends since 1950 (Figure 4.4a, d). A trend of warmer temperatures (Figure 4.3b) and decreased precipitation (Figure 4.3a) enhanced the negative effect of climate in the early-mid 2000s. Warmer temperatures increase respiration while droughts cause water stress, impeding growth. The increases in nitrogen (N) deposition (Figure 4.3c) and atmospheric CO_2 concentrations also enhanced the C sink (Figure 4.4a) and caused forests to accumulate C (Figure 4.4d). Despite the growth enhancements from CO_2 fertilization and N deposition, forests in the Lolo NF experienced a net loss of approximately 5.5 Tg C (Figure 4.4d) between 1950 and 2010. When taking into account potential C losses due to recent disease impacts (Figure 2.1d), Lolo NF likely experienced a larger net loss in total C stocks.

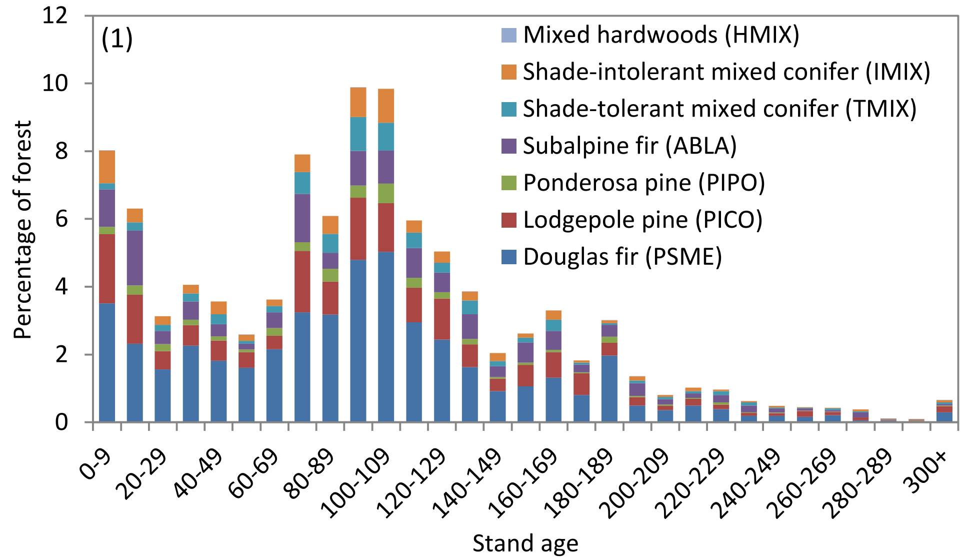


Figure 4.1. Age class distribution in 2010 in the Lolo National Forest displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

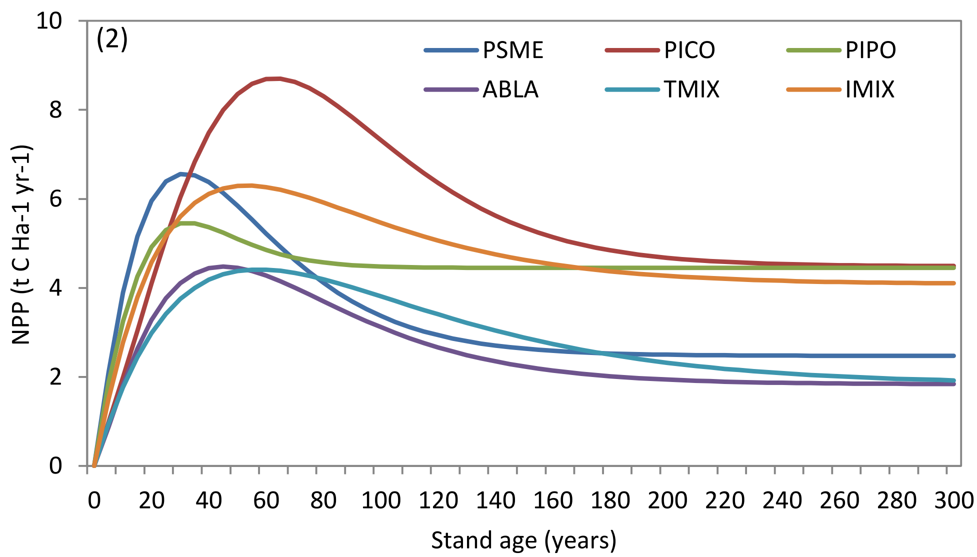


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Lolo National Forest. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

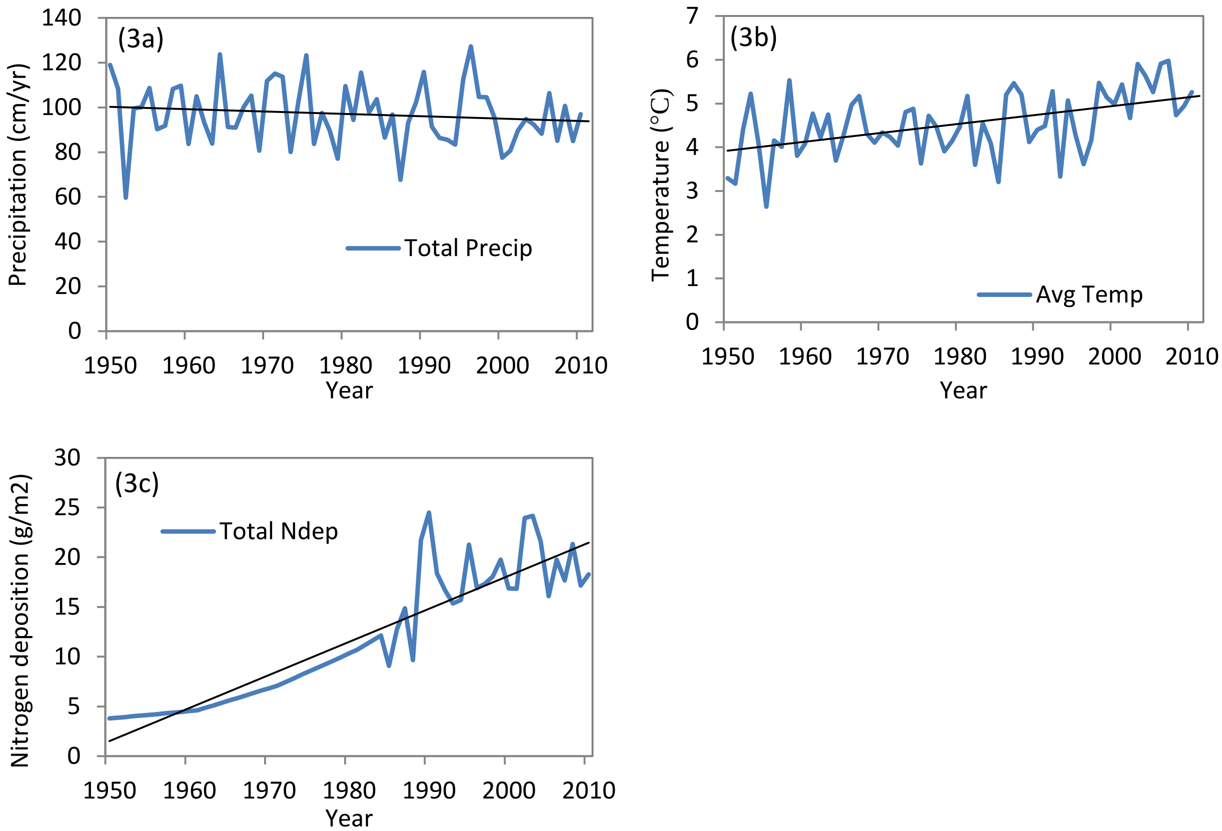


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Lolo National Forest. Linear trend lines shown in black.

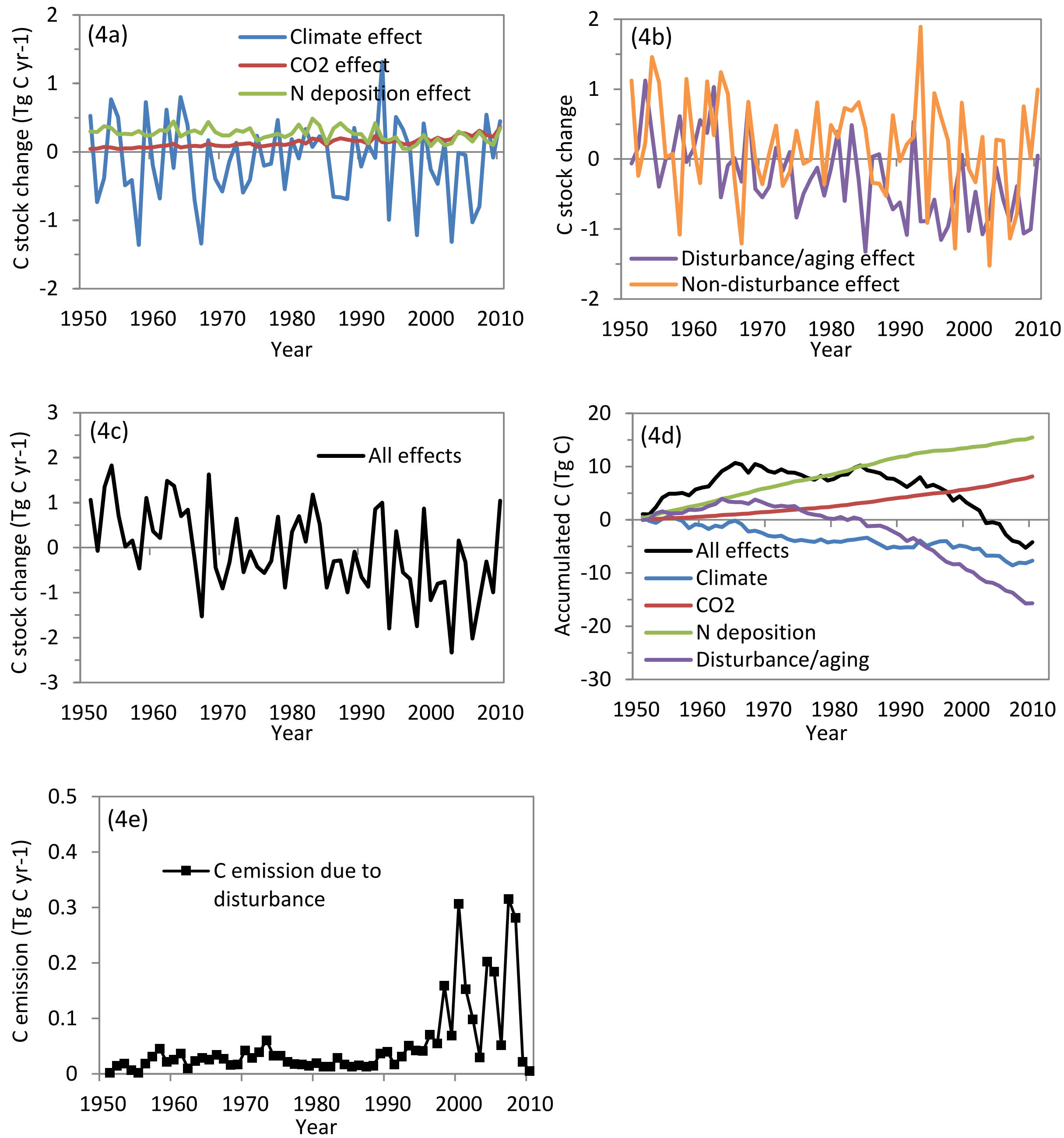


Figure 4.4. Changes in carbon stocks in the Lolo National Forest due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and 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 Figures 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.

Nez Perce-Clearwater National Forests - Idaho

Forests in the Nez Perce-Clearwater National Forests changed from a C sink to a source in the mid-1980s (Figure 4.4c) due to disturbance and aging effects, and to a lesser extent climatic effects (Figure 4.4a-b). In 2010, roughly 40% of the stands were between 70-109 years old (Figure 4.1), following establishment between 1901 and 1940, likely as a result of recovery from major fires and/or disturbances associated with EuroAmerican settlement in the region. Fire suppression, beginning in the early 1900s may have also allowed these young stands to survive and continue to re-grow without fire disturbances. This pulse of stands consisting of mostly shade-tolerant mixed conifer (TMIX) forests followed by Subalpine fir and Douglas fir forests, would have been most productive when they were roughly 35-55 years old (Figure 4.2), or throughout much of the mid-20th century. These stand age characteristics corroborate forests being a C sink (Figure 4.4b) and accumulating C (Figure 4.4d) through the 1950s-1980s as a result of disturbance and aging effects.

The stand age distribution also shows a smaller pulse of trees that were established between 1990 and 2000, which may be a result of recent disturbances (Figure 1.1e). The forest experienced larger fires in the mid-2000s but these were mostly low-moderate severity thus did not cause significant mortality or subsequent stand establishment (Figure 4.1). Immediate C emissions due to disturbances increased in the 1990s through 2010 (Figure 4.4e), also explaining the transition to a C source during this time period (Figure 4.4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Figure 2.1e). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger or more consistent C source since 1990 than the InTEC results indicate.

Climate has had a mostly negative effect on changing C stocks and C accumulation since 1950 (Figure 4.4a, d). The greatest climate-induced decline in C was from the mid-1990s-2010 (Figure 4.4a, d) due to warmer temperatures (Figure 4.3b) and a decrease in precipitation (Figure 4.3a), which together increase respiration and cause water stress thus constraining growth. The increases in nitrogen deposition (Figure 4.3c) and atmospheric CO_2 enhanced the C sink (Figure 4.4a), helping to offset the negative disturbance/aging and climate effects, and causing the forest to accumulate more C (Figure 4.4d). Despite recent declines in C accumulation and the transition to more of a C source, forests in the Nez Perce-Clearwater NFs experienced a net gain of approximately 24 Tg C from 1950-2010. When taking into account potential C losses due to recent disease impacts (Figure 2.1d), Nez Perce-Clearwater NFs likely experienced a much smaller C gain or potentially a C loss.

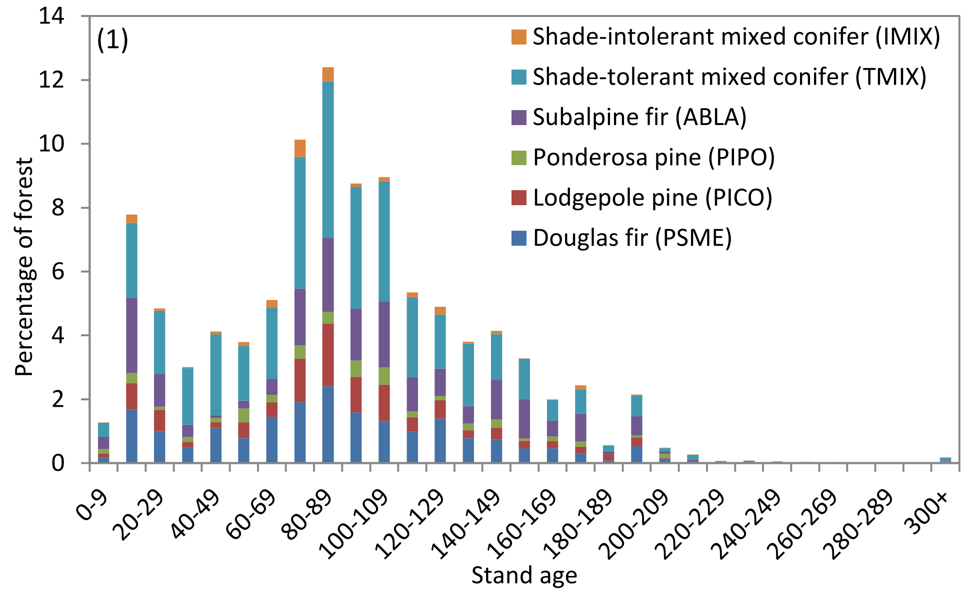


Figure 4.1. Age class distribution in 2010 in the Nez Perce-Clearwater National Forests displaying the percentage of forested of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

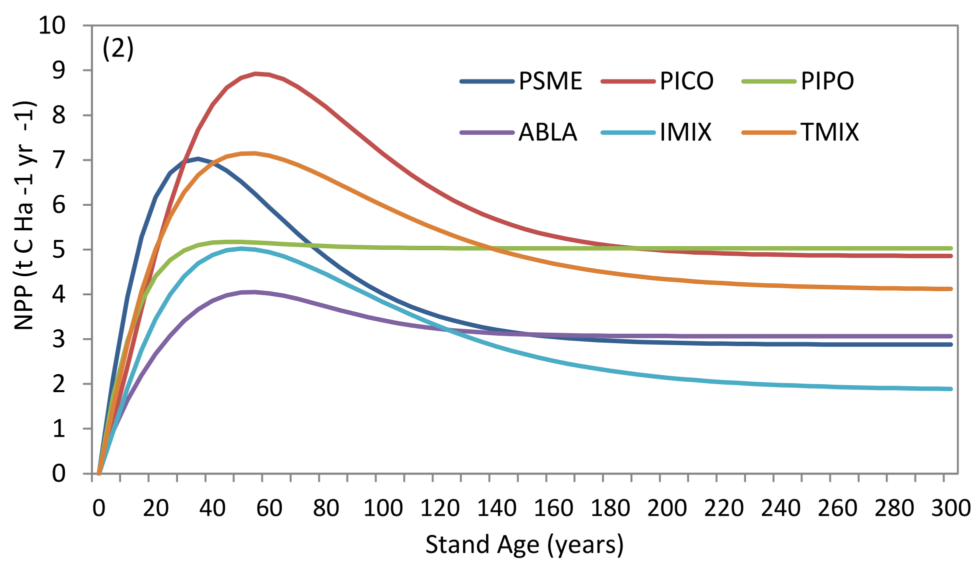


Figure 4.2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type in the Nez Perce-Clearwater National Forests. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

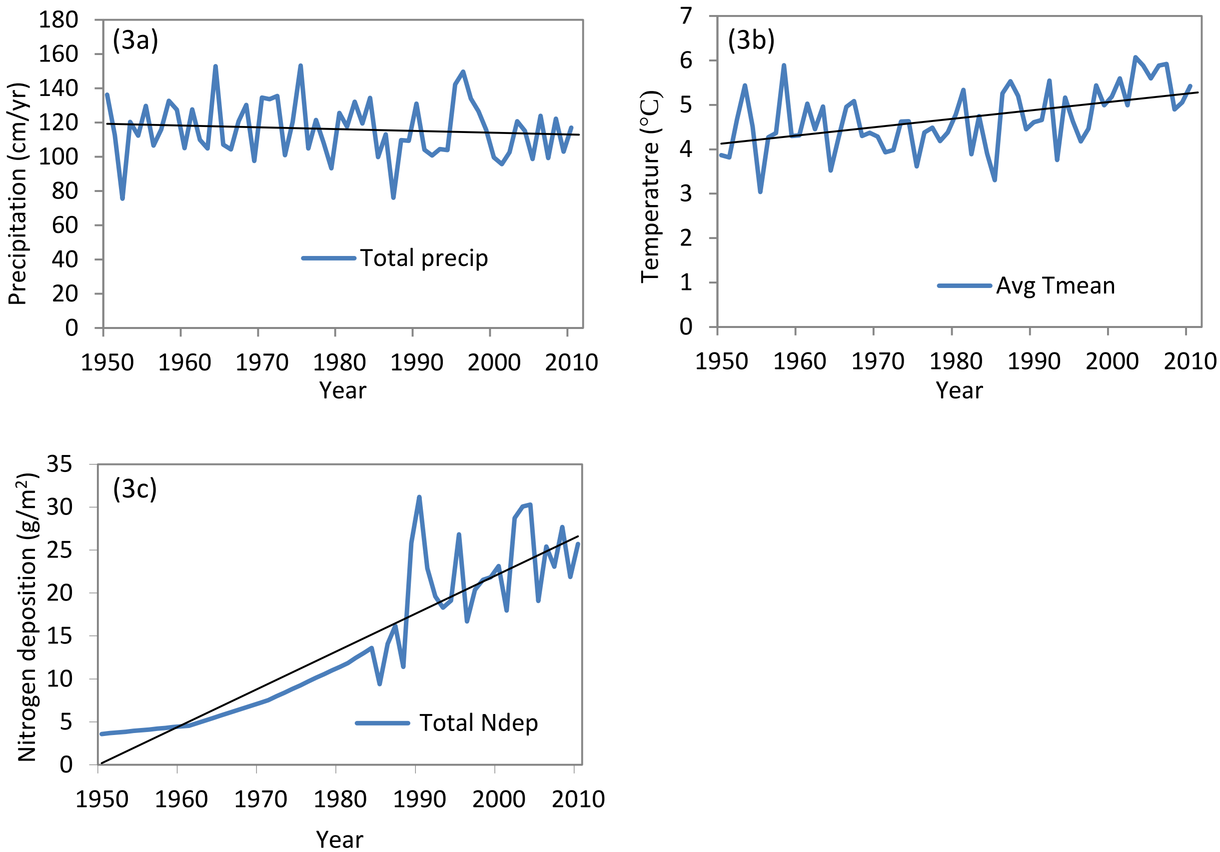


Figure 4.3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 in the Nez Perce-Clearwater National Forests. Linear trend lines shown in black.

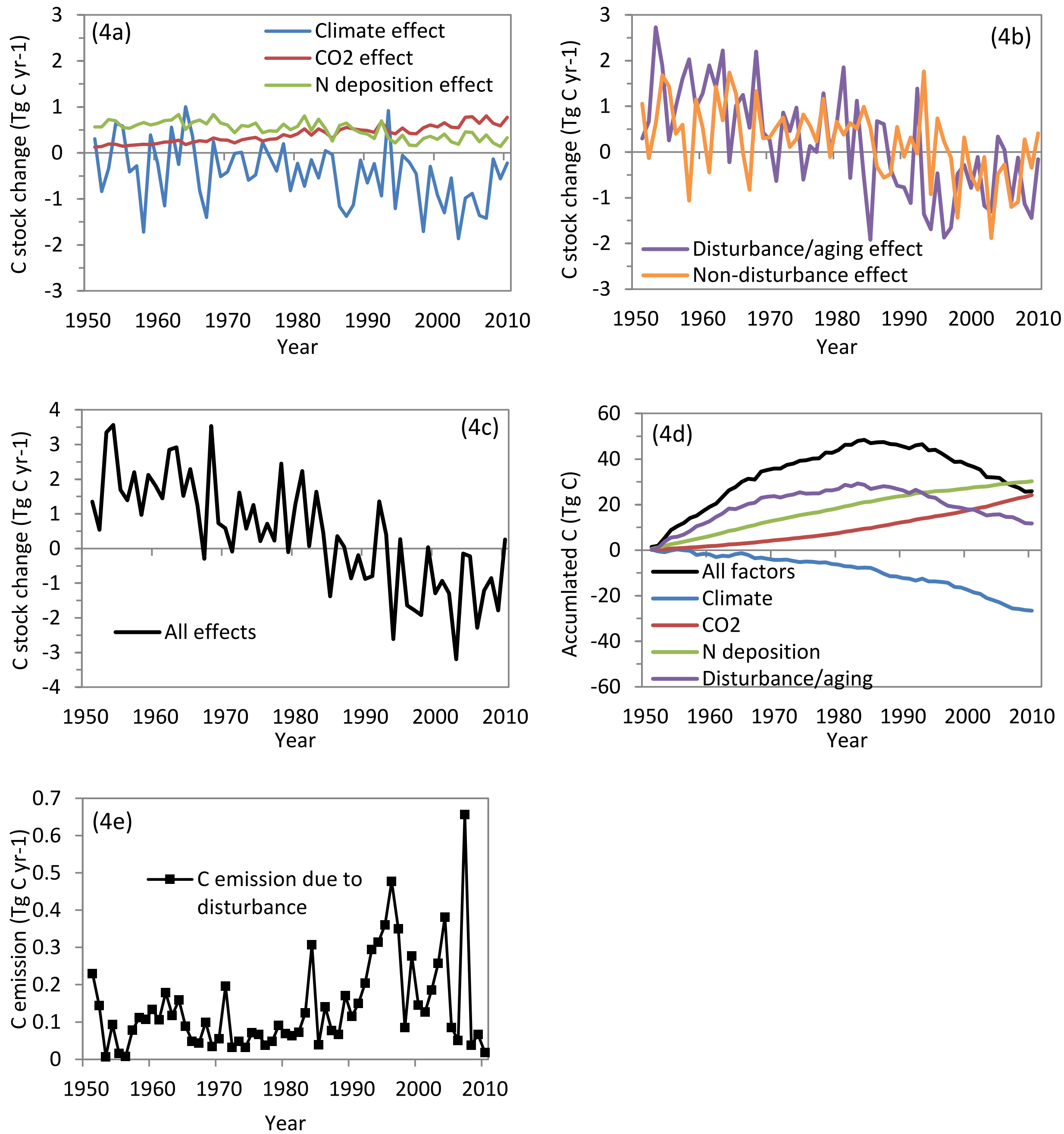


Figure 4.4. Changes in carbon stocks in the Nez Perce-Clearwater National Forests due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth 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 Figures 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.