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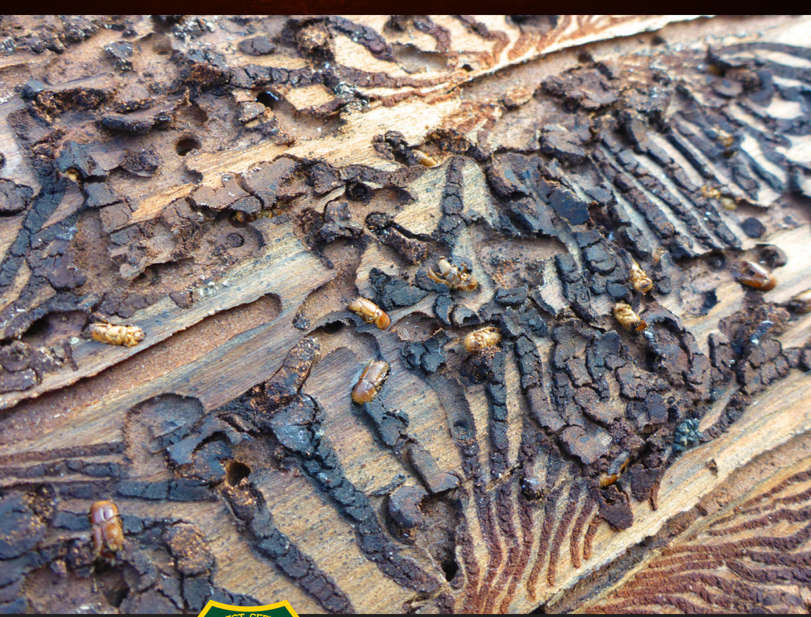
Assessment of the Influence of Disturbance, Management Activities, and Environmental Factors on Carbon Stocks of United States National Forests

Richard Birdsey, Alexa Dugan, Sean Healey, Karen Dante-Wood, Fangmin Zhang, Jing Chen, Alexander Hernandez, Crystal Raymond, James McCarter



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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 concentration, nitrogen deposition). Results are summarized for each region of the National Forest System in the main document. A set of regional appendices to this report 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 non-forest 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

Cover: Examples of disturbance to forests are, clockwise from top left, wildfire in Columbia River Gorge, Oregon (photo: ©Christian Roberts-Olsen via Shutterstock), harvested pine and spruce logs (photo: ©AVN Photo Lab via Shutterstock), broken trees after a powerful hurricane (photo: ©Victor Lauer via Shutterstock), and damage by spruce bark beetles (photo: © Klaus Reitmeier via Shutterstock). Image in top right corner: aspen leaves (photo: ©Labrador Photo Video via Shutterstock).

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Executive Summary

This report assesses how carbon (C) stocks on forest land of the Forest Service, U.S. Department of Agriculture, National Forest System are affected by timber harvesting, natural disturbances, aging, climate variability, increasing atmospheric carbon dioxide (CO_2) concentrations, and nitrogen (N) deposition. Carbon assessments were developed for individual national forests or small groups of national forests which have been administratively combined; assessments were then aggregated to regional scales. The information supports national forest units in making measurable progress toward meeting C assessment requirements of the 2012 Planning Rule and directives. Results of these assessments will help forest managers quantify C outcomes of broad forest management strategies and plan alternatives, and provide context for project-level decisions, separated from the effects of factors that are beyond land managers' control (e.g., climate).

Previously released baseline assessments of C stocks reported observed trends on forest land in each national forest based on Forest Service Forest Inventory and Analysis (FIA) data. These long-term changes represent the aggregate effects of all factors, reflecting the history of land management, disturbance, and environmental variability (e.g., climate). The C stocks in wood products harvested from the national forests at the regional scale were assessed using a harvested wood products (HWP) model, which applied a production accounting approach (Stockmann et al. 2012). These initial baseline assessments (e.g., USDA FS 2015g) were limited in ability to reveal causes of observed trends, which is the main purpose of this report.

The expanded assessments reported here build on the baseline assessments by incorporating detailed disturbance, climate, and atmospheric histories of each national forest, and two additional forest C models: the Forest Carbon Management Framework (ForCaMF) and Integrated Terrestrial Ecosystem Carbon (InTEC) model. The combination of extensive data compilation and modeling allows estimation of the relative impacts of disturbance factors (fires, harvests, insect outbreaks, wind, disease, and recovery and aging) and nondisturbance factors (climate, N deposition, CO_2 concentrations) on C stocks. Disturbance histories account for the main categories of disturbance—fire, harvesting, insects, disease, and abiotic (wind) - compiled by intensity of impact on tree canopy cover. Manually verified disturbance maps were created for the period 1990 through 2011 by integrating satellite imagery with agency records of harvests, the multiagency Monitoring Trends in Burn Severity (MTBS) database of fires, and annual aerial detection surveys of insect and abiotic disturbances. For years prior to 1990, forest stand ages derived from forest inventory data were used as a proxy for historical stand-replacing disturbance events. Additional spatial datasets such as climate records and measurements of N deposition and CO_2 concentrations were integrated to model the effects of environmental factors on forest C stocks and trends.

The ForCaMF model incorporates FIA data, satellite-based disturbance histories, and the Forest Vegetation Simulator (FVS) to provide regional and forest-level assessments of the impact of different kinds of disturbance on ecosystem C storage. These assessments take the form of estimating how much more C would be stored on each national forest if disturbances that took place from 1990 through 2011 had not occurred.

The InTEC model is a process-based biogeochemical model driven by satellite-based disturbance histories and stand-age information, monthly climate and atmospheric data, and productivity parameters to estimate the relative effects of disturbance and nondisturbance factors on forest C accumulation and annual C fluxes. Within the model, disturbance factors alter terrestrial C balances and influence stand-age structures, which in part drive the rate of C uptake. Nondisturbance factors influence photosynthesis, respiration, and other variables related to growth rates that determine C production in the model. Historical C dynamics are estimated progressively through time from 1950 through 2011, and the results at any point in time are the accumulated effects of all factors since the starting year.

In this main report, model results are summarized for the combination of all national forests in each National Forest System region. The available regional appendices provides more detailed information about individual national forests within each region.

The C stock trends (e.g., USDA FS 2015g) and the relative influence of disturbance and environmental factors affecting C stocks in each region between approximately 1990 and 2011 are summarized in table 1 and figure 1. Results indicate that forest C trends and the relative impacts of disturbance and environmental factors are highly variable across the United States. Generally, C stocks are increasing but at a declining rate in forests of the eastern United States as stands continue to grow older after historical harvesting rates and periods of nonforest land use. Carbon stocks in forests of the western United States may be either increasing or decreasing. These changes depend on recent effects of natural disturbances and climate change, which have caused many areas of forest in the West to switch from a C sink to a C source during the last two decades. Climate has had variable effects, largely depending on temperature trends and drought effects. Increasing atmospheric CO_2 concentrations and N deposition have had consistently positive effects on C stocks, partially offsetting C losses from natural disturbances, particularly fire and insects. Changes in the stock of C in wood products and solid waste disposal are relatively small or negative because harvest rates have declined significantly over many decades. Emissions of C from previously harvested wood are about the same as the C that is stored in newly harvested wood.

Results of the various models contained in this assessment and the previous baseline assessments (e.g., USDA FS 2015g) may vary due to differences in datasets used and modeling approaches applied. For instance, changes in forest C stocks reported in the baseline assessments rely completely on empirical FIA data that track long-term changes representing the aggregate effects of all factors. These assessments indicate that C stocks in forests of most regions have been increasing but at variable rates. However, because the inventory remeasurement period is 5 to 10 years, inventories may not fully account for the effect of more recent disturbances, which have been increasing over the last decade, particularly in the West. Both the ForCaMF and InTEC models make use of more contemporary satellite observations of disturbances, so they may better capture the C impacts of recent disturbance events.

Eastern Region Results

As part of the first region to be widely settled in the United States, the forests of the Eastern Region have a long history of unregulated harvesting and conversion to agriculture. Harvesting has been the most common and consistent disturbance type in the region since 1990, although the annual area harvested generally did not exceed 0.25 percent of the landscape. Harvests between 1990 and 2011 resulted in the removal of approximately 1.6 percent of nonsoil C stocks from the forest (fig. 1). Wind and fire also have been significant in the region, accounting

Table 1 - Cumulative changes in carbon (C) stocks (Tg) for regional and national scales, from C assessments for individual national forests, 1990–2011.

Region	Change in forest C stocks[a]	Disturbance impacts[b]	Climate and atmospheric impacts[c]	Change of C stock in wood products[d]	Summary ranking of main factors affecting C stocks[e]
Eastern	93	-9	63	3.5	• Harvesting • Climate and atmosphere • Fire
Southern	193	-21	16	2.8	• Harvesting • Fire • Climate and atmosphere • Insects • Wind
Northern	123	-37	23	0.3	• Fire • Disease • Climate and atmosphere • Harvesting
Rocky Mountain	32	-44	49	1.3	• Insects • Fire • Climate and atmosphere • Harvesting
Intermountain	43	-32	32	0.6	• Fire • Insects • Climate and atmosphere • Harvesting
Pacific Northwest	117	-42	67	-0.8	• Fire • Harvesting • Climate and atmosphere • Insects
Southwestern	-31	-9	4	-0.3	• Fire • Climate and atmosphere • Harvesting
Pacific Southwest	63	-26	42	0.1	• Fire • Climate and atmosphere • Harvesting
Alaska	17	-2	-	0.4	• Harvesting
All regions	650	-225	296	7.9	• Fire • Harvesting • Climate and atmosphere • Insects

[a] Observed changes in C stocks from Carbon Calculation Tool (CCT), which is based on forest inventory data reported in USDA Forest Service (2015a–i). This column represents an independent estimate of net biome production, and is not the sum of other columns.

[b] Harvesting and natural disturbances from Forest Carbon Management Framework (ForCaMF). Results do not include the soil pool.

[c] Net effects of nondisturbance factors—temperature, precipitation, carbon dioxide concentration, and nitrogen deposition - from the Integrated Terrestrial Ecosystem Carbon (InTEC) model. Results for the Northern and Southern Regions are for 1990 through 2010.

[d] Change of C in wood products and landfills based on the IPCC production accounting approach to harvested wood products (IPCC 2006; Stockmann et al. 2012).

[e] Factors ranked by approximate magnitude of effect in descending order of importance.

[f] The effects of forest aging as modeled by InTEC are not explicitly reported as a separate column in this table. However, all factors affecting C stocks, including aging, are inherently included in the *Change in forest C stocks* column.

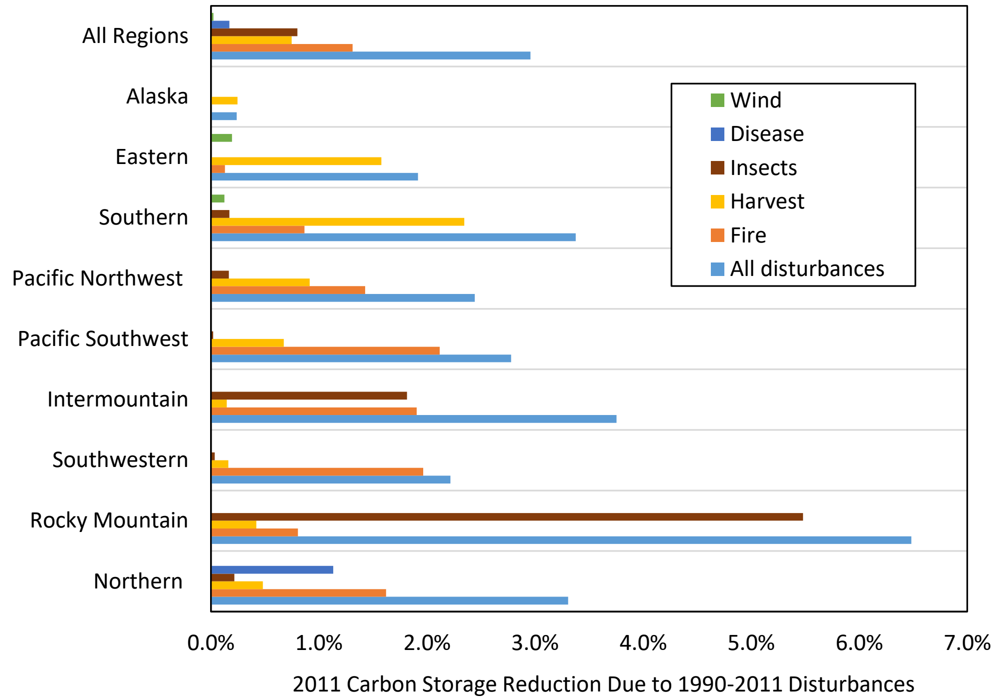

Figure 1. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by National Forest System region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates. Results from the Northern and Southern Regions reflect disturbances occurring from 1990 through 2010.

for the loss of 0.2 percent and 0.1 percent of nonsoil C stocks, respectively. The regionwide stand-age distribution shows that about 50 percent of the forests are greater than 80 years old and indicates a period of elevated stand establishment occurring about 70 to 100 years before the end of the study period or from approximately 1910 to 1940. Both temperature and precipitation have increased slightly over the past few decades, and have had a mostly positive effect on C stocks. Nitrogen deposition has been declining while CO_2 levels have been increasing, with both continuing to have positive effects on C stocks. Considering all factors, the national forests in the Eastern Region have mostly maintained a C sink from 1950 through 2011. The overall trend shows that this C sink has been declining due to disturbance and aging effects but may have stabilized over the past two decades due to the positive effects of nondisturbance factors.

Southern Region Results

In the late 1800s and early 1900s, agricultural expansion and large-scale timber extraction became the dominant driving forces of forest change in the South, followed by the establishment of national forests from marginal lands and a focus on forest restoration beginning around the 1920s. Timber harvesting from 1990 through 2011 accounted for the removal of about 2.4 percent of the nonsoil carbon stocks from the forest ecosystem (fig. 1), though harvests never affected more than 0.5 percent of the landscape in any single year. Fire has also played an important role in the forest C trends in the Southern Region, resulting in the loss of about 0.9 percent of nonsoil C stocks by 2011, while insects and abiotic factors had relatively small effects on C storage across the region (fig. 1). The regionwide stand-age distribution shows that most stands in the Southern Region are older than 70 years, with a pulse of stands that established from about 1910 to 1940. Temperature in the region has been stable and precipitation has increased slightly since 1950, although variability in weather has been significant. Consequently, climate trends have had a moderately positive effect on C stocks, but effects of droughts and heat waves have been periodically sizable. Both atmospheric CO_2 concentrations and N deposition have increased over the past few decades, resulting in a positive effect on C stocks. Overall, national forests in the Southern Region were mostly a C sink because the positive effects of climate, atmospheric CO_2, and N deposition helped to offset the C losses due to disturbances and aging forests.

Northern Region Results

In the 1880s, large areas of forest land were cleared for agriculture, settlements, and railroad expansion. This history is reflected in the stand-age structure and continues to influence C trends. It was not until the 1940s that the Northern Region experienced large-scale logging operations on national forest lands. In addition to timber harvesting, the forest C legacy of the Northern Region is tied to its history of fires and fire suppression. Recently, fires and root disease have been the dominant disturbances affecting carbon stocks, resulting in the loss of about 1.6 percent and 1.1 percent of nonsoil carbon stocks, respectively, between 1990 and 2011 (fig. 1). The regionwide stand-age distribution in 2010 shows that most stands in the Northern Region are older (>80 years old) with a distinct pulse of stands which established between approximately 80 and 110 years before the end of the study period, or from about 1900 to 1930. Consequently, accumulated C in forests has declined, largely as a result of disturbance and aging effects, as most stands have already reached older, less productive ages. Exacerbating these disturbances and aging effects, climate variability and the recent warming trend have had a mostly negative effect on C stocks. Increases in N deposition and atmospheric CO_2 concentrations have both had positive effects, thus helping to partially offset the negative effects of recent disturbances and aging.

Rocky Mountain Region Results

Like many regions of the western United States, the forests of the Rocky Mountain Region were subject to logging, livestock grazing, mining, and clearing of forest for agriculture and human settlements by the latter half of the 19th century. Forest regrowth following historical land use and forest management activities such as fire suppression caused an increase in C accumulation in the mid-20th century, but stocks have declined in recent decades as these stands have aged and become less productive. Timber harvest volumes greatly declined in the early 1990s and have remained relatively low since. The regionwide stand-age distribution shows that most of the stands in the Rocky Mountain Region are older (>80 years old) with a notable pulse of stands which established from about 1880 to 1930. During the latter part of the study period, the Rockies experienced severe bark beetle outbreaks that caused widespread tree mortality and resulted in the loss of around 5.5 percent of forest C stocks between 1990 and 2011 (fig. 1). Over the past few decades, several forests in the region experienced large and severe wildfires. Fires caused the loss of approximately 0.8 percent of nonsoil C stocks in the region, while harvests resulted in the removal of about 0.4 percent of nonsoil C stocks. The climate in the Rocky Mountain Region has on average grown warmer and slightly wetter, though severe droughts are not uncommon. Though the baseline assessments indicate that across the region forests have maintained a C sink, forests are likely to be switching to a C source due to negative disturbance and aging effects. Nondisturbance factors had a positive effect, thus helping to maintain the C sink.

Intermountain Region Results

The forest C legacy of the Intermountain Region is tied to its history of land use and fire management, as well as more recent, severe natural disturbances. Annual timber output declined precipitously in the early 1990s and has remained low ever since. Recently, severe bark beetle outbreaks have resulted in extensive tree mortality in parts of the Intermountain Region. Despite regeneration after recent disturbances, the regionwide stand-age distribution in 2011 shows that about half of the forests are greater than 100 years old and therefore undergoing declines in productivity and C accumulation. From 1990 through 2011, fires significantly affected C storage in the region, reducing nonsoil C stocks by about 1.9 percent (fig. 1). However, extensive tree mortality due to increased insect activity in the latter part of this period substantially altered the regional disturbance signature upon C stocks, reducing nonsoil C stocks by about 1.8 percent. Increasing levels of CO_2 and N deposition caused forests to accumulate more C and helped to counteract the C declines due to disturbances and stand aging. Climate factors, in particular, increasing temperatures, have also caused a decline of forest C since about 2000. Accounting for all effects, the forests have generally had a very low rate of increase in C stocks, and may already be switching from a C sink to a C source.

Pacific Northwest Region Results

In the late 1800s, increased Euro-American settlement and the arrival of the transcontinental railroad transformed the Pacific Northwest into one of the highest timber-producing regions of the country. Annual timber output in the Pacific Northwest increased in the mid-20th century, but has declined since the 1990s and remained low ever since. Due to this history of land use and timber harvesting, the stand-age distribution is shifting toward older ages, causing recent declines in productivity and C accumulation. Of all disturbance factors, wildfires occurring from 1990 to 2011 have had the most significant effect on C storage, causing the loss of about 1.4 percent of nonsoil C stocks by 2011 (fig. 1). Timber harvests reduced nonsoil C storage by approximately 0.9 percent since 1990, while insect outbreaks have also resulted in tree mortality and C losses in parts of the region. Although there has been significant interannual variability in both temperature and precipitation, between the 1950s and 2011 the climate has on average become much warmer and somewhat drier, but has had little effect on C stocks in recent years. Increasing levels of atmospheric CO_2 and N deposition caused forests to accumulate more C and helped to counteract the C declines from disturbances and the aging stands. The national forests in the Pacific Northwest Region have generally increased in C stocks.

Southwestern Region Results

Though Euro-American settlement brought livestock grazing, mining, and timber harvesting to the region, the timber industry of the Southwest has remained relatively modest compared to other regions of the United States. This history of land use as well as wildfires followed by nearly a century of fire suppression policies has resulted in a relatively older age structure, characterized by lower productivity and rates of C accumulation. More recently, fire has also been the primary disturbance shaping forests of the Southwestern Region, and today prescribed burning is commonly used to manage fuel loads. The acceleration of fire activity after 2000 within the region resulted in a surge in fire's impact on C stocks. Between 1990 and 2011, fires resulted in the loss of approximately 2 percent of nonsoil carbon storage (fig. 1). Insects and harvesting each accounted for C losses that were less than 0.5 percent of total C nonsoil storage. Climate has on average become much warmer, while the region has experienced periodic droughts. The national forests in the Southwestern Region were a C source from 1990 through 2011. In the early 2000s, drought conditions combined with elevated temperatures enhanced the C source. The positive effects of increasing N deposition and CO_2 concentrations partially offset the negative disturbance and aging effects and the more recent negative climate effects.

Pacific Southwest Region Results

National forests in California were heavily logged in the late 1800s, and timber harvest volumes increased steadily into the early 1900s to support mining operations, immigration, and development. The regionwide stand-age distribution indicates a pulse of stands establishing from around 1900 to 1940, reflecting recovery after these historical disturbances and land use changes and leading to age-induced declines in C accumulation. Both land use history and recent changes in climate have led to large and severe disturbances in the Pacific Southwest Region over the past few decades. Fires were particularly large in 2000 and 2008, when they affected more than 1 percent of the region's forest land. Fires from 1990 to 2011 resulted in the loss of about 2.1 percent of nonsoil forest C stocks by 2011 (fig. 1). The C impact of harvest within the region was relatively stable from 1990 through 2011, causing the removal of about 0.7 percent of nonsoil C stocks. Forests have had very modest increases in C stocks since 1990, and may already be switching from a C sink to a C source because of disturbance and aging effects, as well as increasing temperatures and droughts. Increases in N deposition and atmospheric CO_2 concentrations have consistently enhanced the C sink and helped to counteract the negative disturbance and aging effects and climate effects.

Alaska Region Results

The forest C legacy of the Alaska Region is tied to the history of timber harvesting and natural disturbances. Extensive timber harvests began in the 1950s, largely in high volume, old-growth stands. Timber harvests steeply declined in the 1990s and since 2000 have remained at low levels, resulting in the removal of approximately 0.2 percent of the nonsoil C stocks (fig. 1). Unlike much of the western United States, fires are relatively minor in south-eastern Alaska as a result of the cool, moist, temperate-rainforest conditions. Harvest activity was the only disturbance process to have a significant effect on C stocks in the region; the detected fire, wind, and insect activity on the two national forests had negligible impact on C storage. Due to its high latitude, Alaska has seen a more rapid increase in temperatures over the last century than any other region in the United States. National forests in Alaska have shown a very modest increase in C stocks since 1990.

1. Introduction

Greenhouse gas (GHG) concentrations have increased significantly since 1750 and have greatly exceeded preindustrial values (IPCC 2007). Human activities such as fossil fuel burning, industrial production, land use change, and agriculture are responsible for releasing large amounts of carbon dioxide (CO_2) and other GHGs into the atmosphere. Globally, about half of the emitted GHGs are absorbed by oceans and land, with the remainder staying in the atmosphere for long periods of time (Le Quéré et al. 2018). Greenhouse gases trap energy in the atmosphere and cause it to warm. This phenomenon, called the “greenhouse effect,” is necessary to sustain life on Earth. However, the large amounts of GHGs that humans are releasing to the atmosphere are causing the surface temperature of the Earth to increase with a number of associated large-scale changes (USGCRP 2017), many of which are detrimental to human health and ecosystems.

The Forest Service, U.S. Department of Agriculture (hereafter, Forest Service) recognizes the vital role that our Nation’s forests and grasslands play in carbon (C) sequestration. Box 1 defines this and other important terms that are commonly used to depict the C cycle and C management activities. Carbon sequestration by forests is one way to mitigate GHG emissions by offsetting a portion of those emissions through removal and storage of C from the atmosphere. Carbon dioxide uptake by forests in the conterminous United States, and storage in live and dead organic matter and harvested wood products, offset approximately 11 percent of the national total CO_2 emissions annually over the last decade (USEPA 2018). Forests and other ecosystems generally act as C sinks because, through photosynthesis, growing plants remove CO_2 from the atmosphere and store it. However, forests may become sources of CO_2 during and after disturbances such as wildfire and timber harvesting. This is usually a temporary effect before the disturbed forests begin to regrow and resume their function as C sinks. Recent estimates of net annual storage indicate that globally and in the United States, forests are an important C sink, removing more C from the atmosphere than they emit (Pan et al. 2011).

The Forest Service also recognizes that C sequestration and storage is one of many ecosystem services provided by forests and grasslands; these services also include clean water, clean air, biodiversity, wood products, wildlife habitat, food, and recreation. Changes in weather patterns and extreme weather events place forest and grassland ecosystems and their services at risk. The National Forest System (NFS) constitutes one-fifth (22 percent) of the Nation’s total forest land area and contains one-fourth (24 percent) of the total C stored in all U.S. forests, excluding interior Alaska. Thus, management of these lands and disturbances influence sequestration and storage of C and mitigation of GHG emissions. The future trajectory of C stocks on the national forests will be influenced by the variability of conditions and disturbance regimes such as wildfire, insect outbreak, and extreme weather across the United States.

Sequestration of C in U.S. forests is projected to decline over the next 25 years primarily due to land use change (net loss of forest area) and forest aging with corresponding slower growth (Wear and Coulston 2015). There are strong regional differences. For example, the forest C sink of the Rocky Mountain Region is projected to decline rapidly or change to a net source due to fire, insect outbreaks, and aging. Eastern forests, which are more intensively managed and lack such widespread disturbances, are expected to continue to be C sinks for

Box 1

Terminology

Accumulation - The increase of carbon in a location over a period of time.

Carbon units - Megagram (Mg): 1,000 kilograms (2,204.6 pounds) = 1 tonne; Teragram (Tg): 1,000,000 tonnes

Mitigation - Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.

Sequestration - Storage of carbon through natural, deliberate, or technological processes in which carbon dioxide is diverted from emission sources or removed from the atmosphere and stored biologically in oceans and terrestrial environments (vegetation, soils, and sediment), or in geologic formations.

Sink - A physical location where carbon is removed from the atmosphere and stored, either through natural or technological processes. Entire ecosystems, specific ecosystem components (e.g., forest, soil), or political boundaries may be characterized as a sink.

Source - A physical location where carbon is released to the atmosphere, either through natural or technological processes. Entire ecosystems, specific ecosystem components (e.g., forest, soil), or political boundaries may be characterized as a source.

Stock - A term referring to the mass of carbon contained within a particular compartment, or pool, within the Earth system.

Storage - The action of putting carbon in a location that prevents its release to the atmosphere for a period of time.

Uptake - The action of taking up carbon dioxide from the atmosphere by plants.

several decades.

Forests are highly dynamic systems that are continuously repeating the natural progression of establishment, growth, death, and recovery, while cycling C throughout the ecosystem and the atmosphere. This cycle, which drives overall forest C dynamics, varies geographically and by forest type, and by the frequency, magnitude, and type of disturbance events. Natural and anthropogenic disturbances can cause both immediate and gradual changes in forest structure, which in turn affect forest C dynamics by transferring C between the different ecosystem and atmospheric C pools (fig. 2). While disturbances may be the predominant drivers of forest C dynamics (Pan et al. 2011), environmental factors (e.g., the concentration of CO_2 in the atmosphere), the availability of key forest nutrients, such as nitrogen (N), and climate variability influence forest growth rates and consequently the cycling of C through a forest ecosystem (Hyvönen et al. 2007; Pan et al. 2009). Thus, an accurate and comprehensive assessment of forest C stocks and trends and the drivers that influence them must include the effects of both disturbances and environmental factors.

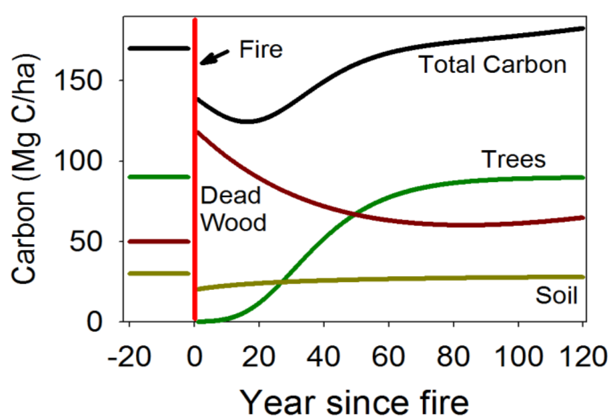

Figure 2. The effect of a stand-replacing fire on forest ecosystem carbon pools and total ecosystem carbon (source: McKinley et al. 2011).

The long-term capacity of forest ecosystems and harvested wood products to sequester and store C depends, in large part, on their health, resilience, adaptive capacity, and utilization of timber (McKinley et al. 2011). Under a changing climate, forests are increasingly affected by many factors such as multiyear droughts, insect and disease epidemics, wildfires, and catastrophic storms (Cohen et al. 2016; Westerling et al. 2006). Maintaining healthy forest structure and composition may not eliminate disturbance, and may in fact entail additional low-magnitude disturbance, but is likely to reduce the risk of large and long-term C losses through catastrophic disturbance (Millar and Stephenson 2015). Forest ecosystems capable of adapting to changing conditions will sequester C and store it more securely over the long term, while also furnishing woody materials to help reduce fossil fuel use. For forests managed for timber products, it is important to account for the C that is retained in harvested wood as well as substitution effects of using wood instead of other energy-intensive materials, because these quantities may be large and should not be considered as emitted CO_2 (Perez-Garcia 2005).

A first step toward managing for healthy forests is understanding how past patterns of disturbance and climate have affected their ecosystem functions such as C storage. A nationally consistent C assessment framework has been developed for the NFS to deliver forest C disturbance information for every region and individual national forest. This report builds on the baseline C storage assessments produced for each region (https://www.fs.fed.us/managing-land/sc/carbon). It focuses on disturbance and environmental effects on ecosystem C, setting aside temporary storage of harvested C in product pools. The storage value of C in harvested wood products is quantified in the existing regional baseline assessments, and related analyses have appeared elsewhere (Healey et al. 2009; Stockman et al. 2012). Ongoing work to integrate ecosystem and product life cycle dynamics will allow the sideboards of future Forest Service assessments to expand beyond the ecosystem boundary.

Box 1 cont.

Processes that Exchange Carbon with the Atmosphere

Combustion - Process of burning something; occurs when a substance such as wood, coal, or natural gas reacts with oxygen to produce carbon dioxide, water vapor, heat and energy.

Decomposition - Natural process of dead organisms being rotted or broken down into smaller bits; decomposers respire carbon dioxide to the surrounding soil and air.

Net biome production - The difference between the amount of organic carbon fixed by photosynthesis in an ecosystem and the loss of carbon from autotrophic and heterotrophic respiration and disturbances.

Net ecosystem production - The difference between the amount of organic carbon fixed by photosynthesis in an ecosystem and the loss of carbon from autotrophic and heterotrophic respiration.

Net primary production - The net uptake of carbon dioxide by plants through gross primary productivity in excess of losses from plant, or autotrophic, respiration.

Photosynthesis - The process by which green plants, algae, and other organisms use sunlight to synthesize energy fromcarbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll, consumes carbon dioxide and water, and generates oxygen as a byproduct.

Respiration - Metabolic pathways that break down complex molecules to release chemically stored energy for maintenance, growth, and reproduction, and that result in the release of waste products such as carbon dioxide, nitrous oxide, or methane.

2. Purpose of the Assessment

This report expands on previous assessments of baseline C stocks across individual national forests and at the regional scale by assessing how stocks at those scales are affected by factors such as timber harvesting, natural disturbances, land use change, climate variability, increasing atmospheric CO_2 concentrations, and N deposition. The likelihood of management activities affecting future disturbance rates is not assessed. Such assessments are pursued through stand- and landscape-level risk analysis (e.g., Ager and Vaillant 2010), and are beyond the scope of this report. The goal of this report is to assess the causes of changes in C stocks as quantified by C monitoring programs such as forest inventories.

Existing guidelines for considering forest C are found in various Forest Service policies, programs, and activities such as

- the 2012 Planning Rule and directives ,
- National Roadmap for Responding to Climate Change (PDF, 3.3MB),
- Climate Change Performance Scorecard (PDF, 2.2MB),
- Ecosystem Restoration Policy and Directive (FSH 2020),
- other internal guidance for planning (Climate Change - Land Management & Project Planning),
- project-level decisions, and
- several State and Private Forestry programs.

The information in this C assessment directly supports NFS units in making measurable progress on Climate Change Performance Scorecard Element 9 (Carbon Assessment and Stewardship), while helping forests meet C assessment requirements of the 2012 Planning Rule and directives. Scorecard Element 9 poses the following questions:

> *Does the Unit have a baseline assessment of carbon stocks and an assessment of the influence of disturbance and management activities on these stocks? Is the Unit integrating carbon stewardship with the management of other benefits being provided by the Unit?*

Initial baseline assessments of C stocks were produced in early 2015 using the Carbon Calculation Tool (CCT), which summarizes the data collected by the Forest Service's Forest Inventory and Analysis program, and data about harvested wood products from regional Forest Service reports. The baseline assessments (USDA FS 2015a–i) meet the intent of assessing observed trends but are limited in ability to reveal detailed causes.

The expanded assessments reported here evaluate the influence of disturbance, management, and environment by integrating two additional forest carbon models - the Forest Carbon Management Framework (ForCaMF) (Healey et al. 2014, 2016) and the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen et al. 2000a; Zhang et al. 2012) - to calculate the relative impacts of disturbance (e.g., fires, harvests, insect outbreaks, disease) and nondisturbance factors (climate, N deposition, CO_2 concentrations). Results of these expanded assessments will help forest managers quantify C outcomes of broad forest management strategies and plan-level decisions, separated from the effects of factors that are beyond their control. See Dugan et al. (2017) for further details on how these C models (CCT, ForCaMF, and InTEC) may be integrated to provide useful information for characterizing C

Box 2

Forest Service Forest Carbon Principles

Although carbon is a relatively new consideration in land management, including it is consistent with sustaining the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. Land management actions on public and private forests and grasslands can be designed to achieve carbon outcomes while meeting other sustainable resource management objectives. Forests are important in capturing and storing carbon, both onsite and in products, and management of these lands can contribute to mitigating climate change. The following principles should be at the forefront when considering carbon along with other management objectives.

1. Emphasize ecosystem function and resilience. (Function First). Carbon sequestration capacity depends on sustaining and enhancing ecosystem function. Long-term sequestration should be planned in the context of changing climate and other environmental drivers. Management actions that help maintain resilient forests or transition vulnerable forests to a fully functioning and resilient state are more likely to store sequestered carbon over the long run.
2. Recognize carbon sequestration as one of many ecosystem services. (One of Many Services.) Carbon sequestration is one of many ecosystem services provided by forests and grasslands. Strategies for including carbon in forest and grassland management must consider the suite of resources and outcomes desired from management actions. A balanced and comprehensive program of sustainable management will consider many ecosystem services, including carbon sequestered in biomass, soils, and wood products.
3. Support diversity of approach (Diverse Approaches). Recognize that decisions about carbon in America's forests are influenced by ownership goals, policy, ecology, geography, socioeconomic concerns, and other factors that vary widely. The Forest Service supports a variety of approaches to managing carbon and deriving value from carbon that are compatible with the objectives of different owners. A wide diversity in approaches can also foster more rapid learning about forest, grassland, and carbon management in the context of climate adaptation.
4. Consider system dynamics and scale in decisionmaking. (Scale and Timeframe). Different ecosystems sequester carbon in different ways, at different rates, and within differing mosaics of landscape plans and trends. The carbon effects of forest and grassland management options should be evaluated within the carbon dynamics of long timeframes and landscape scales, with explicit consideration of uncertainties and assumptions. Where practical, system dynamics should be broadened beyond the ecosystem to consider full life-cycle impacts of decisions, including carbon storage in forest products and substituting wood-based options for fossil fuel-intensive applications.
5. Use the best information and analysis methods. (Decision Quality). Base forest management and policy decisions on the best available science-based knowledge and information about system response and carbon cycling in forests, grasslands, and wood products. Use this information wisely by dealing directly with uncertainties, risks, opportunities, and tradeoffs through sound and transparent risk management practices. Forest plan revision, project-level implementation, and other decision processes should consider tools and approaches that explicitly address uncertainty, risks, and opportunities about climate impacts and forest carbon response.

Including carbon in land management planning activities through these considerations supports the widespread approaches of ecosystem and watershed management and does not require significant alteration of management strategies and approaches. A balanced approach to including carbon in management activities may, however, complement existing objectives and priorities even as it helps mitigate the Nation's GHG emissions and promote climate adaptation.

dynamics and the relative contributions of driving factors, while also fulfilling Forest Service guidance.

Using the baseline and expanded assessments, and the draft Forest Carbon Principles outlined in box 2, NFS units can begin to integrate C stewardship thinking and practices into management activities, thus helping to address the final question of Scorecard Element 9: Is the Unit integrating carbon stewardship with the management of other benefits being provided by the Unit? This requirement could be accomplished through use and application of available information related to C through the land management planning process, program guidance, forest plans, project plans and analyses, or other strategic program planning. Units are encouraged to review the Scorecard Guidance, including Scorecard Appendix F (PDF, 471KB).

Units can apply these data in their forest management planning and practices by asking questions such as:

- Has the land management plan area sequestered and stored C in the recent past, or has it emitted stored C?
- How have disturbances, projects, and activities influenced C stocks (including harvested wood products) in the past and how may they affect C stocks in the future?
- Are existing conditions and trends of forest vegetation and soils indicating that the plan area is a C sink or source?
- Under existing plan guidance and alternatives being considered, what is the likely future trend of the plan area in sequestering and storing C, including in harvested wood products?
- What is the risk of loss to C storage due to potential disturbance factors?
- Are there opportunities to change plan components to influence these trends?

These expanded assessments are produced following methods described in several cited source documents.

3. Forest Carbon Management and Stewardship

The Forest Service is leading government agencies in the national conversation and action on forest C. The basic approach involves managing C through managing the health and productivity of the Nation's forests. The approach focuses on managing risks to the health, productivity, and ability of the resource to provide the goods and services called for in management plans. Management actions have C outcomes and those are considered among the benefits being managed. Forest systems are dynamic and emit and capture C regardless of human intervention. The Forest Service C strategy is embedded in a larger adaptation strategy for managing the resource that considers multiple impacts of natural and anthropogenic stressors.

Carbon management is an aspect of sustainable land management (Janowiak et al. 2017) targeted to maintain the long-term health and productivity of forests and grasslands, and to maintain a flow of all of their benefits. Carbon adds another dimension to the work. There will be both tradeoffs and synergies between C flows and other services, and balancing these interactions will continue to be part of the mission in managing these resource (box 2).

The Forest Service's goal is to manage system vulnerability to multiple stressors through adaptation and mitigation activities. Management principles consider C and other benefits flowing from forests, integrate climate adaptation and mitigation, and balance C uptake and storage among a wide range of ecosystem services. The Forest Service also strives to provide for social, economic, and ecological sustainability.

Forest management strategies include retaining and protecting forest land from conversion to nonforest uses; restoring, maintaining, and enhancing resilient forests that are better adapted to a changing climate and more resistant to catastrophic wildfires and other stressors; and reforesting lands impacted by catastrophic wildfires and other disturbances. Other strategic management options for reducing GHG emissions include changes in land management, afforestation (and other land use changes), avoiding loss of forest land, adding to the harvested wood product pool, and bioenergy (Scorecard Appendix F (PDF, 471KB)).

4. Methods and Uncertainty

The expanded assessments reported here are based on a detailed disturbance, climate, and atmospheric history of each national forest, and two additional forest C models: the Forest Carbon Management Framework (ForCaMF) and Integrated Terrestrial Ecosystem Carbon (InTEC) model. The ForCaMF model provides forest-level assessments of the impact of different kinds of disturbance (e.g., fires, harvests, insect outbreaks, abiotic, disease) on ecosystem C storage. The InTEC model is a process-based biogeochemical model driven by monthly climate data, vegetation parameters, and forest disturbance information to estimate the relative effect of disturbance and aging and nondisturbance factors (climate, N deposition, CO_2 concentrations) on forest-level C accumulation and fluxes. The combination of extensive data compilation and modeling provides an approach to estimate the relative impacts of disturbance (fires, harvests, insect outbreaks, abiotic, disease, aging) and nondisturbance factors (climate, N deposition, CO_2 concentrations) on C stocks.

This report follows the international reporting requirements established under the umbrella of the Intergovernmental Panel on Climate Change (IPCC) as implemented for the forestry sector of the U.S. GHG inventory compiled by the U.S. Environmental Protection Agency (USEPA 2018). The seven main forest sector carbon pools, generally defined by IPCC and adapted for reporting in the United States, are:

Live trees—Live trees with diameter at breast height (d.b.h.) of at least 2.5 cm (1 inch), including carbon mass of coarse roots (greater than 0.2 to 0.5 cm [0.08 to 0.2 inch]; published distinctions between fine and coarse roots are not always clear), stems, branches, and foliage.

Standing dead trees—Standing dead trees with d.b.h. of at least 2.5 cm, including carbon mass of coarse roots, stems, and branches.

Understory vegetation—Live vegetation that includes the roots, stems, branches, and foliage of seedlings (trees less than 2.5 cm d.b.h.), shrubs, and bushes.

Down dead wood—Woody material that includes logging residue and other coarse dead wood on the ground and larger than 7.5 cm (3 inches) d.b.h., and stumps and coarse roots of stumps.

Forest floor—Organic material on the floor of the forest that includes fine woody debris up to 7.5 cm d.b.h., tree litter, humus, and fine roots in the organic forest floor layer above mineral soil.

Soil organic carbon—Belowground carbon without coarse roots, but including fine roots and all other organic carbon not included in other pools, to a depth of 1 meter (39 inches).

Carbon in harvested wood—Includes products in use and in landfills. “Products in use” includes end-use products that have not been discarded or otherwise destroyed. Examples are residential and nonresidential construction, wooden containers, and paper products. “Products in landfills” includes discarded wood and paper placed in landfills, where most carbon is stored long-term and only a small portion of the material is assumed to degrade, at a slow rate.

Carbon is transferred among these seven pools and the atmosphere. The amount of C in each pool is commonly called a stock, and the transfers may be called fluxes or changes in C stocks (box 1). Forest sector C pools and fluxes following disturbances are shown in detail in figure 3. The different C models described in this report, and those in the previously published baseline assessments, include subsets (or expansions) of the seven main reporting C pools (table 2).

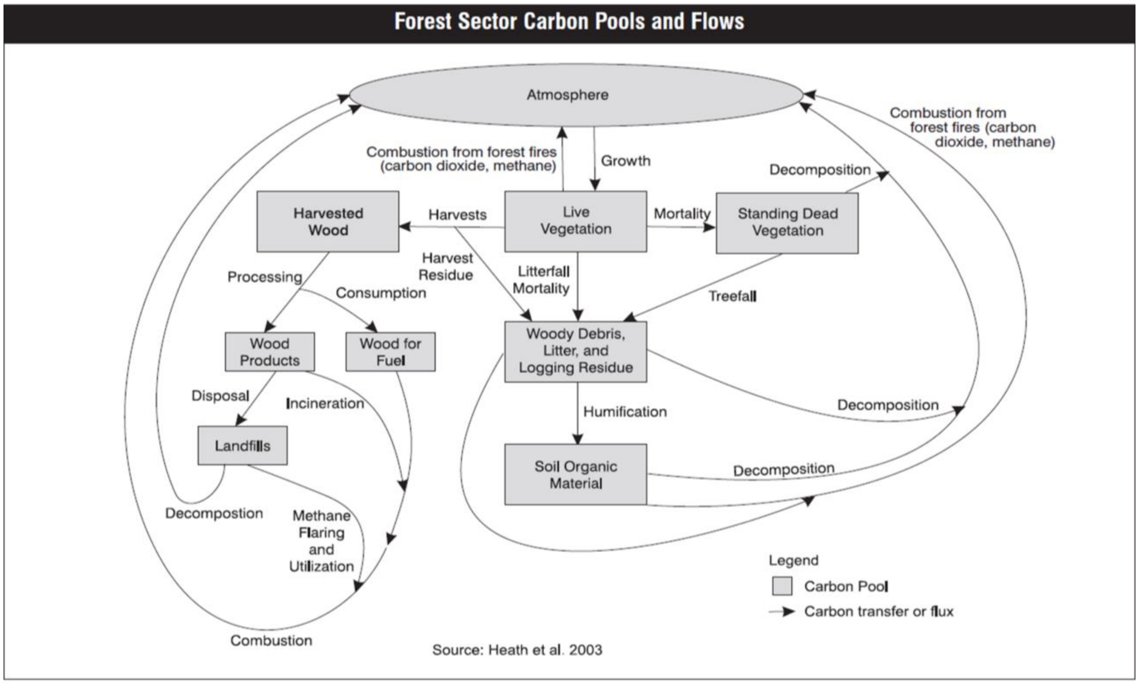

Figure 3. Forest sector carbon pools and flows (source: Heath et al. 2003).

Table 2. The seven main forest carbon pools and their representation in carbon models[a] referenced in this report.

	Carbon models				
Carbon pool	**Carbon Calculation Tool (CCT)**	**USFS Harvested Wood Products[a]**	**Forest Vegetation Simulator (FVS)**	**Forest Carbon Management Framework (ForCaMF)**	**Integrated Terrestrial Ecosystem Carbon (InTEC)**
Live trees	X		X	X	X
Standing dead trees	X		X	X	X
Understory vegetation	X		X	X	X
Down dead wood	X		X	X	X
Forest floor	X		X	X	X
Soil organic carbon	X				X[b]
Carbon in harvested wood		X			

[a] Source: Stockmann et al. (2012). USFS = USDA Forest Service.
[b] Soil carbon pools expanded to facilitate representation of key ecosystem processes: soil structural and soil metabolic detritus, soil microbes, surface microbes, slow organic matter, and passive organic matter.

4.1 Disturbance and Management Activities

4.1.1 Disturbance Data

The starting point for this C assessment is mapped records of disturbance and harvest activity across each national forest from 1990 through 2011. These disturbance maps were created by manually editing initial maps that were based on satellite data and created by the automated Vegetation Change Tracker algorithm (Huang et al. 2010). Editing was conducted at the pixel level to align mapped disturbances with several independent data sources: the multiagency Monitoring Trends in Burn Severity (MTBS) database of fires over 1,000 acres (405 hectares) in size (Schwind et al. 2010); multitemporal composites of Landsat data transformed to one band per year with the Disturbance Index (Healey et al. 2005); high-resolution time series of aerial imagery served through Google Earth; a combination of a tabular database (Forest Activity Tracking System; FACTS) of historical harvest activities and a spatial database (FACTS spatial) that provides an associated spatial representation of activity locations; and annual aerial forest detection survey (ADS) data (Johnson and Wittwer 2008). In the Rocky Mountain Region (NFS Region 2) and the Intermountain Region (NFS Region 4), where insect disturbance was most pronounced, ADS data were enhanced with Landsat-based disturbance maps generated from an ensemble of automated change detection algorithms (Healey et al. 2018). Methods used to produce the disturbance maps in this report were documented by Hernandez et al. (2018).

4.1.2 Uncertainty

Maps of disturbance year and type are not considered to be a significant source of error. To develop these maps, manual methods were used in consultation with independent error records. These records mimic methods used to develop “truth” data in other studies involving disturbance maps created with more automated methods (e.g., Cohen et al. 2010; Schroeder et al. 2014; Thomas et al. 2011).

4.2 Forest Carbon Management Framework

4.2.1 Methods

The Forest Carbon Management Framework takes advantage of corporate Forest Service monitoring data, management records, and management tools, complemented with forest change information from the Landsat series of satellites, to provide forest-level assessments of the impact of different kinds of disturbance on ecosystem C storage. These assessments estimate how much more C would be stored on each national forest if disturbances that took place from 1990 to 2011 had not occurred. Specifically, the impact of disturbance factor F (e.g., harvest, fire, insects, disease) is estimated as the difference, D_F, in the landscape’s nonsoil C stocks between an “undisturbed” scenario (U) where no disturbances occur during the study period and a scenario where only factor F occurs, in each simulation unit (i)(eq. 1).

$$D_F = \sum_{(i=0)}^{n} \left(C_{i\,(U)} - C_{i\,(F)} \right)$$

Equation 1.

Each scenario includes simulation of normal density-dependent tree mortality that is not attributable to disturbance. An estimate of D_F is produced for every year, considering the impact of all disturbances that occurred from 1990 to that date. D_F is a function of mapped starting conditions and disturbance history across 10-hectare (25-acre) sections of the landscape (i) that share the same starting conditions and disturbance patterns. These sections are called “simulation units” because they are the base units of error simulations described in Section 4.4.2, but they are also ForCaMF’s finest level of carbon estimation. D_F is summed across all simulation units to produce a national forest-scale assessment of disturbance impact (eq. 1).

The C storage associated with mapped stand dynamics is obtained by combining the representative field sample measured by the FIA program with the Forest Vegetation Simulator (FVS) (Crookston and Dixon 2005; Hoover and Rebain 2011), a growth model that allows projection of nonsoil C stocks (Rebain 2010; Reinhardt and Crookston 2003) under a variety of disturbance scenarios. The FIA program maintains a plot network across the country consisting of one randomly located plot per approximately 6,000 acres (2,428 hectares). The tree list from each of the FIA plots with at least one forest land condition on NFS land (within the NFS region) is entered into FVS. For each scenario, a generalized C storage model is developed by combining results of simulations with similar starting tree lists. Each group of plots is subjected to a range of simulated disturbances to develop C storage models applicable to the gamut of observed disturbance patterns. Uncertainty measures from the fitting process are stored for later uncertainty analysis, as described more fully by Raymond et al. (2015).

Software in ForCaMF simply applies regionally averaged C dynamics described on the right side of figure 4 to the remotely sensed vegetation and disturbance history information summarized on the left side of the figure. When disturbance affects a simulation unit (as indicated by the disturbance map), it is moved from an FVS-derived “undisturbed” C accumulation function to the appropriate postdisturbance function. If maps show the simulation unit to be disturbed again, it is moved to the new postdisturbance C accumulation function at the appropriate time (Healey et al. 2014). Disturbance impacts on C storage (D_F) are calculated by comparing C storage under an “undisturbed” scenario to a scenario with disturbance factor *F*. In this report, results are reported for *F* = all observed disturbances and for *F* = each individual disturbance factor (e.g., fire, harvest, insects, disease). Where *F* = all, the effects of successive disturbances (e.g., fires following insect disturbance) on C storage were realistically represented by the previously mentioned switching from one postdisturbance C accumulation function to another. Where *F* = only a single disturbance factor, all non-*F* disturbances were zeroed out and this switching did not occur (unless successive disturbances were of the same type). In both cases, calculation of D_F in each year from 1990 to 2011 allowed temporally precise evaluation of how the impact of disturbance evolved over time, particularly in light of events such as large fire years or emerging insect problems that change overall C storage patterns.

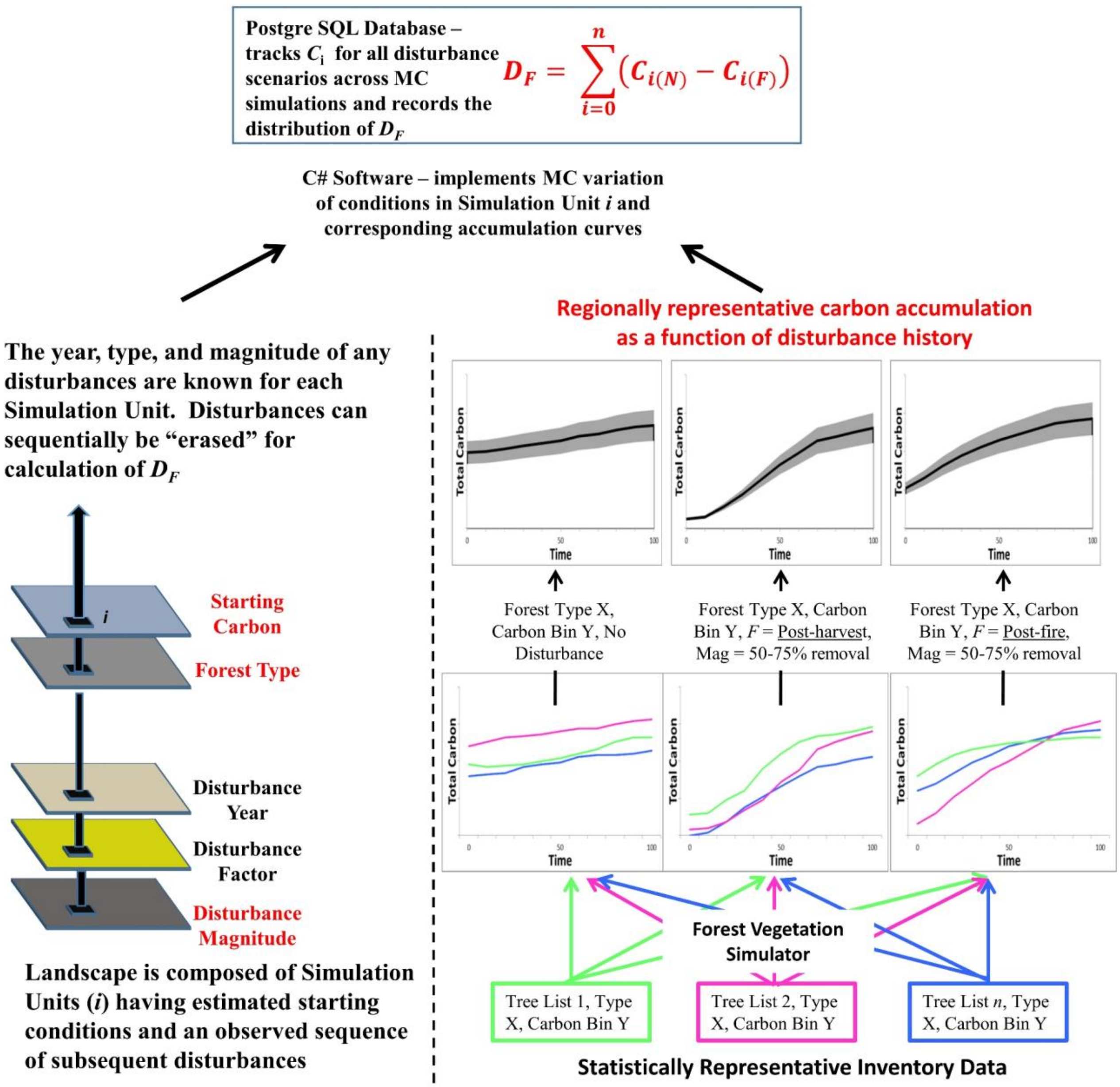

Figure 4. Flowchart of how ForCaMF calculates the impact of each type of disturbance. Carbon (C) storage associated with mapped forest conditions and disturbances is determined by applying regionally generalized C dynamics derived from the combination of USDA Forest Service, Forest Inventory and Analysis data and Forest Vegetation Simulator data. Disturbance-specific, stand-level C scenarios are shown on the right side of figure. Mapped stand dynamics are designated on the left side of the figure.

4.2.2 Uncertainty

There are several potential sources of uncertainty in the ForCaMF workflow described, including (designated in red in fig. 4):

- mapped starting conditions (initial C storage and forest type);
- modeled disturbance magnitude; and
- modeled C accumulation estimates, as obtained from FIA and FVS.

The complexity and interaction of ForCaMF's potential error sources preclude solving for error using an analytical approach. Instead, a Monte Carlo approach is used, where randomly selected alternative values for each input are substituted into the calculation of DF over a large number of error simulations. The variance of D_F in response to simulation of possible error patterns produces an empirical estimate of the system's integrated uncertainty. Healey et al. (2014) described an innovative method of carrying out the Monte Carlo method with mapped inputs such as those used here. This process, called Probability Density Function (PDF) Weaving, uses FIA data to calibrate and constrain error simulations related to mapped forest type and starting-condition maps as well as maps of disturbance magnitude. As a result, ForCaMF analyses are aligned with FIA estimates of historical C storage, distribution of forest type, and forest cover change.

In addition to uncertainty in input map products, ForCaMF simulates uncertainty associated with each of the disturbance-specific, stand-level C scenarios (fig. 4 right side) that ForCaMF links to mapped stand dynamics (fig. 4 left side). Error functions are obtained from fitting each scenario via a process called quantile regression, as previously mentioned and described by Raymond et al. (2015). These models are used to calibrate how C storage patterns are allowed to vary in the ForCaMF Monte Carlo process. The net result of these error simulation processes is that an empirical 95-percent confidence interval can be associated with estimates of D_F for each year.

4.3 Integrated Terrestrial Ecosystem Carbon Model

4.3.1 Methods

The InTEC model builds on ForCaMF by attributing the observed changes in C stocks to a full suite of both natural and anthropogenic factors. InTEC is a process-based biogeochemical model driven by monthly climate data, vegetation parameters, and forest disturbance information to estimate annual forest C and fluxes in C pools at regional and local scales (fig. 5) (Chen et al. 2000a,b,c; Ju et al. 2007). InTEC relies on empirical FIA datasets (USDA FS 2016) containing variables such as stand age, forest (or dominance) type, and net growth, resulting in a hybrid approach which combines a process-based biogeochemical model with empirical models that are comparable to the results from the baseline assessment (CCT) and ForCaMF. Specifically, the FIA-based stand age, dominance (or forest) types, and net primary productivity (NPP)-stand age relationships determine when stands were initially disturbed and, depending on forest (or dominance) type, how the productivity changes with stand age over time.

The C dynamics of a forest region are a function of multiple factors including disturbance, stand age, climate, and atmospheric composition (Chen et al. 2000a). These are grouped into

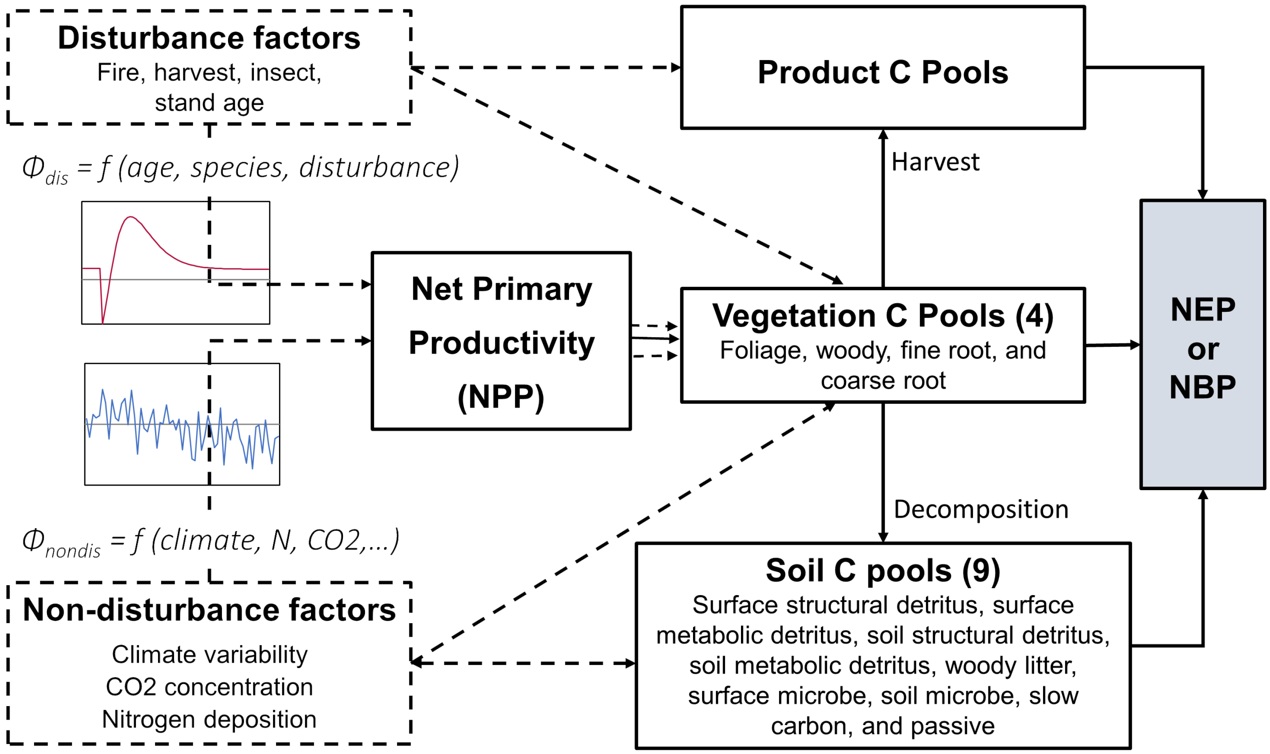

Figure 5. Conceptual scheme of the carbon (C) cycle in the Integrated Terrestrial Carbon Cycle (InTEC) model. Solid arrows indicate C flow and dashed arrows indicate influences. $\phi_{dis}(i)$: disturbance function; $\phi_{nondis}(i)$: nondisturbance function; NEP: net ecosystem productivity; NBP: net biome productivity. NPP is the net production of organic matter by plants, which is equal to the difference between the total amount of C fixed in photosynthesis (gross primary productivity) and C losses from respiration of plants (autotrophic respiration). NEP is equal to the sum of NPP and the C loss to the atmosphere via heterotrophic respiration. NBP is equal to the sum of NEP and C fluxes associated with nonrespiratory losses due to disturbances such as combustion from fire or export to external pools following harvest. If no disturbances occurred in a given year, NBP is equal to NEP (source: Zhang et al. 2012).

disturbance and nondisturbance factors. Disturbance factors include fire, harvest, insects, and forest stand age or time since stand-replacing disturbance, which can include disturbances that are not specifically identified or occurred prior to the satellite-based disturbance maps (pre-1990). Nondisturbance factors include climate (temperature and precipitation), atmospheric CO_2 concentrations, and N deposition. The InTEC model integrates the effects of nondisturbance and disturbance factors since the initial modeling year (1900 in this study). The historical C dynamics are estimated progressively from 1950 through 2011, and the results at any point in time are the accumulated effects of all factors since the starting year (Chen et al. 2003).

The InTEC model is run pixel-by-pixel, with a 90-m (300-foot) pixel size, in each individual national forest. Summary results are calculated by summing or averaging all pixels in a forest, depending on the measure being reported. Carbon pools include aboveground live (wood and foliage), belowground live (coarse roots), forest floor (fine roots, and surface structural and surface metabolic detritus), dead wood (standing and down dead, foliage, and coarse roots), and soil (soil structural and soil metabolic detritus, soil microbes, surface microbes, slow organic matter, and passive organic matter).

4.3.1.1 Disturbance, Regrowth, and Aging Effects

Disturbances are explicitly considered as processes that release C into the atmosphere, modify the terrestrial C balance, initiate regrowth, and subsequently transfer C from one pool to another (e.g., live trees to standing dead) in the disturbance year and thereafter. For the period 1990 to 2011, Landsat-obtained disturbance maps (described in Section 4.1.1) were used to determine the year, location, type (fire, harvest, insects), and magnitude of disturbance events. For years prior to 1990, stand-age maps were obtained from forest inventory data to act as proxies for the timing of the last stand-replacing disturbance. The time since disturbance influences the rate and accumulation of biomass and C during regrowth after disturbance. Each pre-1990 disturbance is considered to be a stand-replacing fire because it is difficult to assign a disturbance type from stand age alone, and any disturbance that reset the stand age to zero would have been stand replacing—most likely a high-severity fire or clearcut harvest. The type and magnitude of each disturbance determine the amount of C released directly to the atmosphere as well as the transfer of C from live to dead pools as a result of mortality, and the changes in C pools during regrowth.

For instance, if a fire has a mortality rate of 100 percent, a portion of the biomass C is immediately released to the atmosphere via combustion, the entire stand dies, and C is transferred from the live to the dead pool. Stand age is set to zero, and the stand regrows beginning the next year following the NPP-stand age relationships specific to each forest type. If a fire has a mortality rate of 50 percent, a portion of the biomass C is immediately released to the atmosphere via combustion, and 50 percent of the live trees die, transferring C to the dead pool. The stand age remains the same, and the forest continues to grow following the NPP-stand age relationship.

For harvests, the C in the harvested wood is transferred to the harvested wood C pool, thus leaving the forest ecosystem. Wood that is not removed from the forest during harvest, such as branches and roots, is transferred to the appropriate ecosystem C pool, such as woody debris. The removed C may be stored in the harvested wood product pools for several decades. Refer to the baseline assessments (USDA FS 2015a–i) for a detailed analysis of C in harvested wood product pools.

Relationships between NPP and stand age vary regionally, by forest types and environmental conditions (He et al. 2012; Zhang et al. 2012). For U.S. forests, NPP typically increases rapidly at a young age, reaches a maximum at middle age at about the time the canopy closes, and then gradually declines and stabilizes with older ages. Consequently, middle-aged forests have a greater capacity for C uptake than young and old forests. In InTEC, the aging effects reflect these changing rates of C sequestration with stand age. After a disturbance, C changes may initially be negative (C source), but later become positive (C sink) and reach a peak as vegetation regrows and decomposition declines (Pregitzer and Euskirchen 2004). Depending on stand age or the number of years since the last disturbance, the disturbance and aging effects on changing C stocks can be positive (causing a C sink) or negative (promoting a C source).

4.3.1.2 Nondisturbance Effects

Both long-term climatic trends and interannual climate variability can impact forest C dynamics by affecting growth, productivity, and decomposition. The InTEC model integrates climate data from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM), which combines empirical measurements from a network of weather stations with elevation and other topographic factors to map precipitation and temperature at monthly timescales across the United States (PRISM Climate Group 2004). Anthropogenic climate change has led to increases in average temperatures in most regions across the United States since 1900, as well as regional shifts in precipitation; some regions have become drier and others wetter (Walsh et al. 2014). In some regions, warmer temperatures can cause moisture stress and more rapid decomposition of surface and soil C (Ju et al. 2007), thus increasing C emissions. In high-latitude or -altitude locations, warmer temperatures can enhance tree growth (Way and Oren 2010). Drought conditions can reduce tree growth both during the drought and up to several years later, in turn making forests less able to act as C sinks (Anderegg et al. 2015). On the other hand, increased precipitation and humidity can promote tree growth and C uptake (Dale et al. 2001; Nemani et al. 2002).

Like climate, atmospheric composition is known to impact plant growth rates and C dynamics (e.g., Hyvönen et al. 2007; Law 2013; Pan et al. 2009). Data collected at field monitoring stations of the National Atmospheric Deposition Program's National Trends Network established coverage maps of N deposition (Pan et al. 2009). The increased N deposition due to human activities can stimulate C sequestration in forests, through increased production of biomass, surface litter, and soil organic matter.

The InTEC model also incorporates annual concentrations of atmospheric CO_2 measured at the Mauna Loa Observatory in Hawaii (Keeling et al. 2009). Atmospheric CO_2 levels have increased steadily from 280 ppm in 1901 to 390 ppm in 2010 due to industrialization and other human activities. Like N deposition, elevated atmospheric CO_2 concentration acts as a fertilizer, stimulating photosynthesis and biomass production (Keenan et al. 2013). Additional details about the datasets and their use by InTEC are available (Dugan et al. 2017).

4.3.1.3 Simulation Scenarios

To model the effects of individual and combined disturbance and nondisturbance factors, a series of simulation scenarios were developed (Zhang et al. 2012, 2015). Six overall scenarios were simulated by InTEC: 1) all factors including all disturbance and aging and nondisturbance effects, 2) disturbance and aging effects only, 3) combined nondisturbance effects only, 4) climate effects only, 5) CO_2 effects only, and 6) N deposition effects only.

4.3.2 Uncertainty

Quantifying model uncertainty using a Monte Carlo approach and multiple simulations is impractical with InTEC because of the time it takes to perform model runs given the numerous forests, high-resolution datasets, long temporal scales, and multiple simulation scenarios analyzed. The uncertainty and validation of the InTEC model for analyses across the contiguous United States were studied in Zhang et al. (2012, 2015). Uncertainties also depend on the quality and quantity of data available for each forest. The climate and atmospheric chemistry data used in InTEC are derived from a sufficiently dense network of observation stations to be accurately representative of regional conditions, although errors may be significant at local scales. As discussed earlier, InTEC is calibrated to FIA data and satellite imagery observations of disturbance and productivity and uses disturbance estimates and age maps, so that the previously assessed uncertainties in these datasets are propagated into the InTEC model results. Given the lack of stand-age data in the early part of the 20th century, modeled results are more uncertain for that period (Zhang et al. 2015); thus, results prior to 1950 are omitted in this report. For additional information regarding InTEC, including calibration, parameterization, and model inputs, see Zhang et al. (2012, 2015).

5. Integration of Modeled Results

These NFS forest C assessments are based on a variety of datasets and several models. Although we have attempted to reach a high level of consistency, appropriate interpretation and use of the results should reflect inherent differences between datasets and models that cannot be fully reconciled (Dugan et al. 2017). Generally, the FIA data represent the most accurate analysis of trends in C stocks as summarized by CCT in the baseline assessments (USDA FS 2015a–i), the effects of disturbances are best captured by ForCaMF, and the effects of environmental variables are reflected in the results from InTEC. However, despite the extensive use of FIA data by all three models (CCT, ForCaMF, and InTEC), results are not completely compatible because ForCaMF and InTEC use additional datasets with different properties and timing of observations and the models include different C pools (table 2). The models themselves are also different. CCT and ForCaMF are empirical models, whereas InTEC is a hybrid empirical and process model. These different approaches are necessary to provide a complete analysis of the main drivers of change, because none of the approaches can represent all of the important drivers. In a broader context, a land manager may be faced with interpreting conflicting results from studies conducted by different parties; therefore, the goal of this section is to provide some guidance for dealing with this situation in the future.

The three models (CCT, ForCaMF, and InTEC) that were integrated for these forest C assessments use common data sources to enhance agreement between model results. For instance, all three models use FIA data as major inputs so that all results are well grounded in observations. FIA data are the primary data source of CCT, as the model calculates C stocks and stock changes from tree-level data from at least two inventories using allometric models (Woodall et al. 2011). ForCaMF also relies on FIA data to simulate forest C trajectories given different disturbance scenarios (Raymond et al. 2015). Last, InTEC is driven by stand-age maps, dominance type maps, and NPP-age relationships, all obtained in part from FIA plot data.

Along with FIA datasets, ForCaMF and InTEC incorporate high-resolution Landsat-obtained disturbance data (Healey et al. 2014). Although FIA captures disturbance events by periodically remeasuring the same sample plots, it may lack the temporal sensitivity to detect the effects of more recent disturbances. This is because FIA field observations are made on a cycle that may be 10 years or even longer. In some cases older observations are based on periodic inventories and newer observations are based on annual inventories of subsets of sample plots, so that the average age of "current" FIA data can be 5 years (typical in the East) or 10 years (typical in the West), or more. The CCT model interpolates and extrapolates these observations to produce an annual time series since 1990, but if the extrapolation is from older data and there have been more recent significant changes such as an increase in disturbances, the extrapolation represents trends that no longer characterize what is occurring in the landscape. In contrast, ForCaMF and InTEC both use more contemporary satellite-based observations of disturbances as a major input, which reflect landscape changes as they occur.

The FIA data may also lack spatial resolution to detect smaller disturbances outside FIA plots, especially in areas where plot density is sparse. On the other hand, the Landsat satellite captures any recent disturbance greater than pixel resolution (30 m; 100 ft) that alters forest canopies, even those occurring outside FIA plot locations. ForCaMF utilizes all identified disturbance types including fire, harvest, insects, disease, and abiotic disturbances (e.g., wind, ice). InTEC excludes disease and abiotic disturbances due to the complexity and uncertainty in including their effects in a process model. However, stand-replacing disturbances that are not attributed to a specific cause or occurred prior to the mapped satellite record, may be captured in the inventory-based stand-age data. In this case, these disturbances are included in the model and treated as stand-replacing fires (Zhang et al. 2012). Except for the Northern Region, which has had significant disease impacts as indicated by ForCaMF, both diseases and abiotic disturbances affect a relatively small percentage of national forests across the United States compared to other disturbance types.

Although InTEC and ForCaMF both evaluate the effects of disturbances and management on C stocks, there are several key differences between the models that make direct comparison of their results difficult. ForCaMF models only the effects of disturbances and management on nonsoil C stocks, while InTEC tracks the complex C cycling through several soil C pools (fig. 5, table 2). Though soil C is often one of the largest single C pools in forest ecosystems, it is very stable and not significantly affected by disturbances. Additionally, ForCaMF is primarily tracking potential lost C storage as a result of disturbances and management, while InTEC is mostly focused on C stock changes and accumulations due to both disturbance and nondisturbance factors. Therefore, while these models complement one another, direct comparisons between the two should take into account these differences.

Model results may also vary due to inherent differences in modeling approaches. For instance, CCT relies on allometric models of volume, species, and tree dimensions to convert tree measurements to biomass and to C (Woodall et al. 2011). ForCaMF is similar in that it also uses individual tree measurements and site characteristics within the FVS growth and yield model to simulate C stocks and trends. InTEC is fundamentally different as it is driven by a mathematical representation of biogeochemical cycles such as photosynthesis, N mineralization, and nutrient dynamics (Zhang et al. 2012, 2015). Thus, it does not rely only on biometrics. These distinctions in modeling techniques are likely to result in some discrepancies between forest C outputs from the three models.

Last, the area of forest land in each national forest may differ by model. Both CCT and ForCaMF use the FIA definition of forest land as areas at least 120 feet (36.6 meters) wide and 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated (O'Connell et al. 2014). Thus, the amount of forest land can change over survey years given deforestation or afforestation activities or administrative boundary changes. However, the changes in FIA sampling design, protocols, and definitions in the late 1990s can introduce discontinuity in attributes such as total forest land area and consequently C estimates over time (Goeking 2015; Woodall et al. 2011). InTEC uses a single forest (or dominance) type map based in part on FIA data (Ruefenacht et al. 2008) and, where available, data sampled by the NFS (e.g., USDA FS 2015j). The model therefore assumes there is no change in area of forest land over the study period. While the extent of the effects of such modeling disparities on forest C estimates has not been evaluated, it is important to consider that model results for individual forests may differ, sometimes considerably, for a variety of reasons.

6. Regional Results

6.1 Eastern Region

6.1.1 Description of Region

The Eastern Region (also referred to as Region 9) in the National Forest System (NFS) consists of 14 national forests from Maine to Minnesota in the north and Maryland to Missouri in the south (fig. 6). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so the Midewin National Tallgrass Prairie in Illinois was not included. To restrict the analysis to lands managed by the Forest Service, U.S. Department of Agriculture, any private inholdings within national forest boundaries were excluded.

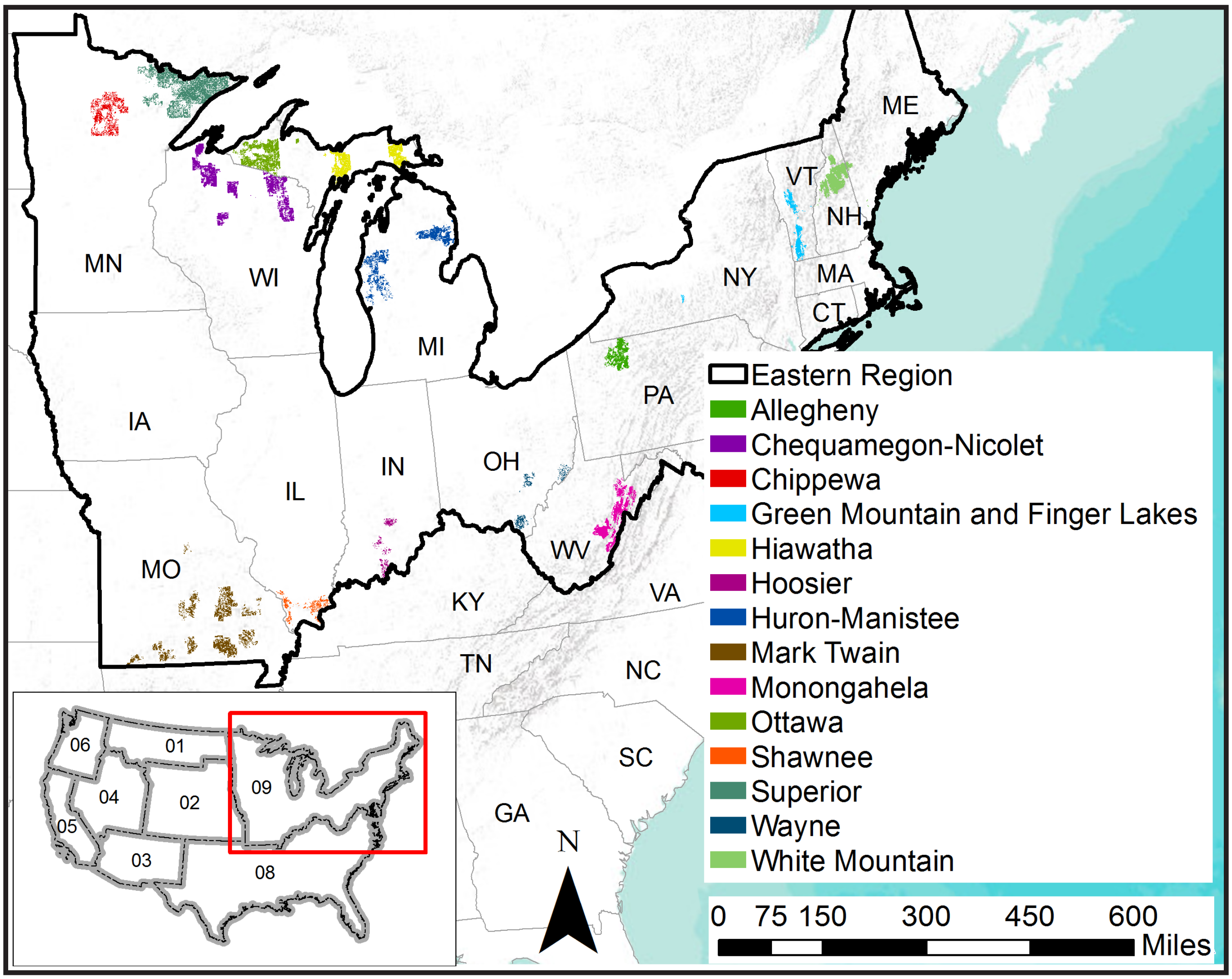

Figure 6. Locations of the national forests in the Eastern Region.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. The Eastern Region was the first region to be widely settled in the United States, so its forests have a long history of unregulated harvesting and conversion to agriculture. For much of the 19th century, the U.S. timber industry was centered in the Northeast, largely in the valuable white pine forests of the Lake States region, until the 1890s (see Appendix 1 for scientific names of species mentioned in this report). However, the depletion of merchantable timber products and the settlement of the West caused the logging industry to move westward. In addition to timber harvesting, fire was regularly employed to clear land for agriculture, but fires occasionally spread, causing the destruction of valuable timber resources. In the late 1800s, several large wildfires destroyed millions of acres of forested land in Michigan, Wisconsin, and Minnesota. By 1900, some 300 years after Euro-Americans first settled the region, the need for forest restoration and protection became evident (Conrad 1997).

After passage of the Weeks Act in 1911 (PDF, 37KB), the Forest Service began buying large areas of these heavily cut-over and submarginal lands, referred to as “the lands nobody wanted” (Shands 1992), throughout the eastern United States. By 1920 approximately 2 million acres (800,000 hectares) of excessively logged and degraded land was purchased as national forest land. Soon forest restoration and recovery became the new goal. With help from the Civilian Conservation Corps, millions of trees were planted, erosion was controlled, and forest fires were fought (Williams 2003). The suspension of the use of fire for clearing land, the increased effort to suppress fires, and the forest restoration efforts allowed forests to regrow and increased stocking of trees. In the 1940s the timber industry in the Eastern Region started to pick up steam again. Timber production increased throughout much of the mid-1900s, peaked in the late 1980s, and then declined rapidly in the 1990s and 2000s (Loeffler et al. 2014b). This history of timber harvesting and forest restoration in the Eastern Region played an important role in shaping forest C dynamics over time.

In addition to timber harvesting and fires, natural disturbances including storms and insects have impacted forests and C stocks in this region. For example, in 1999 a massive wind and rain storm known as the “Independence Day Windstorm” caused an unprecedented blow-down of trees across Superior and Chippewa National Forests (Mattson and Shriner 2001; Nelson et al. 2009). In 2009 a historic derecho (storm with straight-line winds) plowed down some 80,000 to 90,000 acres (32,000 to 36,000 hectares) of forest in the Mark Twain National Forest (Vaughn 2013). Though insect outbreaks in the Eastern Region have been relatively small and resulted in lower mortality or removal compared to harvests and wind-storms, the spread and severity of insect outbreaks including the hemlock woolly adelgid, eastern spruce budworm, forest tent caterpillar, and emerald ash borer are projected to intensify with continued climate change (Dukes et al. 2009).

6.1.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Eastern Region are displayed in figure 7. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Harvest was the most common and consistent type of forest disturbance in the Eastern Region, although harvest rates never greatly exceeded 0.25 percent of the landscape, and there was a general downward trend from the early 1990s to 2011 (fig. 7). Occasional fires and windstorms (labeled “abiotic” in figure 7) caused notable mortality, and localized insect outbreaks were detected in several years. Over this period, disturbances exhibited a relatively even mix of low to high intensities.

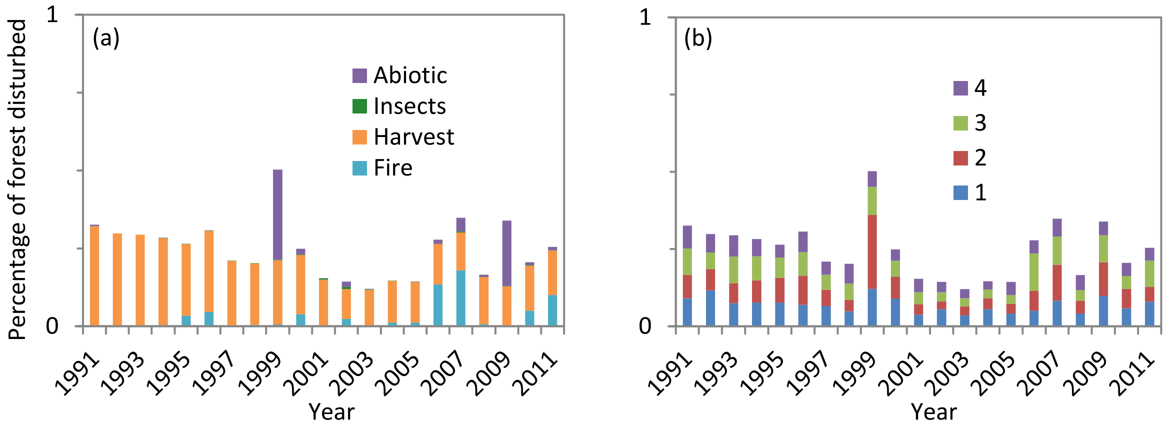

Figure 7. Annual rates of disturbance (0 to 1 percent) in the Eastern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and abiotic; 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.

6.1.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Eastern Region in figure 8. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 1997, for example, the line for fire in figure 8 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF’s accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an “undisturbed” scenario. Thus, figure 8 reflects the real-time impact of disturbance on the forest’s ability to store C in relation to storage likely in the absence of disturbance.

As mentioned, harvest activity was the dominant type of disturbance within the region during the study period, and had the largest impact on C stocks. Harvests occurring from 1990 to 2011 reduced 2011 storage by approximately 154 g/m^2 or 1.54 Mg/ha (fig. 8), or about 81 percent of the disturbance impact on stocks (fig. 9). By 2011, this represented a reduction of about 1.6 percent of the regional nonsoil C stocks (fig. 10) that were reported in the NFS baseline assessment derived from FIA data (USDA FS 2015b). These patterns do not account for offsite storage of C in wood products. Temporary storage of forest C in products and disposal sites can last for decades, significantly delaying climate impacts resulting from atmospheric emissions. Information about the region's storage of C in wood products can be found in the baseline C assessment (USDA FS 2015b).

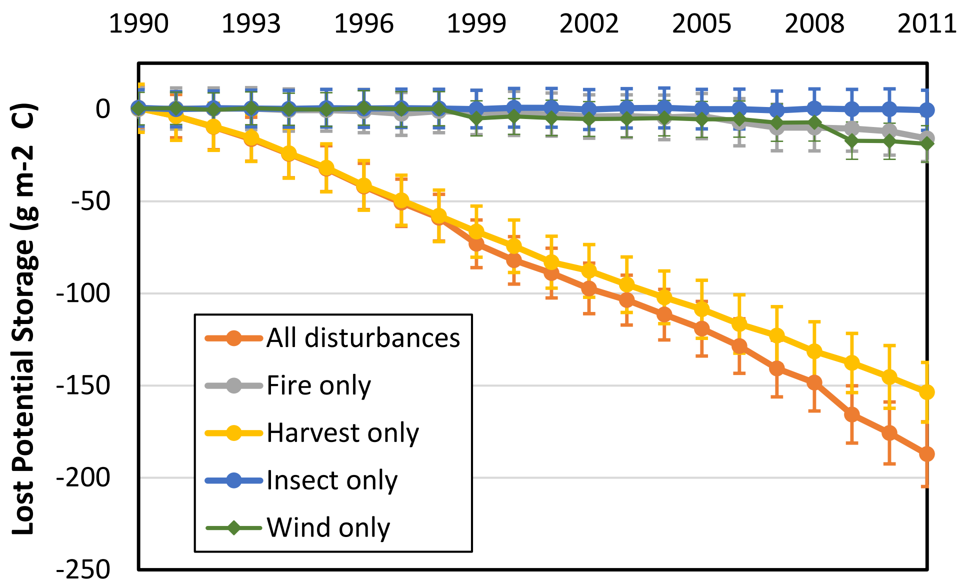

Figure 8. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Eastern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

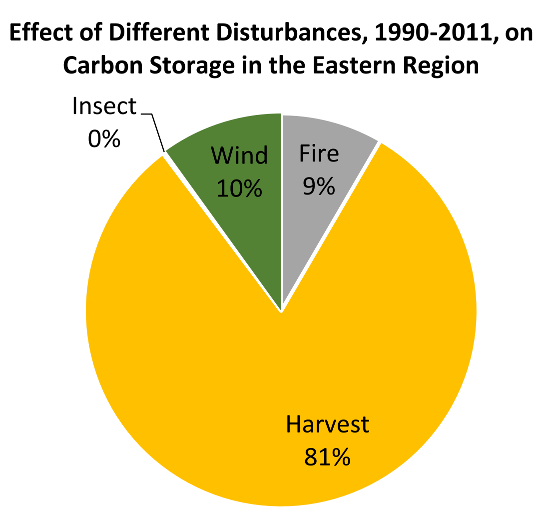

Figure 9. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Eastern Region for the period 1990 through 2011.

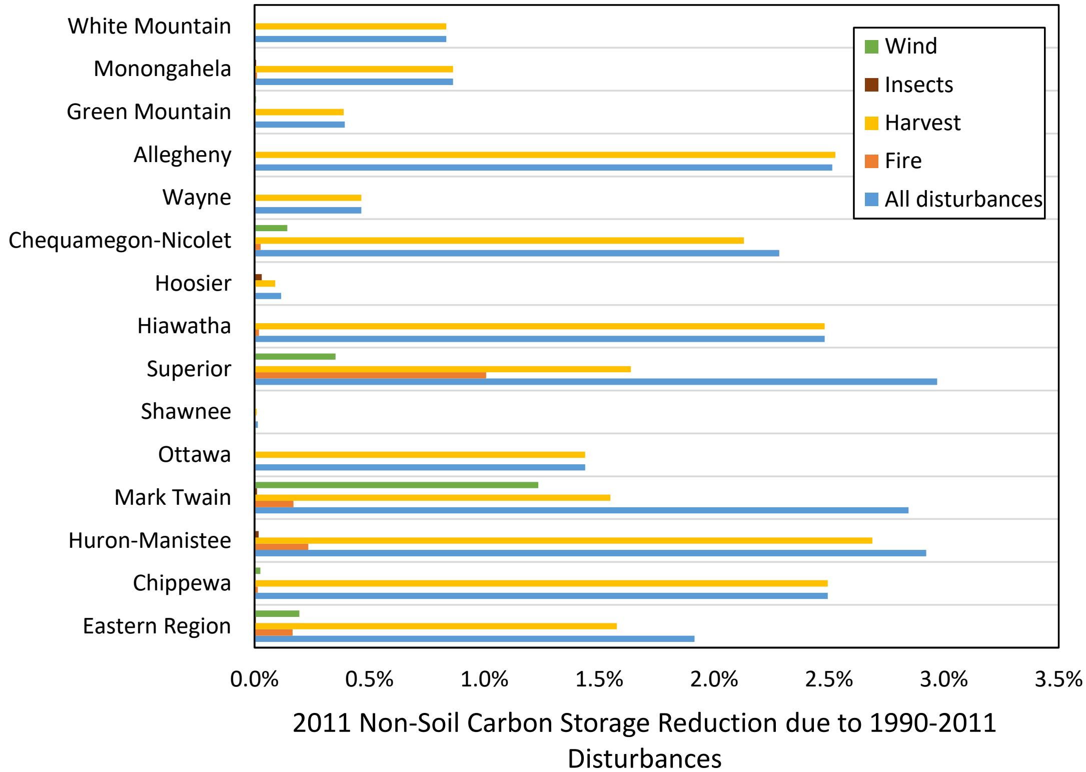

Figure 10. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Eastern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

Wind and fire also had significant impacts on C storage in the region, making up 10 percent and 9 percent of the total effects of disturbance, respectively (fig. 9). Wind resulted in the loss of 0.2 percent of nonsoil C stocks, and fires accounted for a 0.1-percent loss. These disturbances were concentrated in a few years (fig. 7), although figure 8 illustrates how residual effects of discrete events (such as slowly decomposing dead material) can cause ongoing divergence of the amount of C that is stored versus the amount of C that could be stored. The highly localized nature of the region's fire and wind events and their consequent C impacts is discussed for individual forests (Appendix 3: Eastern Region (PDF, 3.4 MB)). The low level of detected insect activity was noteworthy given the relatively high profile of insect events in the region. One reason for this discrepancy may simply be that by the end of the period (2011), the spread of emerald ash borer was still fairly localized. Further, there was a requirement built into the disturbance-mapping process that canopy mortality must be sustained. Seasonal or temporary defoliation due to gypsy moth activity was widely noted, for example, but imagery from subsequent dates often showed no permanent loss of canopy, so these areas were not included in maps of disturbance. This rule was not to imply that these events were not disturbances; it was instead based on the assumption that loss of a single year's foliage had little impact on C storage or stand dynamics. In addition to affecting estimates of insect activity in the Eastern Region, this rule also significantly reduced the amount of area mapped as "disturbed" due to hurricanes in the Southeast.

One caveat must be stated about the confidence intervals depicted in figure 8. The unit of analysis for ForCaMF was the national forest (Appendix 3: Eastern Region (PDF, 3.4 MB)); rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Harvests were clearly the most important disturbance process with respect to C storage, although fire and wind were locally important.

6.1.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 11–14) generated from InTEC model inputs and simulations for individual national forests and summed results across all national forests in the Eastern Region. These regional-scale outputs were generated only from the national forest-specific datasets; therefore, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 3: Eastern Region (PDF, 3.4 MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 14 national forests as modeled by InTEC with this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Eastern Region have been strongly influenced by the history of land use and policies as well as climate change and atmospheric CO_2 concentrations. Despite variation among national forests, the regionwide stand-age distribution in 2011 shows that about 50 percent of the forests are greater than 80 years old (fig. 11). The stand-age distribution also indicates a period of elevated stand establishment occurring about 70 to 100 years before 2011, or from 1910 to 1940 (fig. 11). During the 1940s and thereafter, the rate of stand establishment sharply declined. This early-1900s pulse of stand establishment reflects forest recovery and regeneration after decades of heavy logging and clearing of land for agriculture. Depending on the forest-type group, which is mostly oak/hickory and maple/beech/birch (fig. 11), the stands making up this pulse of establishment would have been growing at maximum productivity when they were about 30 to 50 years old (fig. 12), or around 1940 through most of the mid-20th century. By the 1980s, most of the forests in the Eastern Region had aged beyond their peak productivity, according to the NPP-age relationships. Thus, productivity has since declined although the forests have not yet reached their potential C stocks (Hoover et al. 2012).

Both temperature and precipitation have increased slightly over the past few decades in the Eastern Region (figs. 13a,b). Warmer temperatures can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. On the other hand, the wetter conditions enhance productivity and growth rates. Although long-term climate trends may be subtle, interannual weather variability has been high with several years of notable climatic extremes.

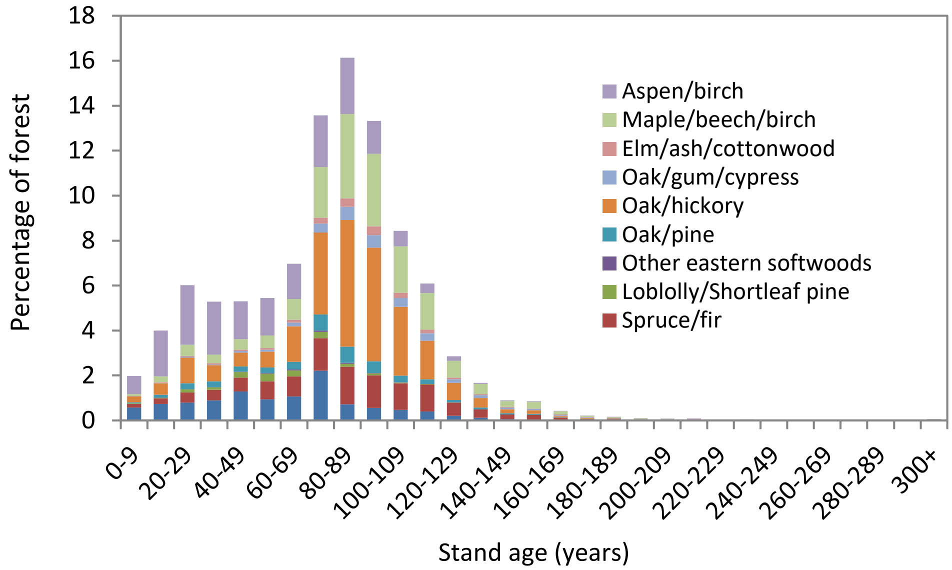

Figure 11. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Eastern Region (see Appendix 1 for scientific names of trees).

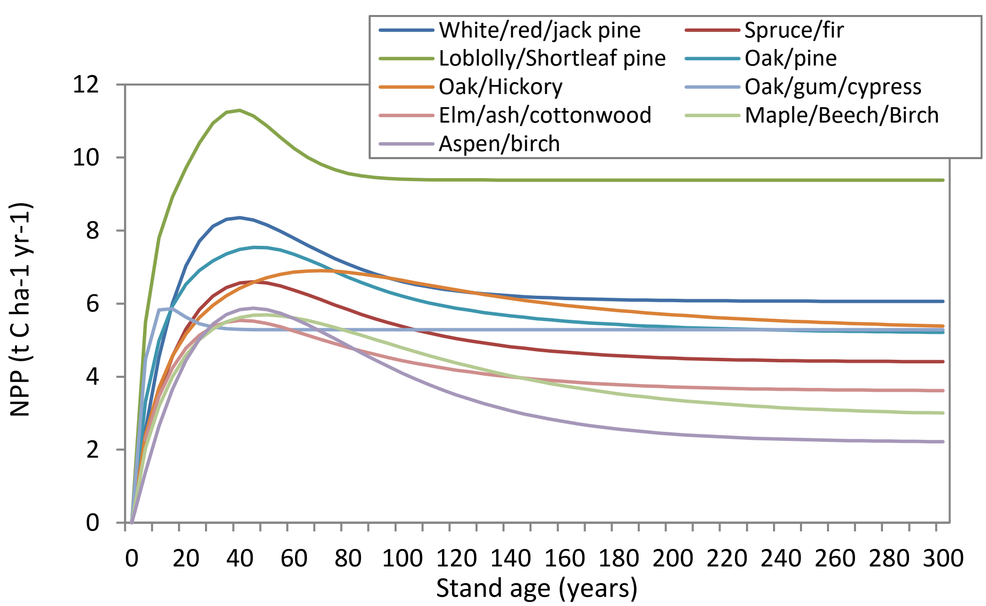

Figure 12. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Eastern Region (see Appendix 1 for scientific names of trees). Due to a small sample of other eastern softwood plots to derive NPP-age curves, the loblolly/shortleaf pine curve was used for these stands.

For instance, much of the Eastern Region experienced a severe drought in the mid-1960s, as well as harsh summer heat waves in 1953 and 1998 (figs. 13a,b). Furthermore, the forests of theEastern Region have experienced some of the highest amounts of N deposition in the United States from the coal industry and automobile emissions. Nitrogen deposition has declined in the past decade due to regulations targeting emissions from power plants and automobiles (fig. 13c). Atmospheric CO_2 concentrations have increased globally over the past few decades and are expected to continue to rise as a result of human activities.

The C stock changes across the national forests in the Eastern Region show that forests have mostly maintained a C sink from 1950 to 2011 (fig. 14c). Modeled results indicate that this C sink has been declining but may have stabilized over the past two decades. This decline in the C sink is a result of forests getting older on average and therefore growing more slowly, highlighted in the disturbance and aging effect (fig. 14b). The pulse of stands 70 to 100 years old (fig. 11) was most productive from the 1940s through approximately the 1970s, but as forests continued to age, their productivity declined (fig. 12). This decline was coupled with lower rates of stand establishment starting in the 1940s (fig. 11). Aside from a few large disturbance events, such as the windstorms in 1999 and 2009, recent disturbances in the Eastern Region have been small and of low magnitude (fig. 7); thus, C emissions from disturbances have also remained low (fig. 14e). As a result, low rates of stand establishment have been persistent since the 1940s and the forest continues to be dominated by these aging stands (fig. 11).

In the early 1950s climate had a mostly negative effect on changing C stocks, causing a lower rate of C accumulation than in more recent years (fig. 14d), which have been characterized by elevated temperatures (fig. 13b). Aside from this early period and a few notably warmer years such as 1998, climate has mostly enhanced the C sink, but overall had a small effect on total C accumulation (fig. 14d). Both the increases in N deposition (fig. 13c) and atmospheric CO_2 concentrations have had consistently positive effects on changing C stocks and C accumulation across all forests in this region (figs. 14a,d). The N deposition effect has mostly stabilized due to declining N deposition rates (fig. 13c) and the potential saturation of N in the forests. However, the CO_2 effect has steadily increased, causing significant C accumulation (fig. 14d). Overall, the positive effects of climate, atmospheric CO_2, and N deposition helped to offset the decline in C stocks due to disturbance and aging effects such that the C stock change and C accumulation due to all effects has stabilized (figs. 14b–d). National forests in the Eastern Region had a combined net gain of 300 Tg of total ecosystem C, including soil C, between 1950 and 2011 (fig. 14d).

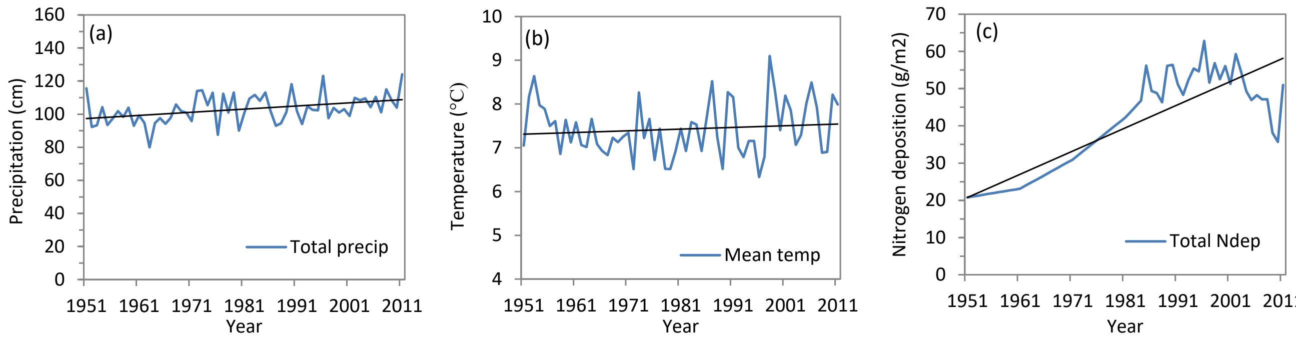

Figure 13a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen (N) deposition from 1951 through 2011 averaged across all national forests in the Eastern Region. Linear trend lines shown in black.

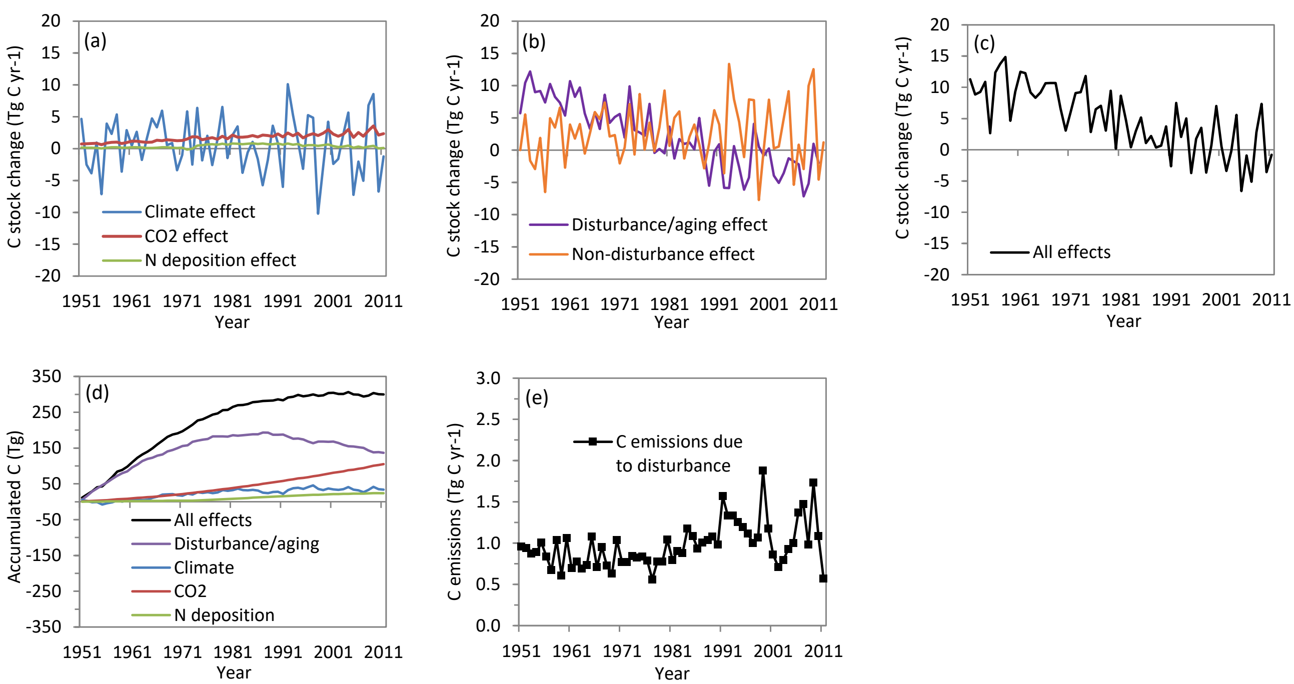

Figure 14a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Eastern Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2010 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

6.2 Southern Region

6.2.1 Description of Region

The Southern Region (also referred to as Region 8) in the National Forest System (NFS) contains 14 national forests or groups of national forests which have been administratively combined, spread across 13 States in the southeastern United States from Virginia to Florida and as far west as Texas and Oklahoma, as well as a national forest in Puerto Rico (fig. 15). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so national grasslands were not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded. Due to a lack of key datasets, El Yunque National Forest in Puerto Rico was not included in this assessment.

The history of development, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. After the Civil War in the 1860s, agricultural expansion and large-scale timber extraction became the dominant driving forces of forest change in the South. The

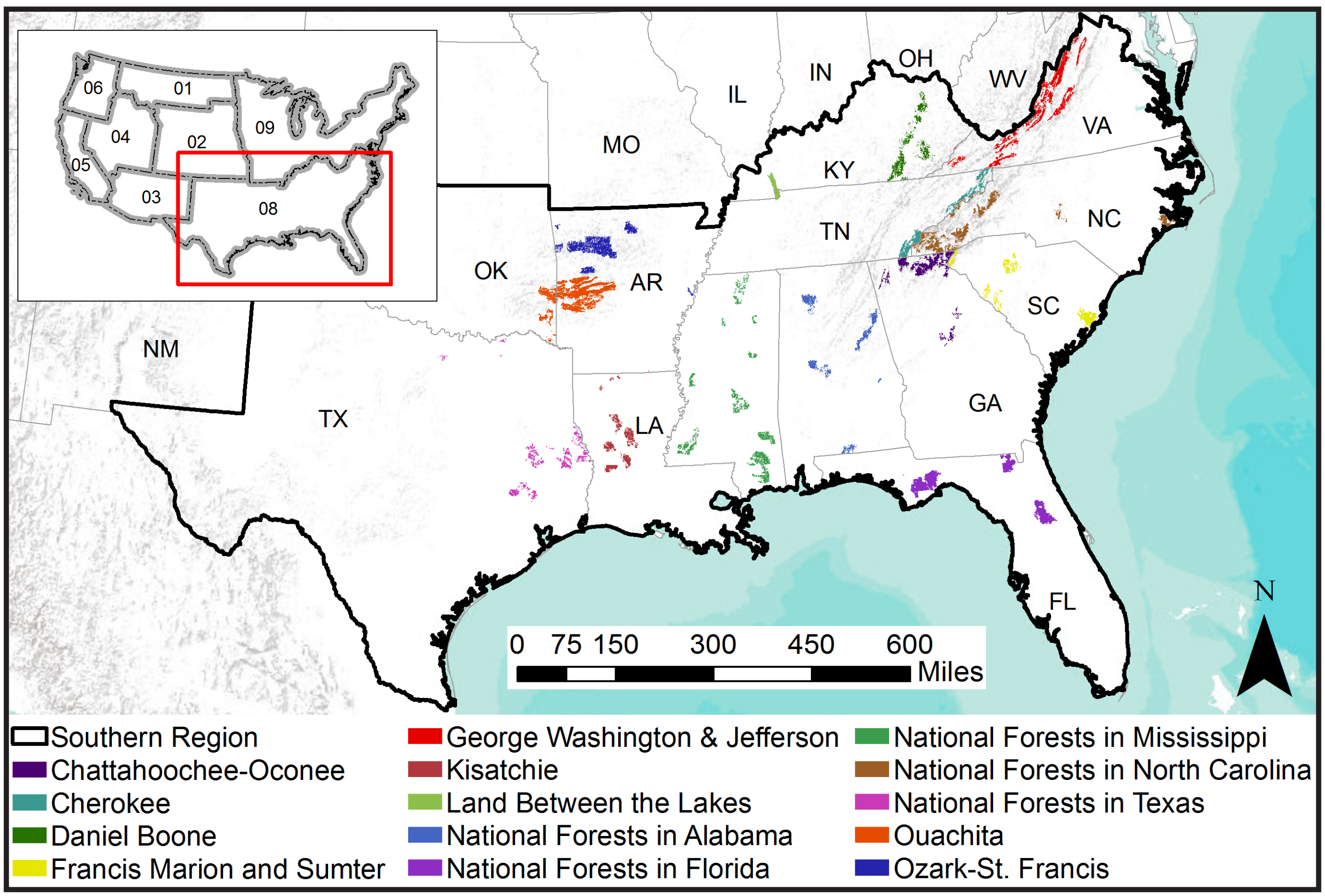

Figure 15. Locations of the national forests in the Southern Region. Not shown: El Yunque National Forest in Puerto Rico.

timber industry soon became centered in the South, and by 1919 the region was producing 37 percent of U.S. lumber (Williams 1989). During this period, most of the remaining primary forests of the South were harvested, and much of the previous forest land was replaced with agriculture and grazing.

After passage of the Weeks Act in 1911, the Forest Service began buying large areas of these heavily cut-over and submarginal lands, referred to as "the lands nobody wanted" (Shands 1992), throughout the eastern United States. By 1920 approximately 2 million acres (800,000 hectares) of excessively logged and degraded land was purchased as national forest land. Soon forest restoration and recovery became the new goal. With help from the Civilian Conservation Corps, millions of trees were planted, erosion was controlled, and forest fires were fought (Williams 2003). The increased effort to suppress fires allowed forests to regrow, which increased stocking of trees. As these forests were restored, the timber industry was also revived. From 1936 to the mid-1950s, timber harvests increased steadily and peaked in the mid-1980s before declining steeply in the 1990s into the 2000s (Loeffler et al. 2014c). The restoration of southern national forests not only is a conservation success story but also shaped the legacy of forest C dynamics in the region.

In addition to land use and policies, natural disturbances have played an important role in the forest C trends in the Southern Region. Except for timber harvesting, fire is the most common disturbance affecting southern forests. Major wildfires occurred during the droughts of the 1930s and 1950s. As research and experience increased understanding of the important role of fire in forest ecosystems, prescribed fire was again used in the South in recent decades to reduce hazardous fuels. Despite prescribed burning to keep hazardous fuels in check, wildfires—most of them human caused (Stanturf et al. 2002)—are still common in the South. The Southern Region also experiences tropical storms and hurricanes that can significantly affect forests. For instance, in 1989 Hurricane Hugo devastated some 3.5 million acres (1.4 million hectares) of the Francis Marion National Forest (Sheffield and Thompson 1992). Outbreaks of insects such as the southern pine beetle and gypsy moth have also impacted forest productivity, C cycling, and overall ecosystem health.

6.2.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Southern Region are displayed in figure 16. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns are marked by declining (and low) harvest levels, periodic large fire years (including 2000, 2004, and 2007), and a recent increase in insect activity. Of all disturbance types, harvests affected the greatest amount of forested area from 1990 to 2011, although annually harvests never exceeded 0.5 percent of the forested area. From 1990 to 2011, disturbances on about two-thirds of the forest land area were low to moderate intensity (<50 percent change in canopy cover). Validation activities for the disturbance maps in this region showed that the effects of hurricanes were underrepresented in the maps, and were thus underrepresented in subsequent ForCaMF assessments of C impact.

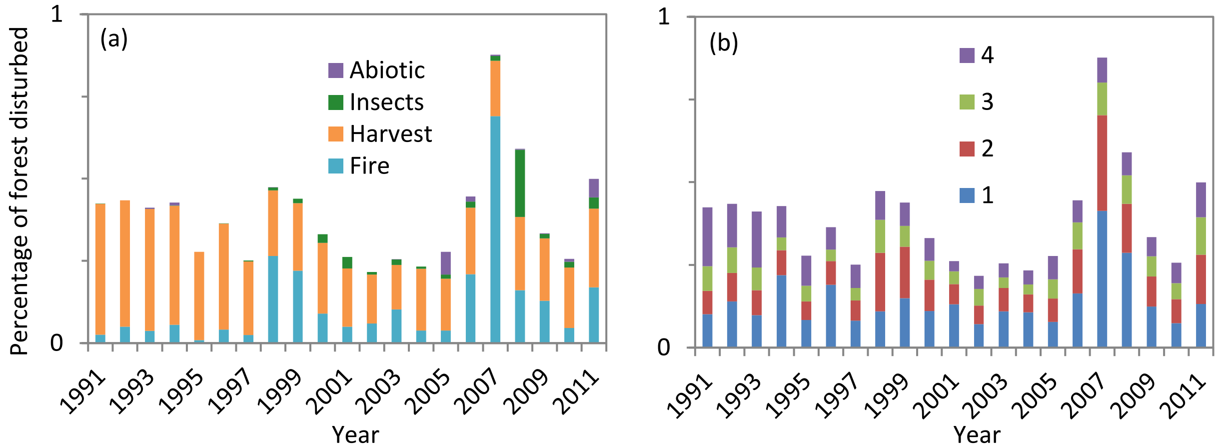

Figure 16. Annual rates of disturbance (0 to 1 percent) in the Southern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and abiotic; 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.

6.2.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Southern Region in figure 16. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires occur only in 2006, for example, the line for fire in figure 17 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an "undisturbed" scenario. Thus, figure 17 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Forest harvest from 1990 to 2011 accounted for about two-thirds of the impact of disturbance on 2011 C stocks (figs. 17, 18). By 2011, this represented a 2.4-percent reduction in the regional nonsoil C stocks (fig. 19) that were reported in the NFS baseline C assessment derived from FIA data (USDA FS 2015h). While harvest rates have been relatively steady in terms of area, and were consistently higher than in other NFS regions, they never affected more than 0.5 percent of the landscape in a single year. These patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the baseline C assessment (USDA FS 2015h).

Fire was responsible for approximately one-fourth of the region's observed disturbance impact (fig. 18), although that impact was not uniformly distributed (fig. 19). As described in Appendix 4: Southern Region (PDF, 4.1MB), the impact of fire per unit area in the National Forests in Florida was greater thanthe impact of all combined disturbance types in any national forest elsewhere in the region. Fires represented 59 percent of the total 1990 to 2011

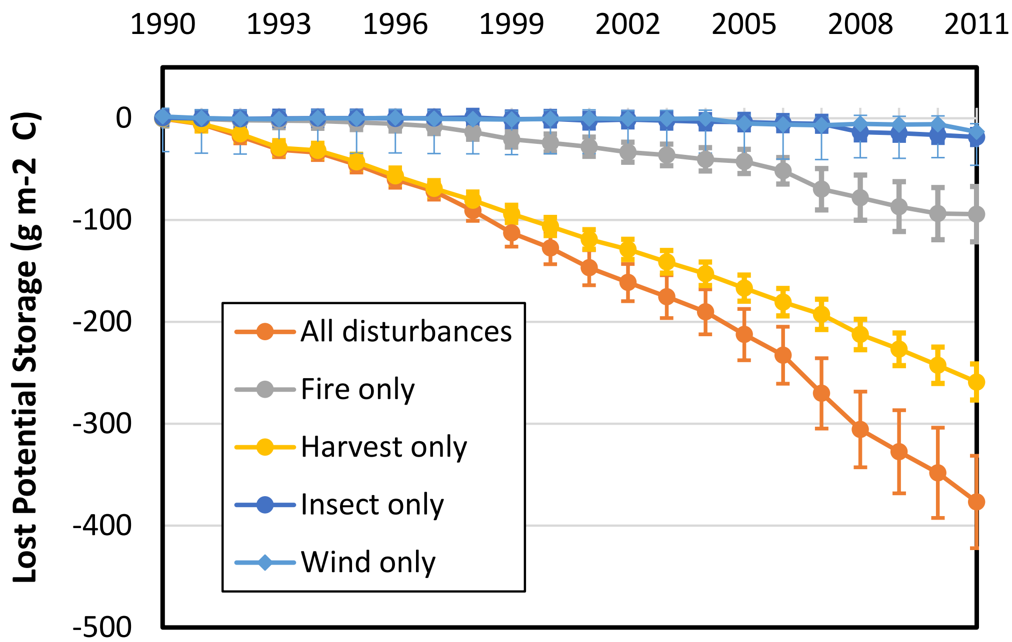

Figure 17. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Southern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

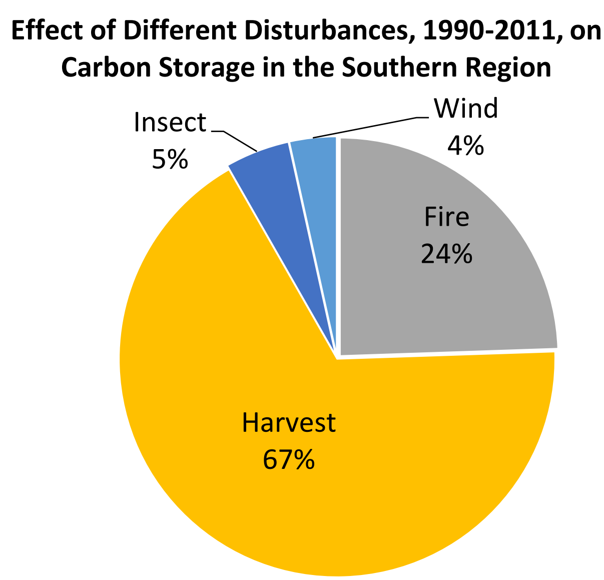

Figure 18. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Southern Region for the period 1990 through 2011.

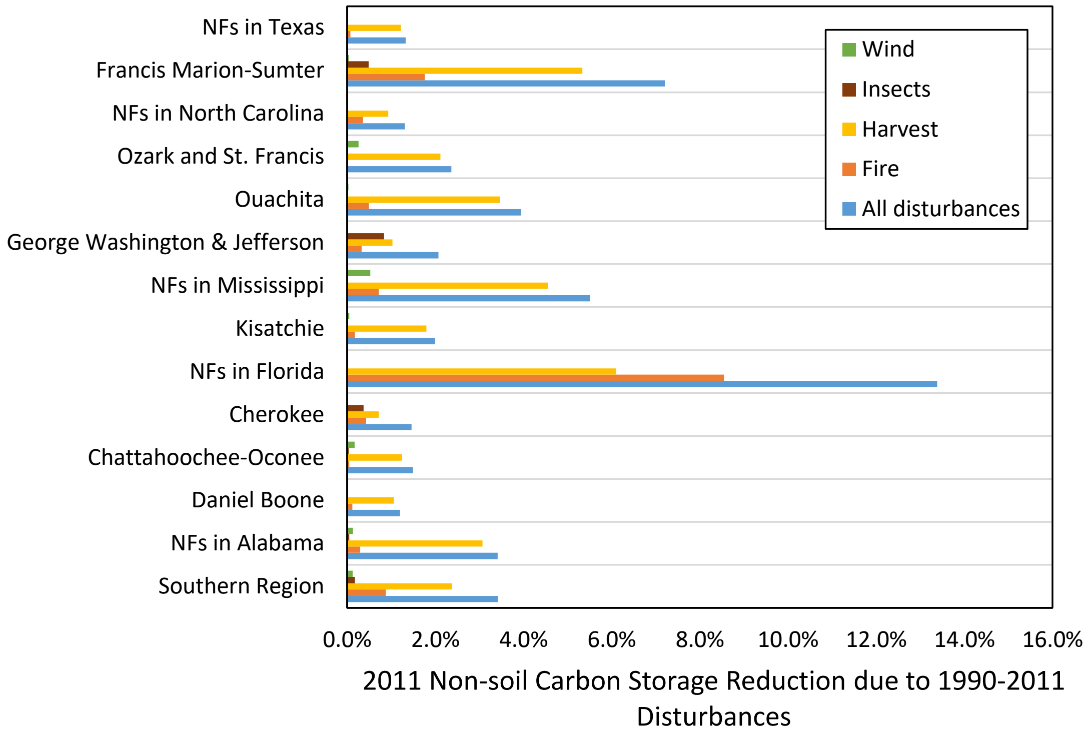

Figure 19. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Southern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

sequestration potential lost to disturbance in Florida, while that percentage was 28 percent for the Cherokee and 23 percent for the Francis Marion and Sumter National Forests. Fire was a more minor component of disturbance for the rest of the region, resulting in the loss of 0.9 percent of nonsoil C stocks by 2011 (fig. 19).

The effect of insects on C storage accounted for approximately 5 percent of the disturbance impact in the region during the study period (fig. 18), and a 0.2-percent decline in total nonsoil C stocks by 2011 (fig. 19). Losses were centered on the George Washington and Jefferson National Forests (38 percent of losses) and the Cherokee National Forest (25 percent of losses). The timing of the outbreaks responsible for these effects can be seen in figure 16, keeping in mind that release of C associated with mortality in any one year is spread out over many subsequent years.

By 2011, wind resulted in a 0.1-percent reduction in total nonsoil C storage in the Southern Region (fig. 19). Wind damage made up only 4 percent of disturbance-related losses in the period (fig. 18). This is a surprisingly low percentage, given the high profile of hurricane activity in the region and the observed impact of tornado events in forests largely unaffected by hurricanes (e.g., the Ozark St. Francis National Forest). In addition to the omission of some storm effects in the disturbance map, mentioned earlier, several factors may have contributed to the difference between perceived impact and what was observed. First, because the study period began in 1990, it missed the extensive effects of Hurricane Hugo in 1989. More subtly, the disturbance records used in this assessment intentionally avoided areas where ephemeral processes temporarily reduced foliage cover but did not result in permanent forest structure change. This distinction was made using subsequent high- and Landsat-resolution imagery. For C accounting purposes ForCaMF therefore ignored temporary defoliation events caused by storms (or insects), based on the assumption that relatively little C is affected in the loss of a single flush of foliage. Last, because there is no "wind" keyword in FVS, the C effects of mapped hurricanes were approximated by implementing harvest dynamics that left all material on the site. This workaround may have underestimated the C release rate.

One caveat must be stated about the confidence intervals depicted in figure 17. The unit of analysis for ForCaMF was the national forest (Appendix 4: Southern Region (PDF, 4.1MB)); rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass esti-mates in one forest were high, for example, the same estimates were also likely to be biased high in other regions. This caveat does not affect overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Harvest was the dominant disturbance process with respect to C cycling, and fire was important in some parts of the region, particularly Florida.

6.2.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 20–23) generated from InTEC model inputs and simulations for individual national forests and summed results across all national forests in the Southern Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 4: Southern Region (PDF, 4.1MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 14 national forests as modeled by InTEC with this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Southern Region have been strongly influenced by the history of land use and land management policies. Although there is significant variability among national forests, the regionwide stand-age distribution in 2010 shows that most stands in the Southern Region are older (>70 years old) with a distinctive pulse of stands which established about 70 to 100 years earlier, or from approximately 1910 to 1940 (fig. 20). After 1940, the rate of stand establishment dramatically declined. This pulse of stand establishment during the early to mid-1900s reflects forest recovery and regeneration after decades of heavy logging and clearing of land for agriculture. Depending on the forest-type group, which was mostly oak/hickory, oak/pine, or loblolly/shortleaf pine (fig. 20), the stands making up this pulse of establishment would have been growing at maximum productivity when they were 30 to 45 years old (fig. 21), or around 1940 through the 1960s (see Appendix 1 for scientific names of species mentioned in this report). Forests in the Southern Region show another much smaller pulse of stands 20 to 30 years old, which established from 1980 to 1990. This second pulse reflects recovery after a range of natural and anthropogenic disturbances such as the Kisatchie Hills Fire in Louisiana in 1987 (Kulhavy and Ross 1988), Hurricane Hugo in 1989,

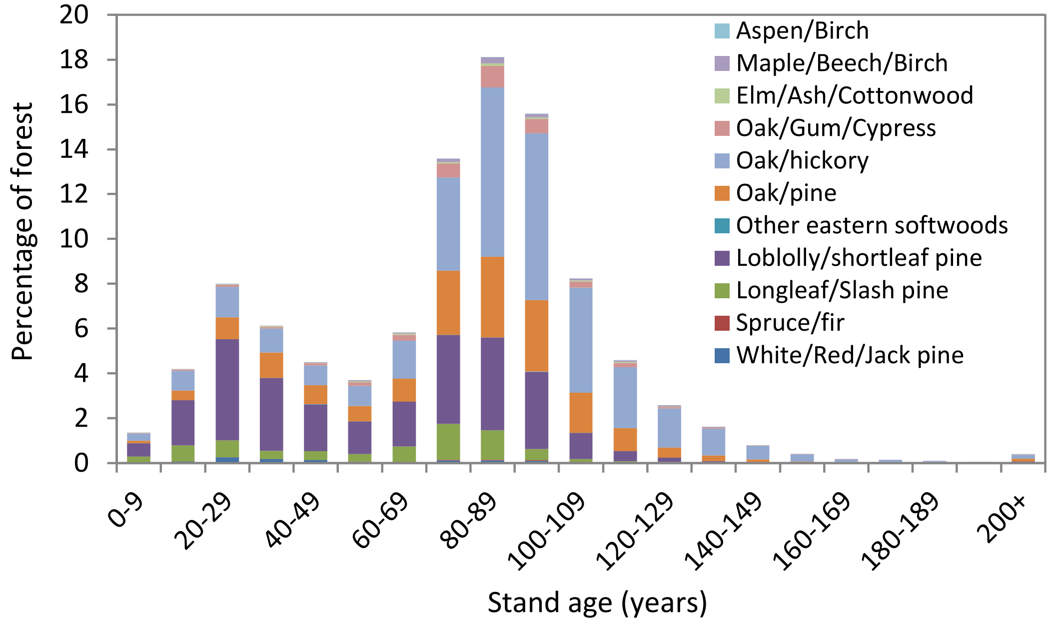

Figure 20. Age-class distribution in 2010 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Southern Region (see Appendix 1 for scientific names of trees).

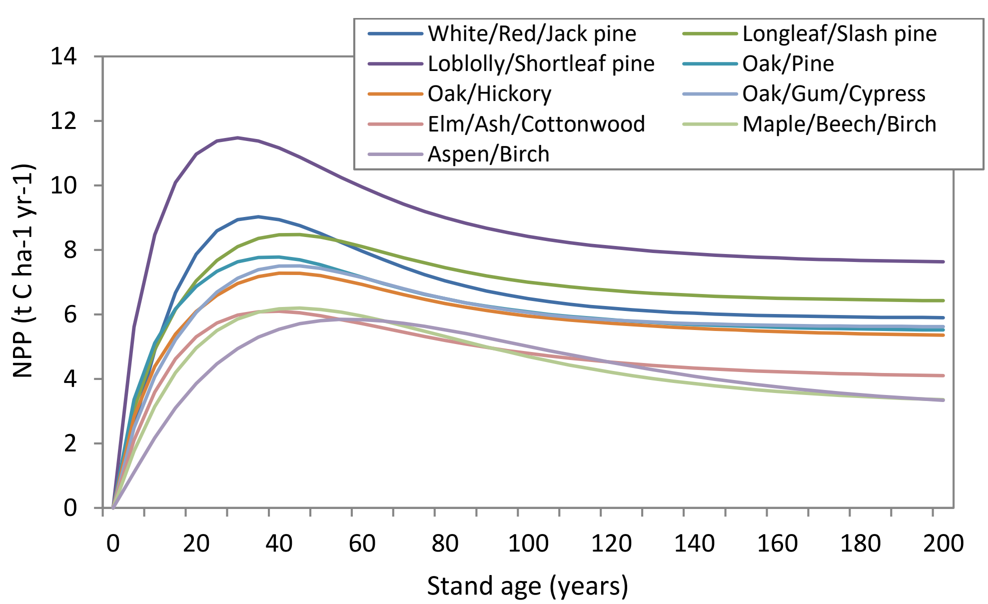

Figure 21. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Southern Region (see Appendix 1 for scientific names of trees).

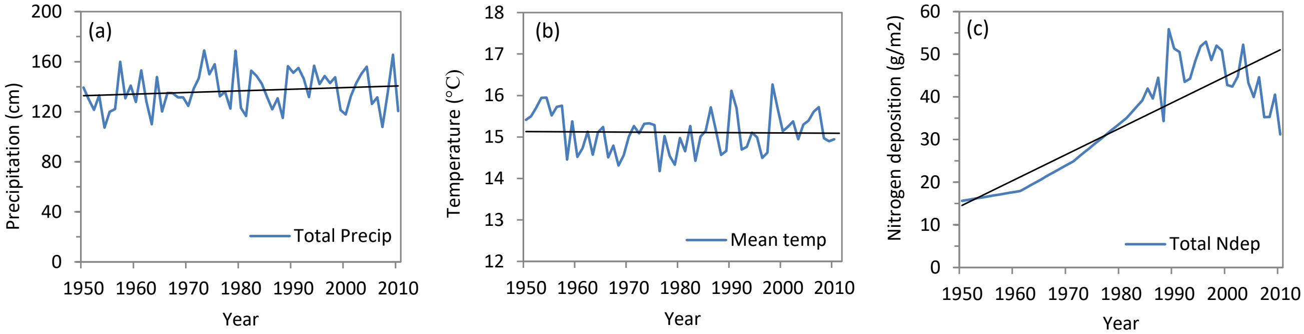

Figure 22a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1950 through 2011 averaged across all national forests in the Southern Region. Linear trend lines shown in black.

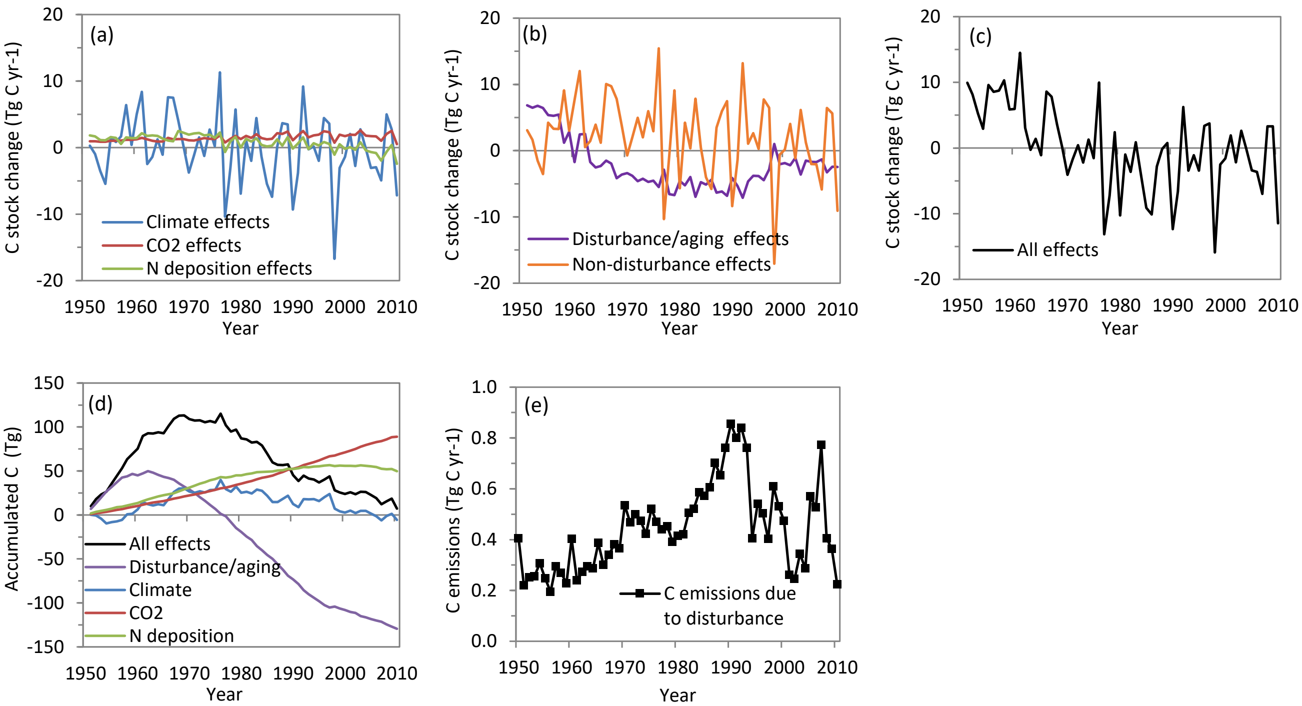

Figure 23a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Southern Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2010 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

and a spike in timber harvesting in the mid-1980s (Loeffler et al. 2014c).

The climate in the Southern Region has become slightly wetter over the past few decades. On the other hand, temperature trends have varied over time, with warmer temperatures in the 1950s, a decline in temperatures from the 1960s to 1980s, followed by another warming period through 2010 (figs. 22a,b). Though change may be minimal over the long term, interannual climate variability has been high with several years of notable climatic extremes. For instance, the Southern Region experienced a prolonged drought compounded with above-average temperatures for much of the 1950s. A prominent summer heat wave in 1998 as well as severe drought conditions in 2007 occurred across much of the southern United States. Warmer temperatures and a drier climate can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. Both atmospheric CO_2 concentrations and N deposition (fig. 22c) have increased over the past few decades as a result of human activities. Nitrogen deposition has been slowly declining since the early 2000s.

The C stock changes across the national forests in the Southern Region show that forests were mostly a C sink from the 1950s through the 1970s, then switched to mostly a C source (fig. 23c) according to the modeled results. This shift from a sink to a source is primarily a result of forests getting older on average and therefore growing more slowly, although climate effects have also played an important though highly variable role (figs. 23a,b). The decline in C stocks due to disturbance and aging can largely be explained by the stand-age distribution. The pulse of stands 70 to 100 years old (fig. 20) was growing at maximum productivity for much of the 1950s and 1960s, but as forests continued to age, their productivity declined (fig. 21) and C losses from decomposition became larger than C gains. This decline was coupled with lower rates of stand establishment in the mid-1900s.

Since the late 1990s, the decline in C accumulation has become less steep, most likely due to the recovery after disturbances in the 1980s and 1990s. These more recent disturbances caused increases in direct C emissions (fig. 23e), but also promoted regrowth and recovery (fig. 20). In about a decade, these stands will be highly productive (fig. 21) and may be able to offset the C losses due to the mostly older, less productive stands.

In the 1950s climate had a mostly negative effect on C accumulation, most likely due to the prolonged drought and warmer temperature (figs. 22a,b). Aside from several notably warmer years such as 1990 and 1998, climate has had a mostly positive effect on changing C stocks from 1950 through 2010 (figs. 23a,d). The increases in N deposition (fig. 22c) and atmospheric CO2 concentrations have both had positive effects on changing C stocks and C accumulation across all forests in this region (figs. 23a,d). The N deposition effect started to stabilize and decline in the 2000s due to declining N deposition rates (fig. 22c). Overall, the positive effects of climate, atmospheric CO_2, and N deposition helped to offset the C losses due to disturbances and aging such that when combined the national forests in the Southern Region experienced a slight net gain of 7.2 Tg of total ecosystem C, including soil C (fig. 23d) between 1950 and 2010.

6.3 Northern Region

6.3.1 Description of Region

The Northern Region (also referred to as Region 1) in the National Forest System (NFS) consists of 11 national forests spread across northwestern South Dakota, Montana, northern Idaho, and northeastern Washington (fig. 24). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so national grasslands such as the Dakota Prairie Grasslands in North Dakota were not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

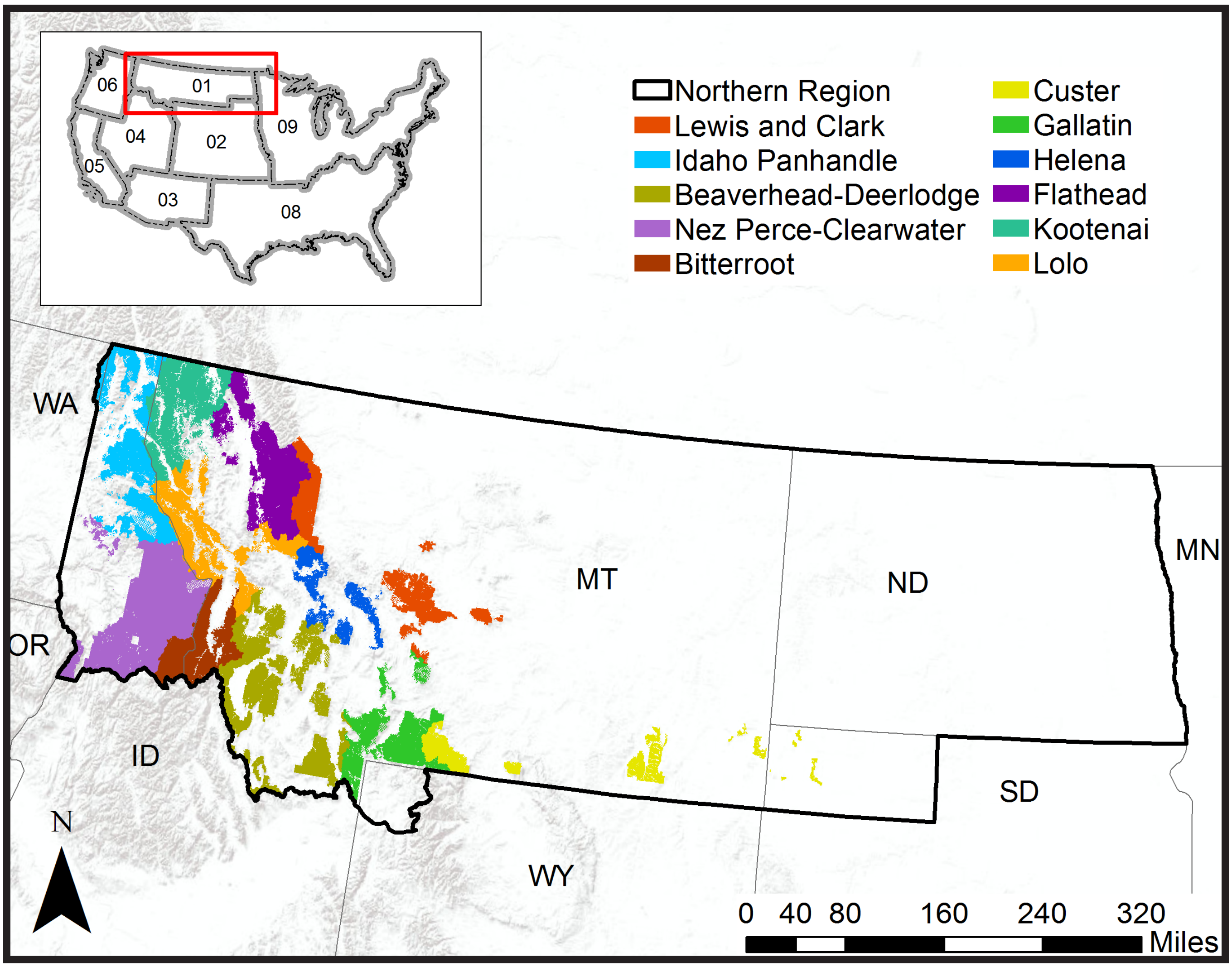

Figure 24. Locations of the national forests in the Northern Region.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. Euro-American settlement first expanded into the Northern Region in the early 1800s, but it was not until the mid- to late 1800s that the major influx of permanent settlers arrived and began altering the landscape. In the 1880s, large areas of land, typically in valleys, were cleared for agriculture, settlements, and railroad expansion. By the 1890s, the completion of the railroad opened up new, national markets that propelled the growth of the region's forest products industry. The railroad also brought more settlers to the region. Although timber harvesting began on a small scale in the late 1800s and continued to expand and intensify through the early 1900s (Baker et al. 1993), it was not until the 1940s that the Northern Region experienced large-scale logging operations on national forest lands. Harvest volumes in the Northern Region greatly declined by the 1990s (Stockmann et al. 2014b).

In addition to timber harvesting, the forest C legacy of the Northern Region is tied to its history of fires and fire management. For instance, thousands of acres of the region's forests were burned by large fires in 1889, prior to the organization of a firefighting system and look-out towers. After the devastating 1910 fire season, which left some 3 million acres (1.2 million hectares) of forest land scorched in Idaho and Montana, fire protection came to the forefront of Forest Service policies. The Forest Service introduced a national fire suppression policy, which entailed intensive efforts to prevent, detect, and suppress all wildfires (Baker et al. 1993; Pyne 1982). A policy shift from fire control to fire management in the 1970s allowed natural fires to burn across landscapes where considered safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Both land use history and recent changes in climate have led to large and intense disturbances in the Northern Region over the past few decades. The Northern Rockies have experienced increases in large wildfires that burn longer, as well as longer fire seasons; much of this change is due to warming temperatures and droughts (Westerling et al. 2006). Over the past few decades, severe bark beetle outbreaks affecting several dominance types (see Appendix 1 for description of dominance types) caused widespread tree mortality, reducing forest C uptake and increasing future emissions from the decomposition of killed trees (Kurz et al. 2008).

6.3.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Northern Region are displayed in figure 25. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns have been marked by declining (and low) harvest levels, periodic large fire years (including 2000, 2004, and 2007), and a recent increase in insect activity. Fire has been the dominant disturbance type, accounting for about two-thirds of all disturbances and affecting a total of about 5 percent of the forests between 1990 and 2011. Over this period, disturbances exhibited a relatively even mix of low and high intensities.

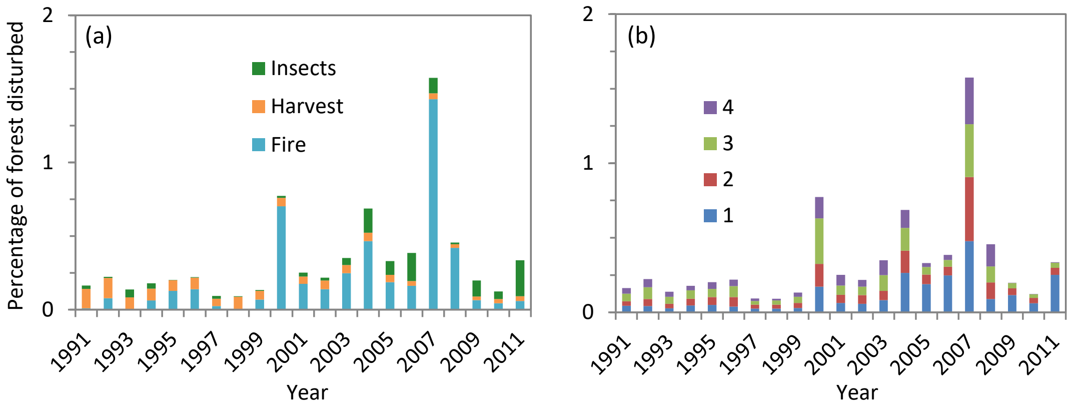

Figure 25. Annual rates of disturbance (0 to 2 percent) in the Northern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and abiotic; 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.

In addition to these processes, root disease is known to substantially affect stand dynamics in parts of the region (Byler and Hagle 2000). Much of the impact of root disease is manifested in reduced growth rates and suppression of regeneration, which can be difficult to detect using remote sensing. However, FIA maintains a regional root disease severity variable (over nine classes), and at the time of this analysis, results had been processed by Northern Region staff for an area covering six of the region's forests: Lolo, Bitterroot, Nez Perce Clearwater, Flathead, Idaho Panhandle, and Kootenai. Twenty-nine percent of the subplots in those forests had detectable signs of root disease in the last available measurement. This assessment assumed this rate of infection to be constant throughout the study period, although infection is dynamic and generally grows over time. While root disease can remain on a site for decades and infection in the region was well established before 1990 (Byler et al. 1990), the assumption may have resulted in some degree of overestimation of disease prevalence early in the study period. On the other hand, no root disease was accounted for in forests not covered by the disease severity variable, certainly causing some omission of disease effects.

6.3.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Northern Region in figure 26. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 2000, for example, the line for fire in figure 26 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an "undisturbed" scenario. Thus, figure 26 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

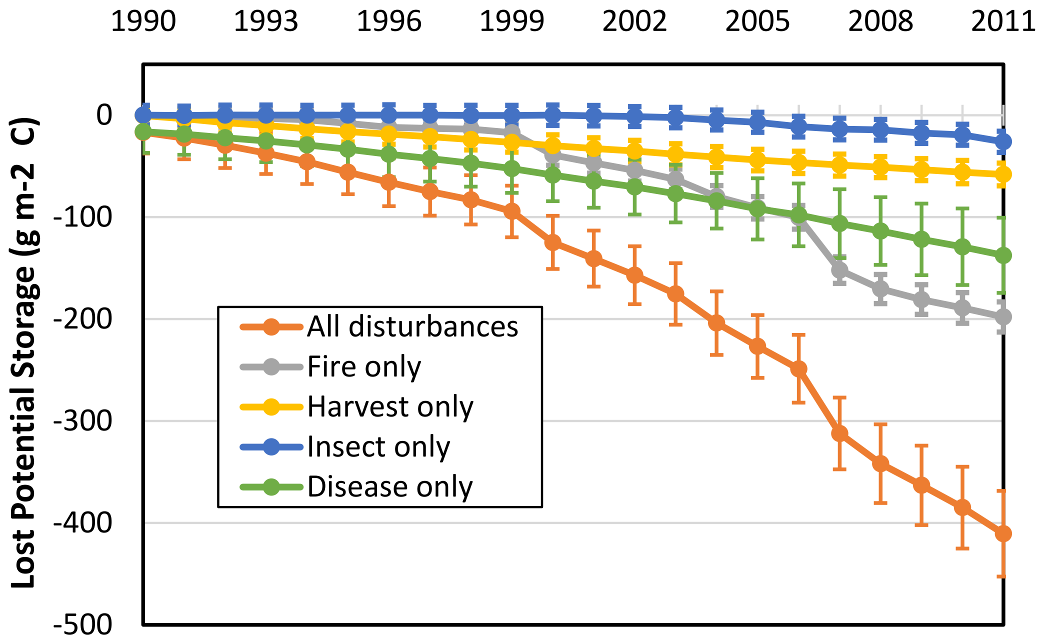

Figure 26. The impact of different kinds of disturbance, occurring from 1990 through 2010, on carbon (C) stores in the Northern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

The long-term impact is especially evident in the estimated effects of harvest. Effects continue to increase, albeit very slowly (relative to C that would have been stored in the absence of harvest) even though harvest activity virtually ceased across the region during the 1990s. These patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the NFS baseline C assessment (USDA FS 2015d). Few fires were detected during the early 1990s, so the line for fire starts near zero. However, following an increase in large fires that began around 2000, the impact of fire on C stocks greatly increased. The residual effects of these fires are likely to persist (and perhaps increase) through future decades both because C added through recovery may not equal C that would have been added through continued growth, and because decomposing material killed by the fire will offset C added through recovery. By 2011, fires resulted in a 1.6-percent reduction in the regional nonsoil C stocks (fig. 28) that were reported in the baseline C assessment (USDA FS 2015d).

Recent increases in the area affected by insect activity (fig. 25) are translated into recent increases in the impact of insects on C storage (fig. 26). Root disease was a dominant disturbance factor (fig. 27) because it affects a large portion of the region, and because its steady suppression of growth and regeneration chronically limits the ability of affected stands to add C. Disease impacts from 1990 through 2011 resulted in the loss of 1.0 percent of nonsoil C storage (fig. 28).

One caveat must be stated about the confidence intervals depicted in figure 26. The unit of analysis for ForCaMF was the national forest; rates of simulated error were constrained by FIA estimates at that level. The regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the regional level, nor does it affect confidence intervals assessed at the national forest level. Fire is clearly the dominant process, but root disease also strongly affects

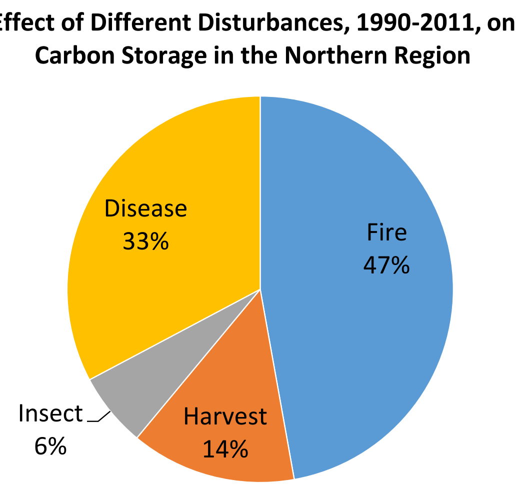

Figure 27. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Northern Region for the period 1990 through 2011.

C storage in the region (figs. 27, 28). The importance of insect activity, while currently relatively small, was virtually undetectable through the 1990s. Its growing importance parallels recent increases in the area affected (fig. 25).

6.3.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 29–32) generated from InTEC model inputs and simulations for individual forests and summed results across all national forests in the Northern Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 5: Northern Region (PDF, 2.9MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 11 national forests as modeled by InTEC using this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Northern Region have been strongly influenced by the history of land use and policies as well as climate change and natural disturbances. Despite variation among these national forests, the regionwide stand-age distribution in 2010 shows that most stands are

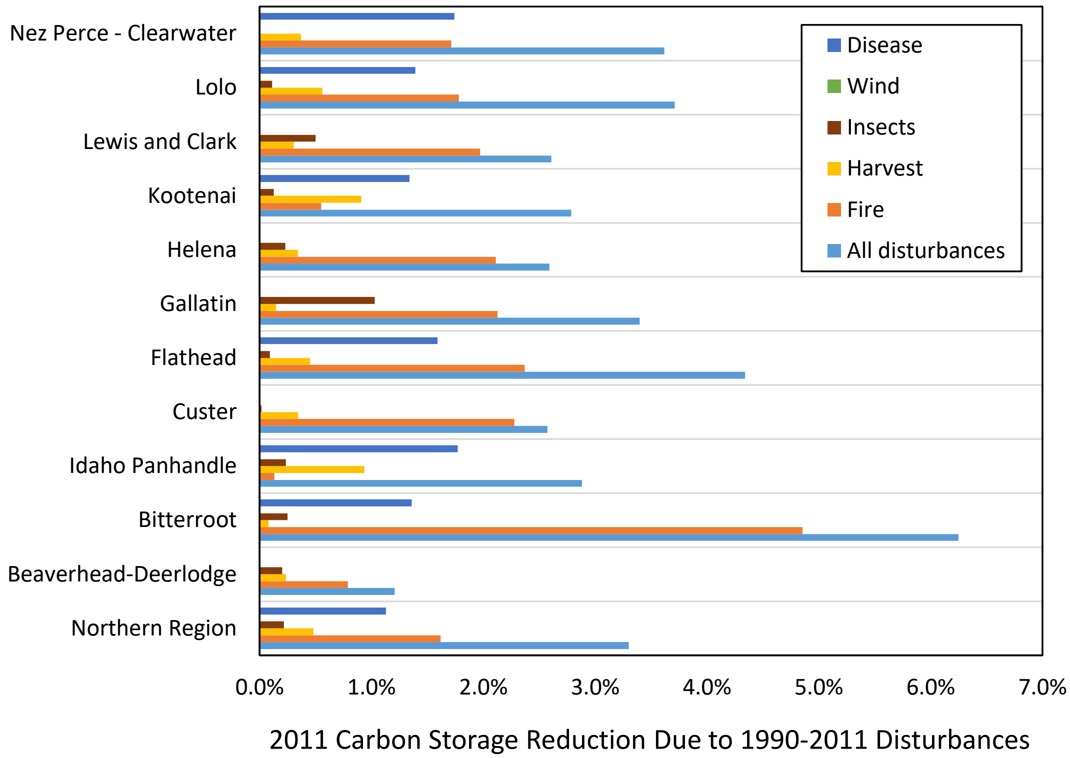

Figure 28. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2010, by each national forest and for all national forests in the Northern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

older (>80 years old) with a distinctive pulse of stands which established about 80 to 110 years earlier, or from approximately 1900 to 1930 (fig. 29). After 1930 the rate of establishment dramatically declined. This early-1900s pulse of stand establishment may be a result of regeneration after the last major fires before fire suppression, such as those in 1889 or 1910, or after timber harvests, which intensified in the early 1900s (Baker et al. 1993). Fire suppression, which began in the early 1900s, would have allowed more of these young, regenerating stands to survive and continue regrowing rather than being disturbed at the more natural rate of fires (Pyne 1982). Depending on the forest dominance type, which is mostly Douglas-fir and subalpine fir, stands making up this pulse of establishment would have reached maximum productivity between 30 and 60 years of age (fig. 30), or throughout the mid- to late 20th century. Forests in the Northern Region show another pulse of young stands (<20 years old) (fig. 29) that established between 1990 and 2010, suggesting regeneration after recent large and often severe disturbances—mostly fires.

Climate has on average become warmer and slightly drier in this region (figs. 31a,b). Warmer temperatures and a drier climate can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to get even warmer and potentially drier into the future. Both atmospheric CO_2 concentrations and N deposition (fig. 31c) have increased over the past few decades as a result of human activities.

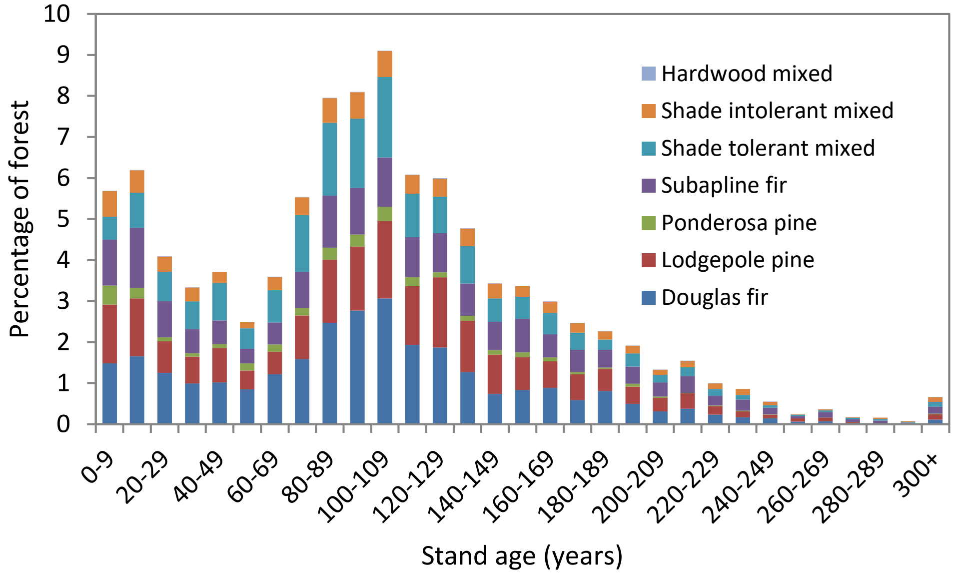

Figure 29. Age-class distribution in 2011 shown as the percentage of forest land in each forest dominance group in 10-year age classes summed across the national forests in the Northern Region (see Appendix 1 for description of dominance types).

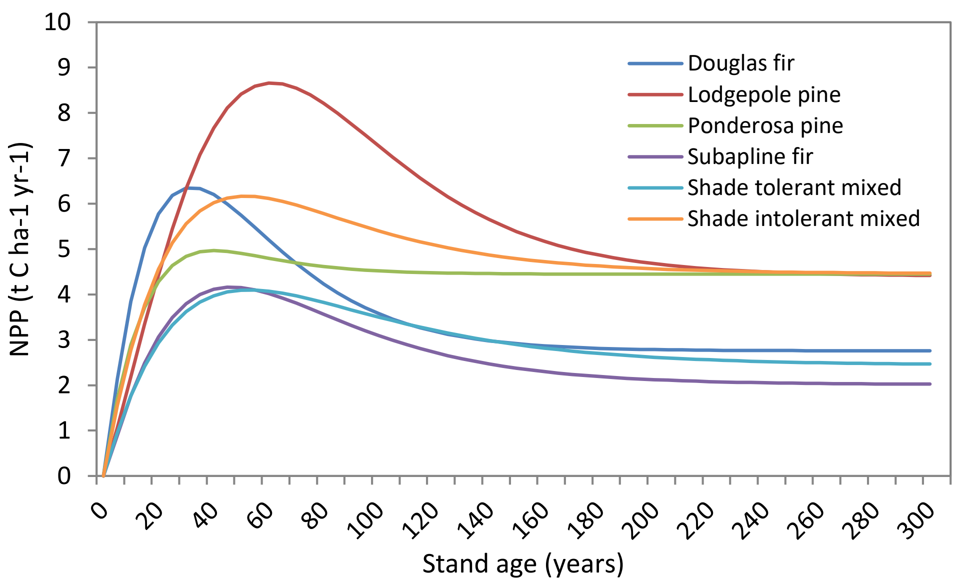

Figure 30. Relationship between net primary productivity (NPP) and stand age for each forest dominance type averaged across all national forests in the Northern Region. Dominance types are Douglas-fir (PSME), subalpine fir (ABLA), lodgepole pine (PICO), ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), and shade-intolerant mixed conifer (IMIX) (see Appendix 1 for description of dominance types). Due to a small sample of hardwood mixed (HMIX) plots to derive NPP-age curves, the IMIX curve was used for the HMIX stands.

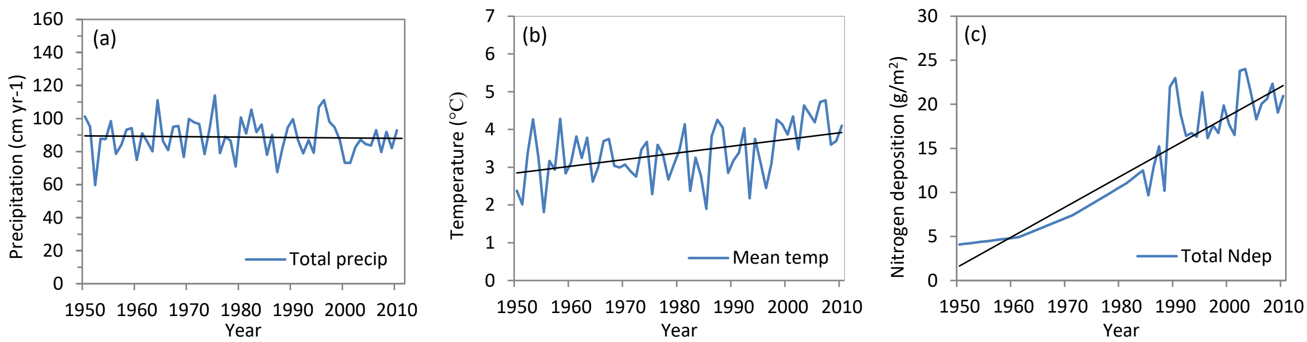

Figure 31a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1950 through 2011 averaged across all national forests in the Northern Region. Linear trend lines shown in black.

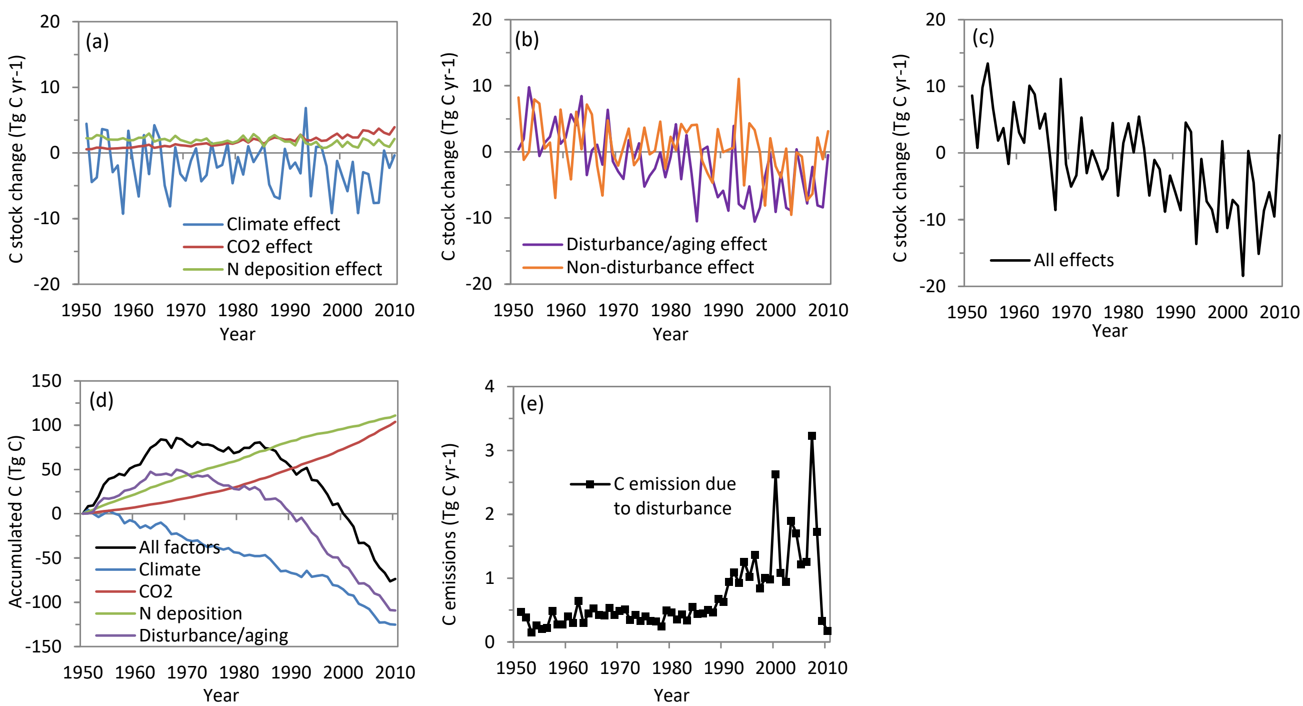

Figure 32a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Northern Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2010 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

The C stock changes across the national forests in the Northern Region show that together the forests have generally undergone a switch from a C sink to a C source (figs. 32 a–c) and a decline in accumulated C (fig. 32d). Disturbance and aging effects have been mostly responsible for declining C stocks (fig. 32b), and correspond to disturbances that shaped forest structure (fig. 29), the NPP-stand age relationships (fig. 30), and increasing disturbances in recent years (fig. 25). From 1950 to around 1980, the forests were mostly a C sink due to positive disturbance and aging effects, as the early-1900s pulse of stands was middle-aged and therefore growing at peak productivity. As these forests further aged, productivity declined, causing the rate of C accumulation to decline (fig. 32d). Meanwhile, the effects of disturbance were increasing to the point where C emissions due to decomposition and disturbances exceeded C gains, and as a result the forests became a C source (figs. 32b,c). This decline was coupled with lower rates of stand establishment in the mid-1900s.

The ForCaMF model results indicate that disease caused a significant loss of potential C storage over the past two decades (fig. 26). The InTEC model did not explicitly consider the effects of disease disturbances. But if disease caused stand-replacing mortality, it would be reflected in the current age structure, and thus included in InTEC. However, any lower-severity disease disturbances were not directly modeled by InTEC. Therefore, it is likely that disturbance and aging caused the C source to be even greater in recent decades than the InTEC results suggest.

Although recent disturbances initially caused increases in C emissions during the year of the disturbance events (fig. 32e), they also promoted regrowth and recovery, as shown by the recent pulse of stands less than 20 years old (fig. 29). As these young stands recover and reach middle-age in the coming decades, they will be growing at higher productivity rates (fig. 30). Thus, forests have the potential to accumulate more C and become C sinks again.

Climate variability and the recent warming trend have had a mostly negative effect on C stocks, also contributing to the switch to a C source (fig. 32a) and loss of C (fig. 32d). Future warming may result in an intensification of these already negative climate effects. The increases in N deposition (fig. 31c) and atmospheric CO_2 concentrations have both had positive effects on changing C stocks and C accumulation across all forests in this region (figs. 32a,d). However, the gains from CO_2 fertilization and N deposition were generally overshadowed by C losses due to negative disturbance and aging effects and climate effects (fig. 32d). Atmospheric CO_2 concentrations are expected to continue increasing for the foreseeable future, potentially counteracting the projected negative effects of climate.

Although a few national forests in the Northern Region had a net gain of total forest C, most forests had a loss from 1950 to 2010 (Appendix 5: Northern Region (PDF, 2.9MB)), resulting in a regionwide loss of approximately 74 Tg of total ecosystem C, including soil C, between 1950 and 2010 (fig. 32d).

6.4 Rocky Mountain Region

6.4.1 Description of Region

The Rocky Mountain Region (also referred to as Region 2) in the National Forest System (NFS) consists of 11 national forests within Colorado, Nebraska, Kansas, and most of Wyoming and South Dakota (fig. 33). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so Thunder Basin, Nebraska, Pawnee, and Cimarron and Comanche National Grasslands were not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. Though Euro-American settlement first expanded into the Rocky Mountain Region in

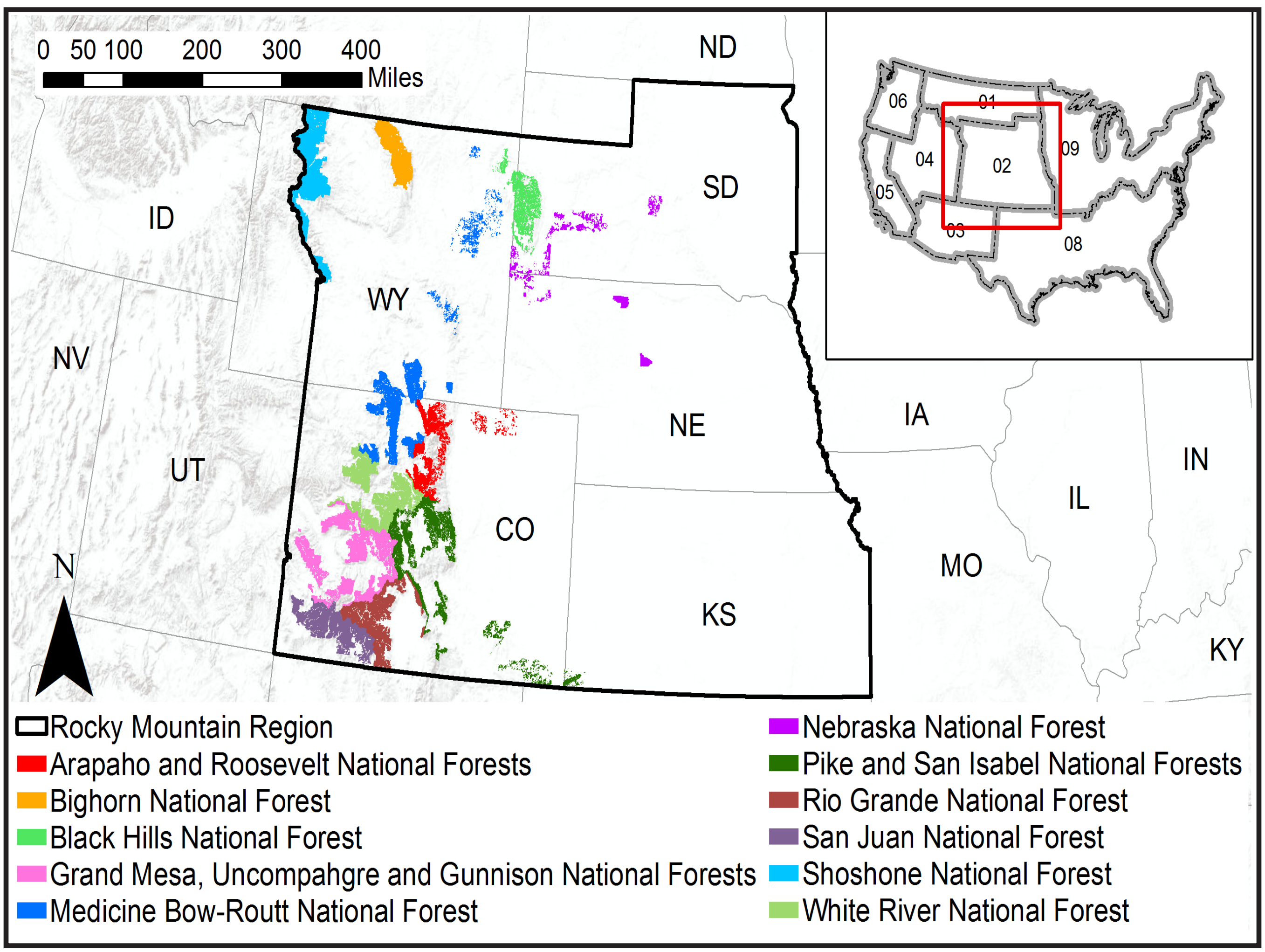

Figure 33. Locations of the national forests in the Rocky Mountain Region.

pursuit of fur trading in the early 1800s, it was not until the mid- to late 1800s that the major influx of permanent settlers arrived and began altering the landscape (Romme et al. 2009). Settlers' activities included logging, livestock grazing, mining, and clearing of forest for agriculture and human settlements. Logging began as early as 1875 in some areas of the region (Romme et al. 2009; Shepperd and Battaglia 2002), but was mostly small-scale and local until the 1890s, when logging greatly intensified with the advent of the railroad in the region. However, timber harvesting in the Rocky Mountain Region remained relatively low until the 1930s, after which it steadily increased before peaking in the late 1980s. Harvest volumes declined sharply in the early 1990s and have since remained relatively low (Stockmann et al. 2014d).

In addition to timber harvesting, the forest C legacy of the Rocky Mountain Region is tied to its history of fires and fire management. Before Euro-American settlement, fire was the dominant disturbance type influencing forest structure and C dynamics in the region. After settlement, extensive livestock grazing throughout the region greatly reduced surface fuels, limiting fire spread and altering fire regimes. Then after the devastating 1910 fire season, which scorched millions of acres of forest across the western United States, fire protection came into the forefront of Forest Service policies. With passage of the Weeks Act in 1911, the Forest Service introduced a national fire suppression policy, which entailed intensive efforts to prevent, detect, and suppress all wildfires (Agee 1998; Pyne 1982). A policy shift from fire control to fire management in the 1970s allowed natural fires to burn across landscapes where considered safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Both land use history and recent changes in climate have led to large and intense disturbances in the Rocky Mountain Region over the past few decades. The Rockies have experienced increases in large wildfires, as well as longer fire seasons. Much of this change is due to warming temperatures and droughts (Westerling et al. 2006). Over the past few decades, severe outbreaks of bark beetles such as the mountain pine beetle have caused widespread tree mortality, reducing forest C uptake and increasing future emissions from the decomposition of killed trees (Kurz et al. 2008) (see Appendix 1 for scientific names of species mentioned in this report).

6.4.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Rocky Mountain Region are displayed in figure 34. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns were dominated by an outbreak of mountain pine beetle, which began killing large numbers of trees in the national forests around 2005. Though comparatively low levels of insect activity were noted in the region throughout the beginning of the study period, disturbance rates (indicating newly observed mortality) remained high after 2005, approaching or exceeding 3 percent of the region's forest land in 3 different years (fig. 34a). However, most of these insect outbreaks were characterized as low to moderate intensity (<50 percent change in canopy cover) (fig. 34b). Harvest rates were relatively consistent at the regional level, affecting approximately 0.25 percent of forest land in each year. Large wildfires occurred in several years after 2000 but impacted a much lower percentage of the forest land than fires in neighboring NFS regions.

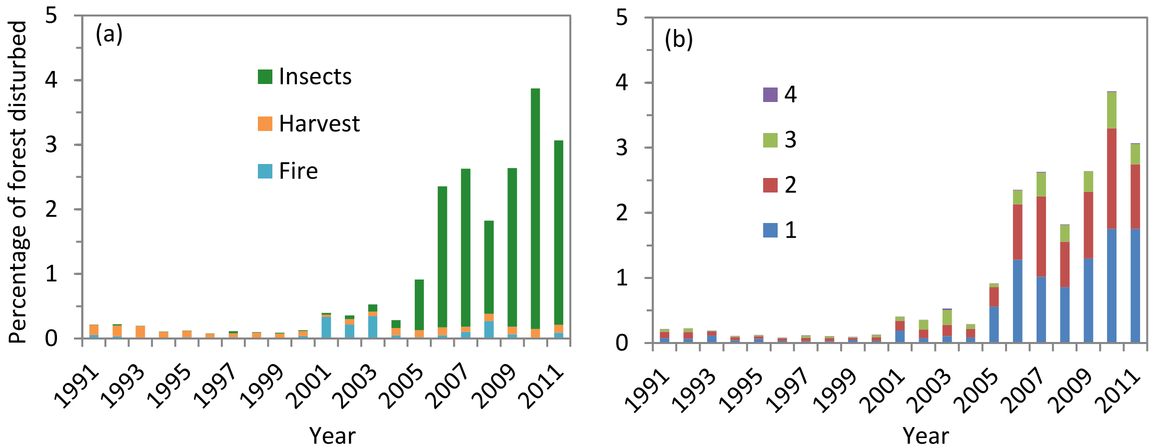

Figure 34a-b. Annual rates of disturbance (0 to 5 percent) in the Rocky Mountain Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, 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.

6.4.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Rocky Mountain Region in figure 35. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 2002, for example, the line of fire in figure 35 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an "undisturbed" scenario. Thus, figure 35 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Insect activity accounted for 82 percent of the disturbance impact on 2011 C stocks (fig. 36). The acceleration of insect activity within the region after 2005 (fig. 34) resulted in a surge in insect impact on C stocks (fig. 35). By 2011, insect activity from 1990 to 2011 caused a 5.5-percent reduction in the regional nonsoil C stocks (fig. 37) that were reported in the NFS baseline C assessment derived from FIA data (USDA FS 2010g). From the beginning of the study period (1990) to 2000, harvest was the disturbance process with the highest impact on C stocks (fig. 35), although that impact was significantly lower than in other regions, such as the Southern Region, where harvest activity was more common. Harvests in the region removed approximately 0.4 percent of nonsoil C stocks by 2011 (fig. 37). These patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the NFS baseline C assessment (USDA FS 2015g).

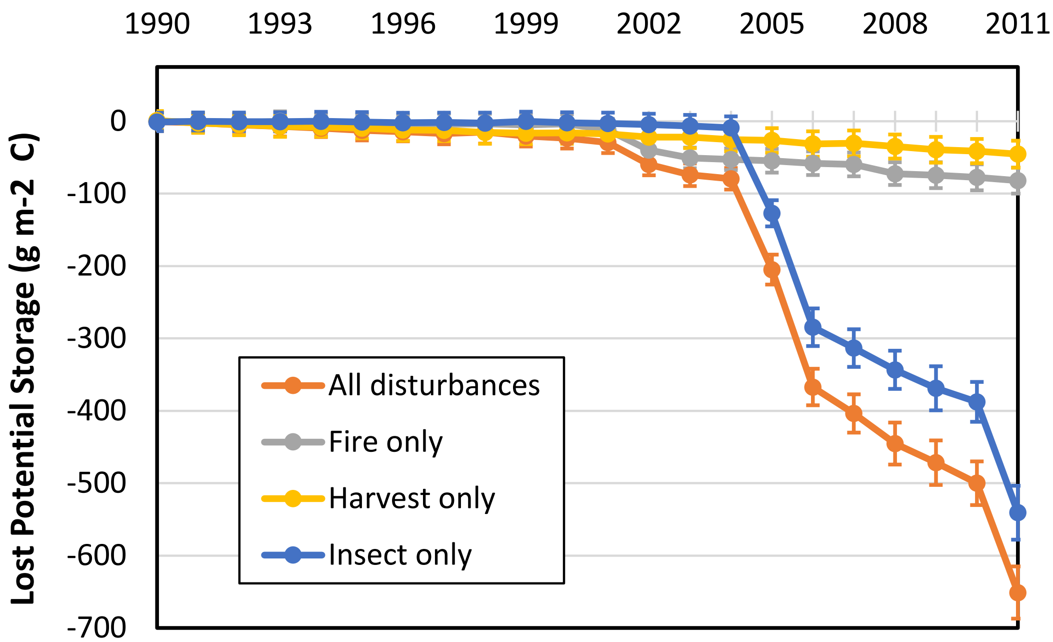

Figure 35. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Rocky Mountain Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

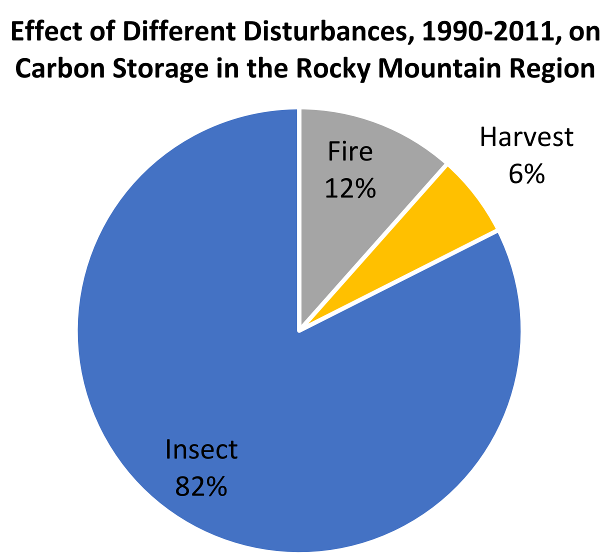

Figure 36. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Rocky Mountain Region for the period 1990 through 2011.

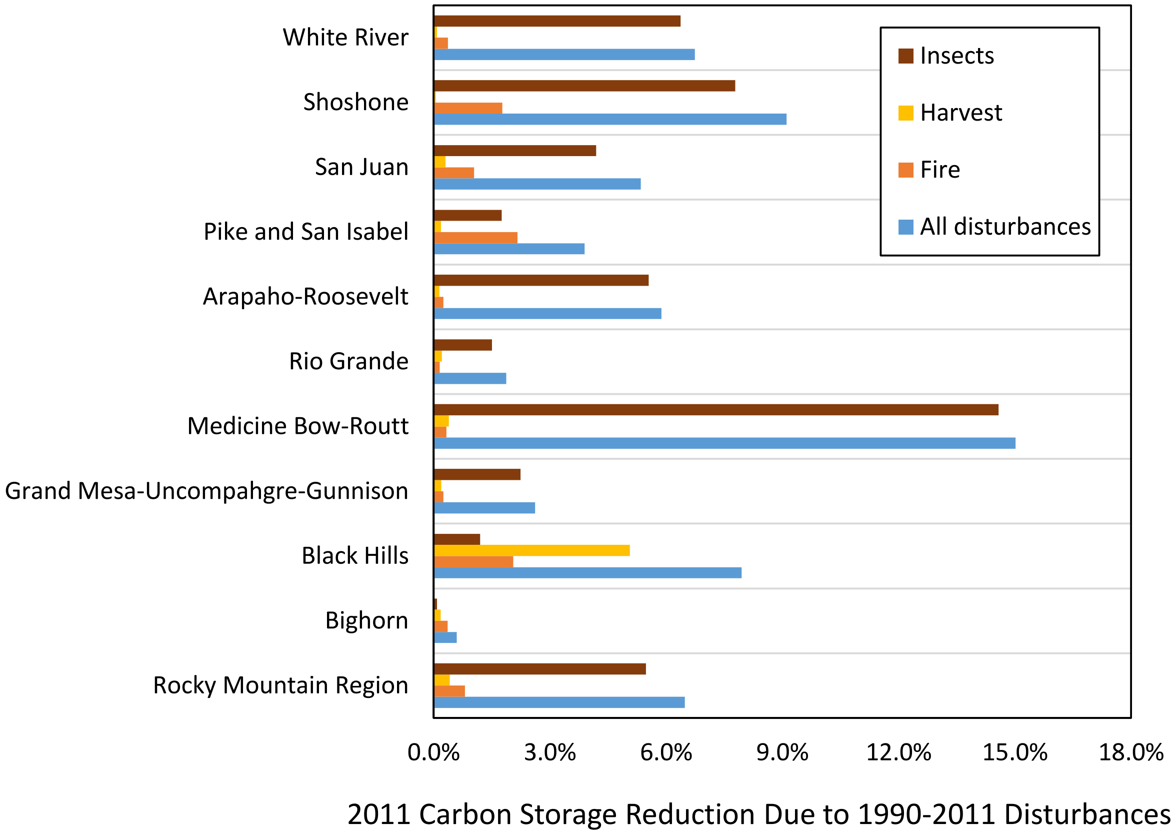

Figure 37. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Rocky Mountain Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

After an increase in fire activity in 2000, fire was the dominant disturbance process affecting C storage until the mountain pine beetle started killing large areas of trees in 2005 (fig. 34). Fires resulted in the loss of about 0.8 percent of nonsoil C stocks by 2011 (fig. 37). Because ForCaMF accounts for emissions of C in a biologically realistic way (using dynamics built into FVS), only a fraction of the full C effects of the beetle outbreak is represented by 2011; most C in beetle-killed trees is still stored in dead pools and will be released over several decades.

One caveat must be stated about the confidence intervals depicted in figure 35. The unit of analysis for ForCaMF was the national forest (Appendix 6: Rocky Mountain, (PDF, 2.7MB)); rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Insect activity was the dominant disturbance affecting C storage; although large amounts of insect mortality were observed only after 2005, the C impact of those outbreaks quickly overwhelmed effects of harvest and fire.

6.4.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 38–41) generated from InTEC model inputs and simulations for individual national forests and summed results across all national forests in the Rocky Mountain Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 6: Rocky Mountain, (PDF, 2.7MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the national forests as modeled by InTEC using this same series of figures. The forested area of the Nebraska National Forest was too small to reliably model C dynamics with InTEC, so it was excluded from these analyses.

According to the historical data and model results, forest C trends across the national forests in the Rocky Mountain Region have been strongly influenced by the history of land use and policies as well as climate change and natural disturbances. Despite variation among these national forests, the regionwide stand-age distribution in 2011 shows that most stands in the Rocky Mountain Region are older (>80 years old) with a distinctive pulse of stands which established about 80 to 129 years earlier, or from approximately 1880 to 1930 (fig. 38). During the 1930s and thereafter, the rate of stand establishment greatly declined. This pulse of stand establishment between the late 1800s and early 1900s reflects recovery after a range of disturbances, such as timber harvesting and grazing associated with settlement or the last major fires in the region before fire suppression. Fire suppression, which began in the early 1900s, would have allowed more of these young, regenerating stands to survive and continue regrowing rather than being disturbed at a more typical historical rate of fires (Pyne 1982). Depending on the forest type, this pulse of establishment would have reached maximum rates of productivity between 30 and 60 years of age (fig. 39), or throughout the mid- to late 20th century. Forests in the Rocky Mountain Region show another pulse of young stands (<10 years old) (fig. 38) that were established in the early 2000s and represent regeneration after recent disturbances—mostly extensive insect outbreaks, but also large and intense wildfires (fig. 34).

Though there is significant interannual variability in both temperature and precipitation, between 1951 and 2011 climate has on average become warmer and slightly wetter in the Rocky Mountain Region. Although the region has become slightly wetter, severe droughts like the one in the early 2000s are not uncommon. Warmer temperatures and drought conditions can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to get even warmer and the vital winter snowfalls are more likely to come as rain in the future. In addition to climate change and variability, both atmospheric CO_2 concentrations and N deposition have increased over the past few decades (fig. 40c) as a result of human activities, and these two factors are known to increase forest productivity in most circumstances.

The C stock changes across the national forests in the Rocky Mountain Region show that together the forests generally underwent a switch from a C sink to a C source (figs. 41a–c) in the late 1980s and early 1990s, causing a decline in accumulated C (fig. 41d). Disturbance and aging effects have been mostly responsible for declining C stocks (fig. 41b), which correspond

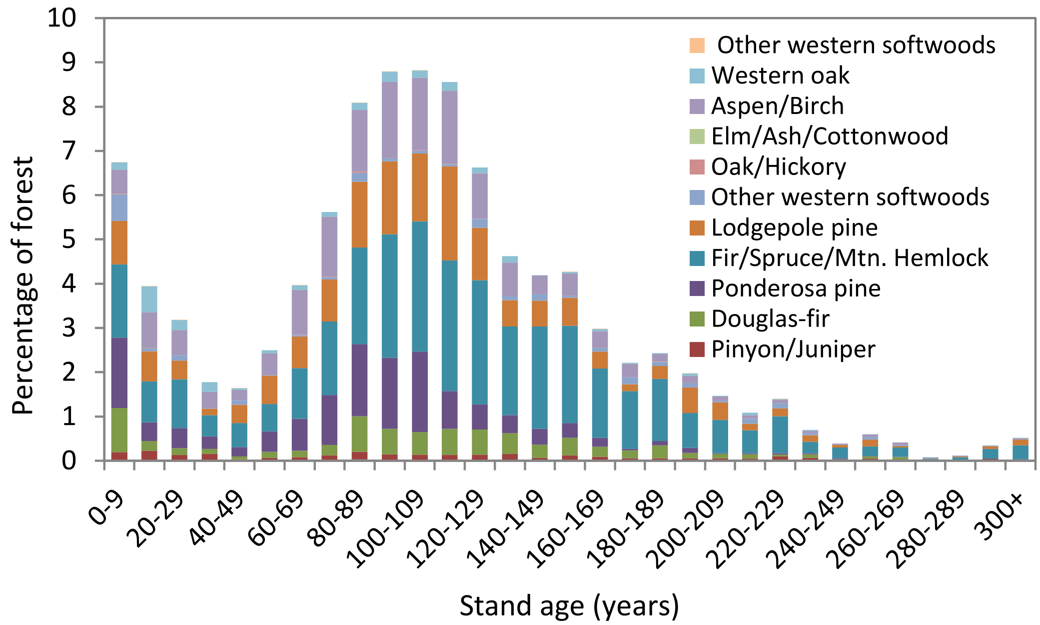

Figure 38. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Rocky Mountain Region (see Appendix 1 for scientific names of trees).

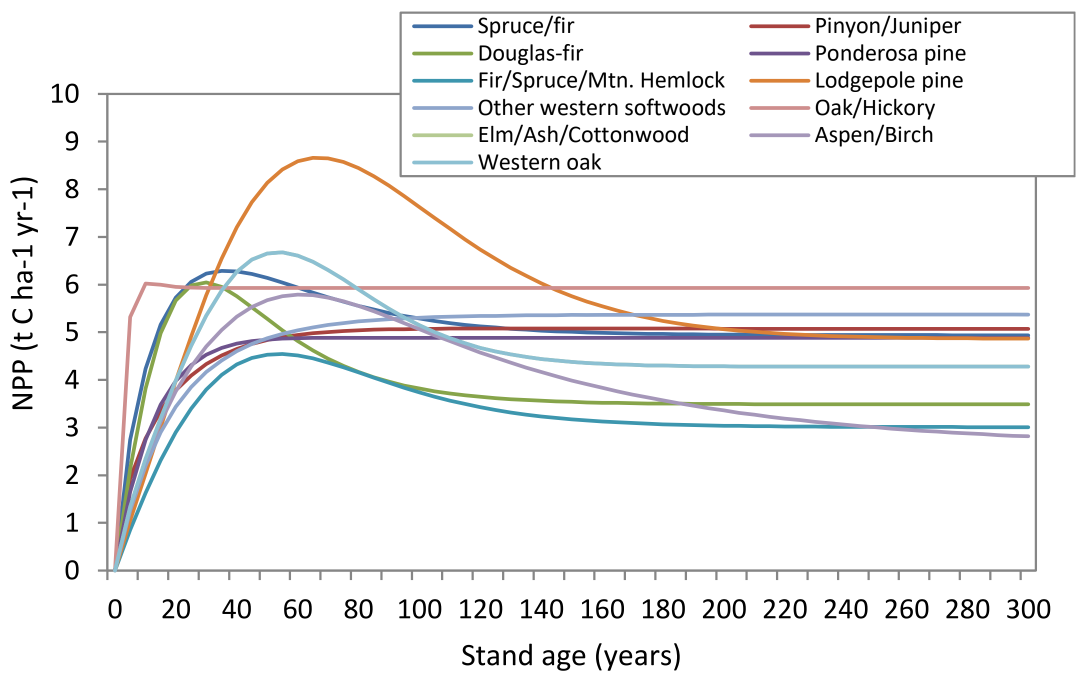

Figure 39. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Rocky Mountain Region (see Appendix 1 for scientific names of trees). Due to a small sample of other western hardwood plots to derive NPP-age curves, the western oak curve was used for these stands.

to disturbances that shaped forest structure (fig. 38), the NPP-stand age relationships (fig. 39), and increasing disturbances in recent years (fig. 34). From 1950 to the 1970s, the forests were a C sink due to disturbance and aging effects, as the 1880-to-1930 pulse of stands that reflect regrowth and recovery after major disturbances was middle-aged and therefore growing at maximum rates of productivity. As these forests further aged, productivity declined, causing the rate of C accumulation to decline (fig. 41d). Meanwhile the effects of disturbance were increasing to the point where C emissions due to decomposition and disturbances exceeded C gains, and as a result the forests became a C source (figs. 41b,c). This decline was coupled with lower rates of stand establishment in the mid-1900s.

Although recent disturbances initially caused increases in C emissions during the year of the disturbance events (fig. 41e), they also promoted regrowth and recovery, as indicated by the recent pulse of stands less than 10 years (fig. 38). As these young stands recover and reach middle-age in the coming decades, they will be growing at maximum productivity (fig. 39). Thus, forests have the potential to accumulate more C and become C sinks again.

As national forests in the Rocky Mountain Region shifted to a C source, nondisturbance effects had a positive effect, thus helping to maintain the C sink for a few more decades (figs. 41b,c). Carbon dioxide levels and N deposition have had a significant positive effect on forest C, perhaps because these forests are normally more nutrient limited. However, by the early 1990s, the C gains from CO_2 concentrations and N deposition were surpassed by the C losses as negative disturbance and aging effects caused the forests to shift to a C sink (fig. 41d). Atmospheric CO_2 concentrations are expected to continue increasing for the foreseeable future, potentially counteracting a portion of the C declines due to disturbance and aging. Despite climate variability and the recent warming trends, climate has not had a significant effect on C stocks compared to other factors (fig. 41d). In the 1950s and early 1960s, climate produced a C source (fig. 41a) due to a period of above-average temperatures (fig. 40b). Thus, projected warming could result in a C source in the future.

Although a few national forests in the Rocky Mountain Region had a net gain of total forest C, most forests had a loss from 1950 to 2011, resulting in a regionwide loss of approximately 15 Tg of total ecosystem C, including soil C, between 1950 and 2011 (fig. 41d).

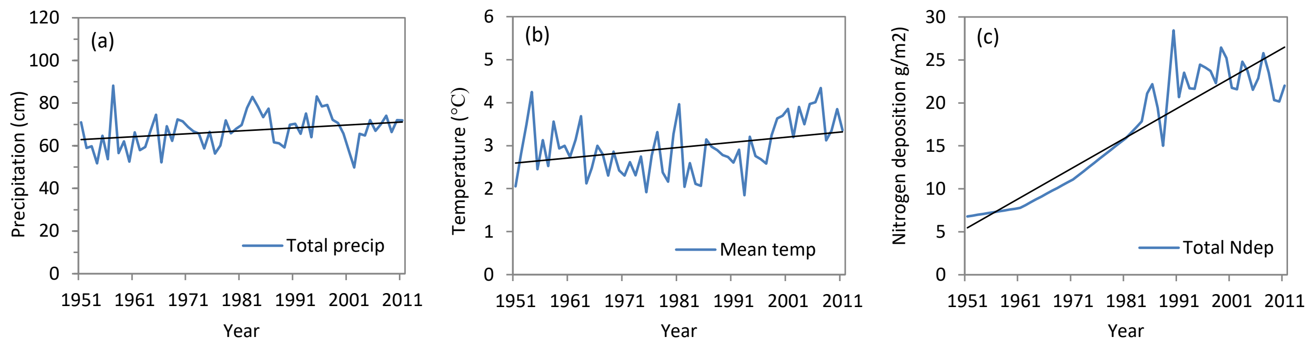

Figure 40a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1951 through 2011 averaged across all national forests in the Rocky Mountain Region. Linear trend lines shown in black.

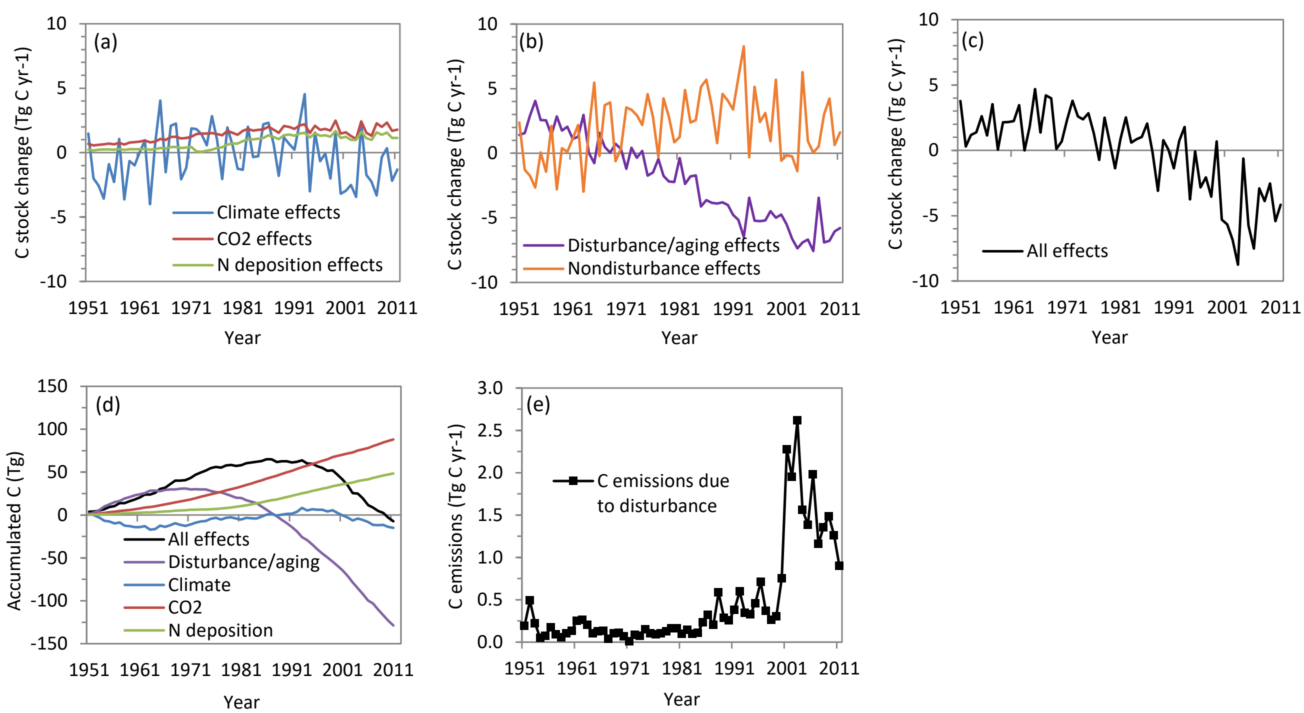

Figure 41a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Rocky Mountain Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2011 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

6.5 Intermountain Region

6.5.1 Description of Region

The Intermountain Region (also referred to as Region 4) in the National Forest System (NFS) consists of 12 national forests spread across Nevada, Utah, western Wyoming, and southern and central Idaho (fig. 42). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so the Curlew National Grassland in southern Idaho was not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

Euro-American settlers came to the Intermountain Region in the mid-1800s mostly for fur trapping. Mormon settlers followed, bringing cattle and oxen grazing to the region (see Appendix 1 for scientific names of species mentioned in this report). The real boom in settlement began in the 1890s, when Euro-Americans came to the region for mining, livestock grazing, and timber. Lumber operations using destructive methods became common

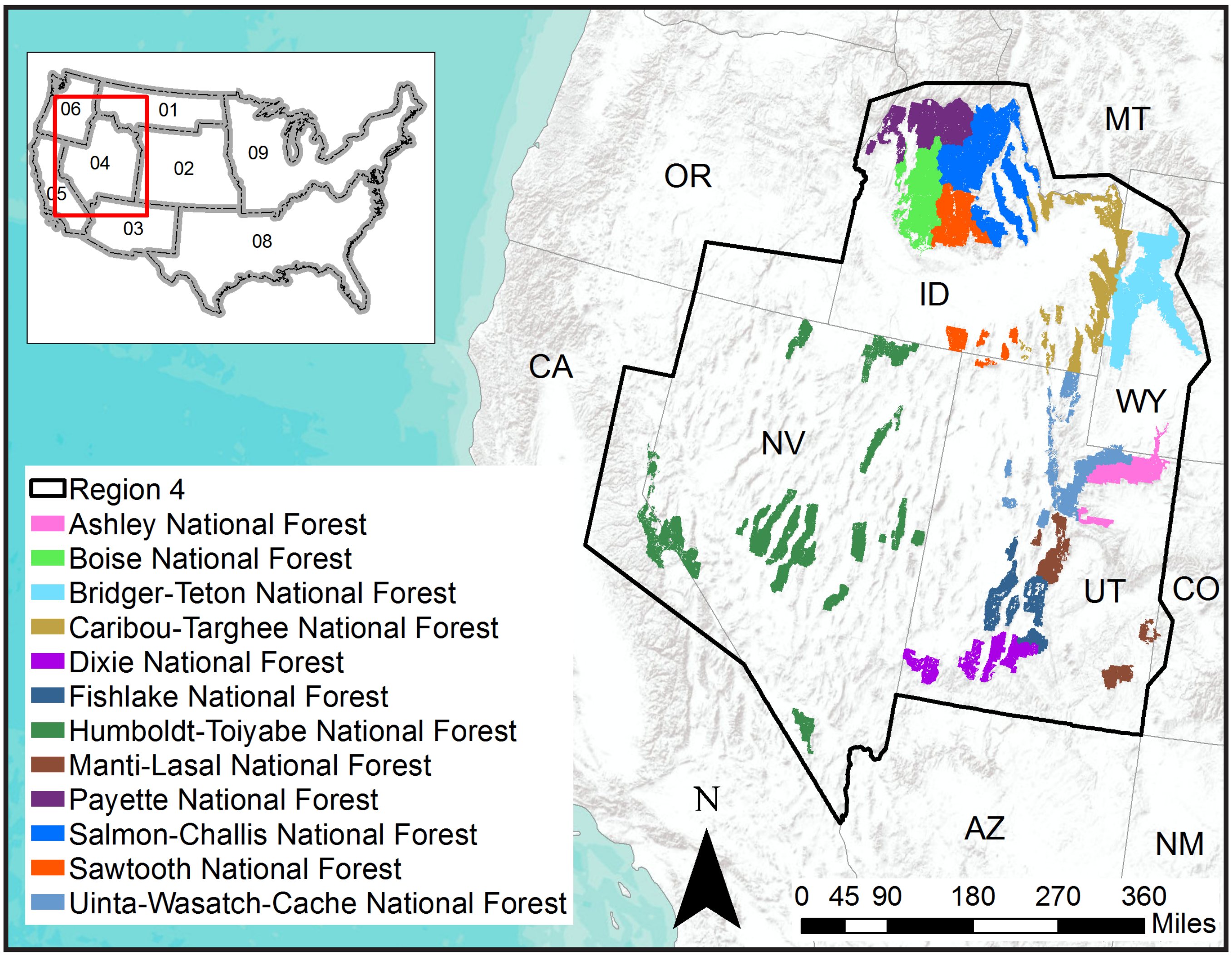

Figure 42. Locations of the national forests in the Intermountain Region.

practice, leaving forests as devastated fire hazards covered in slash, litter, and wasted wood. In the 1890s forests were set aside as forest reserves to protect valuable timber and watersheds from these destructive practices. The land was eventually put under Forest Service control in 1905 and more sustainable timber practices became an objective (USDA FS 1930).
Annual timber output was low in the early 1900s, then increased after the Great Depression in the 1930s and peaked in 1972; it declined precipitously in the early 1990s and has remained low ever since (Stockmann et al. 2014a). In addition to timber harvesting, the forest C legacy of the Intermountain Region is tied to its history of fires and fire management. Historically fire was a major component of the disturbance regimes in the Intermountain forests prior to Euro-American settlement. Devastating fire seasons of 1889, 1910, and 1919 burned millions of acres of valuable forest and timberland in this region and across much of the West. Congress began appropriating funds to support fire suppression activities including improvements to communication and transportation facilities, lookout towers, and firefighting tools led by the Forest Service (Barrett et al. 1997). This national fire suppression policy entailed intensive efforts to prevent, detect, and suppress all wildfires, which greatly reduced the area burned and the frequency of fires and consequently altered the ecological system. A policy shift from fire control to fire management in the 1970s allowed natural fires to burn across landscapes where considered safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Recent changes in climate have also played a role in forest disturbance regimes and C dynamics. The Intermountain Region has experienced an increase in average annual temperature while precipitation has been highly variable. Land use history and climate change have led to large and intense disturbances in the region over the past few decades. Extended fire seasons and large wildfires that burn for longer durations, such as the Clear Creek Complex Fire of 2000 and the Murphy Complex Fire of 2007, both in Idaho, have increased in the Intermountain Region. Much of this change is due to warmer summer temperatures and earlier spring snowmelt, which are projected to continue into the future (Westerling et al. 2006). Over the past few decades, severe bark beetle outbreaks have resulted in tree mortality in parts of the Intermountain Region (Bentz et al. 2010).

6.5.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Intermountain Region are displayed in figure 43. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. For most of the study period (1990 to 2011), regional disturbance patterns were dominated by fire, although the forest area burned in any one year never significantly exceeded 1 percent of the total (fig. 43). Though low levels of insect mortality were observed in several years in the 1990s, insect impacts greatly increased after approximately 2003. In 2011, about 2.5 percent of the region's forest land was affected by insect disturbance. By comparison, insect disturbance (as indicated by newly observed mortality) affected 2.5 percent or more of forest land in the neighboring Rocky Mountain Region in 3 different years during the same period (see Section 6.4.2). Harvest rates have been low throughout the study period, although there was slightly more harvest activity in the early

1990s. Over this period, about 70 percent of the area disturbed was affected by low- to moderate-intensity disturbances (<50 percent change in canopy cover).

6.5.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to understand the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Intermountain Region in figure 44. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires occur only in 1992, for example, the line for fire in figure 44 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an "undisturbed" scenario. Thus, figure 44 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Throughout most of the study period, fire was the disturbance process that most affected C storage in the region (fig. 45). Larger fire years (fig. 43) corresponded to increased fire impacts on C storage (fig. 44). By 2011, fires from 1990 through 2011 resulted in a reduction of 1.9 percent of the regional nonsoil C stocks (fig. 46) that were reported in the NFS baseline C assessment derived from FIA data (USDA FS 2015c). However, increased insect activity in the latter part of the period, particularly after 2007, substantially altered the regional disturbance signature upon C stocks. By 2011, insect activity made up 47 percent of the disturbance impact on C storage (fig. 45), and caused a 1.8-percent reduction in nonsoil C storage (fig. 46). Because ForCaMF accounts for emissions of C in a biologically realistic way (using dynamics built into FVS), only a fraction of the full C effects of the insect and fire activity

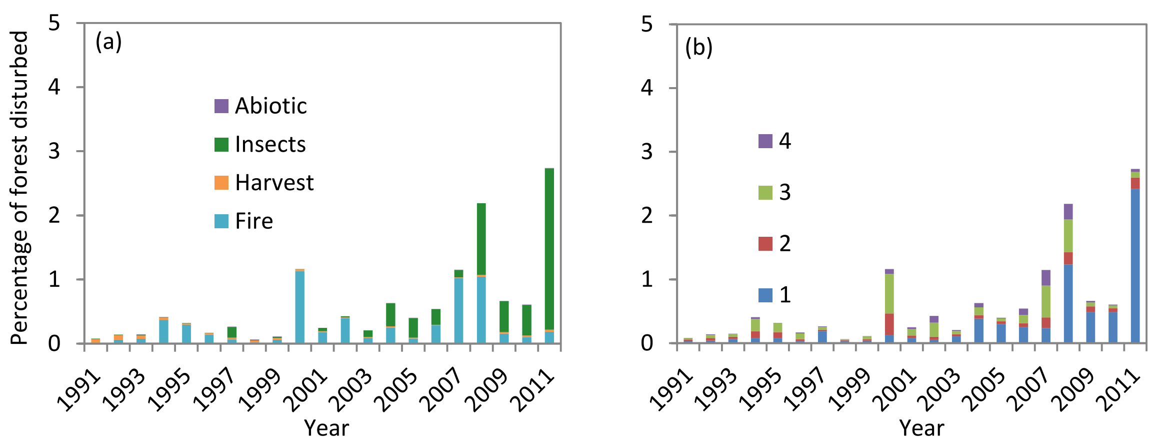

Figure 43. Annual rates of disturbance (0 to 5 percent) in the Intermountain Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and 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.

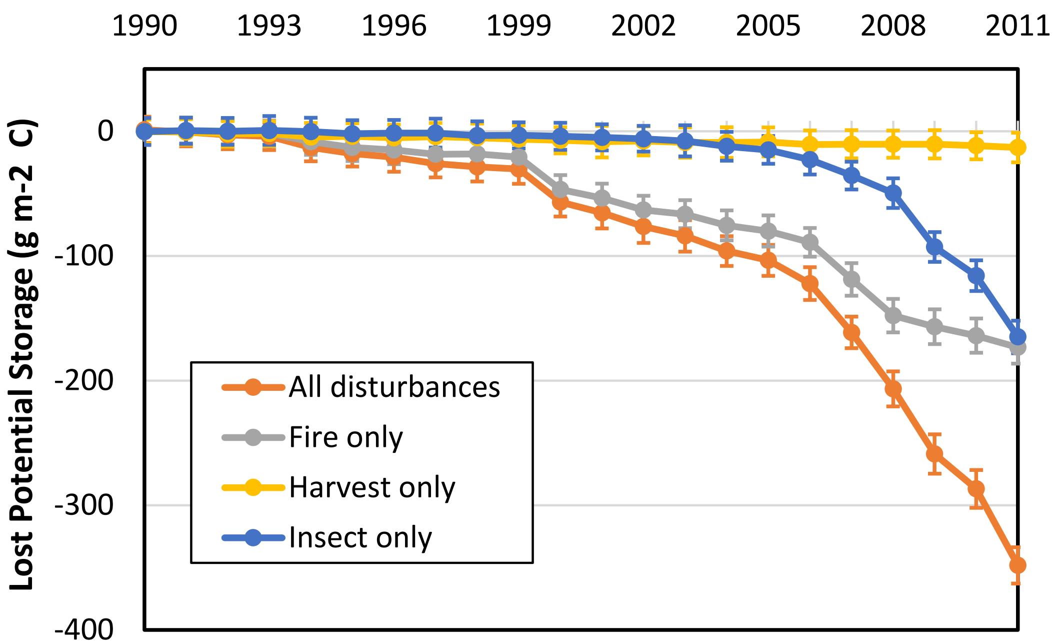

Figure 44. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Intermountain Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

observed from 1990 through 2011 are represented by 2011; most C in fire- or beetle-killed trees is still stored in dead pools and will be released over several decades.

In interpreting the steady, but small, C impact of harvest throughout the period, it is important to reiterate that these patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the baseline C assessment (USDA FS 2015c). One caveat must be stated about the confidence intervals depicted in figure 44. The unit of analysis for ForCaMF was the national forest; rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Insect activity has recently joined fire as an important factor in the amount of C stored by national forests in the Intermountain Region.

6.5.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 47–50) generated from InTEC model inputs and simulations for individual national forests and summed results across all national forests in the Intermountain Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 7: Intermountain Region (PDF, 3.1MB)shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 12 national forests as modeled by InTEC using this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Intermountain Region have been strongly influenced by the history of land use and policies as well as natural disturbances. Despite variation among these national forests, the regionwide stand-age distribution in 2011 shows that approximately 50 percent of the forests are greater than 100 years old (fig. 47). The stand-age distribution also shows a pulse of stands that established about 80 to 119 years before this study, or from approximately 1890 to 1930 (fig. 47). Thereafter, the rate of stand establishment steadily declined until 1982, when it increased once again. This early-1900s pulse of stand establishment reflects recovery after a range of disturbances occurring around the time of Euro-American settlement, such as intensive timber harvesting and large wildfires. Although some fires continued into the mid-1900s, fire suppression, which began in the early 1900s, allowed more of these young, regenerating stands to survive and continue regrowing rather than being disturbed at a more typical historical rate of fires (Pyne 1982). Depending on the forest type, which is mostly Douglas-fir, lodgepole pine, or fir/spruce/mountain hemlock, the numerous stands that were established between 1890 and 1930 reached maximum rates of productivity between 30 and 60 years of age (fig. 48). Therefore, for most of the mid-1900s, more than 25 percent of the forest area was highly productive. Recent fires have had extensive high-severity, stand-replacing components, while insect outbreaks have been widespread and unrelenting (fig. 43). These recent disturbances promoted another pulse of stands that were established over the last two decades. These stands will soon be growing at maximum productivity, potentially accumulating more C (fig. 48).

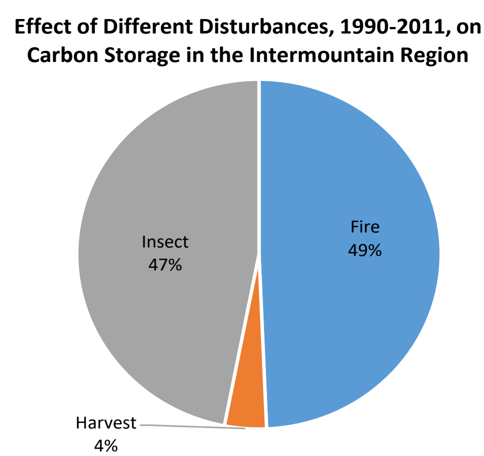

Figure 45. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Intermountain Region for the period 1990 through 2011.

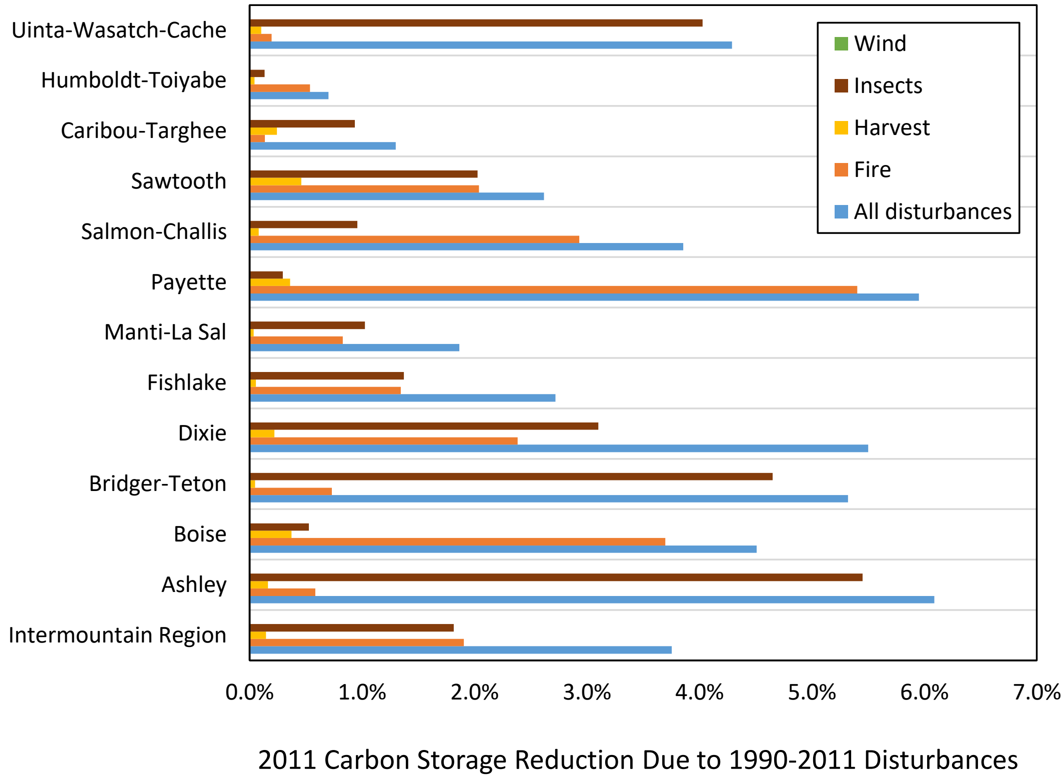

Figure 46. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Intermountain Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

Though there is significant interannual variability in both temperature and precipitation, between 1951 and 2011 climate has on average become much warmer (figs. 49a,b). Precipitation does not show a clear increasing or decreasing trend. However, several droughts such as the one from 1999 through 2002 have been evident through this region. For much of the late 1990s and 2000s, temperatures were consistently higher than average. Warmer temperatures and drought conditions can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to get even warmer, with greater variability in precipitation, and snowfall shifting to rainfall. In addition to climate change and variability, both atmospheric CO_2 concentrations and N deposition (fig. 49c) have increased over the past few decades as a result of human activities. Nitrogen deposition in this region peaked around 1995 but has since remained elevated (fig. 49c).

Though there is significant interannual variability in both temperature and precipitation, between 1951 and 2011 climate has on average become much warmer (figs. 49a,b). Precipitation does not show a clear increasing or decreasing trend. However, several droughts such as the one from 1999 through 2002 have been evident through this region. For much of the late 1990s and 2000s, temperatures were consistently higher than average. Warmer temperatures and drought conditions can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to get even warmer, with greater variability in precipitation, and snowfall shifting to rainfall. In addition to

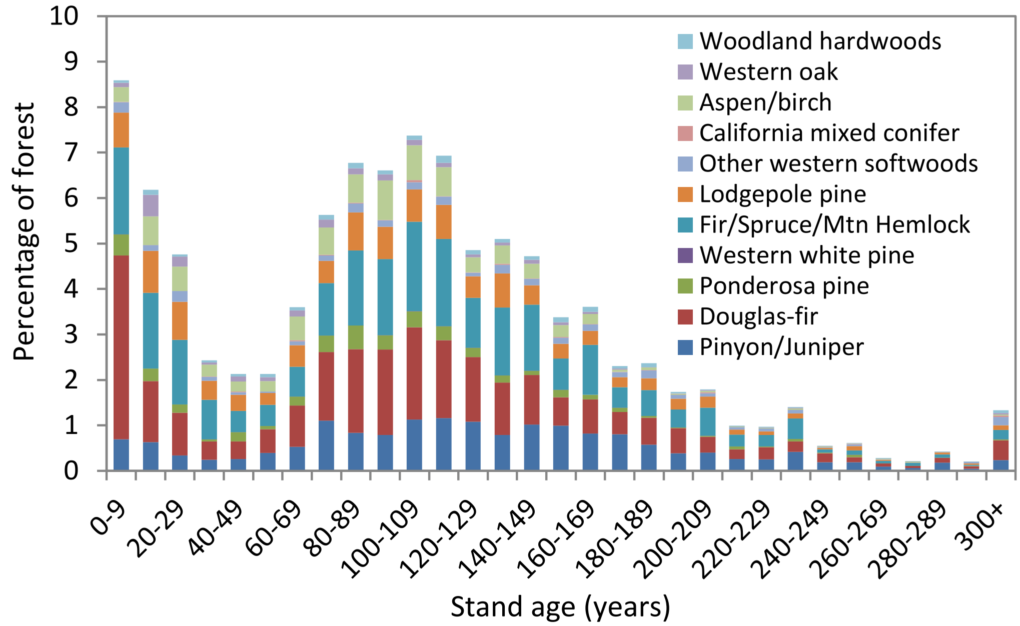

Figure 47. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Intermountain Region (see Appendix 1 for scientific names of trees).

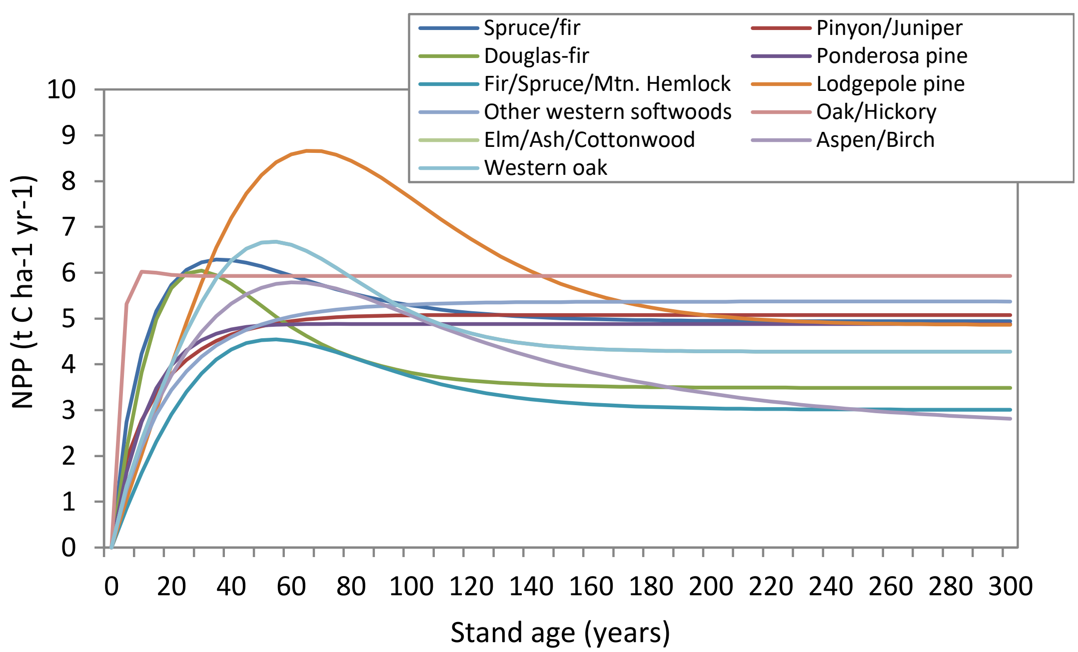

Figure 48. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Intermountain Region (see Appendix 1 for scientific names of trees). Due to small sample sizes, the NPP-age curve for the other western softwoods forest-type group was applied to California mixed conifer stands, and the curve for the ponderosa pine forest-type group was applied to western white pine stands.

climate change and variability, both atmospheric CO_2 concentrations and N deposition (fig. 49c) have increased over the past few decades as a result of human activities. Nitrogen deposition in this region peaked around 1995 but has since remained elevated (fig. 49c).

The C stock changes across the national forests in the Intermountain Region show that together the forests underwent a switch from a C sink to a C source (figs. 50a–c) in the late 1980s to early 1990s. Disturbance and aging effects have been mostly responsible for declining C stocks (fig. 50b), which correspond to disturbances that shaped forest structure (fig. 47), the NPP-stand age relationships (fig. 48), and increasing disturbances in recent years (fig. 43). From 1950 to the early 1980s, the forests were a C sink as forests representing regrowth from previous disturbances were at productive ages. For instance, the 1890 to 1930 pulse of stands was middle-aged and therefore growing at maximum rates of productivity. As these forests further aged, productivity declined, causing the rate of C accumulation to decline (fig. 50d). Meanwhile the effects of disturbance were increasing to the point where C emissions from decomposition and disturbance events exceeded C gains, and the forests consequently became a C source (figs. 50b,c). This decline was coupled with lower rates of stand establishment and increasing rates of timber harvesting after the 1930s.

Recent disturbances such as the large, moderate- to high-severity fires in 2000, 2007, and 2009 and an increase in insect disturbances during the 2000s caused spikes in C emissions (fig. 50e). These disturbances coincided with a drought and high temperatures, which together caused forests to remain a C source from 1996 through 2011 (figs. 50a–c). As forests continue to recover from these disturbance events, as seen in the regional stand-age distribution (fig. 47), and reach middle-age with the highest rates of productivity (fig. 48), regional forests have the potential to become a C sink again in a few decades.

Though disturbance and aging effects initially caused a C sink and then a C source, nondisturbance factors had a mostly positive effect on C stocks in the 1950s and thereafter (figs. 50a,b). Increasing levels of CO_2 and N deposition caused forests to accumulate more C and helped to counteract the C declines due to disturbances and the aging stands. However, by the late 1980s the C gains from CO_2 and N deposition were surpassed by the C losses as negative disturbance and aging effects caused the forests to shift to a C source (fig. 50d). Atmospheric CO_2 concentrations are expected to continue increasing for the foreseeable future, potentially counteracting the C declines from disturbances and aging. Despite increasing temperatures and occasional droughts, climate has had a small effect on total C accumulation for most of the past few decades. Since the early 2000s, however, climate effects have been mostly negative, causing a loss of forest C (fig. 50d). Future projected warming and shifts in precipitation may cause the C source in the Intermountain Region to persist.

Although a few national forests in the Intermountain Region had a net gain of total forest C, most forests had a loss from 1950 to 2011, resulting in a regionwide loss of approximately 89.4 Tg of total ecosystem C, including soil C, between 1950 and 2011 (fig. 50d).

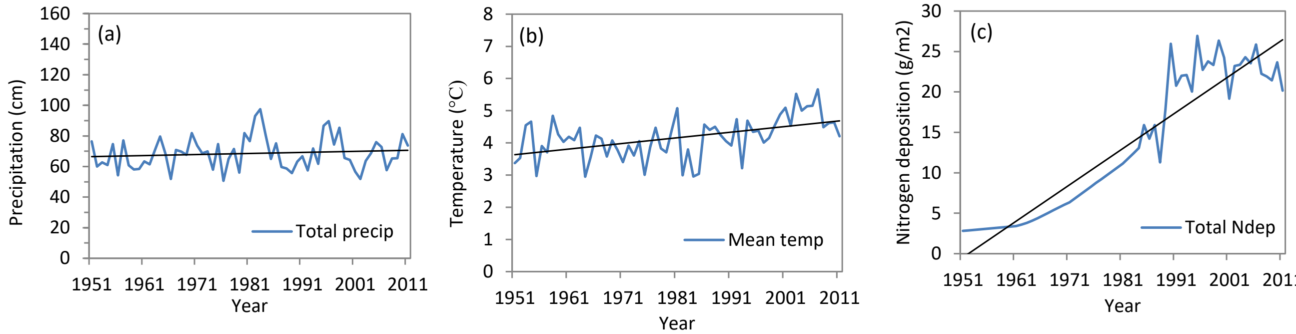

Figure 49a-b. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1951 through 2011 averaged across all national forests in the Intermountain Region. Linear trend lines shown in black.

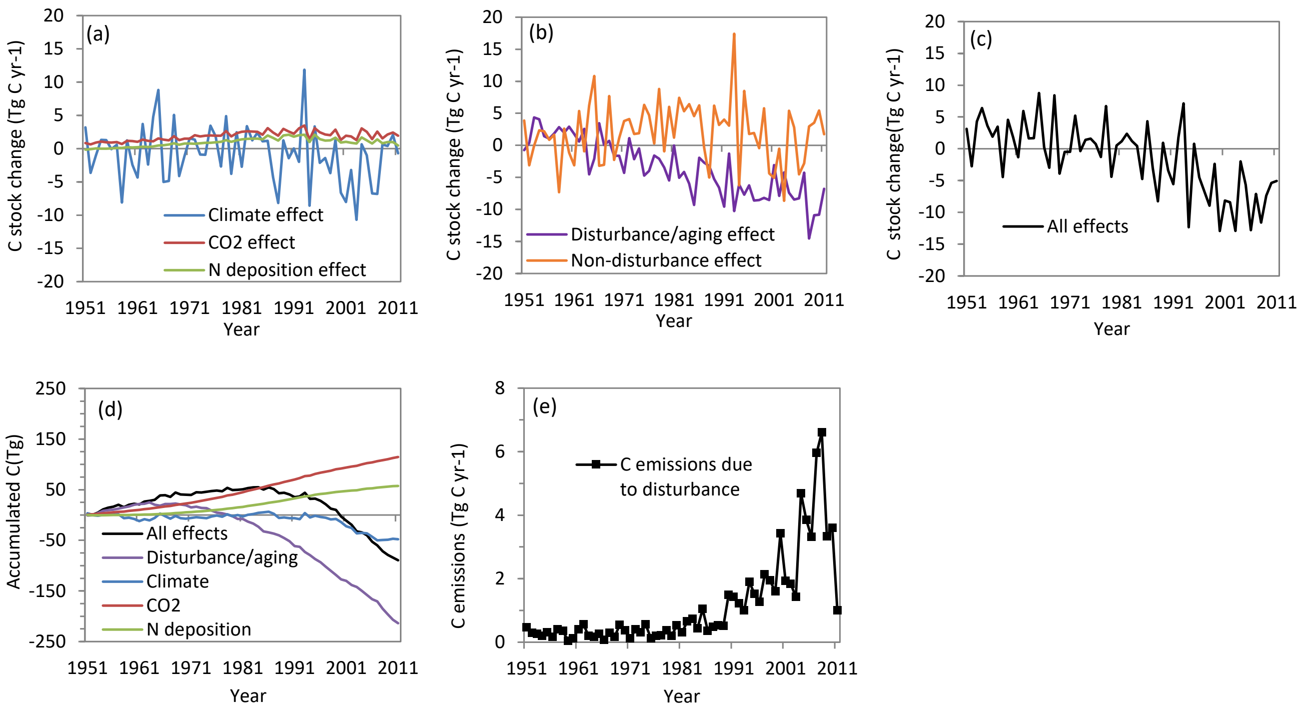

Figure 50a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Intermountain Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2011 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

6.6 Pacific Northwest Region

6.6.1 Description of Region

The Pacific Northwest Region (also referred to as Region 6) in the National Forest System (NFS) consists of 16 national forests and a national scenic area spread across Washington and Oregon (fig. 51). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these administrative units, so national grasslands such as the Crooked River National Grassland in central Oregon were not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. The first Euro-American settlers came to the Pacific Northwest Region in the late 1860s after the Civil War, treaties with Native Americans, and the discovery of gold (Bach 1990). The region was largely uninhabited, however, until the arrival of the transcontinental railroad lines during the 1880s. The railroad helped transform the small-scale timber operations that had

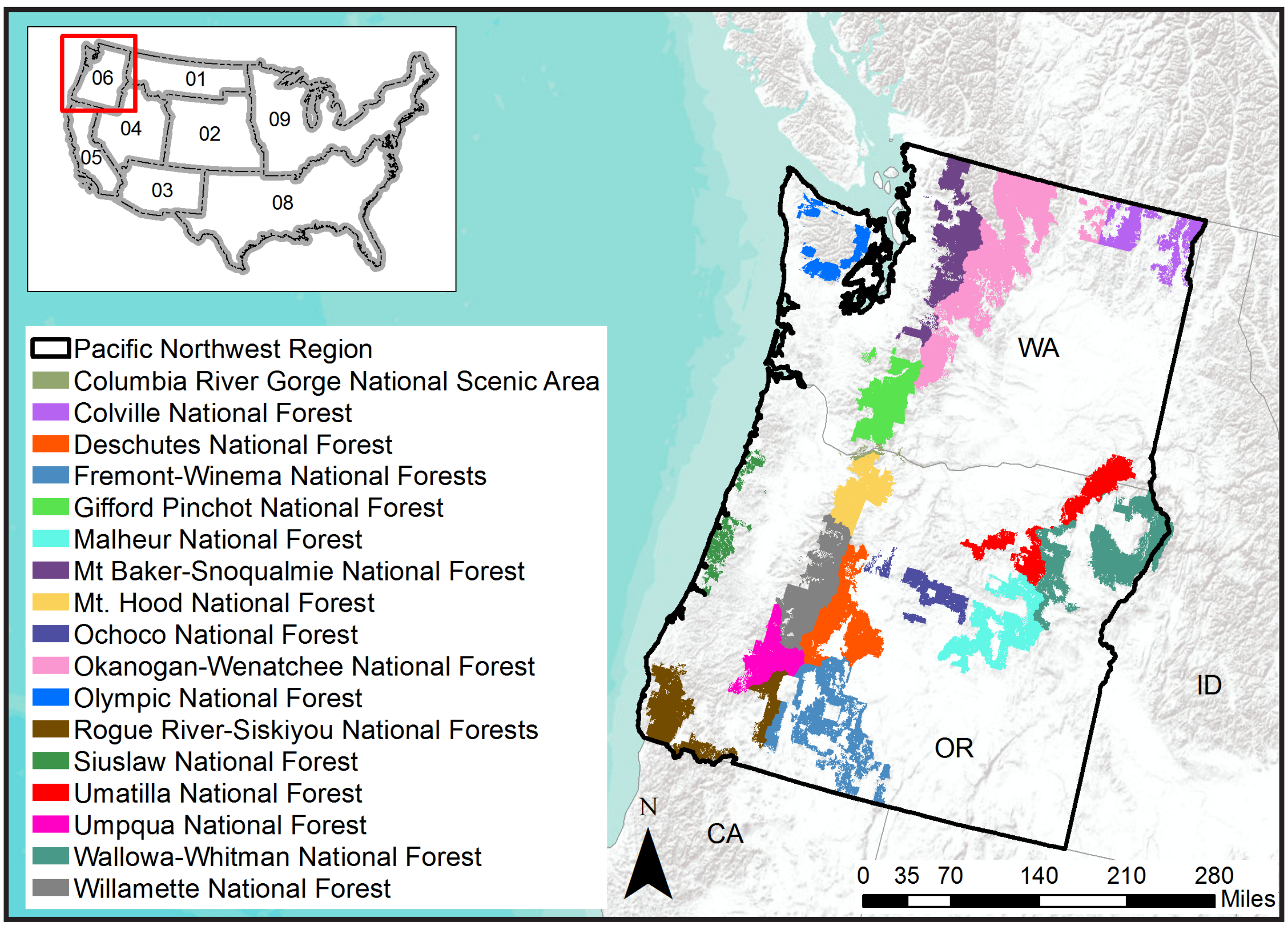

Figure 51. Locations of the national forests and national scenic area in the Pacific Northwest Region.

started in the 1870s (Bach 1990) into one of the most productive and rapidly growing industries in the Pacific Northwest. By 1905, the State of Washington ranked first in the Nation in timber production. In these early settlement years, forests were recklessly clear cut and fires were often accidentally ignited, burning valuable timberland. Annual timber output steadily increased starting in the 1940s, peaked in 1973, but declined precipitously in the early 1990s and has remained low ever since (Butler et al. 2014a). This recent decline in timber harvesting was largely the result of the adoption of the Northwest Forest Plan in 1994, which placed greater restrictions on harvesting in order to protect the northern spotted owl and other species dependent on old-growth forest habitat (Thomas et al. 2006) (see Appendix 1 for scientific names of species mentioned in this report).

In addition to timber harvesting, the forest C legacy of the region is tied to its history of fires and fire management. Historically fire was a major component of the disturbance regimes in the Pacific Northwest forests prior to Euro-American settlement (Agee 1993). However, after the devastating 1910 fire season, which burned millions of acres of valuable forest and timberland in the West, Congress began appropriating money for fire suppression activities led by the Forest Service. This national fire suppression policy entailed intensive efforts to prevent, detect, and suppress all wildfires, greatly altering the ecological system (Agee 1993; Pyne 1982). Despite suppression efforts, major logging-induced fires such as the Tillamook Burn of 1933 in Oregon continued to occur across forests in this region (Morris 1936). A policy shift from fire control to fire management in the 1970s allowed natural fires to burn across landscapes where considered safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Recent changes in climate have also played a role in forest disturbance regimes and C dynamics. The Pacific Northwest has experienced an increase in average annual temperature while precipitation has declined both in the amount of total snowfall and the proportion of precipitation falling as snow. Land use history and climate change have led to large and intense disturbances in the region over the past few decades. Wildfires that are widespread and burn for longer durations and extended fire seasons have increased in the Pacific Northwest. Much of this change is due to warmer summer temperatures and earlier spring snowmelt, which are projected to continue into the future (Climate Impacts Group 2009; Westerling et al. 2006). Over the past few decades, severe bark beetle outbreaks have resulted in tree mortality in parts of the Pacific Northwest (Bentz et al. 2010).

6.6.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Pacific Northwest Region are displayed in figure 52. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns exhibited effects of both wildfire and harvests. Periodic large fire years occurred throughout the period, with approximately 1.2 percent of the region's forests affected by fire in 2002. Harvest decreased through the middle of the study period, though there were slight increases toward the end of the period in 2011. These rates, which did not reach 0.5 percent of the landscape in any single year, were lower than those in the 1970s and 1980s, before enactment of the Northwest Forest Plan in 1994 (Healey et al. 2008). In the last 2 years of the period, insect activity became an important regional disturbance factor, with insects affecting approximately 0.5 percent of the region's forests in 2011 (fig. 52a). From 1990 through 2011, about 60 percent of disturbances were low to moderate intensity (<50 percent change in canopy cover) (fig 52b).

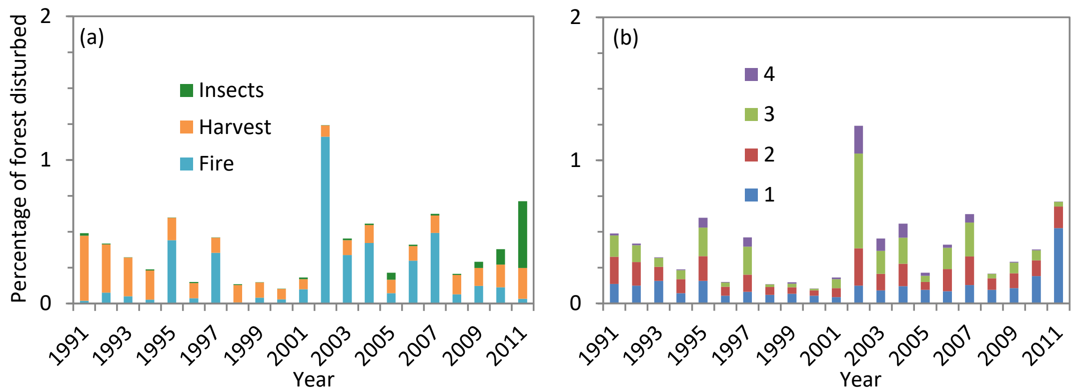

Figure 52a-b. Annual rates of disturbance (0 to 2 percent) in the Pacific Northwest Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, 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.

6.6.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Pacific Northwest Region in figure 53. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 1992, for example, the line for fire in figure 53 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an "undisturbed" scenario. Thus, figure 53 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Harvest activity, particularly in the early 1990s, had a significant effect on the region's C stocks; harvests occurring from 1990 to 2011 reduced 2011 C storage by approximately 167 g/m^2 (or 167 Mg/ha) (fig. 53), and was responsible for 36 percent of the total disturbance effect (fig. 54). By 2011, harvesting resulted in a reduction of approximately 0.9 percent of the regional nonsoil C stocks (fig. 55) that were reported in the NFS baseline C assessment (USDA FS 2015e). These patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the baseline C assessment (USDA FS 2015e).

Fire activity accelerated in 2002 (fig. 53), and fire thereafter became the disturbance factor with the greatest effect on C storage, reducing carbon storage by approximately 1.4 percent by 2011 (fig. 55). By 2011, fires since 1990 had caused 57 percent of the disturbance impact on C stocks, while insect activity had caused 7 percent (fig. 54). Disturbance data (fig. 52) suggest that insects became a significant factor only in 2010 to 2011, and the relative influence of disturbances on C storage (fig. 53) reflects this late emergence of insect activity. Minor wind events were mapped throughout the region, but these events affected relatively small areas and were not considered in this assessment. The unit most affected by wind was the Olympic National Forest, where a total of 0.19 percent of the forest land was affected by wind during the study period, followed by the Gifford Pinchot National Forest (0.10 percent).

One caveat must be stated about the confidence intervals depicted in figure 53. The unit of analysis for ForCaMF was the national forest; rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Although harvests have impacted the C cycle in this region, fire and, more recently, insect activity have also played important roles.

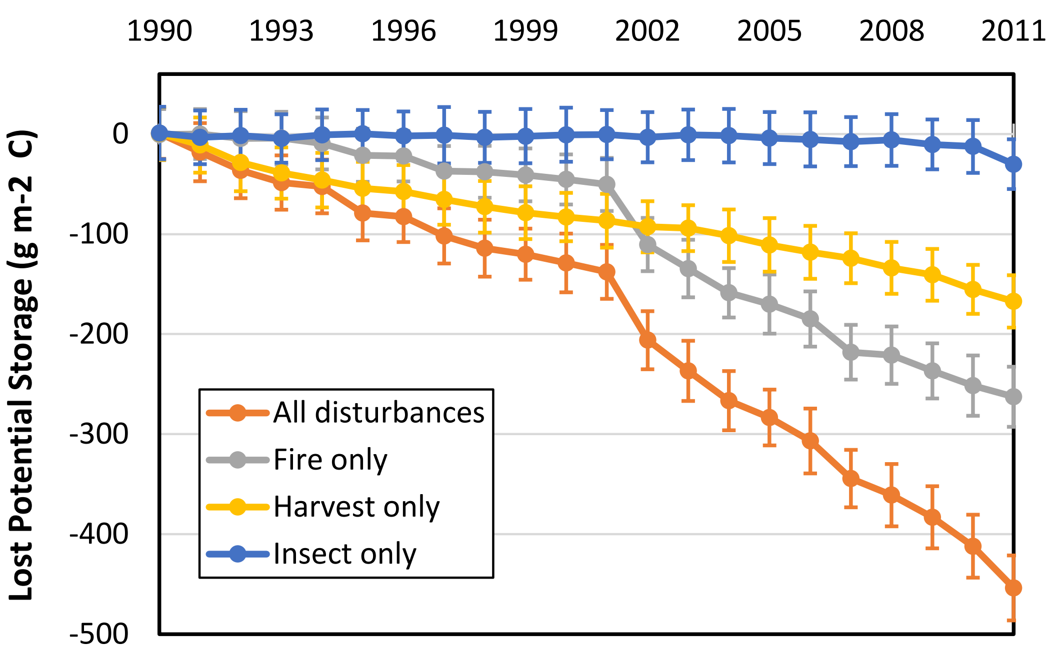

Figure 53. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Pacific Northwest Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

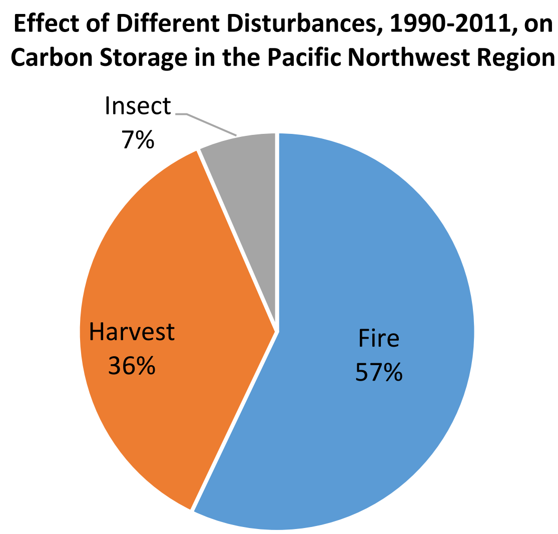

Figure 54. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Pacific Northwest Region for the period 1990 through 2011.

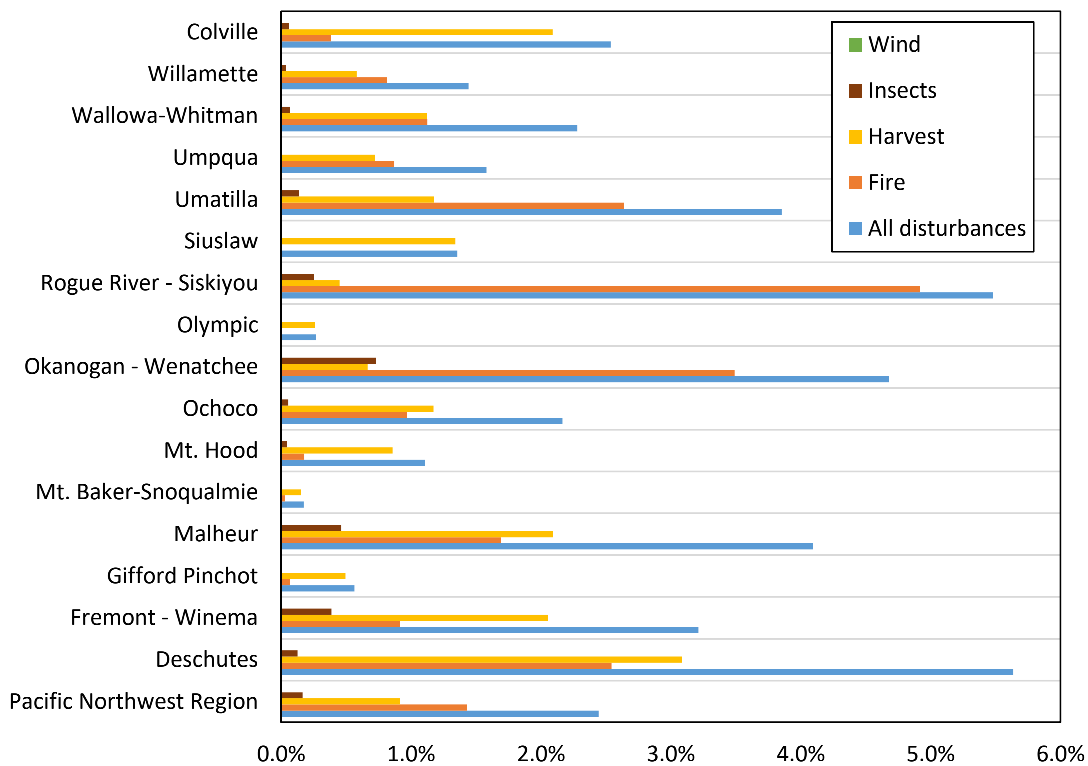

Figure 55. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Pacific Northwest Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

6.6.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 56–59) generated from InTEC model inputs and simulations for individual national forests and summed results across all the national forests in the Pacific Northwest Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 8: Pacific Northwest Region (PDF, 4.2MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 16 national forests and the national scenic area as modeled by InTEC with this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Pacific Northwest Region have been strongly influenced by the history of land use and policies as well as climate change and natural disturbances. Despite variation among these national forests, the regionwide stand-age distribution in 2011 shows that approximately 50 percent of the forests are greater than 100 years old, with about 10 percent of the forests more than 250 years old (fig. 56). The stand-age distribution also shows a pulse of stands that established approximately 70 to 109 years before the end of the study period, or between about 1900 and 1940 (fig. 56). During the 1940s and thereafter, the rate of stand establishment steadily declined. This early-1900s pulse of stand establishment reflects recovery after a range of disturbances occurring around the time of Euro-American settlement, such as intensive timber harvesting and large fires. Although some fires continued into the mid-1900s, fire suppression, which began in the early 1900s, allowed more of these young, regenerating stands to survive and continue regrowing rather than being disturbed at a more typical historical rate of fires (Pyne 1982). Depending on the forest type, this pulse of establishment would have reached maximum rates of productivity at 35 to 45 years of age (fig. 57), or throughout the mid- to late 20th century. Recent disturbances, mostly fires and an increased occurrence of insect outbreaks, have been extensive in some forests and included high-severity, stand-replacing components (fig. 52). In several forests with recent large wildfires, stand establishment has increased, reflecting regrowth and recovery.

Though there was significant interannual variability in both temperature and precipitation, between 1951 and 2011 climate has on average become much warmer and somewhat drier in the Pacific Northwest Region (figs. 58a,b). Severe droughts like the one in the early 2000s have occurred periodically (fig. 58b). Warmer temperatures and drought conditions can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to get even warmer and drier, with snowfall shifting to rainfall. In addition to climate change and variability, both atmospheric CO_2 concentrations and N deposition (fig. 58c) have increased over the past few decades as a result of human activities. Nitrogen deposition in this region peaked around 1990 and has since declined steadily (fig. 58c).

The C stock changes across the national forests in the Pacific Northwest Region show that together the forests generally underwent a switch from a C sink to a C source (figs. 59a–c) in the mid-1980s. Disturbance and aging effects have been mostly responsible for declining C stocks (fig. 59b), which correspond to disturbances that shaped forest structure (fig. 56), the NPP-stand age relationships (fig. 57), and increasing disturbances in recent years (fig. 52). From 1950 to the early 1980s, the forests were a C sink due to positive disturbance and aging effects, as the pulse of stands that were established between 1900 and 1940 was middle-aged and therefore growing at maximum rates of productivity. As these forests further aged, productivity declined, causing the rate of C accumulation to decline (fig. 59d). Meanwhile the effects of disturbance were increasing to the point where C emissions due to decomposition and disturbance events exceeded C gains, so the forests became a C source (figs. 59b,c). The decline in productivity was accompanied by lower rates of stand establishment and increasing rates of timber harvesting from the 1940s until the 1990s.

Recent disturbances such as the large, moderate- to high-severity fires in 2002 (fig. 52) caused spikes in C emissions (fig. 59e). The 2002 fires coincided with an intense drought, which together produced a significant C source in 2002 and 2003 (figs. 59a–c). As forests begin to recover from these disturbance events, as seen in the stand-age distributions for several forests in the region (Appendix 8: Pacific Northwest Region (PDF, 4.2MB)), and reach middle-age with the highest rates of productivity (fig. 57), forests have the potential to rebound and become a C sink again in a few decades.

While disturbance and aging effects initially caused a C sink and then shifted to creating a C source, nondisturbance factors had a mostly positive effect on C stocks in the 1950s and later (figs. 59a,b). Increasing levels of atmospheric CO_2 and N deposition caused forests to accumulate more C and helped to counteract the C declines due to disturbances and the aging stands. By the early 1980s, however, the C gains from CO_2 and N deposition were surpassed by the C losses due to negative disturbance and aging effects, causing the forests to shift to a C source (fig. 59d). Atmospheric CO_2 concentrations are expected to continue increasing for the foreseeable future, potentially offsetting some of the C declines due to disturbances and aging. Despite increasing temperature and decreasing precipitation trends (figs. 58a,b), climate has had a small positive effect on total C accumulation for much of the past few decades. However, since the early 2000s, climate effects have been mostly negative, causing a loss of forest C (fig. 59d). Future projected warming and declines in precipitation may cause the C source in the Pacific Northwest Region to persist.

Although a few national forests in the Pacific Northwest Region had a net loss of total forest C, most forests had C gains between 1950 and 2011 resulting in a regionwide gain of approximately 93.3 Tg of total ecosystem C, including soil C, between 1950 and 2011 (fig. 59d).

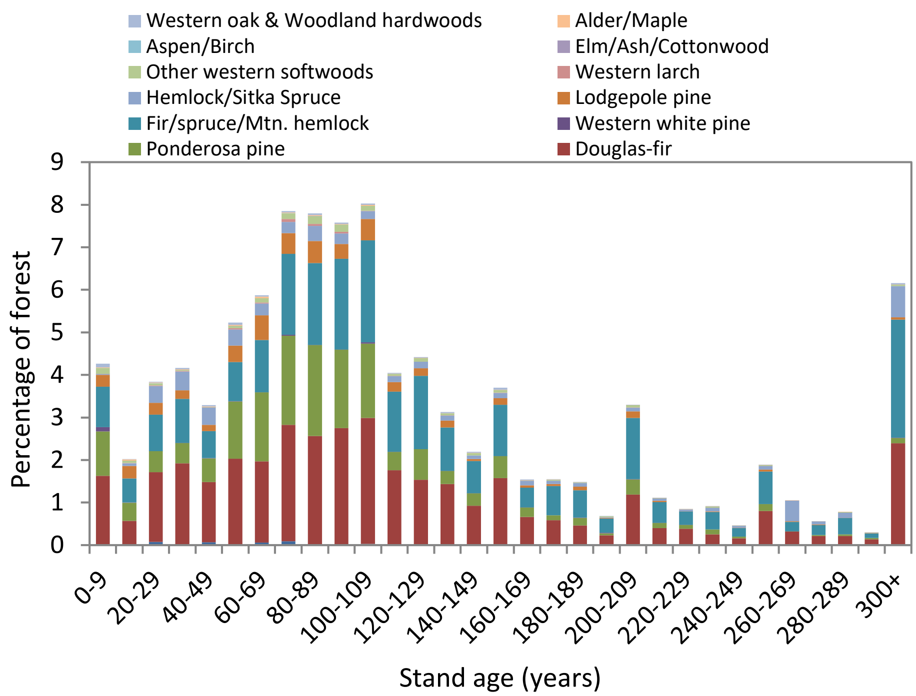

Figure 56. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Pacific Northwest Region (see Appendix 1 for scientific names of trees).

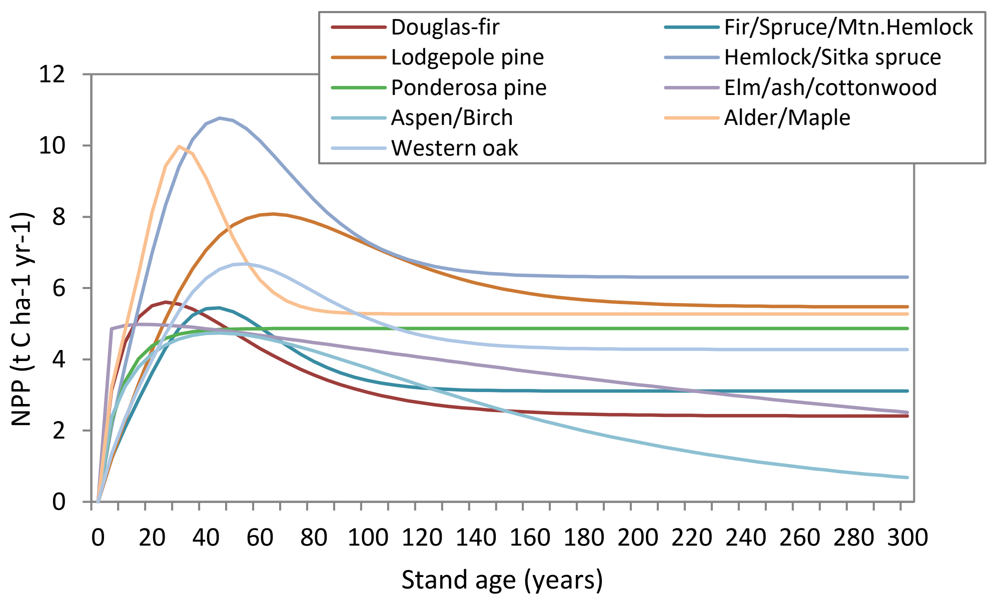

Figure 57. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Pacific Northwest Region (see Appendix 1 for scientific names of trees). Curves were developed by He et al. (2012). The evergreen needleleaf curve was applied to Douglas-fir and western larch stands. The western oak curve was applied to woodland hardwood and other hardwood stands; the ponderosa pine curve was applied to pinyon/juniper, other western softwoods, and western white pine stands.

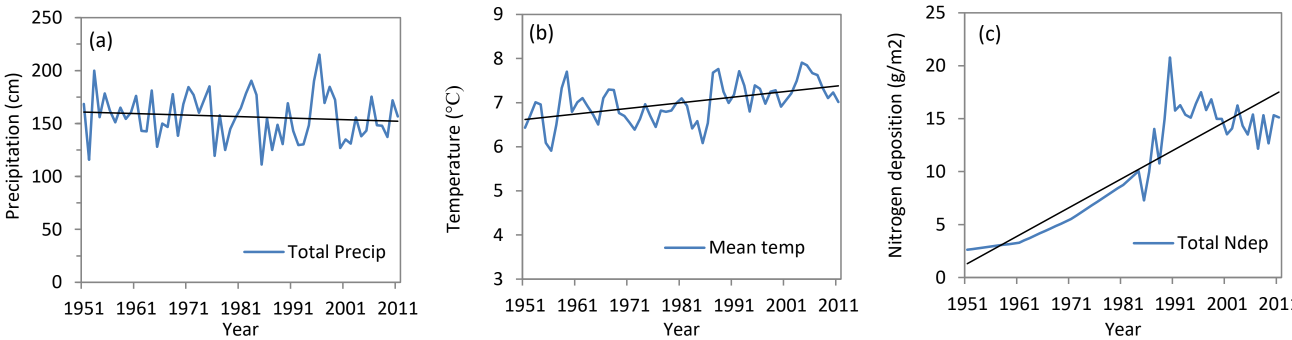

Figure 58a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1951 through 2011 averaged across all national forests in the Pacific Northwest Region. Linear trend lines shown in black.

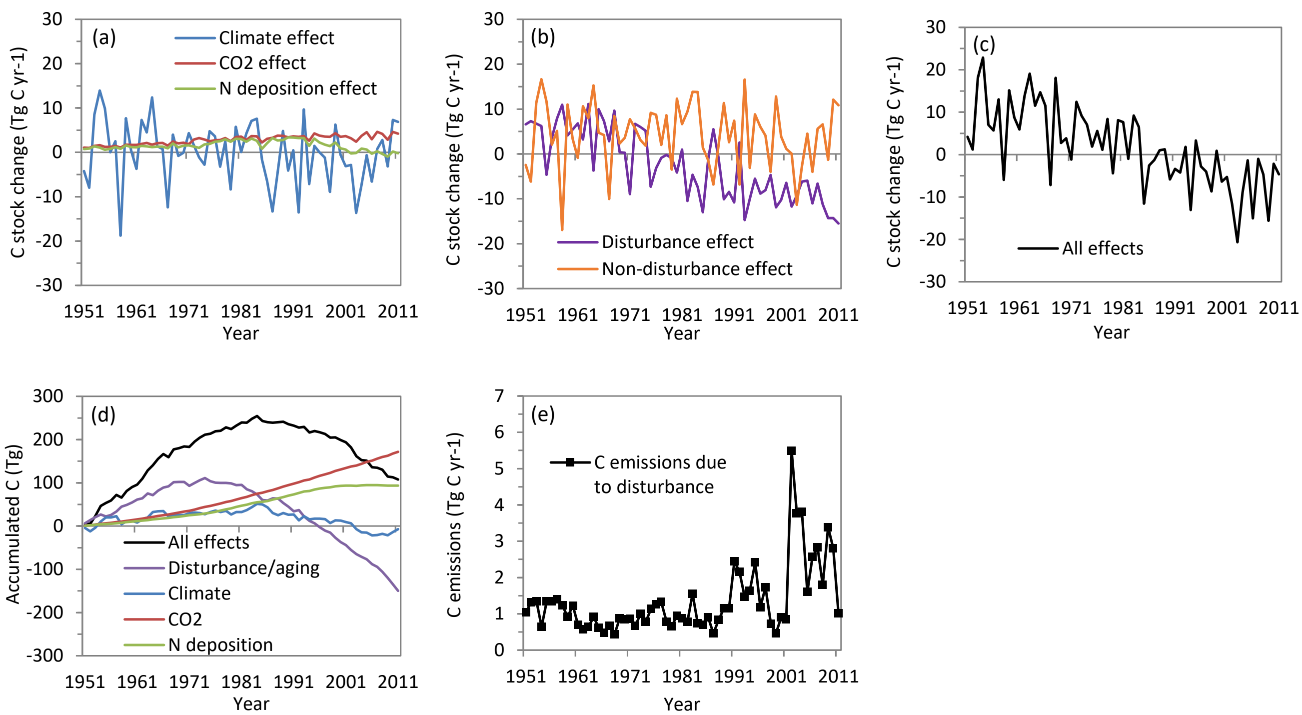

Figure 59a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Pacific Northwest Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2011 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

6.7 Southwestern Region

6.7.1 Description of Region

The Southwestern Region (also referred to as Region 3) in the National Forest System (NFS) consists of 11 national forests across Arizona and New Mexico (fig. 60). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests, so national grasslands such as the Cibola National Grassland in Oklahoma were not included. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

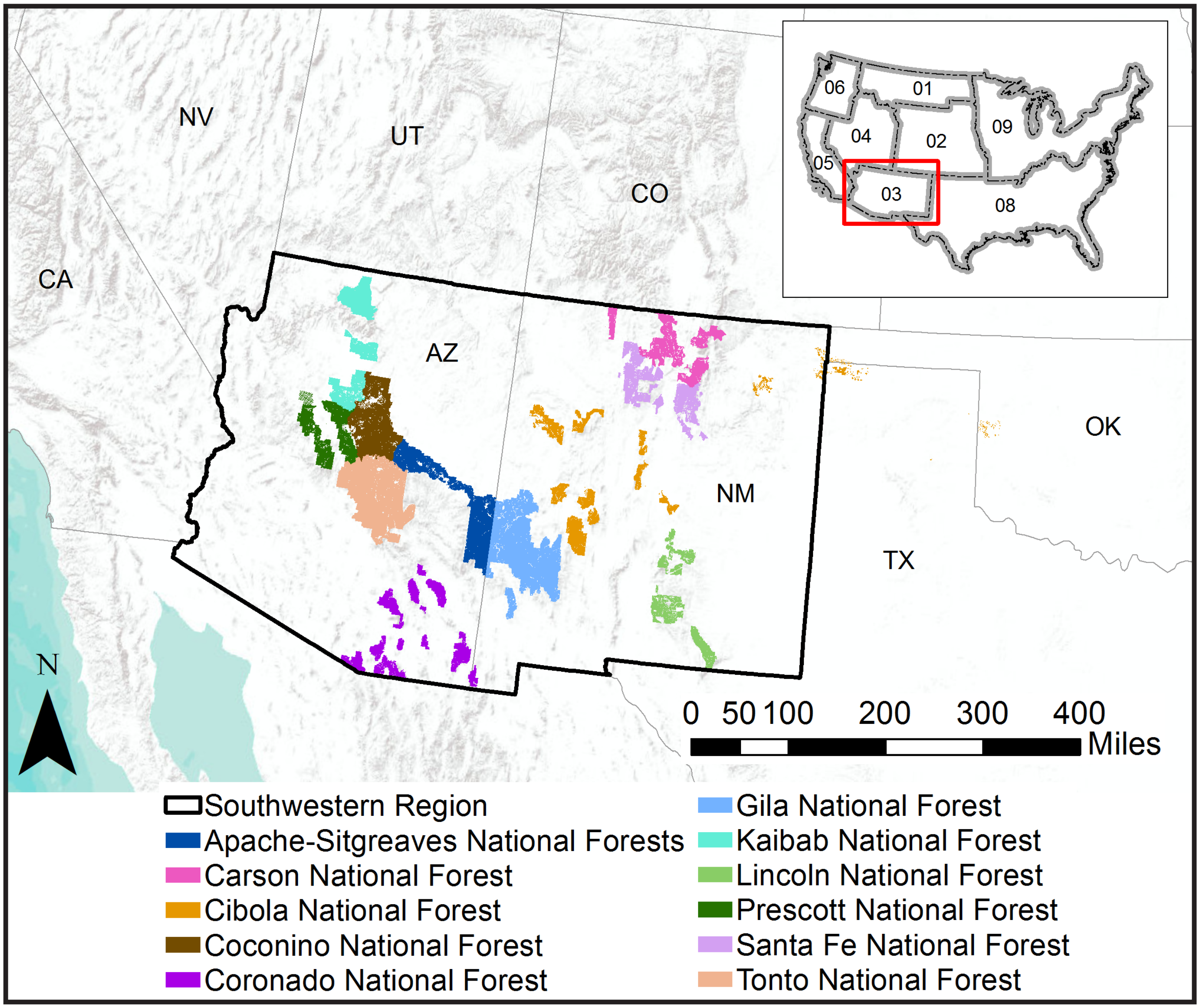

Figure 60. Locations of the national forests in the Southwestern Region.

The history of development, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the forest inventory and model results. Euro-American settlement in the Southwestern Region had a profound effect on forest structure, disturbance regimes, and subsequently forest C dynamics. Settlement began in the mid-1800s and accelerated in the 1880s and 1890s with the completion of key railroad lines. Railroad access in the Southwest also opened up commercial timber opportunities, though the timber industry remained modest compared to other regions in the United States (Baker et al. 1988). Timber output increased slowly from the early 1900s, peaked in 1994, and has since declined to about the levels of the 1920s (Butler et al. 2014b).

Euro-American settlers also brought intensive livestock grazing to the region. Grazing depleted the range and reduced herbaceous fuels, disrupting natural fire regimes and increasing tree density (Covington and Moore 1994). In 1905 when the Forest Service took control of the forest reserves, the era of free use and unrestrained grazing came to an end (Baker et al. 1988).

Although grazing substantially altered these forests, fire has been the primary disturbance shaping forests of the Southwestern Region for hundreds of years. Prior to Euro-American settlement, fires were more frequent and less severe, maintaining lower forest densities (e.g., Covington and Moore 1994), though infrequent, mixed- and high-severity fires also played an important role in shaping forest structure (e.g., Williams and Baker 2012). A policy of fire suppression began in the early 1900s, disrupting natural fire regimes and altering forest structure (Pyne 1982). In the 1970s, fires were once again allowed to burn, and today prescribed burning is commonly used to manage fuel loads and restore historical disturbance regimes. More recently, the region has experienced several very large fires such as the Wallow Fire on the Apache-Sitgreaves National Forests in 2011.

Climate has also played an important role in historical forest structure and subsequent C trends. Historically, periods of increased precipitation triggered pulses of pine establishment (Savage et al. 1996). The Southwestern Region has a unique monsoonal climate. Up to 50 percent of the annual rainfall occurs from July through September (Sheppard et al. 2002), thus enhancing forest growth rates during the growing season. Over the past few decades, climate change has caused unprecedented temperature increases and has increased the risk of future multidecadal megadroughts (e.g., Ault et al. 2014).

6.7.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Southwestern Region are displayed in figure 61. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns were dominated by fire, with at least some of the region burning in each of the monitored years (fig. 61a). There were several years in which the area affected by fire approached 1 percent of the forest land, with most of those years occurring after 2000. Though harvest affected more area than fire in the first 3 years of the study period, harvest rates generally decreased afterward, while fire became more common. In several years, disturbance due to insect activity was measurable, although not high. As with fire, years with higher levels of insect damage were generally

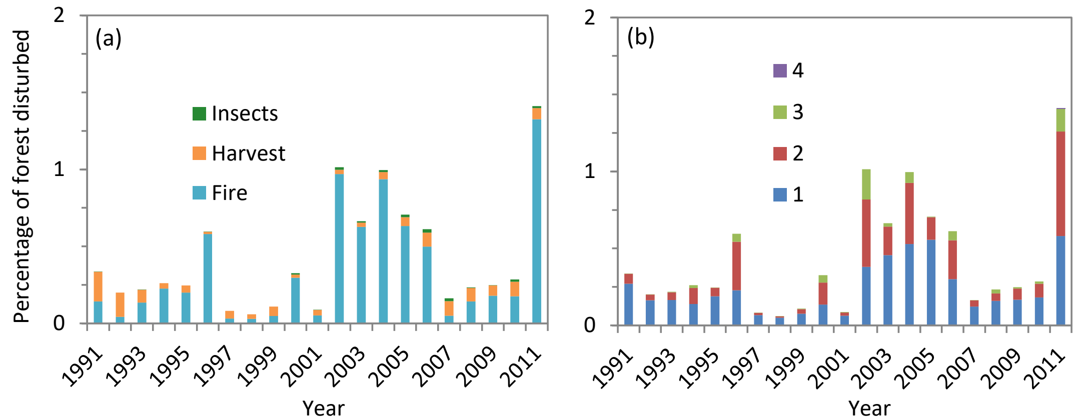

Figure 61a-b. Annual rates of disturbance (0 to 2 percent) in the Southwestern Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, 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.

concentrated after 2000. Over 90 percent of the disturbed area from 1990 through 2011 was characterized by low- to moderate- intensity impacts (<50 percent change in canopy cover) (fig. 61b).

6.7.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Southwestern Region in figure 62. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires occur only in 1992, for example, the line of fire in figure 62 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an undisturbed scenario. Thus, figure 62 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Fire accounted for more than 90 percent of the disturbance impact from 1990 through 2011 on 2011 C stocks (fig. 63). By 2011 fire was responsible for a 2.0-percent reduction in total nonsoil C stocks (fig. 64). The acceleration of fire activity after 2000 within the region (fig. 61) resulted in a surge in fire's impact on C stocks (fig. 62). The stable harvest rate in the region had a relatively low impact on C stocks (fig. 63), by 2011 resulting in removal of 0.2 percent of the regional nonsoil C stocks (fig. 64) that were reported in the NFS baseline C assessment derived from FIA data (USDA FS 2015i). These patterns do not account for offsite storage of C

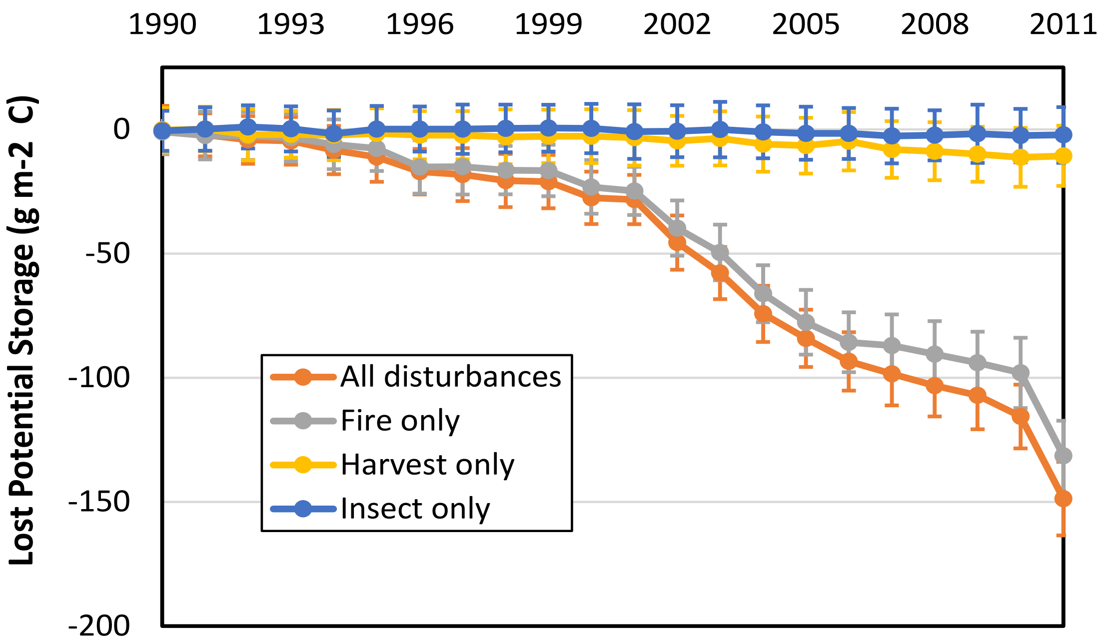

Figure 62. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Southwestern Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

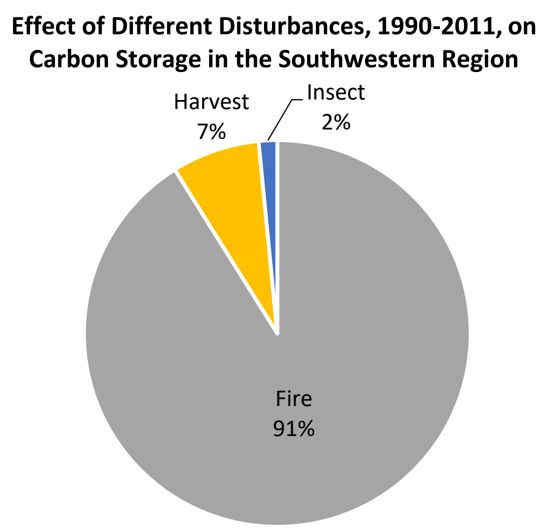

Figure 63. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Southwestern Region for the period 1990 through 2011. Insect impacts made up less than 1 percent of the regional total.

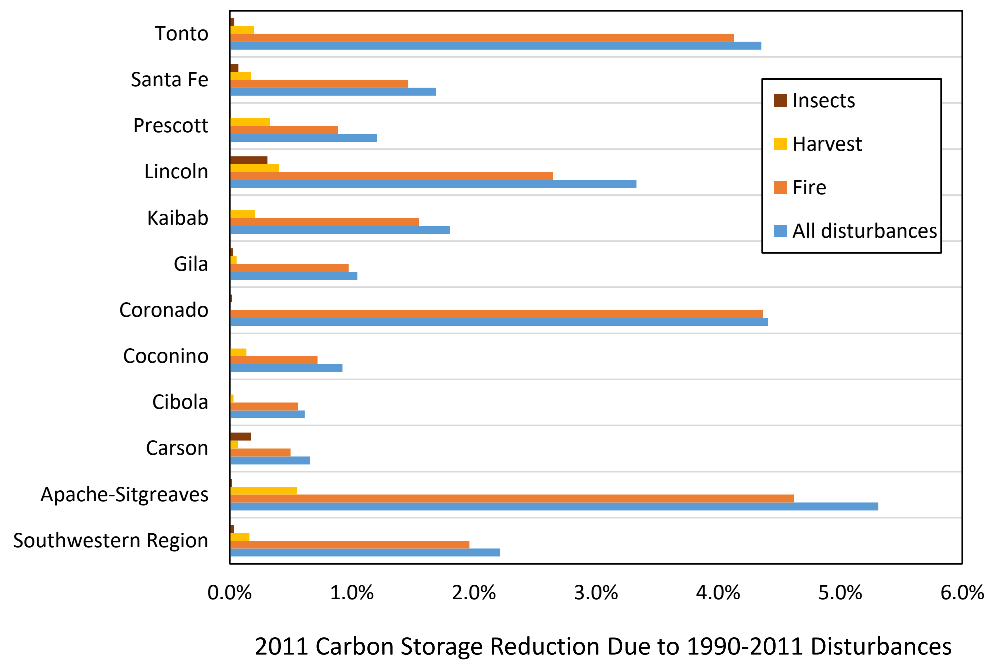

Figure 64. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests in the Southwestern Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

in wood products. Information about the region's product C storage can be found in the baseline C assessment (USDA FS 2015i).

The effect of insects on C storage accounted for less than 1 percent of the potential C storage lost in the region during the study period (fig. 63). Most observed insect activity occurred at the end of the study period (2008 or later) (fig. 62), and it is unclear whether this disturbance process will continue to increase in importance.

One caveat must be stated about the confidence intervals depicted in figure 62. The unit of analysis for ForCaMF was the national forest (Appendix 9: Southwestern Region, (PDF, 2.9MB)); rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Fire is by far the dominant disturbance affecting C storage in the region, and its influence is growing. Despite relatively frequent fire activity, the C storage impact of disturbance within the region on a per unit area basis was relatively low, in part because the landscape generally stores less C than national forests in other regions. Another partial explanation may be the relatively slow decay factors built into regional variants of FVS, which generated the C dynamics used here. Despite relatively low absolute impacts of disturbance, the Southwestern Region is notable for the pronounced dominance of one disturbance process (fire).

6.7.4 Effects of Disturbance, Management, and Environmental Factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 65–68) generated from InTEC model inputs and simulations for individual national forests and summed results across all national forests in the Southwestern Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. The Appendix 9: Southwestern Region, (PDF, 2.9MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 11 national forests as modeled by InTEC using this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Southwestern Region have been strongly influenced by the history of land use and policies as well as climate variability. Despite variation among these national forests, the regionwide stand-age distribution in 2011 shows that most stands are older (>80 years old) with a pulse of stand establishment which occurred about 80 to 119 years earlier, or from approximately 1891 to 1930 (fig. 65). This spike in establishment may be a result of several factors or a sequence of factors, such as regeneration after intensive settlement activities, recovery after the last major fires before fire suppression, lower fire frequency because of livestock grazing, or favorable climate conditions. Fire suppression, which began in the early 1900s, allowed more of these young, regenerating stands to survive and continue regrowing in the absence of fire. Depending on the forest type, which is mostly pinyon-juniper and ponderosa pine, forests would have reached maximum productivity around 45 years old; then productivity would have stabilized and remained relatively constant (fig. 66). However, after reaching peak productivity, all the other forest types would have shown a decline as forests continued to age. Furthermore, after the 1930s, stand establishment dramatically declined, especially between the 1950s and 1991. Stand establishment increased again in the 1990s and 2000s (fig. 65), likely due to recovery after increases in fire disturbances (fig. 61).

Climate has on average grown much warmer in the region, while precipitation has been variable. Though lacking a clear regional trend, precipitation has increased for some individual forests and decreased for others in the second half of the period (figs. 67a,b). Warmer temperatures can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity in the absence of increasing rainfall. Consequently, more C is released to the atmosphere. As climate continues to change, this region is expected to become warmer with higher risks of severe, multidecadal droughts (e.g., Ault et al. 2011). Nitrogen deposition increased substantially between the 1950s and 2000s, but stabilized and declined in 2008 and 2009 before increasing again (fig. 67c). Atmospheric CO_2 concentrations have increased across the United States and globally as a result of human activities since the onset of industrialization. Elevated CO_2 levels and N deposition can enhance forest growth and increase water-use efficiency, resulting in a positive effect on C stocks.

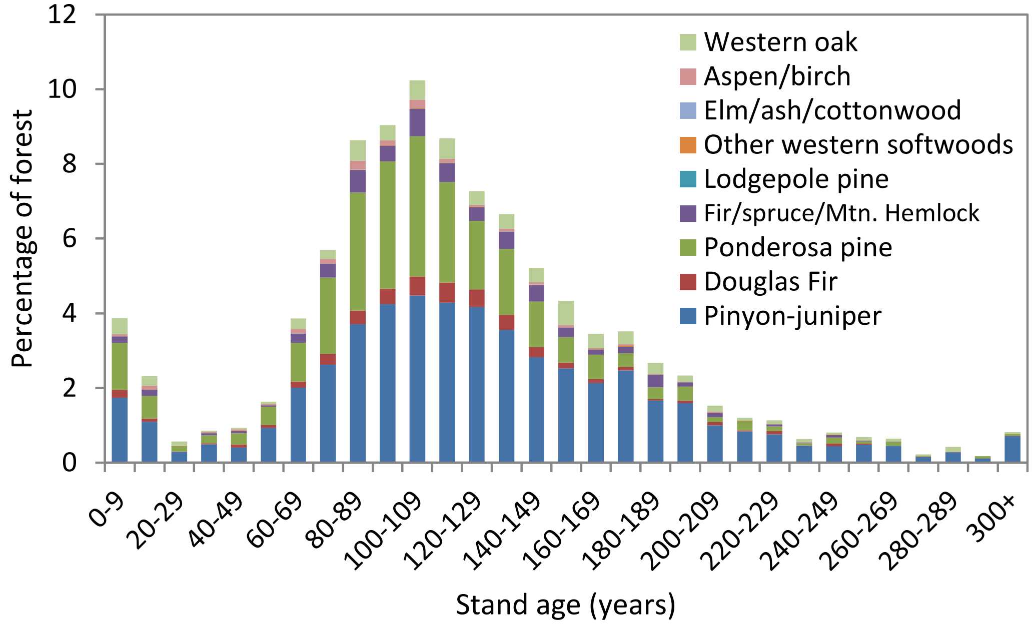

Figure 65. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Southwestern Region (see Appendix 1 for scientific names of trees).

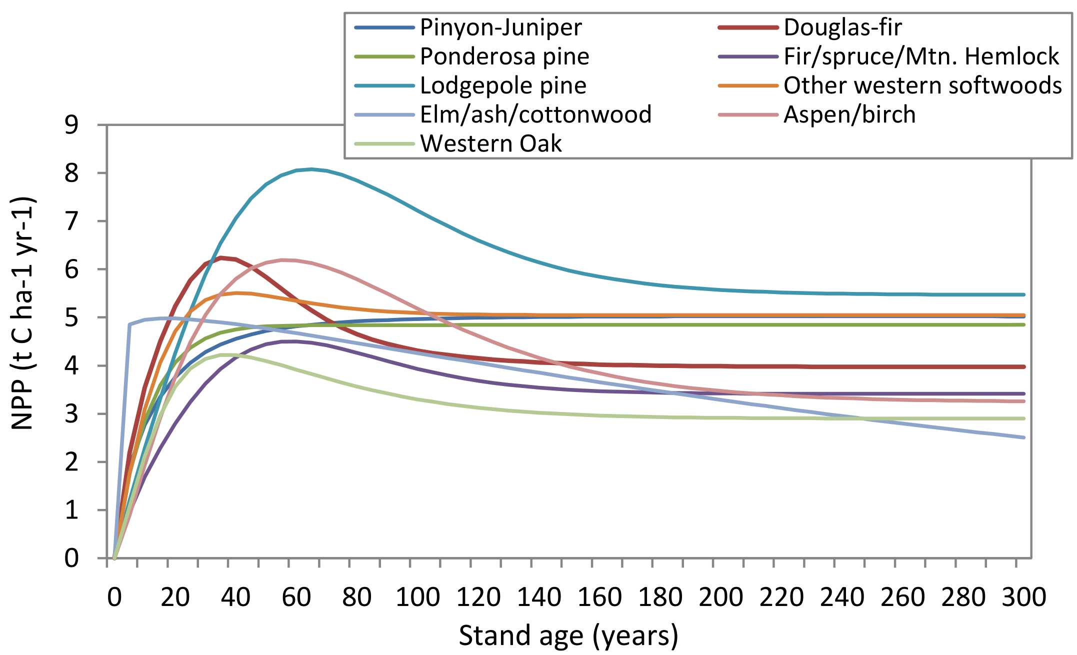

Figure 66. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Southwestern Region (see Appendix 1 for scientific names of trees).

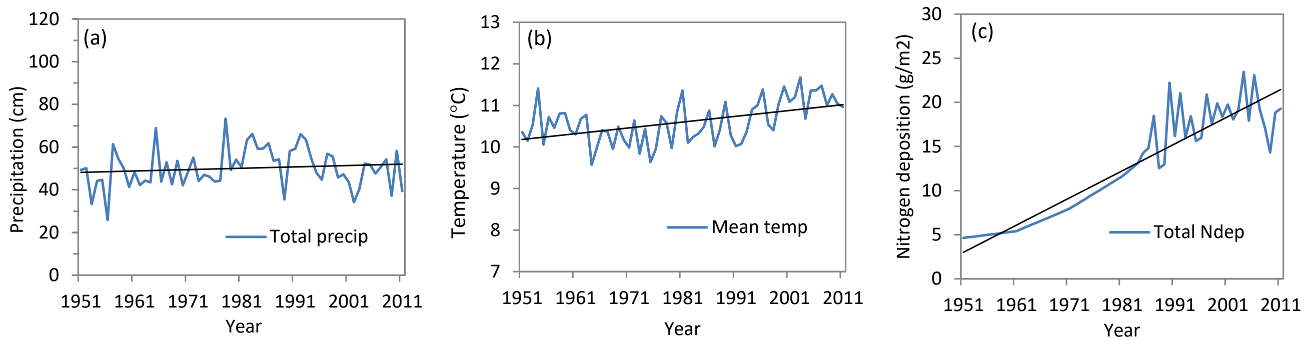

Figure 67a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1950 through 2011 averaged across all national forests in the Southwestern Region. Linear trend lines shown in black.

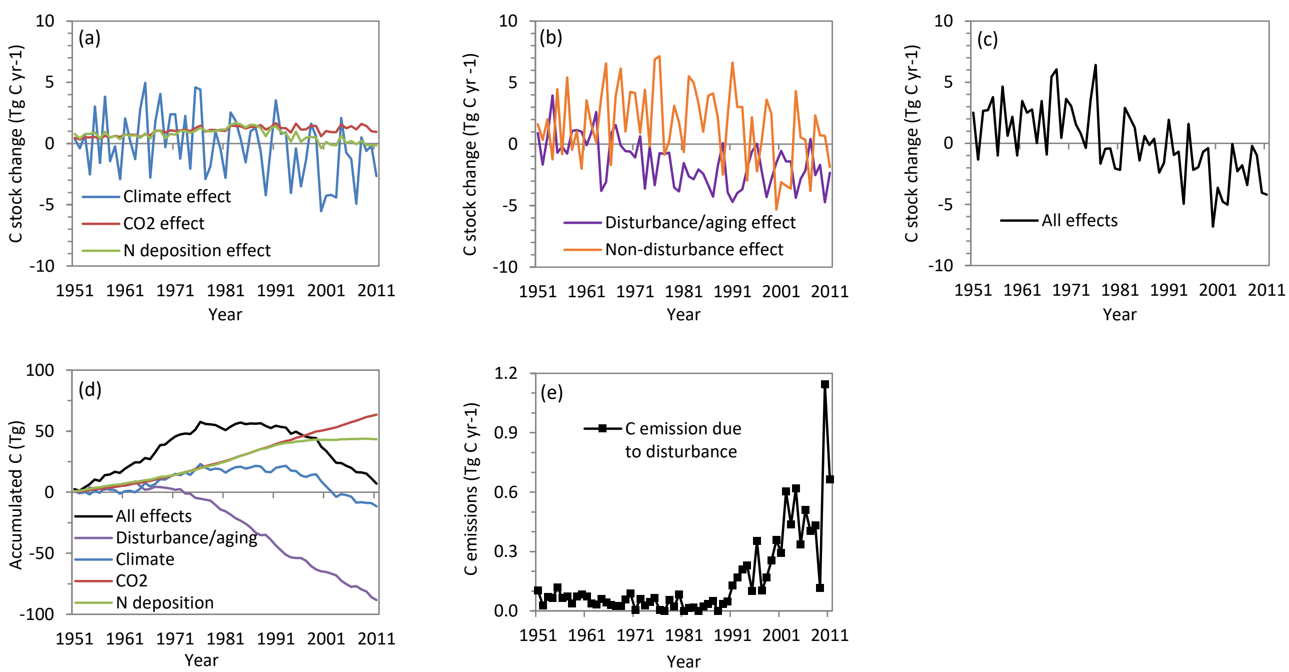

Figure 68a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Southwestern Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO_2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2011 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

The C stock changes across the national forests in the Southwestern Region show that forests were mostly a net C sink from the 1950s through the mid-1970s, then gradually shifted to a C source in the 1980s and 1990s, before becoming a consistent C source in the 2000s (fig. 68c). Changing C stocks and C accumulation have been influenced strongly by disturbance and aging effects and, to a lesser extent, climate effects (figs. 68a–d). Together the forests were a C sink when the stands making up the pulse of establishment between 1890 and 1930 had reached maximum productivity around 45 years old (1930s–1970s). During this period, climate effects were mostly positive, especially during the 1960s and 1970s, when temperatures were slightly lower than average (fig. 67b) and promoted further accumulation of C in forests (fig. 68d). The forests shifted to a C source in the mid-1970s as stand establishment significantly declined and temperatures started increasing more steadily. The C losses from decomposition and respiration started to exceed C gains, causing forests to become a C source.

In the early 2000s, drought conditions, combined with high temperatures (figs. 67a,b), further exacerbated the C source (fig. 68a). At the same time, low- to moderate-severity fires (fig. 61) also increased, causing a spike in disturbance-induced C emissions (fig. 68e). However, these recent disturbances also promoted regrowth and recovery as shown by the small pulse of stands less than 20 years old (fig. 65). If these young stands are able to survive and reach middle-age in coming decades, they will be growing at a higher productivity rate. Forests could potentially accumulate C faster and become a C sink again.

From the 1950s on, atmospheric CO_2 concentrations and N deposition consistently had positive effects on forest C, enhancing the C sink and C accumulation (figs. 68a,d). In fact, the positive effects of N deposition and CO_2 were able to at least partially offset the negative disturbance effects since the 1970s and the more recent negative climate effects since the early 2000s, such that national forests in the Southwestern Region (Appendix 9: Southwestern Region, (PDF, 2.9MB)) experienced a small net gain of 7 Tg of total ecosystem C, including soil C, between 1950 and 2011 (fig. 68d).

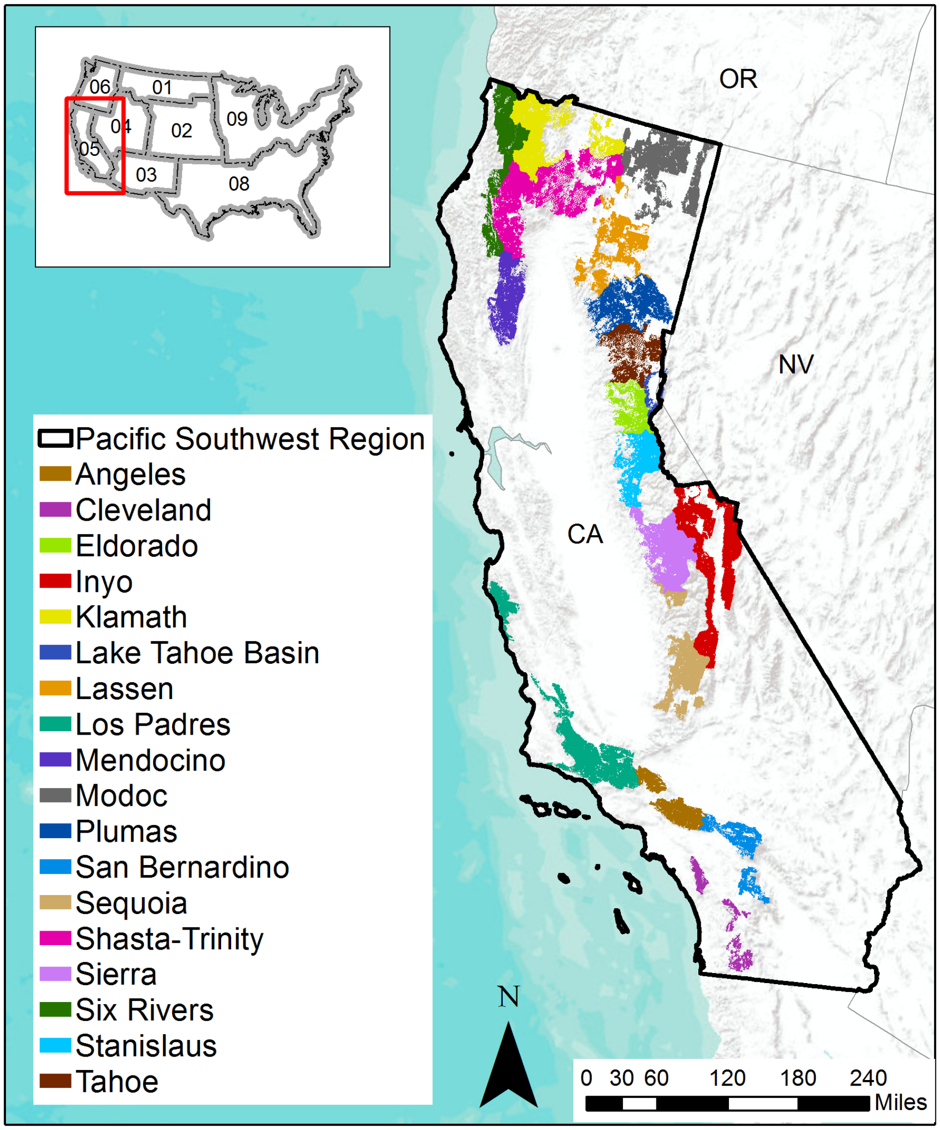

Figure 69. Locations of the national forests in the Pacific Southwest Region.

6.8 Pacific Southwest Region

6.8.1 Description of Region

The Pacific Southwest Region (also referred to as Region 5) in the National Forest System (NFS) consists of the Lake Tahoe Basin Management Unit and 18 national forests spread throughout California and into Oregon and Nevada (fig. 69). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these units. To restrict the analysis to only lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. Despite colonization by the Spanish in the mid-1700s and a trickle of immigrants over the Sierra Nevadas in the 1820s, it was the discovery of gold in 1849 that brought a flood of immigrants to California. The development of gold mining operations triggered a population explosion and great demand for wood products. As a result, the forests were cleared to support mining operations, railroad construction, and the spread of towns and cities through the Sierra Nevada region, along the Pacific coast north of San Francisco, and in the pine forests of Southern California (USDA FS 1927) (see Appendix 1 for scientific names of species mentioned in this report). Timber harvesting continued to increase steadily into the early 1900s (Stockman et al. 2014c). Settlers also brought herds of grazing cattle and sheep which trampled, foraged, and eroded forest lands. While early Indians used fire to clear land for hunting and protection, the advent of Euro-American settlers led to more extensive, frequent, and uncontrolled fires in the forests of California. However, many of these gold seekers and settlers were forward-thinking and pressed for forest conservation (USDA FS 1927). Their advocacy inspired the first instance in which the U.S. Government set aside park land for public use and recreation. Lands set aside in 1864 under the Yosemite Grant were initially managed by the State of California, and administration of this grant paved the way for the creation of the first national park in Yellowstone.

By the 1890s, the first forest reserves were designated and more sustainable timber, livestock grazing, and fire management became an objective. The California lumber industry declined during the Great Depression in the 1930s before rapidly increasing again in the 1950s and 1960s (Stockman et al. 2014c). A national policy of fire suppression, which began after the devastating 1910 fire season, entailed intensive efforts to prevent, detect, and suppress all wildfires (Baker et al. 1993; Pyne 1982). This policy caused significant declines in fire frequency and area burned throughout the Cascades, Klamath Mountains, Tahoe Basin, and Sierra Nevada region, allowing forests to regenerate and survive in the absence of fire (Beaty and Taylor 2008). A policy shift from fire control to fire management in the 1970s enabled natural fires to burn across landscapes where safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Both land use history and recent changes in climate have led to large and severe disturbances as well as more frequent and severe droughts in the Pacific Southwest Region over the past few decades. Between 1984 and 2006 the extent of high-severity, stand-replacing fires has dramatically increased in California and fires are burning at generally higher severities than before Euro-American settlement (Miller et al. 2009). Since the 1970s the frequency of wildfires has also increased in much of the western United States due to warmer and drier conditions as well as the build-up of surface fuels resulting from a history of fire suppression (Westerling et al. 2006). Elevated tree mortality in California has been linked to multiyear droughts characterized by low winter to spring snowpack, followed by high spring and summer temperatures (Guarín and Taylor 2005; van Mantgem et al. 2009). The super El Niño of 1982 to 1983 brought damaging storms with strong winds, heavy snowfall, and flooding rains across all of California.

Recent tree mortality is one of the most urgent issues facing the region and California. This unprecedented event is crossing all land ownerships and affecting entire landscapes and ecosystems. With California in its fifth consecutive year of severe drought, lack of moisture and elevated bark beetle activity have killed an estimated 66 million trees throughout the State since 2010. The west slope of the southern Sierra Nevadas, including the Stanislaus, Sierra, and Sequoia National Forests, has been the hardest hit area.

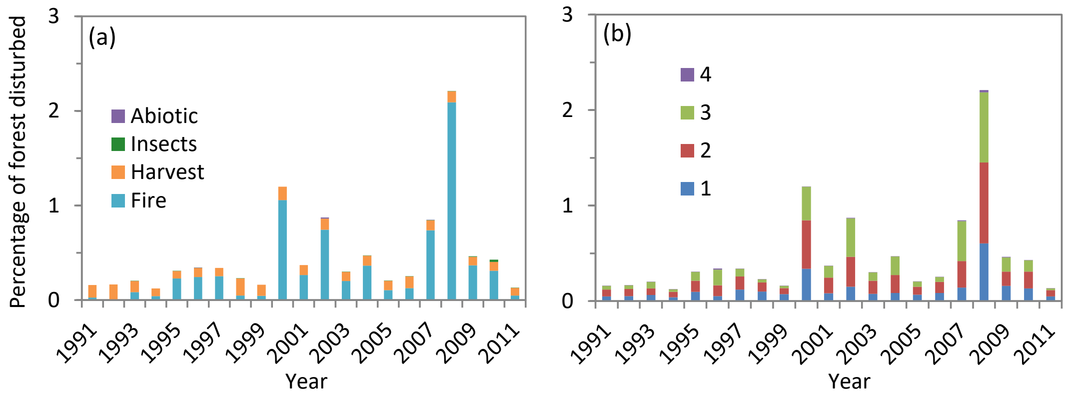

Figure 70. Annual rates of disturbance (0 to 3 percent) in the Pacific Southwest Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, 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.

6.8.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Pacific Southwest Region are displayed in figure 70. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Regional disturbance patterns are marked by relatively low, but stable, harvest rates, and periodic large fire years that have occurred since 2000 (fig. 70a). Fires were largest in 2000 and 2008, disturbing about 1 percent and 2 percent of the forested area, respectively. Disturbances were mostly moderate intensity (25 to 75 percent change in canopy cover), with very little area affected by high-intensity, stand-replacing disturbances (76 to 100 percent change in canopy cover) (fig. 70b).

6.8.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Pacific Southwest Region in figure 71. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 2006, for example, the line of fire in figure 71 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an undisturbed scenario. Thus, figure 71 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

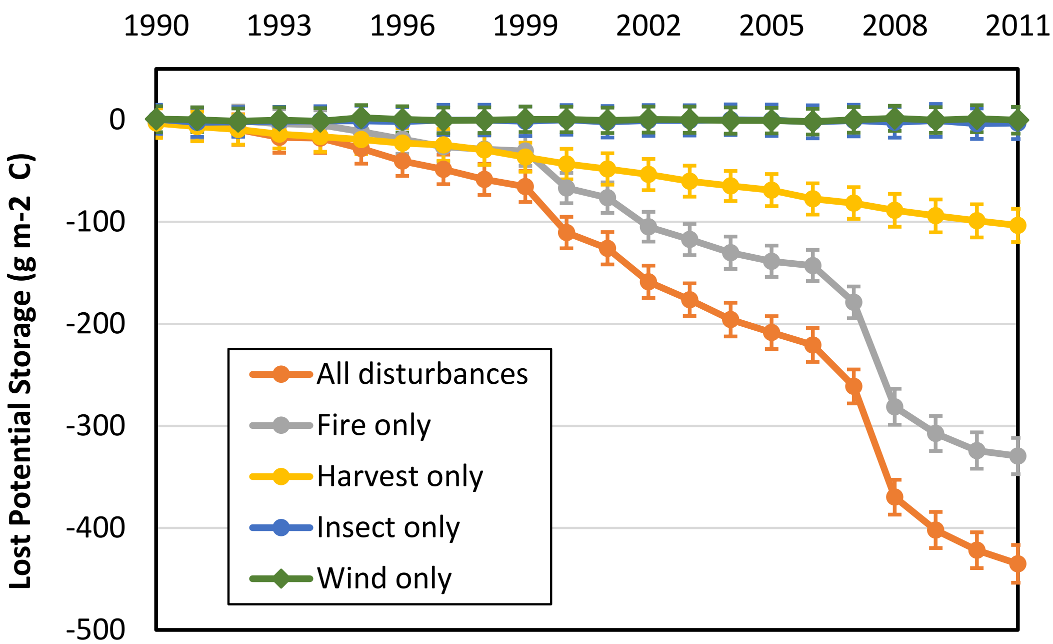

Figure 71. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Pacific Southwest Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

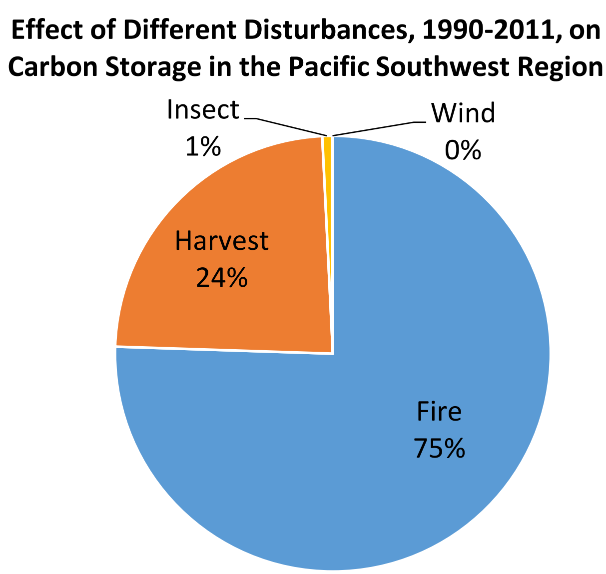

Figure 72. Proportional effect of different kinds of disturbance on carbon storage in all national forests in the Pacific Southwest Region for the period 1990 through 2011.

Fire accounted for approximately three-quarters of the disturbance impact on 2011 C stocks (fig. 72). The area of forests affected by fires started to increase in the 2000s, which was approximately the point during the study period when the impact of fire exceeded the impact of harvest in the region (fig. 71). Fires were particularly large in 2000 and 2008, when they affected more than 1 percent of the region's forest land. In 2008, about 2 percent of the region's forests was affected by fire, and local rates on some forests were much higher. A substantial increase in the impact of fire on the region's C storage may be seen in 2008 (fig. 71). By 2011, fires accounted for a 2.1-percent reduction in nonsoil C storage in the region (fig. 73).

The C impact of harvest within the region was relatively stable from 1990 through 2011 (fig. 71), because harvest levels, while low, were consistent throughout the period. Harvest represented about one-quarter of the disturbance impact on 2011 landscape C storage (fig. 72). By 2011, this represented a reduction of about 0.7 percent of the regional nonsoil C stocks (fig. 73) that were reported in the NFS baseline C assessment derived from FIA data (USDA FS 2015e). These patterns do not account for offsite storage of C in wood products. Information about the region's product C storage can be found in the baseline C assessment (USDA FS 2015e).

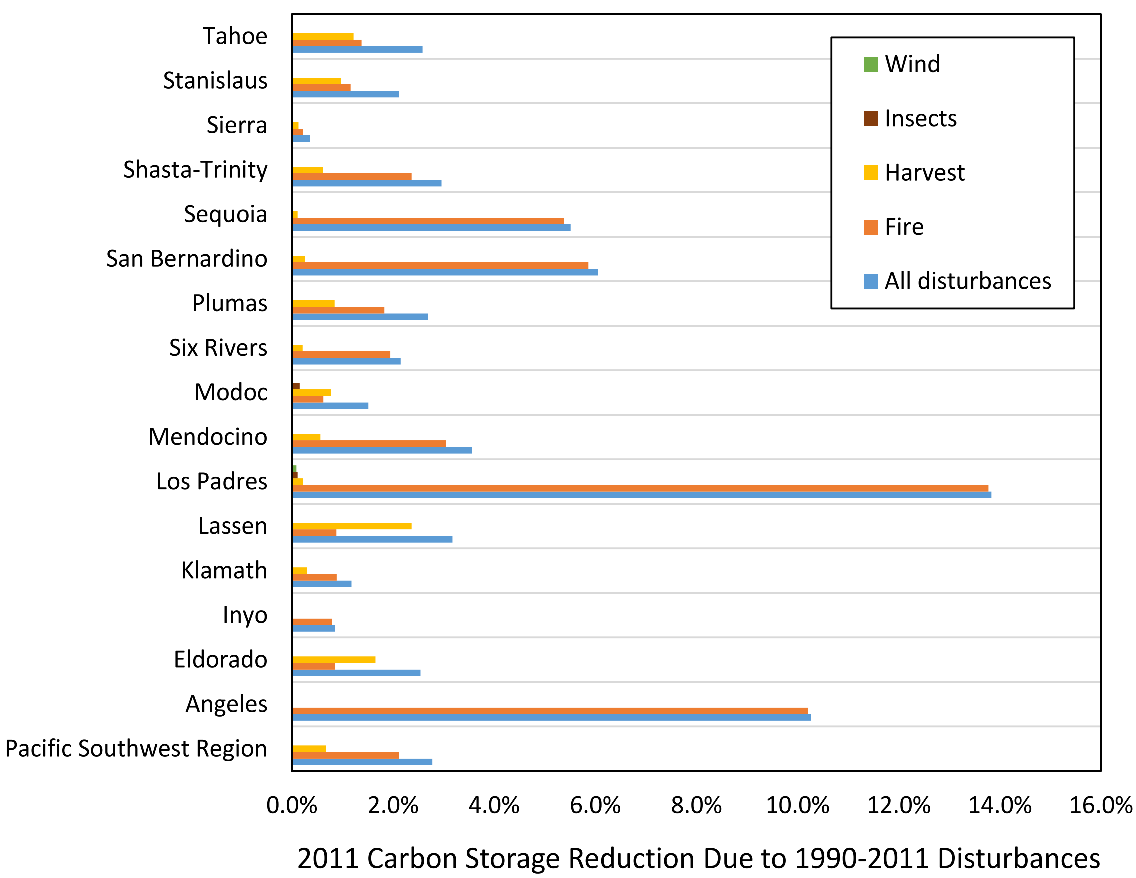

Figure 73. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Pacific Southwest Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

The effect of insects on C storage represented approximately 1 percent of the disturbance impact on the region during the study period (fig. 72), with relatively higher impacts only in the Modoc National Forest (approximately 10 percent; Appendix 10: Pacific Southwest Region (PDF, 4.2MB)). Insect activity caused a small reduction (0.02 percent) in nonsoil C storage by 2011 (fig. 73). Most observed insect activity occurred at the end of the study period (2008 or later).

One caveat must be stated about the confidence intervals depicted in figure 71. The unit of analysis for ForCaMF was the national forest; rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests. This assumption very likely overstated certainty at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in other units. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Fire has been the dominant disturbance affecting C storage in the region, and its influence is growing. On a per unit area basis, the C storage impact of fire in the Pacific Southwest was by far the greatest of all the regions.

6.8.4 Effects of Disturbance, Management, and Environmental factors

This section provides a regional summary of the predicted (modeled) effects of natural disturbances, land management, and environmental factors on forest C dynamics depicted in a series of figures (figs. 74–77) generated by InTEC simulations for individual national forests and summed results across all national forests in the Pacific Southwest Region. These regional-scale outputs were generated only from the national forest-specific datasets; thus, these outputs do not represent lands within the region that are outside of the national forest boundaries. Appendix 10: Pacific Southwest Region (PDF, 4.2MB) shows the effects of disturbance and nondisturbance factors on forest C dynamics within each of the 18 national forests as modeled by InTEC using this same series of figures.

According to the historical data and model results, forest C trends across the national forests in the Pacific Southwest Region have been strongly influenced by the history of land use and policies as well as climate change. Despite variation among these national forests, the regionwide stand-age distribution in 2010 shows a distinct pulse of stands established approximately 70 to 109 years earlier, or from about 1901 to 1940 (fig. 74). This pulse of stand establishment reflects forest recovery from disturbances after the onset of rapid settlement of California following the discovery of gold in the mid-1800s. In the early 1900s, California's national forests were designated and more sustainable land use became a focus, helping forests to regenerate. Another important factor during the regeneration phase was fire suppression, which may have allowed more stands to survive and continue regrowing rather than being disturbed at a more typical historical rate of fires (Pyne et al. 1982). Depending on the forest type, which is mostly California mixed conifer followed by Douglas-fir and fir/spruce/mountain hemlock (fig. 74), these pulses of stand establishment would have reached their maximum productivity at 35 to 45 years old (fig. 75), or from the 1930 through 1980s.

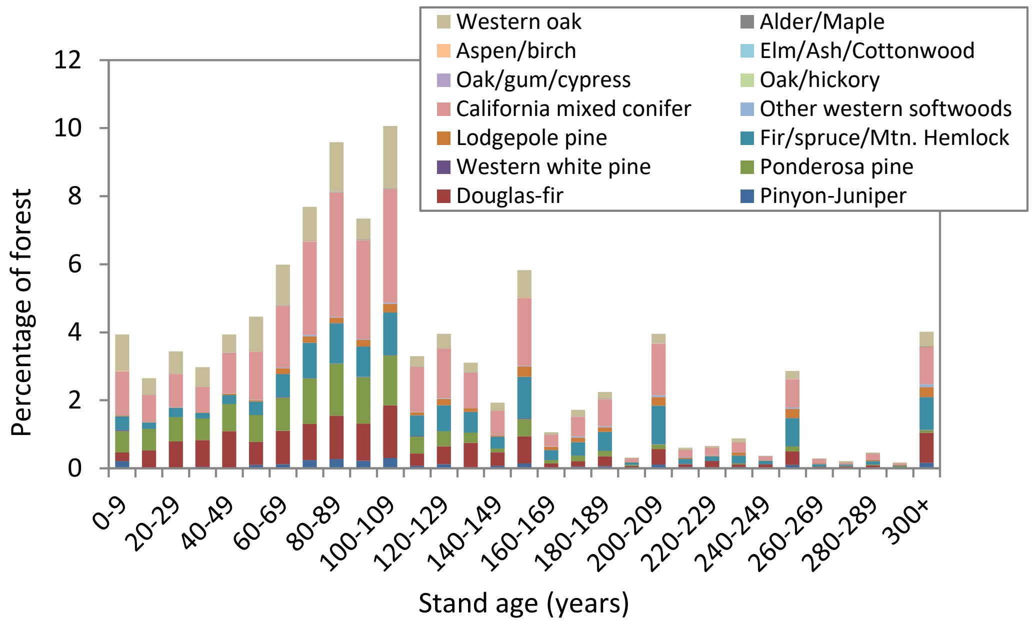

Figure 74. Age-class distribution in 2011 shown as the percentage of forest land in each forest-type group in 10-year age classes summed across the national forests in the Pacific Southwest Region (see Appendix 1 for scientific names of trees).

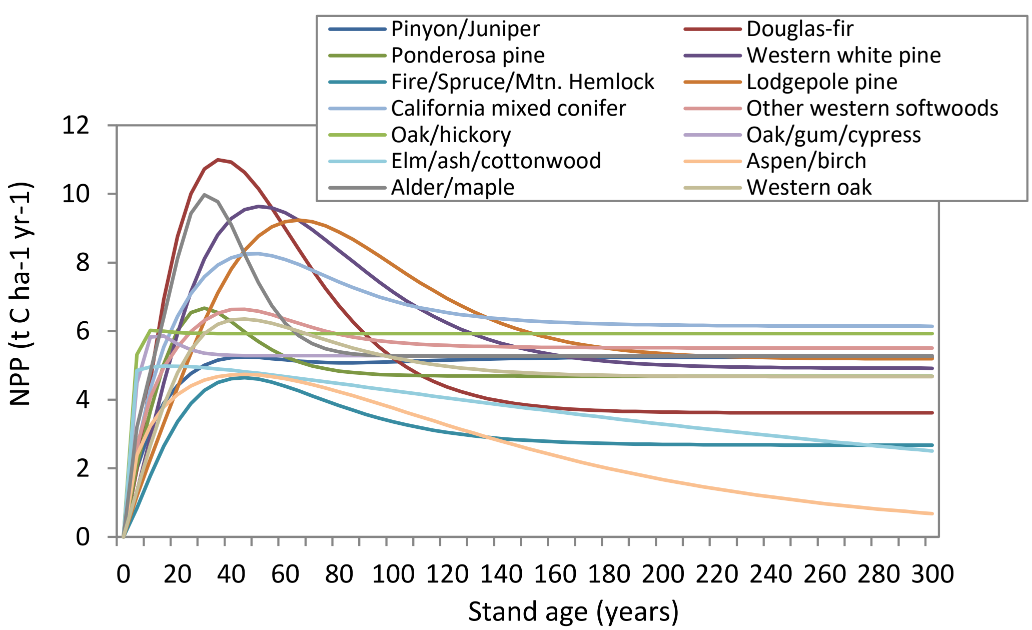

Figure 75. Relationship between net primary productivity (NPP) and stand age for each forest-type group averaged across all national forests in the Pacific Southwest Region (see Appendix 1 for scientific names of trees).

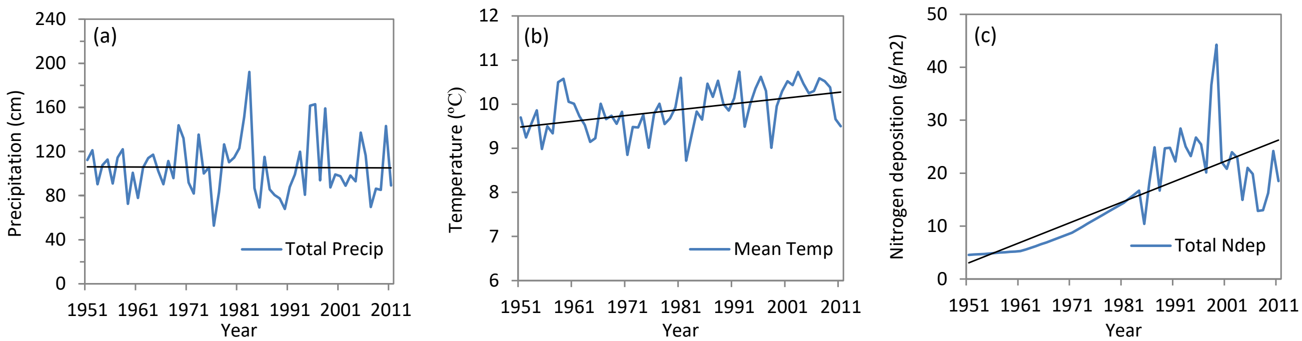

Figure 76a-c. (a) Total annual precipitation, (b) average annual temperature, and (c) total annual nitrogen deposition from 1951 through 2011 averaged across all national forests in the Pacific Southwest Region. Linear trend lines shown in black.

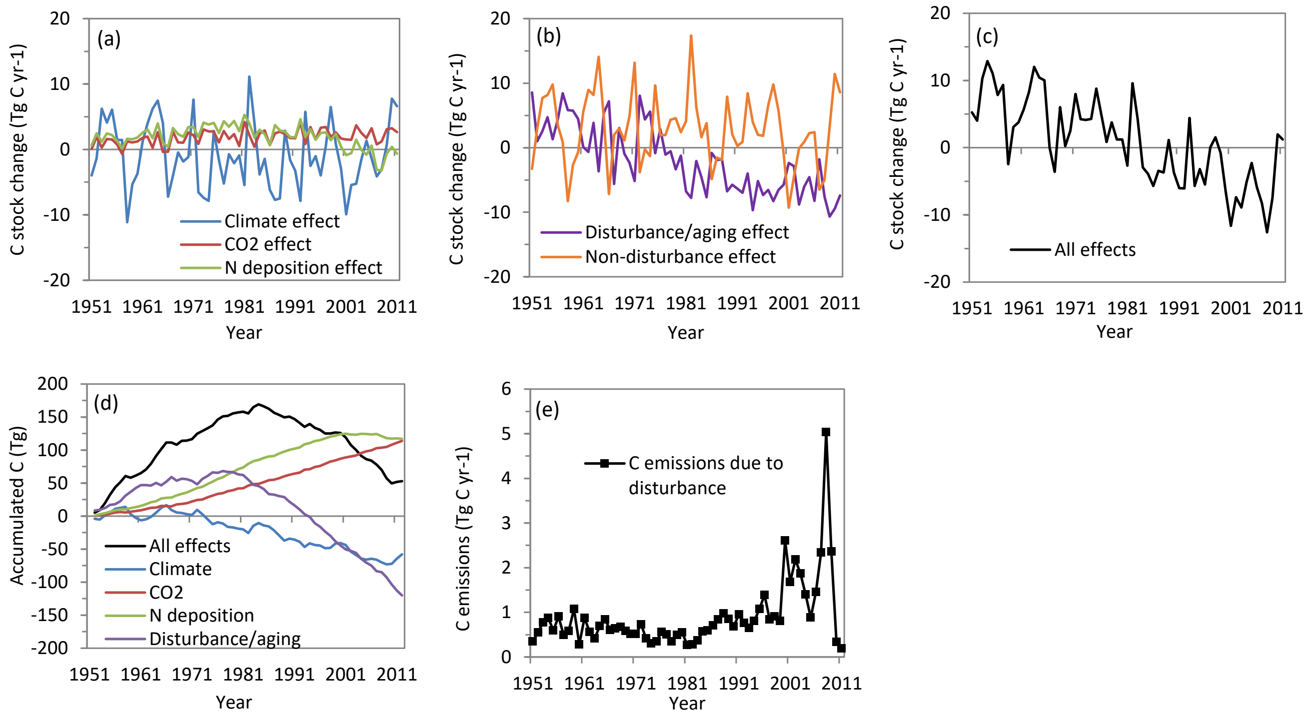

Figure 77a-e. Estimated forest carbon (C) changes and accumulations summed across the national forests in the Pacific Southwest Region. Changes in C stocks are attributed to: (a) individual nondisturbance factors alone, including climate variability, atmospheric carbon dioxide (CO2) concentration, and nitrogen deposition; (b) all disturbance and aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all nondisturbance factors combined; and (c) all factors combined, which is the sum of disturbance and aging and nondisturbance effects. (d) Accumulated C due to individual disturbance and aging and nondisturbance factors and all factors combined from 1950 through 2011 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in graphs (a) through (c) represent net C sinks from the atmosphere, or increases in C stocks, whereas negative values represent net C sources to the atmosphere, or decreases in C stocks.

The forest C dynamics in the Pacific Southwest Region have also been influenced by a recent increase in disturbances. Although the percentage of forest land harvested remained around 0.1 percent annually from 1991 to 2011, the percentage of forests burned by moderate-severity fires has greatly increased since 2000. In 2008 fires affected more than 2 percent of all forested areas in these national forests (fig. 70a). Despite this increase in disturbances, the stand-age distribution does not yet reflect an increase in regeneration (fig. 74).

While precipitation from 1951 to 2011 did not show a consistent trend, the 1982 to 1983 “super” El Niño event stands out as a period of significantly elevated precipitation (fig. 76a). Wetter conditions can enhance forest growth and C uptake. On the other hand, temperatures increased substantially from 1951 to 2011 (fig. 76b). Warmer temperatures can increase soil respiration and evaporative demands, leading to water stress and declines in net ecosystem productivity. Consequently, more C is released to the atmosphere. As climate continues to change, this region along with most of the United States is expected to get warmer while precipitation will continue to vary annually. Nitrogen deposition increased steadily from 1951 through the mid-1990s before spiking in 1998 to 1999 (fig. 76c). Nitrogen deposition then declined in the 2000s, possibly as the result of tighter environmental regulations or drought conditions decreasing the amount of wet deposition. Atmospheric CO_2 concentrations have risen dramatically and are expected to continue to rise for the foreseeable future.

The C stock changes and accumulations across national forests in this region show that forests generally experienced a switch from a C sink to a C source around the early 1980s (figs. 77a–c). As a result of this shift, C accumulation has been steadily declining since the mid-1980s (fig. 77d). Disturbance and aging effects have been mostly responsible for declining C stocks (fig. 77b), which can be attributed to the timing of Euro-American settlement, land use change, or potentially large fires that shaped forest structure (fig. 74). From the 1950s to the early 1980s, the forests were mostly a C sink due to positive disturbance and aging effects, as the early-1900s pulse of stands was middle-aged and therefore growing at maximum productivity. As these forests further aged, productivity declined and subsequently the rate of C accumulation declined. Meanwhile the effects of disturbance were increasing to the point where C emissions due to decomposition and disturbances exceeded C gains, and as a result the forests became a C source (figs. 77b,c). This decline was coupled with lower rates of stand establishment in the mid-1900s. Additionally, recent large fires caused pulses of C emissions to the atmosphere (fig. 77e), and disturbance and aging effects maintained a C source through 2011 (fig. 77b).

Climate has had a highly variable effect on changing C stocks following interannual variability in temperature and precipitation (figs. 76a,b). Generally climate had a positive effect on C stock change during cooler or wetter years such as 1971 and 2010, and especially during the El Niño of 1982 to 1983 (fig. 77a). On the other hand, climate effects caused a C source during warmer or drier years such as 1958 to 1959 and 2001. The increasing trend in temperatures has had a negative effect on C stocks and contributed to the switch to a C source (fig. 77a) and decline in C accumulation in recent decades (fig. 77d).

Increases in N deposition (fig. 76c) and atmospheric CO2 concentrations have consistently enhanced the C sink and helped to counteract the negative disturbance and aging and climate effects (figs. 77a,d). Without these positive effects from N deposition and CO_2 fertilization, forests would have experienced a net loss of C between 1950 and 2011. However, the N deposition effect decreased in the 2000s (fig. 77a) as N deposition levels were significantly reduced (fig. 76c). The increasing atmospheric CO_2 concentrations have the potential to continue to counteract the negative disturbance and aging and climate effects into the future.

Although a few national forests in the Pacific Southwest Region had a net loss of forest C, most forests had C gains from 1950 to 2011, resulting in a regionwide gain of approximately 53 Tg of ecosystem C, including soil C, between 1950 and 2011 (fig. 77d).

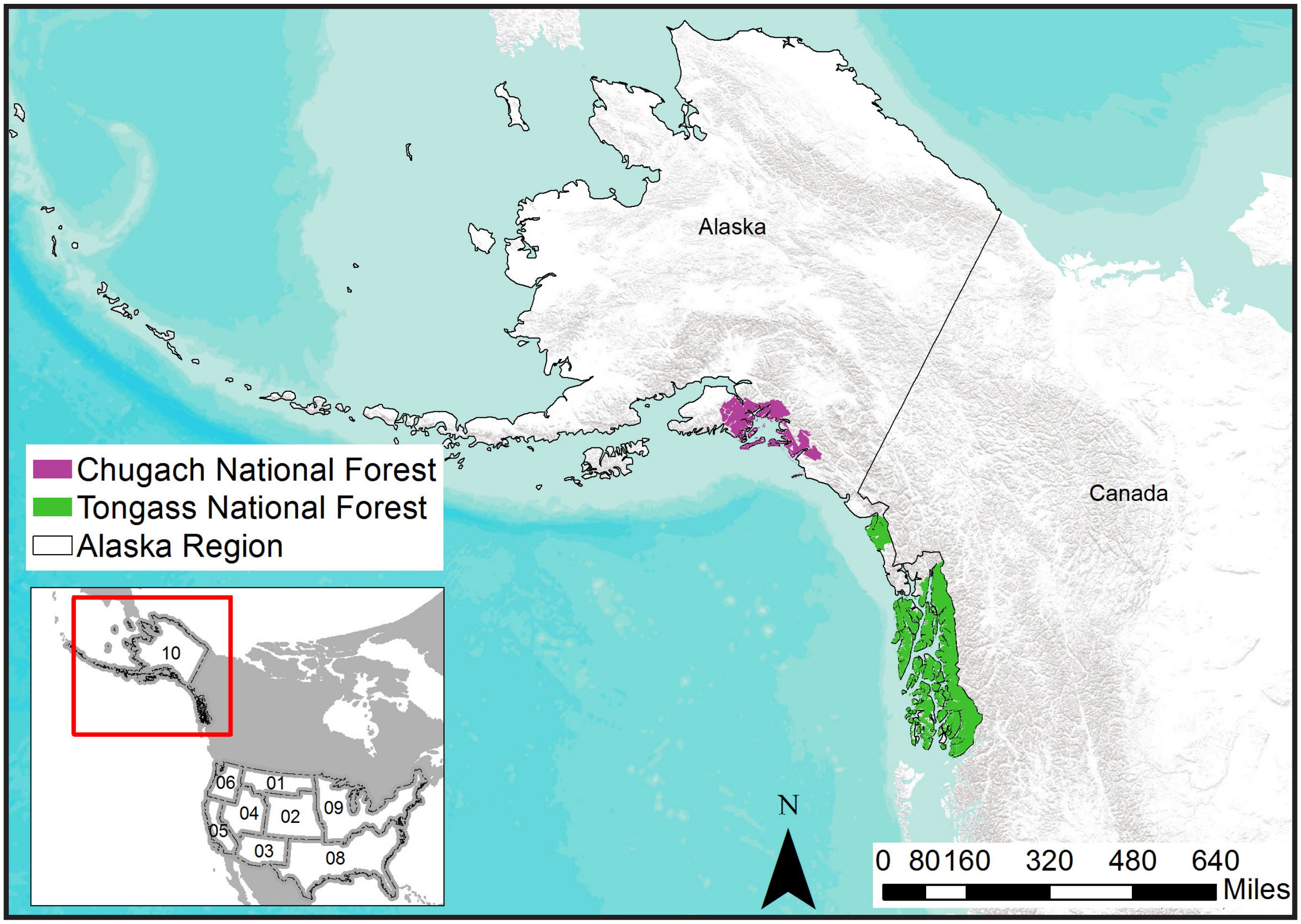

Figure 78. Locations of the national forests in the Alaska Region.

6.9 Alaska Region

6.9.1 Description of Region

The Alaska Region (also referred to as Region 10) in the National Forest System consists of two of the largest national forests in the United States. These units are located on the mainland and islands of southeastern Alaska (fig. 78). The analysis of factors contributing to C stocks and trends was conducted only on the forested areas of these national forests. To restrict the analysis to lands managed by the Forest Service, any private inholdings within national forest boundaries were excluded.

The history of Euro-American settlement, land use, and policies provides useful context for understanding the regional forest C trends that are indicated by the inventory and assessment results. The first Euro-American settlers came to Alaska for the fur trade, the salmon industry, and mining operations. Not until the Klondike gold discovery in 1888, however, was a major boom in settlement spawned in southeastern Alaska. Early timber operations generally supported local development and the needs of the fishing and mining industries but remained small-scale as the distance to prime markets hindered expansion. Despite the influence of the conservation movement in the early 1900s, which led to the establishment of forest reserves in Alaska (e.g., the Tongass and Chugach National Forests in 1907), the forest products industry grew steadily in southeastern Alaska (Haycox 2002).

Both World Wars caused an increase in harvesting operations to support aircraft manufacturing. In 1947, Congress passed the Tongass Timber Act, which authorized long-term timber contracts to support pulp mills in southern Alaska. Annual timber harvests consequently quadrupled in the 1950s. Most of the commercial timber harvests in southeastern Alaska had historically occurred in high-volume old-growth stands. Ecological concerns over the value of intact old-growth forest led to a policy shift from mandated timber harvesting to multiple resource use management of the national forests in the Alaska Region (Sisk 2007). Overall, annual timber harvests in the Alaska Region peaked in the 1970s and late 1980s, but declined precipitously in the 1990s. Since 2000 they have remained at the low levels of the early 1900s (Loeffler et al. 2014a).

Aside from the timber industry, the forest C legacy of the Alaska Region is tied to the history of natural disturbances. Unlike much of the western United States, fires are relatively minor. Since 1900, few fires in southeastern Alaska have burned more than 100 acres (40 hectares), as a result of the cool, moist, temperate-rainforest conditions. In contrast, wind is a common and highly destructive disturbance agent within these coastal forests. The most damaging windstorm was the 1968 Thanksgiving Day storm, which was characterized by up to 100 mile per hour (160 km/hr) winds and left some 1 billion board feet (2 million m^3) of timber in a single concentrated blowdown as well as several smaller scattered blowdowns (Harris and Farr 1974).

In addition to wind, insects such as the spruce beetle are a key disturbance agent in the Alaska Region (Bentz et al. 2010). From 1990 to 2000 an extensive spruce beetle outbreak resulted in the mortality of about 4.7 million acres (1.9 million hectares) of forests in south-central Alaska. Warming temperatures increase the susceptibility to spruce beetle out-breaks while also altering the life-cycle of spruce beetles, thus increasing their numbers

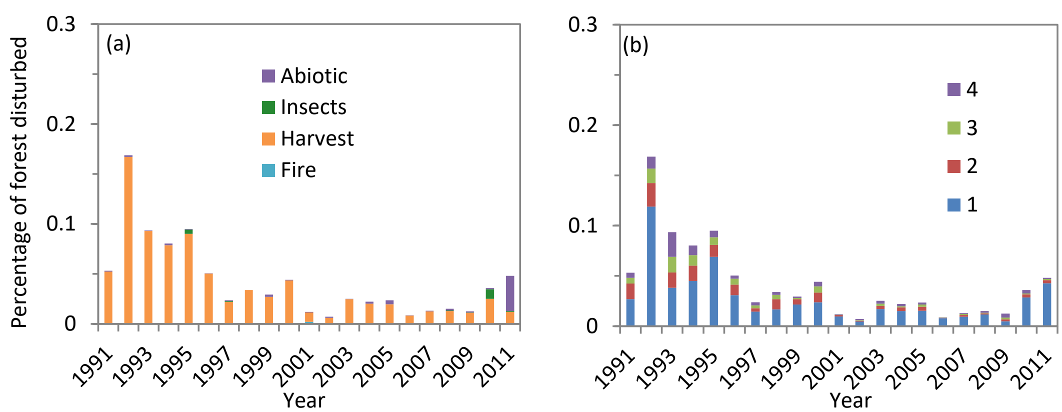

Figure 79a-b. Annual rates of disturbance (0 to 0.3 percent) in the Alaska Region, mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991 through 2011 by (a) disturbance types including fire, harvests, insects, and 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.

(Werner et al. 2006). Due to its high latitude, Alaska has seen a more rapid increase in temperatures during the last century than any other U.S. region, so climate change impacts on the region's forests are especially intense (Haufler et al. 2010).

6.9.2 Disturbance Trends

Mapped rates of fire, harvest, and insect activity and the intensity of these disturbances (change in canopy cover) for the Alaska Region are displayed in figure 79. The disturbance maps were derived from Landsat satellite imagery; a systematic process of manual editing and attribution of disturbance type using spatial records of harvests, fire, and insects; and high- and medium-resolution imagery. Harvest was the most common and consistent type of forest disturbance in the region although harvest rates exceeded 0.1 percent of the landscape in only 1 year during the study period and there was a general downward trend from the early 1990s to 2011 (fig. 79a). Low-level insect disturbance occurred throughout the period, and storm damage was relatively extensive in 2011. During this period, more than 60 percent of the disturbed area was characterized as low intensity (<25 percent change in canopy cover) (fig. 79b).

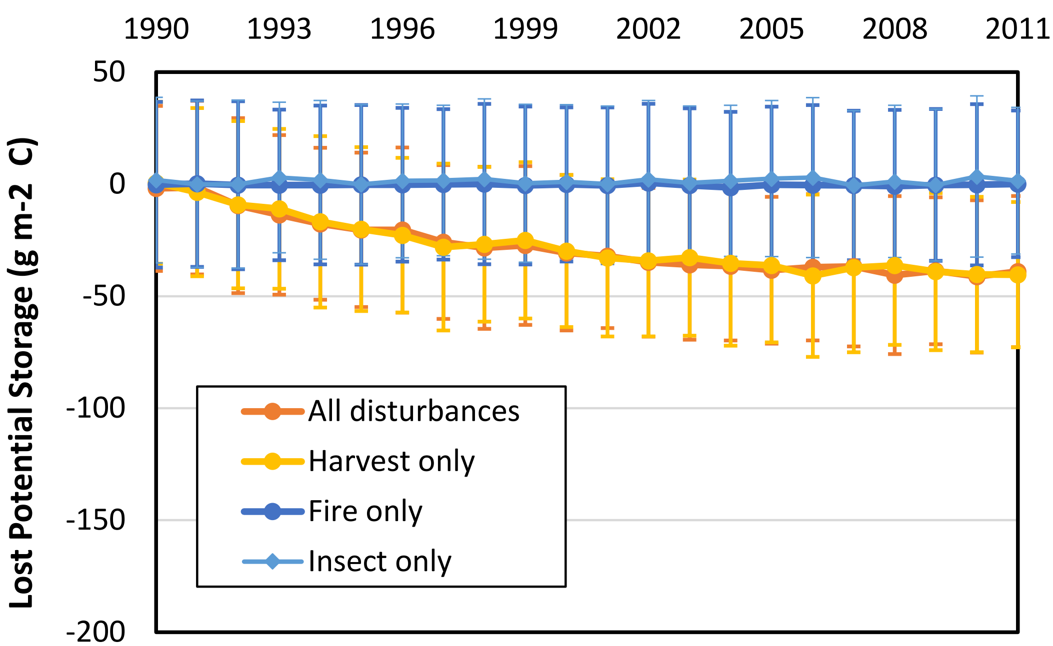

Figure 80. The impact of different kinds of disturbance, occurring from 1990 through 2011, on carbon (C) stores in the Alaska Region. The difference in storage for each year is shown between an "undisturbed" scenario and a scenario that includes only observed amounts of the specified type of disturbance. Error bars represent a 95-percent confidence interval; 100 g/m^2 equals 1 metric tonne (or Mg)/ha.

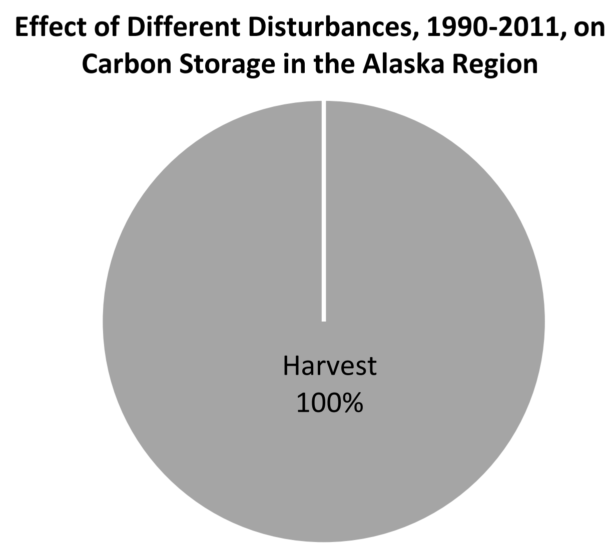

Figure 81. Proportional effect of different kinds of disturbance on carbon storage in both national forests in the Alaska Region for the period 1990 through 2011.

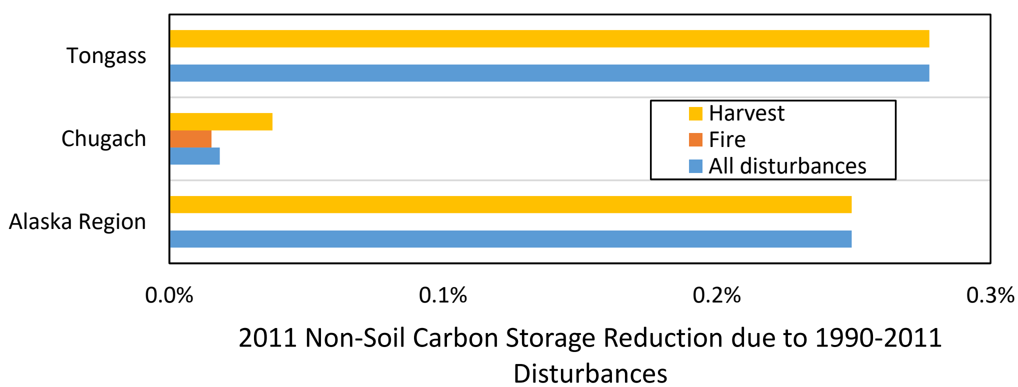

Figure 82. Carbon stock reduction in 2011 due to disturbances occurring from 1990 through 2011, by each national forest and for all national forests combined in the Alaska Region. Percent reduction represents how much nonsoil carbon was lost from the baseline forest inventory carbon stock estimates.

6.9.3 Effects of Disturbance and Management Activities

The primary purpose of ForCaMF is to estimate the relative impacts of different kinds of disturbance in the last two decades on current C stocks, displayed for the Alaska Region in figure 80. The impact of disturbance (D_F, as defined in eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires first occur in 1992, for example, the line of fire in figure 80 will only start to diverge from zero in that year. The fire line may continue to diverge because ForCaMF's accounting of postfire C stocks will (realistically) reflect gradual release of fire-killed material, partially offsetting C gained through regrowth and persistently increasing the difference between postfire C storage and storage likely under an undisturbed scenario. Thus, figure 80 reflects the real-time impact of disturbance on the forest's ability to store C in relation to storage likely in the absence of disturbance.

Harvest activity was effectively the only disturbance process to have an impact on C stocks in the region (figs. 80, 81); the detected fire and insect activity on the two national forests had negligible impact on C stocks at the regional level. Harvest impact, though larger than the other types of disturbance, was among the smallest of any of the regions because cutting generally affected less than 0.05 percent of forest land per year (fig 79). Harvests occurring between 1900 and 2011 resulted in a 0.2-percent reduction in 2011 nonsoil C storage (fig. 82).

One caveat must be stated about the confidence intervals depicted in figure 80. The unit of analysis for ForCaMF was the national forest (Appendix 11: Alaska Region, (PDF, 1.0MB)); rates of simulated error were constrained by FIA estimates at that level. Regional aggregation used a secondary Monte Carlo analysis based on the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in the other forest. This assumption very likely overstated certainty slightly at the regional level; if initial biomass estimates in one forest were high, for example, the same estimates were also likely to be biased high in the other unit. This caveat does not change the overall trends seen at the aggregated regional level, nor does it affect confidence intervals assessed at the national forest level. Harvests were clearly the most important disturbance process with respect to C storage, although fire and wind were locally important.

6.9.4 Effects of Disturbance, Management, and Environmental Factors

The InTEC model was not applied to the national forests in Alaska.

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Appendix 1: Description of Forest-Type Group and Forest Dominance-Type Aggregations, and Common and Scientific Names of Flora and Fauna Mentioned in this Report Forest Inventory and Analysis Forest-Type Groups

Following are forest types and forest-type groups as defined by the Forest Inventory and Analysis (FIA) program of the Forest Service, Department of Agriculture (Burrill et al. 2018). An FIA database code is also associated with each forest type or forest-type group. Carbon modeling in all national forest system regions, except for the Northern Region, used this FIA forest-type group classification. Scientific names accompany each genus or species.

100 White/red/jack pine group
- 101 Jack pine (*Pinus banksiana*)
- 102 Red pine (*Pinus resinosa*)
- 103 Eastern white pine (*Pinus strobus*)
- 104 Eastern white pine/eastern hemlock (*Pinus strobus/Tsuga canadensis*)
- 105 Eastern hemlock (*Tsuga canadensis*)

120 Spruce/fir group
- 121 Balsam fir (*Abies balsamea*)
- 122 White spruce (*Picea glauca*)
- 123 Red spruce (*Picea rubens*)
- 124 Red spruce/balsam fir (*Picea rubens/Abies balsamea*)
- 125 Black spruce (*Picea mariana*)
- 126 Tamarack (*Larix laricina*)
- 127 Northern white-cedar (*Thuja occidentalis*)
- 128 Fraser fir (*Abies fraseri*)
- 129 Red spruce/Fraser fir (*Picea rubens/Abies fraseri*)

140 Longleaf/slash pine group
- 141 Longleaf pine (*Pinus palustris*)
- 142 Slash pine (*Pinus elliotti*)

150 Tropical softwoods group
- 151 Tropical pines (*Pinus* spp.)

160 Loblolly/shortleaf pine group
- 161 Loblolly pine (*Pinus taeda*)
- 162 Shortleaf pine (*Pinus echinata*)
- 163 Virginia pine (*Pinus virginiana*)
- 164 Sand pine (*Pinus clausa*)
- 165 Table mountain pine (*Pinus pungens*)
- 166 Pond pine (*Pinus serotina*)

167 Pitch pine (*Pinus rigida*)
168 Spruce pine (*Pinus glabra*)

170 Other eastern softwoods group
171 Eastern redcedar (*Juniperus virginiana*)
172 Florida softwoods

180 Pinyon/juniper group
182 Rocky Mountain juniper (*Juniperus scopulorum*)
184 Juniper woodland (*Juniperus* spp.)
185 Pinyon/juniper woodland (*Pinus* spp./*Juniperus* spp.)

200 Douglas-fir group
201 Douglas-fir (*Pseudotsuga menziesii*)
202 Port-Orford-cedar (*Chamaecyparis lawsoniana*)
203 Bigcone Douglas-fir (*Pseudotsuga macrocarpa*)

220 Ponderosa pine group
221 Ponderosa pine (*Pinus ponderosa*)
222 Incense-cedar (*Calocedrus decurrens*)
224 Sugar pine (*Pinus lambertiana*)
225 Jeffrey pine (*Pinus jeffreyi*)
226 Coulter pine (*Pinus coulteri*)

240 Western white pine group
241 Western white pine (*Pinus monticola*)

260 Fir/spruce/mountain hemlock group
261 White fir (*Abies concolor*)
262 Red fir (*Abies magnifica*)
263 Noble fir (*Abies procera*)
264 Pacific silver fir (*Abies amabilis*)
265 Engelmann spruce (*Picea engelmannii*)
266 Engelmann spruce/subalpine fir (*Picea engelmannii/Abies lasiocarpa*)
267 Grand fir (*Abies grandis*)
268 Subalpine fir (*Abies lasiocarpa*)
269 Blue spruce (*Picea pungens*)
270 Mountain hemlock (*Tsuga mertensiana*)
271 Alaska-yellow-cedar (*Chaemaecyparis nootkatensis*)

280 Lodgepole pine group
281 Lodgepole pine (*Pinus contorta*)

300 Hemlock/Sitka spruce group
301 Western hemlock (*Tsuga heterophylla*)
304 Western redcedar (*Thuja plicata*)
305 Sitka spruce (*Picea sitchensis*)

320 Western larch group
321 Western larch (*Larix laricina*)

340 Redwood group
341 Redwood (*Sequoia sempervirens*)
342 Giant sequoia (*Sequoiadendron giganteum*)

360 Other western softwoods group
361 Knobcone pine (*Pinus attenuata*)
362 Southwestern white pine (*Pinus strobiformis*)
363 Bishop pine (*Pinus muricata*)
364 Monterey pine (*Pinus radiata*)
365 Foxtail pine/bristlecone pine (*Pinus balfouriana/Pinus aristata*)
366 Limber pine (*Pinus flexilis*)
367 Whitebark pine (*Pinus albicaulus*)
368 Miscellaneous western softwoods
369 Western juniper (*Juniperus occidentalis*)

370 California mixed conifer group
371 California mixed conifer

380 Exotic softwoods group
381 Scotch pine (*Pinus sylvestris*)
383 Other exotic softwoods
384 Norway spruce (*Pinus abies*)
385 Introduced larch (*Larix* spp.)

390 Other softwoods group
391 Other softwoods

400 Oak/pine group
401 Eastern white pine/northern red oak/white ash (*Pinus strobus/Quercus rubra/Fraxinus americana*)
402 Eastern redcedar/hardwood (*Juniperus virginiana*/hardwood)
403 Longleaf pine/oak (*Pinus palustris/Quercus* spp.)
404 Shortleaf pine/oak (*Pinus echinata/Quercus* spp.)
405 Virginia pine/southern red oak (*Pinus virginiana/Quercus falcata*)
406 Loblolly pine/hardwood (*Pinus taeda*/hardwood)
407 Slash pine/hardwood (*Pinus elliottii*)

409 Other pine/hardwood (*Pinus* spp./hardwood)

500 Oak/hickory group

501 Post oak/blackjack oak (*Quercus stellata/Quercus marilandica*)
502 Chestnut oak (*Quercus prinus*)
503 White oak/red oak/hickory (*Quercus alba/Quercus* spp./*Carya* spp.)
504 White oak (*Quercus alba*)
505 Northern red oak (*Quercus rubra*)
506 Yellow-poplar/white oak/northern red oak (*Liriodendron tulipifera/Quercus alba/ Quercus rubra*)
507 Sassafras/persimmon (*Sassafras albidum/Diospyros* spp.)
508 Sweetgum/yellow-poplar (*Liquidambar styraciflua/Liriodendron tulipifera*)
509 Bur oak (*Quercus macrocarpa*)
510 Scarlet oak (*Quercus coccinea*)
511 Yellow-poplar (*Liriodendron tulipifera*)
512 Black walnut (*Juglans nigra*)
513 Black locust (*Robinia pseudoacacia*)
514 Southern scrub oak (*Quercus ilicifolia*)
515 Chestnut oak/black oak/scarlet oak (*Quercus* spp./*Quercus velutina/Quercus coccinea*)
516 Cherry/white ash/yellow-poplar (*Prunus* spp./*Fraxinus americana/Liriodendron tulipifera*)
517 Elm/ash/black locust (*Ulmus* spp./*Fraxinus* spp./*Robinia pseudoacacia*)
519 Red maple/oak (*Acer rubrum/Quercus* spp.)
520 Mixed upland hardwoods

600 Oak/gum/cypress group

601 Swamp chestnut oak/cherrybark oak (*Quercus michauxii/Quercus pagoda*)
602 Sweetgum/Nuttall oak/willow oak (*Liquidambar styraciflua/Quercus texana/ Quercus phellos*)
605 Overcup oak/water hickory (*Quercus lyrata/Carya aquatica*)
606 Atlantic white-cedar (*Chamaecyparis nootkatensis*)
607 Baldcypress/water tupelo (*Taxodium* spp./*Nyssa aquatica*)
608 Sweetbay/swamp tupelo/red maple (*Magnolia virginiana/Nyssa biflora/Acer rubrum*)
609 Baldcypress/pondcypress (*Taxodium* spp./*Taxodium ascendens*)

700 Elm/ash/cottonwood group

701 Black ash/American elm/red maple (*Fraxinus nigra/Ulmus americana/Acer rubrum*)
702 River birch/sycamore (*Betula nigra/Platanus* spp.)
703 Cottonwood (*Populus* spp.)
704 Willow (*Salix* spp.)
705 Sycamore/pecan/American elm (*Platanus* spp./*Carya illinoiensis*)
706 Sugarberry/hackberry/elm/green ash (*Celtis laevigata/Celtis* spp./*Ulmus* spp./

Fraxinus pennsylvanica)
707 Silver maple/American elm (*Acer saccharinum/Ulmus americana*)
708 Red maple/lowland (*Acer rubrum*/lowland)
709 Cottonwood/willow (*Populus* spp./*Salix* spp.)
722 Oregon ash (*Fraxinus texensis*)

800 Maple/beech/birch group

801 Sugar maple/beech/yellow birch (*Acer saccharum/Fagus* spp./*Betula alleghaniensis*)
802 Black cherry (*Prunus serotina*)
805 Hard maple/basswood (*Acer* spp./*Tilia* spp.)
809 Red maple/upland (*Acer rubrum*/upland)

900 Aspen/birch group

901 Aspen (*Populus* spp.)
902 Paper birch (*Betula papyrifera*)
903 Gray birch (*Petula populifolia*)
904 Balsam poplar (*Populus balsamifera*)
905 Pin cherry (*Prunus pensylvanica*)

910 Alder/maple group

911 Red alder (*Alnus rubra*)
912 Bigleaf maple (*Acer macrophyllum*)

920 Western oak group

921 Gray pine (*Pinus sabiniana*)
922 California black oak (*Quercus kelloggii*)
923 Oregon white oak (*Quercus garryana*)
924 Blue oak (*Quercus douglasii*)
931 Coast live oak (*Quercus agrifolia*)
933 Canyon live oak (*Quercus chrysolepis*)
934 Interior live oak (*Quercus wislizeni*)
935 California white oak (valley oak) (*Quercus lobaba*)

940 Tanoak/laurel group

941 Tanoak (*Lithocarpus densiflorus*)
942 California laurel (*Umbellaria californica*)
943 Giant chinkapin (*Chrysolepis chrysophylla* var. *chrysophylla*)

960 Other hardwoods group

961 Pacific madrone (*Arbutus menziesii*)
962 Other hardwoods

970 Woodland hardwoods group

971 Deciduous oak woodland

972 Evergreen oak woodland
973 Mesquite woodland (*Prosopis* spp.)
974 Cercocarpus (mountain brush) woodland
975 Intermountain maple woodland
976 Miscellaneous woodland hardwoods

980 Tropical hardwoods group

982 Mangrove (*Avicennia germinans, Conocarpus erectus, Laguncularia racemosa, Rhizophora mangle*)
983 Palms (family Arecaceae)
984 Dry forest
985 Moist forest
986 Wet and rain forest
987 Lower montane wet and rain forest
989 Other tropical hardwoods

990 Exotic hardwoods group

991 Paulownia (*Paulownia tomentosa*)
992 Melaleuca (*Melaleuca quinquenervia*)
993 Eucalyptus (*Eucalyptus* spp.)
995 Other exotic hardwoods

988 Cloud forest

999 Nonstocked

Dominance Types in the Northern Region

Carbon modeling for the Northern Region made use of forest dominance types instead of the FIA forest-type groups shown previously. Dominance types are defined by the species with the greatest abundance of canopy cover, basal area, or trees per acre (hectare) within a setting. The species that define the dominance type are always of the same lifeform; therefore, it is first necessary to identify the dominant lifeform and subclass. The following dominance types have been identified in the Northern Region (Brown and Barber 2012):

Douglas-fir (PSME): Douglas-fir (*Pseudotsuga menziesii*) composes 60 percent or more of total relative tree abundance.

Lodgepole pine (PICO): Lodgepole pine (*Pinus contorta*) composes 60 percent or more of total relative tree abundance.

Subalpine fir (ABLA): Subalpine fir (*Abies lasiocarpa*) composes 60 percent or more of total relative tree abundance.

Ponderosa pine (PIPO): Ponderosa pine (*Pinus ponderosa*) composes 60 percent or more of total relative tree abundance.

Hardwood mixed (HMIX): Abundance of all hardwood trees exceeds 40 percent of total relative tree abundance.

Shade-intolerant mixed (IMIX): Abundance of all hardwood and shade-intolerant conifer trees exceeds 50 percent of total relative tree abundance.

Shade-tolerant mixed (TMIX): Abundance of all hardwood and shade-intolerant conifer trees is less than 50 percent of total relative tree abundance.

Common and Scientific Names of Fauna Mentioned in this Report

hemlock woolly adelgid (*Adelges tsugae*)

emerald ash borer (*Agrilus planipennis*)

cattle, oxen (*Bos taurus*)

eastern spruce budworm (*Choristoneura fumiferana*)

bark beetle (family Curculionidae, subfamily Scolytinae)

southern pine beetle (*Dendroctonus frontalis*)

mountain pine beetle (*Dendroctonus ponderosae*)

spruce beetle (*Dendroctonus rufipennis*)

gypsy moth (*Lymantria dispar*)

forest tent caterpillar (*Malacosoma disstria*)

sheep (*Ovis aries*)

northern spotted owl (*Strix occidentalis caurina*)

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Appendix 2: Online Resources

Appendices 3-11: Regional Disturbance Carbon Assessments

Appendix 3: Eastern Region
Appendix 4: Southern Region
Appendix 5: Northern Region
Appendix 6: Rocky Mountain Region
Appendix 7: Intermountain Region
Appendix 8: Pacific Northwest Region
Appendix 9: Southwestern Region
Appendix 10: Pacific Southwest Region
Appendix 11: Alaska Region

Baseline Carbon Reports - https://www.fs.fed.us/managing-land/sc/carbon

Northern Region (R1) Report
Rocky Mountain Region (R2) Report
Southwestern Region (R3) Report
Intermountain Region (R4) Report
Pacific Southwest Region (R5) Report
Pacific Northwest Region (R6) Report
Southern Region (R8) Report
Eastern Region (R9) Report
Alaska Region (R10) Report
Regional Baseline Rational

Climate Change - Land Management & Project Planning -
https://www.fs.fed.us/emc/nepa/climate_change/index.shtml

Climate Change Performance Scorecard -
https://www.fs.fed.us/climatechange/advisor/scorecard/scorecard-guidance-08-2011.pdf

Ecosystem Restoration Policy and Directive (FSH 2020) - https://www.federalregister.gov/documents/2016/04/27/2016-09750/ecosystem-restoration-policy

National Roadmap for Responding to Climate Change -
https://www.fs.fed.us/climatechange/pdf/Roadmapfinal.pdf

Research Data Archive - https://www.fs.usda.gov/rds/archive/catalog/RMRS-GTR-402-s1

Scorecard Appendix F: Carbon Asessment Technical Guidance -
https://www.fs.fed.us/climatechange/advisor/scorecard/appendix/F%201-21-2011.pdf

U.S. Forest Planning Rule - https://www.fs.usda.gov/planningrule

Weeks Act - https://www.fs.fed.us/land/staff/Documents/Weeks%20Law.pdf

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