Climate as a Driver of Change in U.S. Forests

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Abstract: Climate exerts a major influence on the productivity, distribution, composition, and structure of forests. Temperatures are increasing globally, and these widespread temperature increases are resulting in local changes in temperature, precipitation, and extreme weather events across the continental United States. Changes have varied by region, and many of these regional differences will continue in the coming decades. The western United States has been experiencing an increase in drought, wildfire, and mountain pine beetle (*Dendroctonus ponderosae*) damage that is leading to losses in productivity. In the Midwest and East, increased heavy rain events and decreased winter severity have altered forest hydrology and induced range shifts for trees and biological stressors. The east coast is experiencing rising sea levels that threaten coastal forests with flooding and increased salinity. This region could also be subject to more severe hurricanes and other tropical storms in the coming decades. Climate change impacts may affect forest management operations, reduce windows of opportunity to conduct prescribed burns and harvest, or necessitate changes in timing of those activities. Direct and indirect effects of climate change on the Nation's forests will influence the benefits that they provide, such as timber and nontimber forest products, recreation opportunities, clean water, and cultural values, in the coming decades. Climate change also presents opportunities to manage forests for increased carbon sequestration and develop strategies to adapt to change, which can help reduce the magnitude of some of these impacts.

KEY WORDS: climate change, precipitation changes, temperature changes, extreme weather, forest productivity, range shifts, forest management

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Introduction

Climate is a major factor in determining the distribution of forests world-wide. Climate has influenced the distribution, competitive dynamics, and assemblages of vegetation as global temperatures have cooled and warmed significantly over millions of years. Temperatures have been rising over the past century, and these increases are linked to rising concentrations of carbon dioxide and other greenhouse gases in the atmosphere (Intergovernmental Panel on Climate Change [IPCC] 2014). Global climate models project increases in temperature globally and across the United States over the next century as greenhouse gas emissions continue to rise (U.S. Global Change Research Project [USGCRP] 2017). Forests in the continental United States are likely to undergo many direct and indirect effects from these changes (Vose et al. 2012). This paper summarizes trends over the historical record and projections over the next century for key climate drivers of forests across the continental United States. It also summarizes implications for forests and the forest sector.

Trends and Projections in Physical Drivers

Carbon Dioxide

Levels of atmospheric carbon dioxide (CO_2) have been increasing since the beginning of the industrial era and now exceed 405 parts per million on average (Tans and Keeling 2018). By 2050, CO_2 concentrations could potentially reach levels of 500 to 600 parts per million (USGCRP 2017). Studies that have experimentally increased CO_2 levels in forests have shown higher CO_2 concentrations can increase photosynthetic rates, increase carbon storage, alter nutrient cycling, and improve water use efficiency (Ainsworth and Long 2005, Farrior et al. 2015). It is unclear whether these responses will continue in magnitude and direction as CO_2 levels continue to rise, and how responses may interact with or be offset by other stressors.

Temperature

Average temperature in the United States increased about 0.68 °C (1.23 °F) between 1986 and 2016 compared to the first 60 years of the 20th century (USGCRP 2017). Increases have been more dramatic in some parts of the country than others. The Southeast has experienced less than half as much warming as the rest of the United States, and Alaska, the northern Great Plains, and the Southwest have experienced the most warming. Average annual temperatures are projected to increase another 1.4 °C (2.5 °F) for the years 2021 through 2050 compared to 1976 through 2005 as greenhouse gases such as CO_2, methane, and nitrous oxide continue to rise (USGCRP 2017). Temperature increases can have direct and indirect effects on forests as described in the following sections.

Heavy Rain Events

Heavy precipitation events have increased in both frequency and intensity over the historical record across the United States (USGCRP 2017). Increases have been most pronounced in the Northeast, where the frequency of extreme rain events has increased by 74 percent (Easterling et al. 2017). Model projections suggest that heavy rain events will continue to increase over the next century, and will increase even in areas where total precipitation is projected to decrease (USGCRP 2017). This increase in heavy rain events could lead to greater surface runoff, erosion, and flooding and subsequently loss of topsoil, lower water quality, damage to recreation sites, and changes in nutrient cycling in forests.

Drought

Drought can lead to stress and mortality of trees and make forests more vulnerable to fire and insect pests. Recent trends in drought vary regionally (Vose et al. 2016). The West has been experiencing an increase in drought in recent decades, which has been attributed to declining snowpack and winter precipitation (Wehner et al. 2017). Observed trends in the

East are more variable and complex; small pockets have had more drought and most of the land area has shown either no change or decreased drought frequency, especially compared to the Dust Bowl era of the 1930s (Ficklin et al. 2015). There is currently a low degree of confidence in drought projections across the United States (USGCRP 2017). One exception is the Southwest, which is generally projected to experience an increase in drought. It is likely, however, that warmer temperatures will lead to reductions in soil moisture through increased evapotranspiration in other parts of the continental United States (Wehner et al. 2017).

Tropical Storms and Hurricanes

Hurricanes and other tropical storms can lead to widespread tree mortality and breakage from wind as well as flood-induced stress and mortality in coastal forests. The observational record has limitations, including a lack of satellite-detected hurricane records before the last few decades and a lower density of ships making on-the-ground observations. Consequently, it is difficult to conclude whether the frequency or severity of hurricanes and other tropical storms has changed over the past 100 years due to warming global temperatures (Geophysical Fluid Dynamics Laboratory 2017, Kossin et al. 2017). Despite considerable uncertainty in future projections, models project an increase in the number of the strongest (Category 4 and 5) hurricanes by the end of the century, with increases in precipitation rates and intensity (Kossin et al. 2017).

Changes in Winter Severity

Winter severity, determined by cold temperatures as well as snow, can have a strong direct and indirect influence on forests in the United States. In the last few decades, snow cover across much of the United States has decreased in depth, extends over a smaller area, and melts sooner in the spring, leading to wide-ranging effects on forests (Vose et al. 2012). Less snowpack combined with earlier melting provides less insulation for plants and soil, exposing roots to frosts and freezing temperatures. Early snowmelt also alters the timing of runoff into streams; large flows occur earlier, followed by diminished flows late in the growing season. Current and projected increases in winter minimum temperature can exacerbate forest disturbance by reducing winter mortality of insect pests and increasing their range northward, such as mountain pine beetle (*Dendroctonus ponderosae*), southern pine beetle (*D. frontalis*), and hemlock woolly adelgid (*Adelges tsugae*) (Lesk et al. 2017, Paradis et al. 2008, Safranyik et al. 2010). Winter recreation in forests, such as skiing and snowmobiling, may be reduced in many areas as temperatures continue to increase (Wobus et al. 2017). However, some recent research suggests that some areas may experience increases in extreme cold events due to a weakened polar vortex (a large area of low pressure and cold air surrounding the Earth's poles) in the northern hemisphere (Kretschmer et al. 2017).

Sea Level Rise

Sea level has been rising and is expected to continue to rise due to thermal expansion and melting of polar ice caps (IPCC 2014). Global sea levels have risen 20 centimeters (8 inches) since the 1880s. Sea level changes have been variable by location. Sea level did not rise as much as the global average along the Pacific coast until recently. Along the Atlantic coast sea level rise was below the global average in the Southeast and exceeded the global average in the Northeast. By the end of the century, global sea level is projected to rise by 0.3 to 2.4 meters (1 to 8 feet) (Sweet et al. 2017). Sea level rise is projected to be greater in parts of the Gulf coast and the northeastern Atlantic coast than other parts of the coastal United States. This rise, along with potentially more coastal storms, will increase the risk for erosion, storm surge, and flooding events, affecting coastal ecosystems and infrastructure. Sea level rise may also result in saltwater intrusion into coastal forests, which may lead to widespread stress, reduced seedling recruitment, and mortality (Saha et al. 2011).

Growing Season Length

The frost-free season, often used to define the length of the growing season, has lengthened across the United States since temperature records began; the largest increase—more than 17 days—has been observed in the West (Hibbard et al. 2017). The first freeze is happening later in the fall, and the first thaw is happening earlier in the spring. The increase in length of the frost-free and growing seasons is expected to continue in this century. Earlier snowmelt and springtime have led to earlier emergence of leaves and earlier flowering in some plants, which may increase the productivity of forests if adequate water and nutrients are available later in the growing season. However, there may also be some negative aspects to a longer growing season, such as asynchrony in plant and pollinator timing or more insect life cycles. In addition, many plants have specific requirements for chilling during winter that may limit their ability to respond to warmer spring temperatures (Zhang et al. 2007). Changes in growing season length may also affect the length of the recreation season (Brice et al. 2017) and reduce opportunities for management during the dormant season (Rittenhouse and Rissman 2015, Scott et al. 2004).

Wildfire

Climate is an important driver of wildfire in forest ecosystems. Warming temperatures are generally expected to increase fire risk, although this relationship varies by forest type, region, and fire regime (McKenzie et al. 2011). As a result of longer growing seasons and altered precipitation, the length of the fire season and the annual area burned have been increasing in the West and are expected to continue to increase in the future (Abatzoglou and Williams 2016, Wehner et al. 2017). There is insufficient information regarding trends or projections for other parts of the United States (Wehner et al. 2017). However, it is expected that rising temperatures combined with seasonal dry periods and more insect outbreaks will trigger more wildfires by the end of the century, even in the East.

Key Impacts to Forests

Biological Stressors

Changes in climate can influence biological disturbance agents in forests. The mountain pine beetle has had dramatic impacts on western forests in part due to milder winter temperatures (Raffa et al. 2015). In the upper Midwest, the native larch beetle (*D. simplex*) appears to be benefiting from warmer temperatures, leading to increased larch (*Larix* species) mortality (Raffa et al. 2015). Along the east coast, the native southern pine beetle and the invasive hemlock woolly adelgid have both expanded their ranges northward (Lesk et al. 2017, Paradis et al. 2008). Forest pathogens may also be affected by changes in climate. For example, bur oak blight (caused by the fungus *Tubakia iowensis*) may be increasing in severity, partly because of wetter spring conditions (Harrington et al. 2012). Invasive plant species may also benefit directly from warmer temperatures. For example, kudzu (*Pueraria montana*), which has caused dramatic economic losses in the South, could migrate to the Midwest and Northeast (Bradley et al. 2010).

Altered Productivity

Increases in temperature and higher levels of CO_2 in the atmosphere can both lead to increased photosynthesis and growth. In areas where forest productivity is currently limited by temperature and growing season length, productivity may increase with warming temperatures (IPCC 2014). In the West, increased wildfire, bark beetle disturbance, and drought have decreased productivity and are likely to further decrease productivity in the coming decades (Vose et al. 2012). In the eastern United States, elevated CO_2 and temperature may increase forest growth and potentially carbon storage, at least in the short term if sufficient water is available. Mortality from increased disturbances combined with higher soil respiration rates may outweigh the gains in productivity from longer growing seasons and higher photosynthetic rates over the long term, however (Rustad et al. 2012).

Species Range Shifts

As temperature increases and precipitation changes, the range of suitable habitats for many forest species will also change. The suitable habitat range of some tree species may shift northward or upslope to higher elevations to align with cooler temperatures, or may shift in other directions to track changes in moisture. Species outside their suitable habitat ranges may experience more stress, reductions in productivity, difficulty regenerating, or reduced seedling establishment. Forest fragmentation is already slowing natural rates of migration, and it is unlikely that species will be able to migrate as fast as their suitable habitat is shifting even in the absence of fragmentation. In the Pacific Northwest, climate is projected to become unfavorable for Douglas-fir (*Pseudotsuga menziesii*) and many other conifer species in the area (Vose et al. 2012). Northern and boreal tree species at the southern edge of their current range in the Midwest and Northeast will decrease in abundance as habitat suitability for oak (*Quercus*) and hickory (*Carya*) species increases (Iverson et al. 2019). In the Southeast, red spruce (*Picea rubens*) and eastern hemlock (*Tsuga canadensis*), already declining in some areas, are projected to be extirpated from the region by 2100 as a result of the combined stresses of warming, air pollution, and insects.

Implications for the Forest Sector

Changes in climate are likely to have substantial implications for the U.S. forest sector and forest ecosystem goods and services in the coming decades. Changes in productivity are expected to vary regionally, with some timber-producing areas experiencing gains and others losses. Habitat suitability for southern pines (*Pinus* species), which are the main source of the Nation's pulp and paper, may shift northward, leading to reductions in production and economic loss in some areas (Vose et al. 2012). As growing seasons lengthen, production could expand in the Northeast and Midwest (Kirilenko and Sedjo 2007). In the West, fire, drought, and mountain pine beetle outbreaks could reduce productivity (Kurz et al. 2008).

Other goods and services provided by forests may also be affected. Opportunities for forest-based winter recreation activities such as snowmobiling and skiing may decrease as snow decreases and winters become milder (Bowker at al. 2012, Wobus et al. 2017). Summers may become too hot for outdoor recreation across much of the country, and more recreation may shift to cooler seasons in the South (Brice et al. 2017, Scott et al. 2004). Nontimber forest products may also be affected. Changing conditions, such as increased temperatures and altered freeze-thaw cycles, may have negative impacts on sugar maples (*Acer saccharum*) in some parts of the United States, reducing sugar maple health (Houle et al. 2015, Hufkens et al. 2012) and syrup quantity and quality (Matthews and Iverson 2017). Maple syrup production may move to the far Northeast and parts of Canada (Skinner et al. 2010). Additionally, increasing temperatures are projected to change the timing and duration of fall foliage colors (Archetti et al. 2013) and shift habitats and migratory patterns for birds and other wildlife (Langham et al. 2015). Such changes have implications for tourism-related economies (Thomas et al. 2013).

Climate change may also alter the timing and intensity of forest management. For example, in response to longer and more intense fire seasons, more resources will be diverted to fire fighting and suppression, resulting in fewer resources available for other management activities (USDA Forest Service 2015). Prescribed fire seasons may also need to shift in some areas if conditions become too wet or dry. More resources may be required to detect and treat invasive species, forest pests, and pathogens if these species benefit from warmer climates. Timber harvesting opportunities on frozen ground may also be reduced, and harvesting may need to switch to periods when soils are dry instead of frozen (Rittenhouse and Rissman 2015).

A changing climate may provide incentives for efforts to partially offset fossil fuel emissions and increase carbon storage in forests and wood products (Janowiak et al. 2017). Forest management strategies include land use change to increase forest area (afforestation) or to avoid deforestation (or both), and optimizing carbon management in existing forests. Strategies for forest product use include using wood wherever possible as a structural substitute for materials such as steel and concrete that have a large carbon footprint, and using wood as biofuel. If wood-based biofuel becomes an attractive strategy for emissions reduction, it could drive up demand for wood products.

As climate change impacts become apparent, managers are beginning to take action to adapt their forests to climate change (Ontl et al. 2017). Management strategies can be employed to protect existing species and ecosystems, such as identifying areas that may serve as refugia (Morelli et al. 2016) or reducing stocking to reduce competition for water during drought (D'Amato et al. 2013). Other adaptation actions may focus on enhancing species or genetic diversity to increase the probability that some species or individuals may be able to withstand current stressors. Finally, actions may be taken to assist the migration of species or populations to newly suitable areas because of conservation or economic concerns (Williams and Dumroese 2013). Adaptation actions that are not effective or yield unintended consequences could have additional negative impacts on forests.

Conclusions

Climate will continue to be a major driver influencing the distribution, species composition, and structure of forests. Climate-driven disturbances, such as storms, droughts, floods, wildfire, and pest outbreaks will have a strong influence on the productivity and composition of forests in the United States over the coming decades. These disturbances will influence the availability of forest products and other forest-derived services. Forest managers will be faced with the challenge of adapting to these changes while also ensuring that forests continue to provide important ecosystem services.

Acknowledgments

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