7. Forestry

Convening Lead Authors
Linda A. Joyce, U.S. Forest Service
Steven W. Running, University of Montana

Lead Authors
David D. Breshears, University of Arizona
Virginia H. Dale, Oak Ridge National Laboratory
Robert W. Malmsheimer, SUNY Environmental Science and Forestry
R. Neil Sampson, Vision Forestry, LLC
Brent Sohngen, Ohio State University
Christopher W. Woodall, U.S. Forest Service

Key Messages

1. **Climate change is increasing the vulnerability of forests to ecosystem change and tree mortality through fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but could be more sensitive to periodic drought.**
2. **U.S. forests currently absorb about 13% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.**
3. **Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.**
4. **The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.**

Forests provide valuable commodities, like wood products, as well as benefits like recreational opportunities and lifestyle amenities that are more difficult to assess in monetary terms (Vose et al. 2012). Increasingly, forest managers, policymakers, and the public recognize that forests are valuable in many ways, providing everything from clean drinking water to wildlife habitat. This recognition has resulted in increased conservation management on both public and private land in recent decades.

In addition to these economic, social and ecological values, forests provide opportunities to reduce future climate change by capturing and storing carbon, as well as by providing resources for bioenergy production. The total amount of carbon stored in U.S. forest ecosystems and wood products equals roughly 25 years of U.S. heat-trapping gas emissions at current rates of emission, providing an important national "sink" that could grow or shrink depending on the extent of climate change, forest management practices, and other factors (EPA 2012; Woodall et al. 2011). For example, in 2010, U.S. forest ecosystems and the associated wood products industry captured and stored roughly 13% of all carbon dioxide emitted in the U.S. (EPA 2012). Forestland resources also have vast potential to produce bioenergy from 504 million acres of timberland and 91 million acres of other forestland (DOE 2011).

Economic considerations have historically influenced both the overall area of forestlands and their management, and will continue to do so. From 1700 to 1935, forests were extensively harvested for wood to use for heating and building materials and then converted to other uses, primarily for agriculture (Birdsey et al. 2006). This historic reduction in forest cover has partially reversed through forest regrowth on abandoned agricultural lands. However, conversion of forests to other uses, like urban expansion, continues (USFS 2012).

Today, private entities own 56% of the forestlands in the United States, primarily in the eastern states. The remaining 44% of forests are on public lands, primarily in the western U.S. Different challenges and opportunities exist for public and for private forest management decisions, especially when climate-related issues are considered on a national scale.

Forest health decline and an increase in forest disturbances on both public and private land are projected due to increases in wildfire, insects, disease, drought, and extreme events. At the same time, there is growing awareness that forests may play an expanded role in carbon management. Addressing climate change effects on forests requires considering the interactions among land-use practices, energy options, and climate change (Dale et al. 2011).

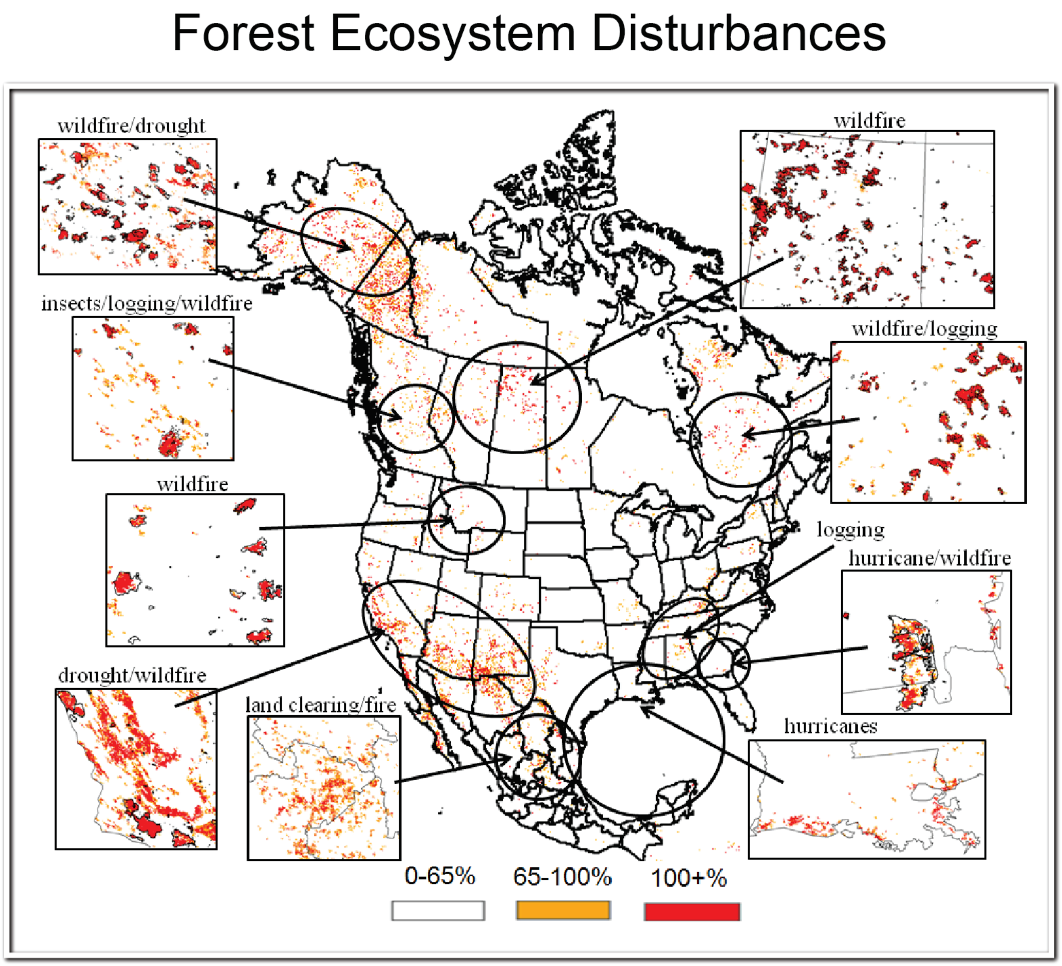


Figure 7.1: Forest Ecosystem Disturbances

Caption: The distribution of major forested ecosystem disturbance types in North America varies by topography, vegetation, weather patterns, climate gradients, and proximity to human settlement. Severity is mapped using the MODIS Global Disturbance Index, with moderate (orange) and high (red) severity. Fire along with other disturbances dominates much of the western forested ecosystems. Storms affect the Gulf Coast of the U.S., insect damage is widespread but currently concentrated in western regions, and timber harvest prevails in the Southeast. Figure source: (Goetz et al. 2012); Copyright 2012 American Geophysical Union.

Increasing Forest Disturbances

Climate change is increasing the vulnerability of forests to ecosystem change and tree mortality through fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but could be more sensitive to periodic drought.

Insect outbreaks and pathogens, invasive species, wildfires, and extreme events such as droughts, high winds, ice storms, hurricanes, and landslides induced by storms (Dale et al. 2001) are all disturbances that affect U.S. forests and their management. These disturbances are part of forest dynamics, are often interrelated, and can be amplified by underlying trends – for example, decades of rising average temperatures can increase damage to forests when a drought occurs (Jentsch et al. 2007). Forest disturbances with large ecosystem effects occur relatively infrequently, making detection of changes related to climatic extremes more difficult than for changes in average conditions (CCSP 2009a; IPCC 2012; Smith 2011).

Factors affecting tree death, such as drought, higher temperatures, and/or pests and pathogens, are often interrelated, which means that isolating a single cause of mortality is rare (Allen et al. 2010; Dukes et al. 2009; McDowell et al. 2008). However, rates of tree mortality due to one or more of these factors have increased with higher temperatures in western forests (Van Mantgem et al. 2009; Williams et al. 2010) and are well correlated with both rising temperatures and associated increases in evaporative water demand (Williams et al. 2012). These factors are consistent with recent large-scale die-off events for multiple tree species observed across the United States (Allen et al. 2010; Raffa et al. 2008). In eastern forests, forest composition, forest structure, and pollutants appear to be more important than climate in causing large-scale tree mortality over recent decades. Nonetheless, tree mortality is sensitive to rising temperature (Dietze and Moorcroft 2011), and is expected to increase as climate warms. Because disturbances are normal yet rare at large scales, the extent to which recent forest disturbances can be directly attributed to climate change is uncertain. However, a growing body of research documents clear linkages between climatic conditions projected for the future and subsequent ecosystem responses, and confirms emerging risks to forests.

Future disturbance rates in forests will depend on changes in the frequency of extreme events as well as the projected underlying trends (Jentsch et al. 2007; Smith 2011). While past forest dynamics have been driven predominantly by drought only, future dynamics will be responding to drought and higher temperatures. Trees die faster when higher temperatures accompany drought; thus a shorter drought can trigger mortality. Short droughts occur more frequently than long droughts, therefore the direct effect of rising temperatures, without a change in drought frequency, could result in substantially greater mortality (Adams et al. 2009). Further, this type of disturbance will be compounded by other interacting factors, such as more frequent and/or severe drought, biotic disturbances, and land-use change.

Given strong relationships between climate and fire, even when modified by land use and management, projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010). Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires, such as has been seen in Florida (see Ch.17: Southeast).

Extensive tree mortality or decline in growth rates are projected to increase under future climate conditions for western forests and eastern forests, in response to drought, rising temperatures, and/or pests and pathogens (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010). Although rising temperatures and CO_2 levels can increase growth or migration of tree species (Saxe et al. 2008; Vose et al. 2012; Woodall et al. 2009), most eastern species groups exhibit increases in mortality with rising temperature (Dietze and Moorcroft 2011). Tree mortality is often a combination of many factors, thus increases in pollutants, droughts, and wildfires will increase the probability of a tree dying. Under projected climate conditions, rising temperatures could become more important than, or work together with, stand characteristics and these other stressors to increase mortality. As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off or decline (Dale et al. 2010b) similar to recent die-offs in western forests (Allen et al. 2010; Raffa et al. 2008), which already have been more severe even than recent estimates (IPCC 2007). New evidence indicates that most tree species maintain only a small hydraulic safety margin, reinforcing the idea that mesic as well as semiarid forests are vulnerable to drought-induced mortality under warming climates (Choat et al. 2012).

Consequences of large scale die-off and wildfire disturbance events pose major challenges to forest management, as impacts cut across all major categories of ecosystem goods and services. These events could have potential impacts occurring at up to regional scales for timber, flooding and erosion risks, other changes in water budgets, biogeochemical changes including carbon storage, and aesthetics (Adams et al. 2010; Allen et al. 2010; Anderegg et al. 2012; Breshears et al. 2011; Campbell et al. 2009; Ehrenfeld 2010; Hicke et al. 2012). Rising disturbance rates can increase harvested wood output and potentially lower prices, particularly given that annual U.S. forest growth currently exceeds harvesting. However, higher disturbance rates will make forest investments more risky and more costly; thus output are likely to be lowered. Western forests could also lose substantial amounts of carbon storage capacity as a result of high disturbance events. For example, high disturbance events such as increased wildfires, insect outbreaks and droughts that are severe enough to alter soil moisture and nutrients can result in changes in tree density or species composition (Hicke et al. 2012). This would result in considerable carbon losses, and as a consequence, alter long-term carbon storage or the rate of carbon cycling (Hicke et al. 2012). In addition, projections to date of potential increases in carbon storage may not adequately estimate die-off and wildfire conditions under higher temperatures (McDowell et al. 2011; North et al. 2009).

Effectiveness of Fuel Treatments

Figure 7.2: Effectiveness of Fuel Treatments

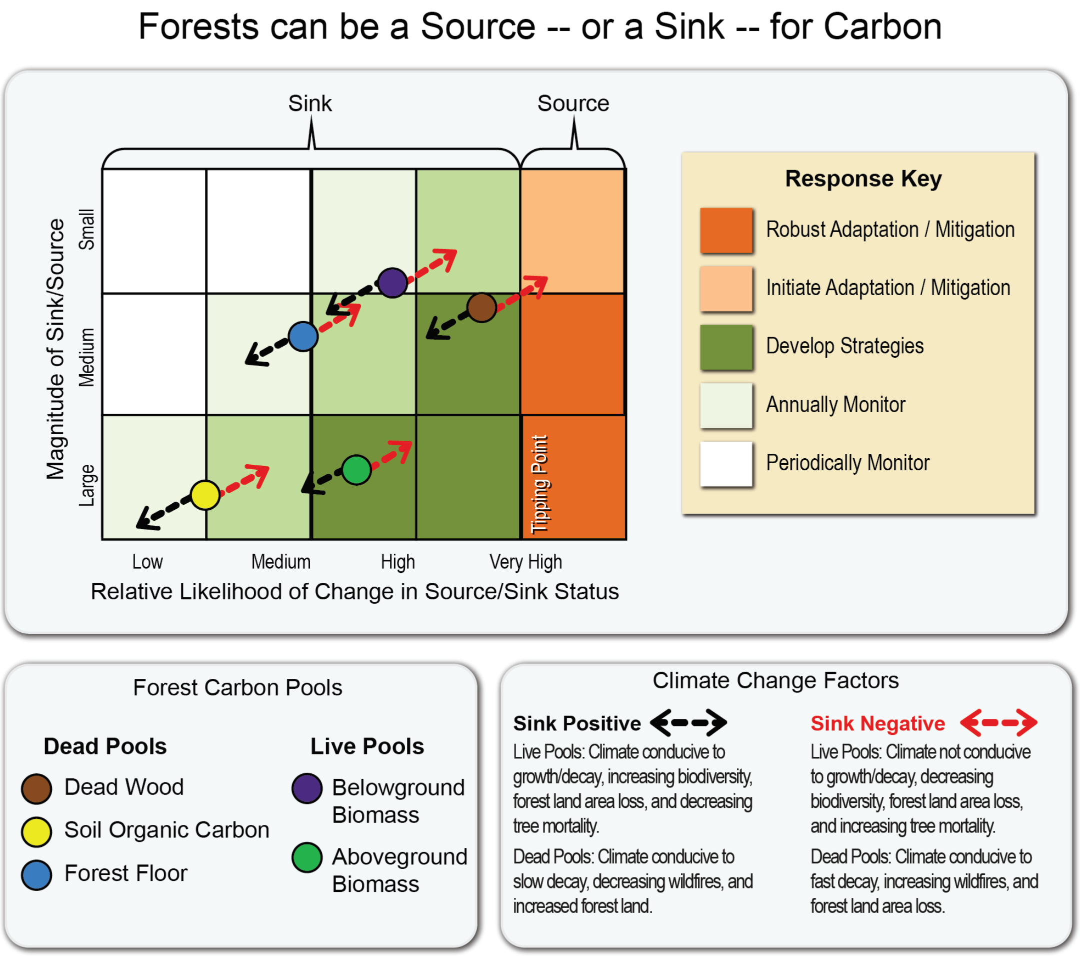
Caption: Forest treatments that maintain uneven-aged forest structure and create small openings in the forest can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona's 2002 Rodeo-Chediski fire, which burned more than 400 square miles, at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercial sized trees, and followed a prescribed fire in 1999, while the upper right side of the photo shows burned area in untreated slope below Limestone Ridge. (Photo credit Jim Youtz, U.S. Forest Service)

Changing Carbon Uptake

U.S. forests currently absorb about 13% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.

Climate-related Effects on Trees and Forest Productivity

Forests within the U.S. grow across a wide range of latitudes and altitudes and occupy all but the driest regions. Current forest cover has been mostly shaped by topography, disturbance frequency, and human activity. Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth was limited by low temperatures and short growing seasons, but are gradually being altered by climate change (Boisvenue and Running 2006; Caspersen et al. 2000; Joos et al. 2002; McKenzie et al. 2001). However, these trends are not universal. Under some observed and projected case studies, while growing season lengthened, the number of days with snow on the ground decreased and water stress increased, as it did in the Rocky Mountain forests (Boisvenue and Running 2010). In the eastern U.S., elevated CO_2 and temperature may increase forest growth and potentially carbon storage, if sufficient water is available. Ecological models project that much of the U.S. will experience species shifts in forests and other vegetation types, suggesting major changes in species composition on more than 5% to 20% of the land area in the U.S. by 2100 (Ch. 8: Ecosystems).



Live Pools: Climate conducive to growth/decay, increasing biodiversity, forest land area loss, and decreasing tree mortality.

Dead Pools: Climate conducive to slow decay, decreasing wildfires, and increased forest land.

Live Pools: Climate not conducive to growth/decay, decreasing biodiversity, forest land area loss, and increasing tree mortality.

Dead Pools: Climate conducive to fast decay, increasing wildfires, and forest land area loss.

Figure 7.3: Forests can be a Source – or a Sink – for Carbon

Caption: Chart shows risk analysis of forest carbon processes as related to availability of current and future soil moisture. Western forests are currently considered limited by moisture and thereby highly susceptible to future changes in environmental conditions. The beneficial effects of elevated CO_2 and the extended growing season length in moderately moist eastern forests will allow opportunity for carbon gain, even though water stress in summer months may increase if precipitation decreases. In contrast, dry eastern forests, though adapted to periodic moisture deficits, will see loss of carbon. Source: (Vose et al. 2012).

Forest Carbon Sequestration and Carbon Management

From the onset of European settlement to the start of the 20th century, changes in U.S. forest cover due to expansion of agriculture, tree harvests, and settlements resulted in net emissions of carbon (Birdsey et al. 2006; McKinley et al. 2011). More recently, with cropland abandonment to forests, technological advances in harvesting, and changes in forest management, U.S. forests now serve as a substantial carbon sink, capturing and storing more than 270 million tons of carbon per year (EPA 2012; King et al. 2007). The amount of carbon taken up by U.S. land sinks is dominated by forests which have annually absorbed 7% to 24% (with a best estimate of about 13%) of fossil fuel CO_2 emissions in the U.S. over the past two decades. (See also the "Carbon Sink" box in Ch. 15: Biogeochemical Cycles.)

The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (see above), as well as shifts in tree species, ranges, and productivity (Dale et al. 2010b; McKinley et al. 2011). Economic factors will affect the future carbon cycle of forests, as the age class and condition of forests are affected by the acceleration of harvesting (EPA 2005; Goodale et al. 2002), land-use changes such as urbanization (USFS 2012), changes in forest types (Sohngen and Brown 2006), and bioenergy development (Choi et al. 2011; Daigneault et al. 2012; DOE 2011; USFS 2012). Societal choices about forest policy will also affect the carbon cycles on public and private forestland.

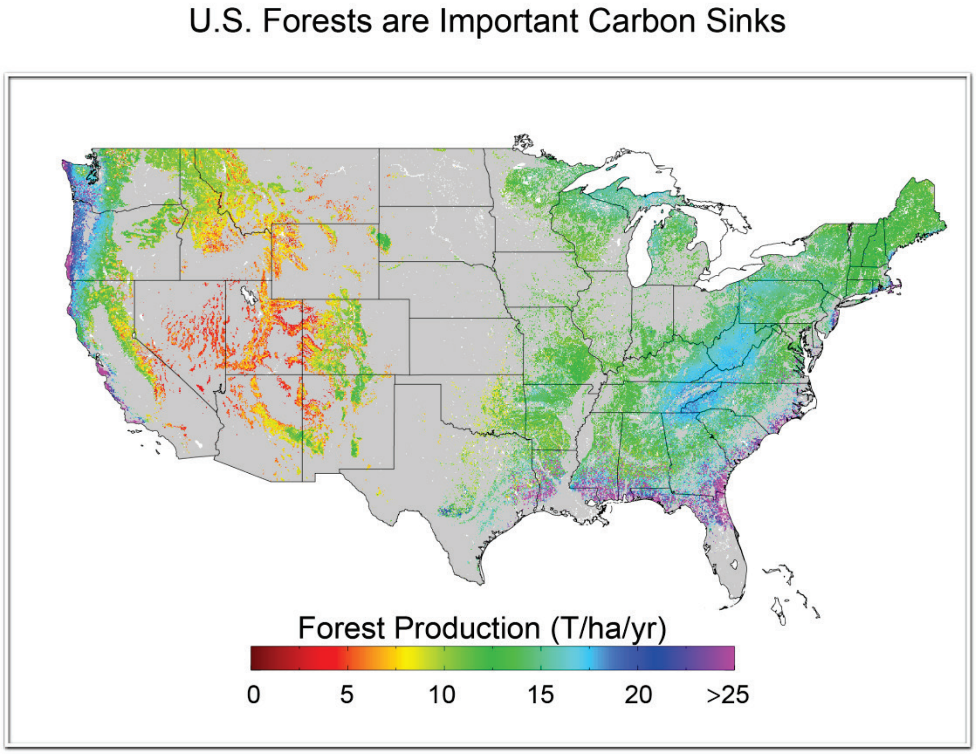


Figure 7.4: U.S. Forests are Important Carbon Sinks

Caption: U.S. Forests currently absorb about 13% of national carbon dioxide emissions. Southwest forests absorb considerably less than many eastern forests and those along the western coast. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake. Figure shows carbon uptake rates for U.S. forests in tons per hectare per year (methods from Running et al. 2004).

Efforts to reduce atmospheric CO_2 levels through forest management and forest product use focuses on three strategies: 1) land-use change to increase forest area (afforestation) and/or to avoid deforestation; 2) carbon management in existing forests; and 3) use of wood as a tool to reduce future climate change (for example, using wood to replace materials such as steel and concrete that require more carbon emissions to produce, to replace fossil fuels for energy production; or in wood products for carbon storage).

In the U.S., afforestation (active establishment or planting of forests) could capture and store a maximum of 225 million tons of carbon per year from 2010−2110 (EPA 2005; King et al. 2007). Tree and shrub encroachment into grasslands, rangelands, and savannas provides a large potential carbon sink that could exceed half of what existing U.S. forests capture and store annually (King et al. 2007).

Expansion of urban and suburban areas is responsible for much of the current and expected loss of U.S. forests (USFS 2012). In addition, the increasing prevalence of extreme conditions that encourage wildfires can convert some forests to shrublands and meadows (Westerling et al. 2011), or permanently reduce carbon stocks on existing forests if fires occur more frequently (Balshi et al. 2009; Harden et al. 2000).

Carbon management on existing forests can include practices that increase forest growth, such as fertilization, irrigation, switching to fast-growing planting stock, shorter rotations, and weed, disease, and insect control (Albaugh et al. 2003; Albaugh et al. 2004; Allen 2008; Amishev and Fox 2006; Borders et al. 2004; Nilsson and Allen 2003). In addition, forest management can increase average forest carbon stocks by increasing the interval between harvests or decreasing harvest intensity (Balboa-Murias et al. 2006; Harmon and Marks 2002; Harmon et al. 2009; Jiang et al. 2002; Kaipainen et al. 2004; Seely et al. 2002). Since 1990, CO_2 emissions from wildland forest fires in the lower 48 United States have averaged about 67 million tons of carbon per year (EPA 2009, 2010). While fuel treatments reduce on-site carbon stocks, they can contribute to reducing future climate change by providing a feedstock for bioenergy, and by possibly avoiding future, potentially larger, wildfire emissions (Vose et al. 2012).

Increased use of wood products in construction, particularly for nonresidential buildings, can reduce the use of materials that emit more CO_2 in their manufacture, and thus substantially offset CO_2 emissions (McKinley et al. 2011). The carbon emissions offset from using wood rather than alternate materials for a range of applications can be two or more times the carbon content of the product (Sathre and O'Connor 2010).

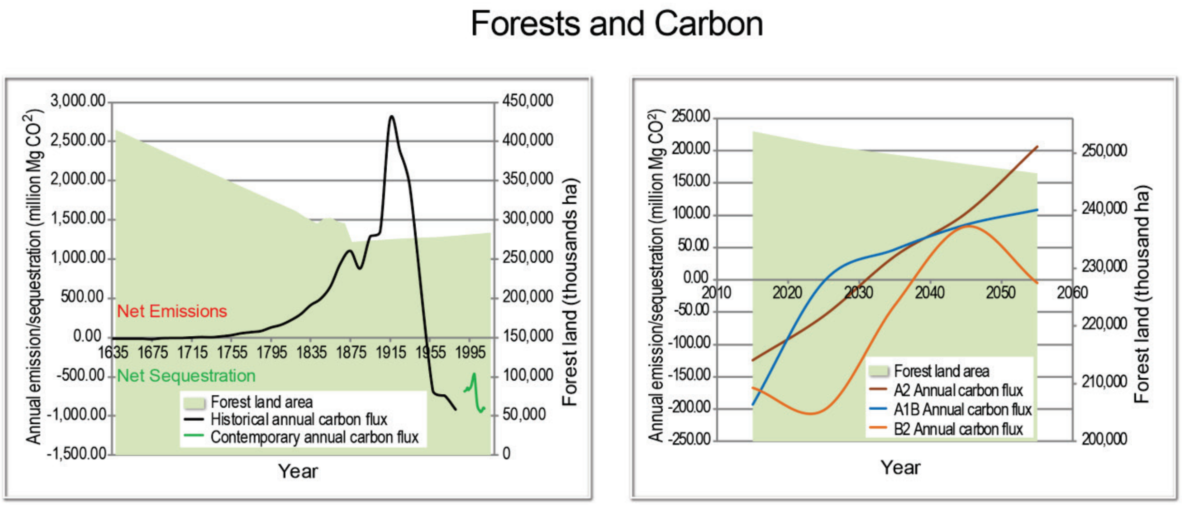


Figure 7.5: Forests and Carbon

Caption: Historic, contemporary, and future projections of annual rates of forest ecosystem and harvested wood product CO_2 net emissions/sequestration in U.S. forests, from 1635 to 2055. In the left panel, the change in the historical annual carbon emissions (black line) in the early 1900s corresponds to the peak in the transformation of large parts of the U.S. from forested land to agricultural land uses. In the right panel, future projections are shown under high (A2) and lower (B2 and A1B) emissions scenarios. (From EPA 2012; USFS 2012).

Bioenergy Potential

Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.

Bioenergy refers to the use of plant-based material to produce energy, and comprises about 28% of the U.S. renewable energy supply (Ch. 10, Water, Energy, Land). The *maximum* projected potential for forest bioenergy ranges from between 3% and 5% of total current U.S. energy consumption (Smith et al. 2012). Bioenergy from all sources, both agricultural and forest resources, could theoretically replace up to 30% equivalent of U.S. petroleum consumption, but only if all relevant policies were optimized (DOE 2011). Forest biomass energy could be one component of an overall bioenergy strategy to reduce emissions of carbon from fossil fuels (Perlack et al. 2005; Zerbe 2006), while also improving water quality (Dale et al. 2010a; Robertson et al. 2008) and maintaining lands for timber production in the face of other pressures (DOE 2011). Active biomass energy markets using wood and forest residues have emerged in the South and Northeast, particularly in states that have adopted renewable fuel standards.

The economic viability of using forest product for bioenergy depends on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution, and use (Efroymson et al. In press; NRC 2011). Socioeconomic effects include social well-being, energy security, trade, profitability, resource conservation, and social acceptability (Dale et al. in press).

The potential for biomass energy to increase timber harvests has led to debates about whether forest biomass energy leads to higher carbon emissions. (Bright et al. in press; Daigneault et al. 2012; Hudiburg et al. 2011; Schulze et al. 2012; Zanchi et al. 2011). The debate revolves around model assumptions in policy analyses, temporal horizons defined, and the life cycle domain defined. The change in carbon balance over time may differ, depending on forest management scenarios. For example, utilizing natural beetle-killed forests will yield a different carbon balance than growing and harvesting a live, fast-growing plantation.

Markets for energy from biomass appear to be ready to grow in response to energy pricing, policy, and demand (Daigneault et al. 2012), although recent increases in the supply of natural gas have reduced the perceived urgency for new biomass projects. Further, because energy facilities typically buy the lowest-quality wood at prices that rarely pay much more than cutting and hauling costs, they often require a viable saw timber market nearby to ensure an adequate, low-cost supply of material (Galik et al. 2009). As bioenergy markets require a stable resource for efficient mill/plant supply, disturbances may introduce opportunities for enhanced supply through salvage efforts. These disturbances, while providing biomass for energy production, may be potentially disruptive to the mill supply chain for traditional wood products. While this bioenergy market allows managers to eliminate wastes and conduct forest health, stand improvement, and climate adaptation operations, it has yet to be made a profitable enterprise in most U.S. regions.

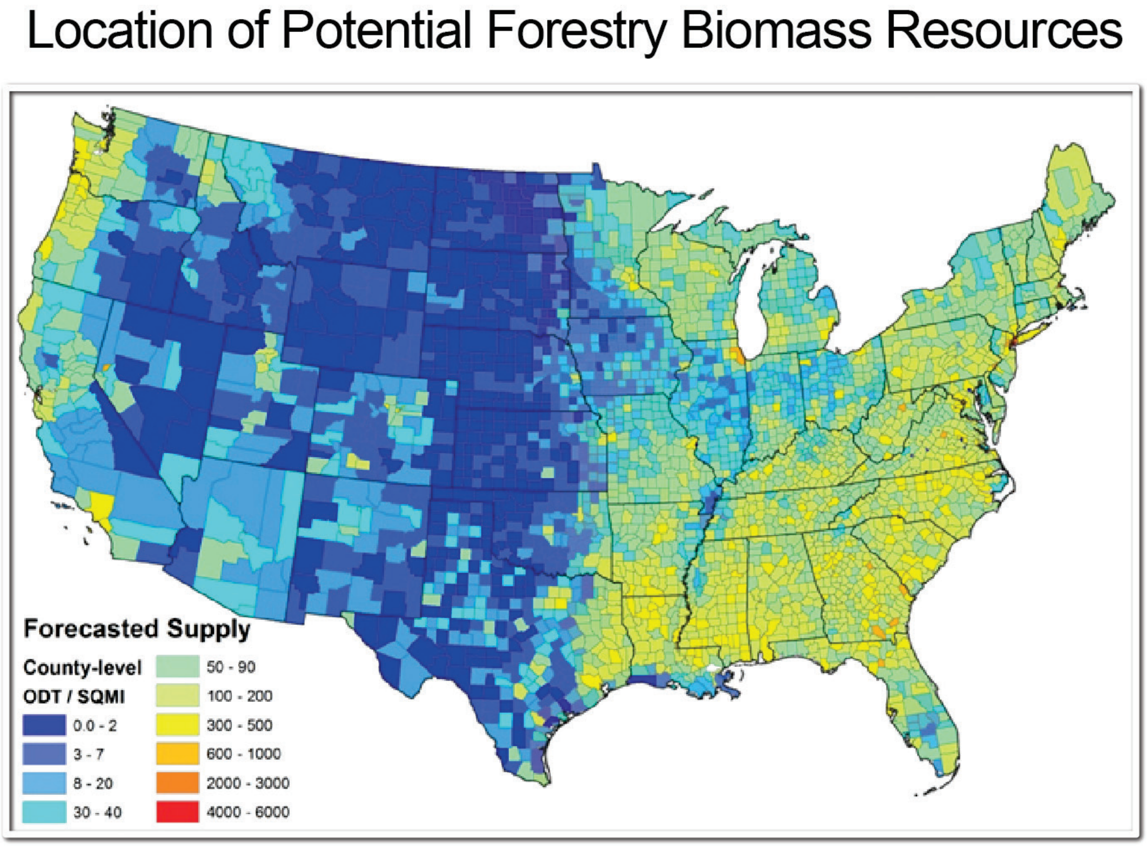


Figure 7.6: Location of Potential Forestry Biomass Resources

Caption: Potential forestry bioenergy resources by 2030 at $80 per dry ton of biomass based on current forest area, production rates based on aggressive management for fast-growth, and short rotation bioenergy plantations. Units are Oven Dry Tons (ODT) per Square Mile at the county level, where an ODT is 2,000 pounds of biomass from which the moisture has been removed. Includes extensive material from existing forestland such as residues, simulated thinnings, and some pulpwood for bioenergy, among other sources. Source: based on (DOE 2011).

Influences on Management Choices

The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.

Owner objectives, markets for wood products, monetary value of private land, and policies governing private and federal forest land influence the actions taken to manage U.S. forestlands (56% private, 44% public). Less than 1% of the volume of commercial trees from U.S. forestlands is harvested annually, and 92% of this harvest comes from private forestlands (Smith 2009). Among corporate owners (18% of all forestland), ownership has shifted from forest industry to investment management organizations that may or may not have active forest management as a primary objective. Non-corporate private owners, an aging demographic, manage 38% of forestland. Primary objectives for many of these private landowners are maintaining aesthetics, sustaining the privacy that the land provides, and retaining its importance as part of their family legacy (Butler 2008). Many family forest owners feel it is necessary to keep the woods healthy but many are not familiar with forest management practices (Butler 2008).

The market for timber will continue to be driven by development (or lack of development) in large scale forest-product enterprises that serve increasingly competitive global markets (Ince 2007). The emerging market for bioenergy is not yet profitable in most parts of the U.S. A significant economic factor facing private forest owners is the value of their forestlands for conversion to urban or developed uses. Urban conversions of forestland in the Midwest, Northeast, and South regions could result in the loss of 29.5 to 35.9 million acres (Plantinga et al. 2011). The willingness of private forest owners to actively manage forests in the face of climate change will be affected primarily by market and policy incentives, not climate change itself.

Forty-four percent of U.S. forestland (329 million acres) is controlled by public agencies: federal (33%); state (9%); and county and municipal government (1%) (Smith et al. 2009). These lands serve many objectives such as wildlife habitat, watershed protection for urban drinking water, recreation, and timber harvest. Incentives for active forest management are influenced by societal values on public land management and, just as on private land, by the wood products market.

The ability of forest owners and forest managers to adapt to, and/or reduce, future climate change is enhanced by their capacity to alter management regimes relatively rapidly in the face of changing conditions. Private forest owners have been highly responsive to market and policy signals, especially in the southeastern U.S. (Wear and Prestemon 2004). Thus, private landowners may be able to capitalize on existing options for forest management to reduce disturbance effects, increase the capture and storage of carbon, and promote adaptation of new species under climate change. Management practices that can be used to reduce disturbance effects include: altering tree planting and harvest strategies through species selection and timing; factoring in genetic variation; managing for reduced stand densities, which could reduce wildfire risk (particularly at rural-urban interfaces); reducing other stressors such as poor air quality; using forest management practices to minimize drought stress; and developing regional networks to aid in impacts on ecosystem goods and services (Breshears et al. 2011; Joyce et al. 2008; Millar et al. 2007; Vose et al. 2012). Legally binding regulatory requirements may penalize adaptive or innovative management in the face of climate change, as regulators may force actions that are required, but inconsistent with changing or future conditions. These regulations presume a static environment where plants, animals, and ecosystems are not responding to climate change (Millar and Swanston 2012).

Lack of fine-scale information on the possible effects of climate changes on locally managed forests limits the ability of managers to weigh these risks to their forests against the economic risks of implementing forest management practices such as adaptation and/or mitigation treatments. This knowledge gap will impede the implementation of effective management on public or private forestland in the face of climate change.

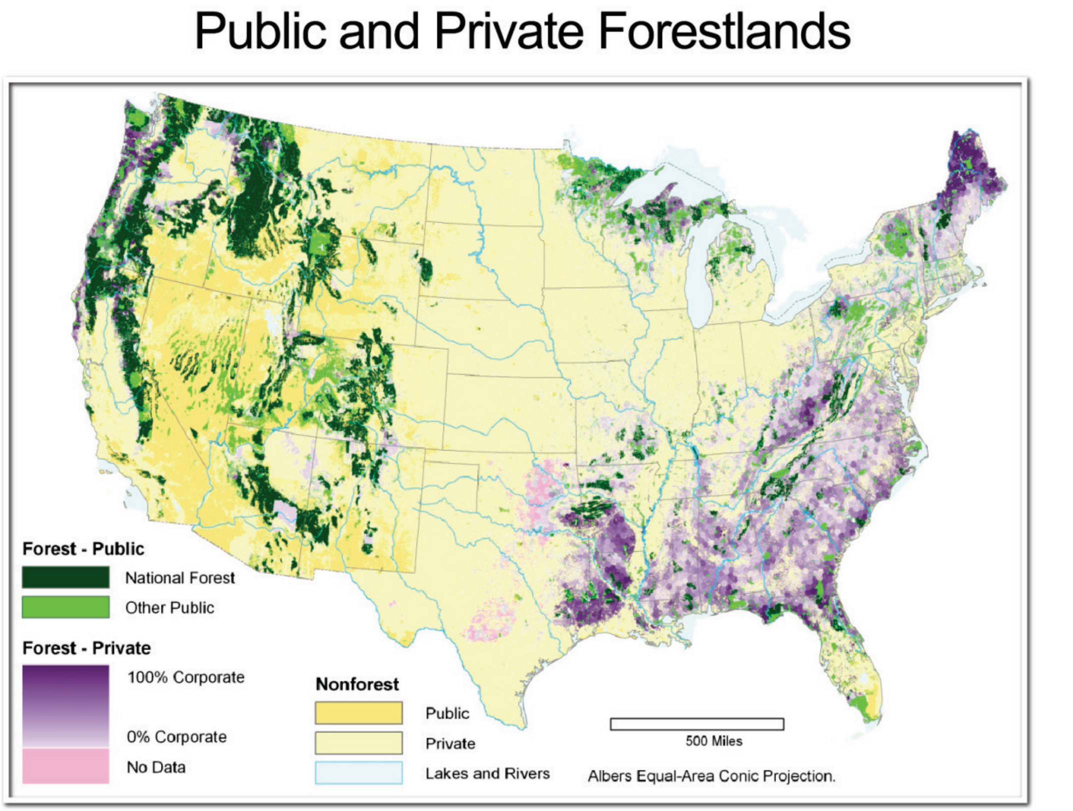


Figure 7.7: Public and Private Forestlands

Caption: Forest land by ownership category in the contiguous U.S., 2007 (USFS 2012). Western forests are most often located on public lands, while eastern forests, especially in Maine and in the Southeast, are more often privately held.

Traceable Accounts

Chapter 7: Forestry

Key Message Process: A central component of the process was a workshop held in July 2011 by the USDA Forest Service to guide the development of the technical input report. This session, along with numerous technical teleconferences, led to the foundational technical input report, the National Climate Assessment—Forest Sector Technical Report. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station (Vose et al. 2012).

The chapter authors engaged in multiple technical discussions via teleconference between January and June 2012, which included careful review of the foundational and of 55 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each message.

Key message	**Climate change is increasing the vulnerability of forests to fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but are projected to be more sensitive to periodic drought.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Dale et al. 2001 addressed a number of factors that will affect U.S. forests and how they are managed. This is supported by additional publications focused on effects of drought and by more large scale tree die-off events (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010), wildfire (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010), insects and pathogens (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010). Other studies support the negative impact of climate change by examining the tree mortality rate due to rising temperatures (Adams et al. 2009; Allen et al. 2010; Dale et al. 2010b; Jentsch et al. 2007; Raffa et al. 2008; Van Mantgem et al. 2009; Williams et al. 2010; Williams et al. 2012) which is projected to increase in some regions (Adams, 2009). Although it is difficult to detect a trend in disturbances because they are inherently infrequent and it is impossible to attribute an individual disturbance event to changing climate, there is nonetheless much that past events, including recent ones, reveal about expected forest changes to future climate. Correlations with climate that include extreme events and/or modifications in atmospheric demand related to warmer temperature show strong associations with forest disturbance in observational (Williams et al. 2012) and experimental (Adams et al. 2009) studies. Figure 1. This figure uses a figure from (Goetz et al. 2012) which uses the MODIS Global Disturbance Index (MGDI) results from 2005 to 2009 to illustrate the geographic distribution of major ecosystem disturbance types across North America (based on (Mildrexler et al. 2009; Mildrexler et al. 2007)). The MGDI uses remotely sensed information to assess the intensity of the disturbance. Following the occurrence of a major disturbance, there will be a reduction in Enhanced Vegetation Index (EVI) because of vegetation damage; in contrast, Land Surface Temperature (LST) will increase because more absorbed solar radiation will be converted into sensible heat as a result of the reduction in evapotranspiration from less vegetation density. MGDI takes advantage of the contrast changes in EVI and LST following

	disturbance to enhance the signal to effectively detect the location and intensity of disturbances (http://www.ntsg.umt.edu/project/mgdi). Moderate severity disturbance is mapped in orange and represents a 65–100% divergence of the current year MODIS Global Disturbance Index value from the range of natural variability, High severity disturbance (in red) signals a divergence of over 100%. (from Goetz et al. 2012).
New information and remaining uncertainties	Forest disturbances have large ecosystem effects, but high interannual variability in regional fire and insect activity makes detection of trends more difficult than for changes in mean conditions (CCSP 2009a; IPCC 2012; Smith 2011). Therefore, there is generally less confidence in assessment of future projections in disturbance events than for mean conditions (for example, growth under slightly warmer conditions) (IPCC 2012). There are insufficient data on trends in windthrow, ice storms, hurricanes, and landslide-inducing storms to infer that these types of disturbance events are changing. Factors affecting tree death, such as drought, warmer temperatures, and/or pests and pathogens are often interrelated, which means that isolating a single cause of mortality is rare (Adams et al. 2009; Allen et al. 2010; Dukes et al. 2009; McDowell et al. 2008; McDowell et al. 2011; Williams et al. 2012).
Assessment of confidence based on evidence	**Very High**. There is very high confidence that under projected climate changes there is high risk (high risk = high probability and high consequence) that western forests in the United States will be impacted increasingly by large and intense fires that occur more frequently (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010). This is based on the strong relationships between climate and forest response, shown observationally (Williams et al. 2012) and experimentally (Adams et al. 2009). Expected responses will increase substantially to warming, to warming in combination with drought, and also in conjunction with other changes such as an increase in the frequency and/or severity of drought and amplification of pest and pathogen impacts. Eastern forests are less likely to experience immediate increases in wildfire unless/until a point is reached at which warmer temperatures, concurrent with seasonal dry periods or more protracted drought, trigger wildfires.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 7: Forestry

Key Message Process: See Key Message #1.

Key message #2/4	**U.S. forests currently absorb 13 percent of all carbon dioxide (CO_2) emitted in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A recent study (EPA 2012) has shown that the forests are a big sink of CO_2 nationally. However, permanence of this carbon sink is contingent on changing forest disturbance rates and economic conditions that may accelerate harvest of forest biomass.(Dale et al. 2010a). Market response can cause shifts in forest age (EPA 2005; Goodale et al. 2002), land-use changes and urbanization reduce/limit forested areas (USFS 2012), forest type changes shift the dynamics of the area (Sohngen and Brown 2006), and bioenergy development can change how we manage forests (Choi et al. 2011; Daigneault et al. 2012; DOE 2011; USFS 2012). Additionally, publications have reported that fires can convert a forest into a shrubland or meadow (Westerling et al. 2011), with frequent fires permanently reducing the carbon stock (Balshi et al. 2009; Harden et al. 2000).
New information and remaining uncertainties	That economic factors and societal choices will affect future carbon cycle of forests is known with certainty; the major uncertainties come from the future economic picture, accelerating disturbance rates, and how societal responses to those dynamics.
Assessment of confidence based on evidence	Based on the evidence and uncertainties, confidence is **high** that, in the U.S., climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake**.** The U.S. has already seen large-scale shifts in forest cover from interactions between forest land use and agriculture (for example, onset of European settlement to the present). Demands for forest land use exist today. The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (key message 1) growth rates, and harvest demands.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 7: Forestry

Key Message Process: See Key Message #1.

Key message #3/4	**Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.**
Description of evidence base	The key message and supporting text summarize extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Studies have shown that harvesting forest bioenergy can prevent carbon emissions (Perlack et al. 2005; Zerbe 2006) and replace a portion of U.S. energy consumption to help reduce future climate change. Some newer literature has explored how use of forest bioenergy can replace a portion of current U.S. energy production from oil (DOE 2011; Smith 2011). Some more recent publications have reported some environmental benefits, such as improved water quality (Dale et al. 2010a; Robertson et al. 2008) and better management of timber lands (US DOE, 2011), and numerous socioeconomic benefits (Dale et al. in press) that can result from forest bioenergy implementation.
New information and remaining uncertainties	The implications of forest product use for bioenergy depend on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution and use (Efroymson et al. In press; NRC 2011). The potential for biomass energy to increase forest harvests has led to debates about whether biomass energy is net carbon neutral (Bright et al. in press; Hudiburg et al. 2011; Schulze et al. 2012; Zanchi et al. 2011). The debate revolves around model assumptions in energy conversion analyses, temporal horizons and the life cycle domain defined. The market for energy from biomass appears to be ready to grow in response to energy pricing, policy and demand; however, this industry is yet to be made a large-scale profitable enterprise in most regions of the United States.
Assessment of confidence based on evidence	**High**. Forest growth substantially exceeds annual harvest for normal wood and paper products, and much forest harvest residue is now un-utilized. Forest bioenergy will become viable if policy and economic energy valuations make it competitive with fossil fuels.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 7: Forestry

Key Message Process: See Key Message #1.

Key message #4/4	**The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for energy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The forest management response to climate change has been studied from varying angles. Publications on the effects of private ownership have shown both negative (Plantinga et al. 2011) and positive aspects (Wear and Prestemon 2004). An earlier study explored the effects of globalization (Ince 2007) and a newer study looked at the effect of U.S. climate change policy (Millar and Swanston 2012). One of the biggest issues deals with the lack of information that results in inaction from many forest owners (Butler 2008).
New information and remaining uncertainties	Global and national economic events will have an integral impact, but it is uncertain to what magnitude.
Assessment of confidence based on evidence	**Medium**. Human concerns regarding the effects of climate change on forests and the role of adaptation and mitigation will be viewed from the perspective of the values that forests provide to human populations, including timber products and water, recreation, and aesthetic and spiritual benefits (Vose et al. 2012). Many people, organizations, institutions, and governments influence the management of U.S. forests. Economic opportunities influence the amount and nature of private forestland (and much is known quantitatively about this dynamic) and societal values have a strong influence on how public forestland is managed. However, it remains challenging to project exactly how humans will respond to climate change in terms of forest management.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

References

Adams, H., A. Macalady, D. Breshears, C. Allen, N. Stephenson, S. Saleska, T. Huxman, and N. McDowell, 2010: Climate-induced tree mortality: earth system consequences. *Eos*, **91**

Adams, H.D., M. Guardiola-Claramonte, G.A. Barron-Gafford, J.C. Villegas, D.D. Breshears, C.B. Zou, P.A. Troch, and T.E. Huxman, 2009: Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences*, **106,** 7063

Albaugh, T.J., H. Lee Allen, B.R. Zutter, and H.E. Quicke, 2003: Vegetation control and fertilization in midrotation Pinus taeda stands in the southeastern United States. *Annals of Forest Science*, **60,** 619-624

Albaugh, T.J., H. Lee Allen, P.M. Dougherty, and K.H. Johnsen, 2004: Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *Forest Ecology and Management*, **192,** 3-19

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb, 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259,** 660-684 doi: 10.1016/j.foreco.2009.09.001, [Available online at http://www.sciencedirect.com/science/article/pii/S037811270900615X]

Allen, H.L., 2008: Silvicultural treatments to enhance productivity. Blackwell Science Ltd.

Amishev, D.Y. and T.R. Fox, 2006: The effect of weed control and fertilization on survival and growth of four pine species in the Virginia Piedmont. *Forest Ecology and Management*, **236,** 93-101

Anderegg, W.R.L., J.M. Kane, and L.D.L. Anderegg, 2012: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change* doi: 10.1038/NCLIMATE635

Balboa-Murias, M.Á., R. Rodríguez-Soalleiro, A. Merino, and J.G. Álvarez-González, 2006: Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. *Forest Ecology and Management*, **237,** 29-38

Balshi, M., A. McGuire, P. Duffy, M. Flannigan, D. Kicklighter, and J. Melillo, 2009: Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. *Global Change Biology*, **15,** 1491-1510

Bentz, B.J., J. Regniere, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negron, and S.J. Seybold, 2010: Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience*, **60,** 602-613 doi: Doi 10.1525/Bio.2010.60.8.6, [Available online at <Go to ISI>://000281299400006]

Birdsey, R., K. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States: 1600–2100. *Journal of Environmental Quality*, **35,** 461–1469

Boisvenue, C. and S.W. Running, 2006: Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. *Global Change Biology*, **12,** 862-882

——, 2010: Simulations show decreasing carbon stocks and potential for carbon emissions in Rocky Mountain forests over the next century. *Ecological Applications*, **20,** 1302-1319

Borders, B., R. Will, D. Markewitz, A. Clark, R. Hendrick, R. Teskey, and Y. Zhang, 2004: Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. *Forest Ecology and Management*, **192,** 21-37

Bowman, D.M.J.S., J.K. Balch, P. Artaxo, W.J. Bond, J.M. Carlson, M.A. Cochrane, C.M. D'Antonio, R.S. DeFries, J.C. Doyle, and S.P. Harrison, 2009: Fire in the Earth system. *Science*, **324,** 481-484

Breshears, D.D., L. López-Hoffman, and L.J. Graumlich, 2011: When Ecosystem Services Crash: Preparing for Big, Fast, Patchy Climate Change. *AMBIO: A Journal of the Human Environment*, **40,** 256-263

Bright, R.M., F. Cherubini, R. Astrup, N. Bird, A.L. Cowie, M.J. Ducey, G. Marland, K. Pingoud, I. Savolainen, and A.H. Strømman, in press: A comment to "Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral": Important insights beyond greenhouse gas accounting. *Global Change Biology Bioenergy*

Butler, B.J., 2008: Family forest owners of the United States, 2006. *Gen. Tech. Rep. NRS-27. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station*, **73**

Campbell, J.L., L.E. Rustad, E.W. Boyer, S.F. Christopher, C.T. Driscoll, I.J. Fernandez, P.M. Groffman, D. Houle, J. Kiekbusch, A.H. Magill, M.J. Mitchell, and S.V. Ollinger, 2009: Consequences of climate change for biogeochemical cycling in forests of northeastern North America. *Canadian Journal of Forest Research*, **39,** 264-284, [Available online at http://www.ingentaconnect.com/content/nrc/cjfr/2009/00000039/00000002/art00005]

Caspersen, J., S. Pacala, G. Hurtt, P. Moorcraft, R. Birdsey, and J. Jenkins, 2000: Carbon accumulation in US forests is caused overwhelmingly by changes in land use rather than CO2 or N fertilization or climate change. *Science*, **290,** 1148-1151

CCSP, 2009a: Thresholds of Climate Change in Ecosystems. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. D. B. Fagre, and Coauthors, Eds., U.S. Geological Survey, 156

Choat, B., S. Jansen, T.J. Brodribb, H. Cochard, S. Delzon, R. Bhaskar, S.J. Bucci, T.S. Feild, S.M. Gleason, and U.G. Hacke, 2012: Global convergence in the vulnerability of forests to drought. *Nature* doi: 10.1038/nature 11688

Choi, S.W., B. Sohngen, and R. Alig, 2011: An assessment of the influence of bioenergy and marketed land amenity values on land uses in the Midwestern US. *Ecological Economics*, **70,** 713-720

Daigneault, A.J., B. Sohngen, and R. Sedjo, 2012: An Economic Approach to Assess the Forest Carbon Implications of Biomass Energy. *Environmental Science & Technology*, **46,** 5664-5671

Dale, V., RA Efroymson, KL Kline, MH Langholtz, PN Leiby, GA Oladosu, MR Davis, ME Downing, and M. Hilliard, in press: Indicators to support assessment of socioeconomic sustainability of bioenergy systems for assessing socioeconomic sustainability of bioenergy systems: A short list of practical measures. Ecological Indicators. *Ecological Indicators*, **in press; 26,** 87-102

Dale, V.H., R.A. Efroymson, and K.L. Kline, 2011: The land use–climate change–energy nexus. *Landscape Ecology***,** 1-19

Dale, V.H., R. Lowrance, P. Mulholland, and G.P. Robertson, 2010a: Bioenergy sustainability at the regional scale. *Ecology and Society*, **15,** 23

Dale, V.H., M.L. Tharp, K.O. Lannom, and D.G. Hodges, 2010b: Modeling transient response of forests to climate change. *Science of The Total Environment*, **408,** 1888-1901

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B. Michael Wotton, 2001: Climate Change and Forest Disturbances. *BioScience*, **51,** 723-734 doi: 10.1641/0006-3568(2001)051[0723:ccafd]2.0.co;2, [Available online at http://dx.doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO]

Dietze, M.C. and P.R. Moorcroft, 2011: Tree mortality in the eastern and central United States: patterns and drivers. *Global Change Biology* doi: 10.1111/j.1365-2486.2011.02477.x

DOE, 2011: U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. ORNL/TM-2011-224. R.D. Perlack, and B.J. Stokes, U.S. Department of Energy, Office of Biomass Program, Oak Ridge National Laboratory, 227pp

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

Efroymson, R.A., V.H. Dale, K.L. Kline, A.C. McBride, J.M. Bielicki, R.L. Smith, E.S. Parish, P.E. Schweizer, and D.M. Shaw, In press: Environmental indicators of biofuel sustainability: What about context? *Environmental Management*

Ehrenfeld, J.G., 2010: Ecosystem consequences of biological invasions. *Annual review of ecology, evolution, and systematics*, **41,** 59-80

EPA, 2005: Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture. [Available online at http://www.epa.gov/sequestration/greenhouse_gas.html]

——, 2009: Land use, land-use change, and forestry. In: Inventory of U.S. greenhouse gas emissions and sinks: 1990-2007. U. S. E. P. Agency, Ed., U.S. Environmental Protection Agency,.

——, 2010: Inventory of US greenhouse gas emissions and sinks: 1990-2008.

——, 2012: Land use, land-use change, and forestry. Annex 3.12. Methodology for estimating net carbon stock changes in forest land remaining forest lands. In: Inventory of U.S. greenhouse gas emissions and sinks: 1990-2009

Galik, C.S., R. Abt, and Y. Wu, 2009: Forest Biomass Supply in the Southeastern United StatesImplications for Industrial Roundwood and Bioenergy Production. *Journal of Forestry*, **107,** 69-77

Goetz, S., B. Bond-Lamberty, B. Law, J. Hicke, C. Huang, R. Houghton, S. McNulty, T. O'Halloran, M. Harmon, and A. Meddens, 2012: Observations and assessment of forest carbon dynamics following disturbance in North America. *Journal of Geophysical Research*, **117,** G02022

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, and S. Liu, 2002: Forest carbon sinks in the Northern Hemisphere. *Ecological Applications*, **12,** 891-899

Harden, J., S. Trumbore, B. Stocks, A. Hirsch, S. Gower, K. O'neill, and E. Kasischke, 2000: The role of fire in the boreal carbon budget. *Global Change Biology*, **6,** 174-184

Harmon, M. and P. Marks, 2002: Effects of silvicultural practices on carbon stores in Douglas-fir – western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. *Canadian Journal of Forest Research*, **32,** 863-877 doi: doi:10.1139/x01-216, [Available online at http://www.nrcresearchpress.com/doi/abs/10.1139/x01-216]

Harmon, M.E., A. Moreno, and J.B. Domingo, 2009: Effects of partial harvest on the carbon stores in Douglas-fir/western hemlock forests: a simulation study. *Ecosystems*, **12,** 777-791

Hicke, J.A., C.D. Allen, A.R. Desai, M.C. Dietze, R.J. Hall, E.H. Hogg, D.M. Kashian, D. Moore, K.F. Raffa, R.N. Sturrock, and J. Vogelmann, 2012: Effects of biotic disturbances on forest carbon cycling in the United States and Canada. *Global Change Biology*, **18,** 7-34 doi: 10.1111/j.1365-2486.2011.02543.x, [Available online at <Go to ISI>://WOS:000298598900003]

Hudiburg, T.W., B.E. Law, C. Wirth, and S. Luyssaert, 2011: Regional carbon dioxide implications of forest bioenergy production. *Nature Climate Change*, **1,** 419-423

Ince, P.J., 2007: *Globalization and structural change in the US forest sector: an evolving context for sustainable forest management.* US Department of Agriculture, Forest Service, Forest Products Laboratory.

IPCC, 2007: Summary for Policymakers. *Climate Change 2007: The Physical Science Basis*, S. Solomon, and Coauthors, Eds., Cambridge University Press, 1-18. [Available online at http://ds.heavyoil.utah.edu/dspace/bitstream/123456789/9951/1/ClimateChange2007-1.pdf]

——, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation–A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. C. Field, and Coauthors, Eds., Cambridge University Press, .

Jentsch, A., J. Kreyling, and C. Beierkuhnlein, 2007: A new generation of climate-change experiments: events, not trends. *Frontiers in Ecology and the Environment*, **5,** 365-374

Jiang, H., M.J. Apps, C. Peng, Y. Zhang, and J. Liu, 2002: Modelling the influence of harvesting on Chinese boreal forest carbon dynamics. *Forest Ecology and Management*, **169,** 65-82

Joos, F., I.C. Prentice, and J.I. House, 2002: Growth enhancement due to global atmospheric change as predicted by terrestrial ecosystem models: consistent with US forest inventory data. *Global Change Biology*, **8,** 299-303

Joyce, L.A., G.M. Blate, J.S. Littell, S.G. McNulty, C.I. Millar, S.C. Moser, R.P. Neilson, K. O'Halloran, and D.L. Peterson, 2008: National Forests. *Preliminary Review of Adaptation Options for Climate-sensitive Ecosystems and Resources*, S. H. Julius, and J. M. West, Eds., U.S. Environmental Protection Agency, 3-1 to 3-127. [Available online at http://downloads.climatescience.gov/sap/sap4-4/sap4-4-final-report-Ch3-Forests.pdf]

Kaipainen, T., J. Liski, A. Pussinen, and T. Karjalainen, 2004: Managing carbon sinks by changing rotation length in European forests. *Environmental Science & Policy*, **7,** 205-219

Keane, R.E., J.K. Agee, P. Fule, J.E. Keeley, C. Key, S.G. Kitchen, R. Miller, and L.A. Schulte, 2009: Ecological effects of large fires on US landscapes: benefit or catastrophe? *International Journal of Wildland Fire*, **17,** 696-712

King, A., L. Dilling, and G. Zimmerman, 2007: The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, 242pp. *U.S.Climate Change Science Program, Washington, D.C.*

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling, 2009: Climate and wildfire area burned in western US ecoprovinces, 1916-2003. *Ecological Applications*, **19,** 1003-1021

McDowell, N., W.T. Pockman, C.D. Allen, D.D. Breshears, N. Cobb, T. Kolb, J. Plaut, J. Sperry, A. West, and D.G. Williams, 2008: Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist*, **178,** 719-739

McDowell, N.G., D.J. Beerling, D.D. Breshears, R.A. Fisher, K.F. Raffa, and M. Stitt, 2011: The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology & Evolution*, **26,** 523-532

McKenzie, D., A.E. Hessl, and D.L. Peterson, 2001: Recent growth of conifer species of western North America: assessing spatial patterns of radial growth trends. *Canadian Journal of Forest Research*, **31,** 526-538

McKinley, D.C., M.G. Ryan, R.A. Birdsey, C.P. Giardina, M.E. Harmon, L.S. Heath, R.A. Houghton, R.B. Jackson, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog, 2011: A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications*, **21,** 1902-1924 doi: 10.1890/10-0697.1, [Available online at http://dx.doi.org/10.1890/10-0697.1]

Mildrexler, D.J., M. Zhao, and S.W. Running, 2009: Testing a MODIS global disturbance index across North America. *Remote Sensing of Environment*, **113,** 2103-2117

Mildrexler, D.J., M. Zhao, F.A. Heinsch, and S.W. Running, 2007: A new satellite-based methodology for continental-scale disturbance detection. *Ecological Applications*, **17,** 235-250

Millar, C.I. and C.W. Swanston, 2012: Strategies for Adapting to Climate Change, Chapter 4. IN: Vose, J.M.; Peterson, D.L.; Patel-Weynand, T. (eds.). 2012. National Climate Assessment--Forest Sector Technical Report. General Technical Report PNW-GTR-870., F. S. U.S. Department of Agriculture, Pacific Northwest Research Station. , Ed.

Millar, C.I., N.L. Stephenson, and S.L. Stephens, 2007: Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, **17,** 2145-2151

Nilsson, U. and H.L. Allen, 2003: Short-and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *Forest Ecology and Management*, **175,** 367-377

North, M., M. Hurteau, and J. Innes, 2009: Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. *Ecological Applications*, **19,** 1385-1396

NRC, 2011: Renewable Fuel Standard. [Available online at http://www.nap.edu/catalog.php?record_id=13105]

Perlack, R.D., L.L. Wright, A.F. Turhollwo, R.L. Graham, B.J. Stokes, and D.C. Erbach, 2005: Biomass as Feedstock for a Bioenerby and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. *Agriculture*, **Online,** 78

Plantinga, A., D. Haim, R. Alig, and B. Sohngen, 2011: Climate change and future land use in the United States: An economic approach. *Climate Change Economics*, **2,** 27-51

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme, 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience*, **58,** 501-517

Robertson, G.P., V.H. Dale, O.C. Doering, S.P. Hamburg, J.M. Melillo, M.M. Wander, W.J. Parton, P.R. Adler, J.N. Barney, and R.M. Cruse, 2008: Agriculture. Sustainable biofuels redux. *Science (New York, NY)*, **322,** 49

Running, S.W., R.R. Nemani, F.A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto, 2004: A continuous satellite-derived measure of global terrestrial primary production. *BioScience*, **54,** 547-560

Sathre, R. and J. O'Connor, 2010: Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy*, **13,** 104-114

Saxe, H., D.S. Ellsworth, and J. Heath, 2008: Tree and forest functioning in an enriched CO2 atmosphere. *New Phytologist*, **139,** 395-436

Schulze, E.D., C. Körner, B.E. Law, H. Haberl, and S. Luyssaert, 2012: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, **4,** 611-616 doi: 10.1111/j.1757-1707.2012.01169.x

Seely, B., C. Welham, and H. Kimmins, 2002: Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management*, **169,** 123-135

Smith, M.D., 2011: An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *Journal of Ecology*, **99,** 656-663

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh, 2009: Forest Resources of the United States, 2007. Gen. Tech. Rep. WO-78. U. S. F. S. U.S. Department of Agriculture, Ed., 336 p.

Smith, W.K., C.C. Cleveland, S.C. Reed, N.L. Miller, and S.W. Running, 2012: Bioenergy potential of the United States constrained by satellite observations of existing productivity. *Environmental Science & Technology*, **46,** 3536-3544

Sohngen, B. and S. Brown, 2006: The influence of conversion of forest types on carbon sequestration and other ecosystem services in the South Central United States. *Ecological Economics*, **57,** 698-708

USFS, 2012: Future of America's forest and rangelands: 2010 Resources Planning Act assessment. General Technical Report WO-XX. . U. S. F. Service, Ed.

Van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, A.J. Larson, J.M. Smith, and A.H. Taylor, 2009: Widespread increase of tree mortality rates in the western United States. *Science*, **323,** 521-524

Vose, J., D.L. Peterson, and T. Patel-Weynand, 2012: National Climate Assessment – Forest Sector Technical Report

Wear, D.N. and J.P. Prestemon, 2004: Timber market research, private forests, and policy rhetoric. *Notes*

Westerling, A.L., M.G. Turner, E.A.H. Smithwick, W.H. Romme, and M.G. Ryan, 2011: Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences* doi: 10.1073/pnas.1110199108, [Available online at http://www.pnas.org/content/early/2011/07/20/1110199108.abstract

http://www.pnas.org/content/108/32/13165.full.pdf]

Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt, 2010: Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences*, **107,** 21289-21294

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, and H.D. Grissino-Mayer, 2012: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*

Woodall, C., C. Oswalt, J. Westfall, C. Perry, M. Nelson, and A. Finley, 2009: An indicator of tree migration in forests of the eastern United States. *Forest Ecology and Management*, **257,** 1434-1444

Woodall, C.W., K. Skog, J.E. Smith, and C.H. Perry, 2011: Maintenance of forest contribution to global carbon cycles (criterion 5). *National report on sustainable forests-2010. FS-979.* , G. Robertson, P. Gaulke, and R. McWilliams, Eds., U.S. Department of Agriculture, U.S. Forest Service.

Zanchi, G., N. Pena, and N. Bird, 2011: Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*

Zerbe, J.I., 2006: Thermal energy, electricity, and transportation fuels from wood. *Forest Products Journal*, **56,** 6-14