Chapter 1
Recent Changes in Climate and Forest Ecosystems

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1.1 Atmospheric Environment

At the time this chapter is being written (January 2013), the United States has just experienced a drought that was unprecedented in the climatic record for its overall magnitude, spatial extent, and persistence (Karl et al. 2012), including being the warmest year since 1895, the beginning of formal measurements (NCDC n.d.). The standardized temperature anomaly for spring and summer of 2012 was a 1 in 1,600-year event for maximum temperature and a 1 in 450-year event for minimum temperature (Karl et al. 2012). July 2012 recorded the highest monthly mean temperature ever measured, and there were many individual-month records and near-records for various states. Globally, 2012 had the warmest summer on record (June through August), and in the United States only 2011 and 1936 had warmer summers (NCDC n.d.). In 2012, crop yields were reduced on nearly 80 % of U.S. agricultural lands (NIDIS n.d.), reducing the rate of national economic growth (Wiseman 2012). In late October, Hurricane Sandy swept northward from the Caribbean along the eastern coastal region, killing over 250 people, displacing tens of thousands from their homes, disrupting energy supplies, and causing $65 billion in damage. Spanning 1,800 km in diameter, Sandy was the largest Atlantic hurricane and the second costliest hurricane on record (Sullivan and Doan 2012; Wikipedia n.d.).

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The weather patterns of 2012 in the United States represent extreme conditions that may be associated with a well-documented, long-term warming trend. Between 1948 and 2010, mean temperature increase in North America was 0.2 °C per decade (Isaac and van Wijngaarden 2012), and 7 of the 10 warmest years on record occurred since 1990 (USEPA n.d.(a)). Over the last 50 years, annual mean temperature in Alaska has increased twice as much as the rest of the United States (Karl et al. 2009). Minimum temperature in U.S. urban areas has increased about 25 % faster than in rural areas (Mishra et al. 2012), and minimum temperatures have been increasing faster than maximum temperatures (Mishra and Lettenmaier 2011).

Over the last 40 years, the mean duration of dry episodes has increased in the eastern and southwestern United States (Groisman and Knight 2008). In the West and Southwest, droughts have increased in duration, severity, and frequency as a result of increased temperature (Andreadis and Lettenmaier 2006). In the Southeast, the area of moderate to severe drought has increased by 14 % in summer and 12 % in spring (Karl et al. 2009). In the Southwest, droughts have been more severe since 2000 than in the twentieth century (Breshears et al. 2005), and the western United States has experienced continuous drought at some location since 1999 (MacDonald 2007).

Recent increases in temperature and drought are consistent with the projected effects of elevated ambient carbon dioxide (CO_2), which reached 399 ppm at the long-term monitoring station on Mauna Loa, Hawaii, in June 2013 (Tans and Keeling n.d.). This level represents an increase of 80 ppm since 1960 and approximately 110 ppm since 1850 when fossil fuel combustion began contributing to atmospheric CO_2. The growth rate for global average CO_2 for 2000–2006 was higher than at any time since measurements began at Mauna Loa (1959); the annual rate of increase for total human-caused CO_2 emissions in the 2000s was nearly 3 %, compared to 0.7 % in the 1990s. The annual rate of fossil fuel CO_2 emissions increased from 1.3 % in the 1990s to over 3 % in the 2000s (Tans and Keeling n.d.); fossil fuel and cement emissions were 35 % higher in 2006 than in 1990 (Canadell et al. 2007). In the United States, CO_2 emissions have increased by 12 % since 1990 (USEPA n.d.(b)).

1.2 Trends and Extreme Events in Forest Ecosystems

One of the biggest changes in U.S. forested ecosystems in recent decades has been a decrease in the quantity and persistence of snow (Grundstein et al. 2010). Since the 1920s, snowfall has been declining in the West and the mid-Atlantic coast, and more recently in the Northeast (Kunkel et al. 2009). The ratio of snowfall to precipitation has decreased greatly in the Northwest because of lower snowfall (Feng and Hu 2007). Snowpack in the northern portion of the U.S. Rocky Mountains has decreased significantly since the 1980s (Pederson et al. 2011). Snow water equivalent (SWE) throughout the West has been lower since 1980 than during the rest of the twentieth century (McCabe and Wolock 2010), and winter precipitation in the northwestern United States has decreased since 1950 (Mote al. 2005). In the Colorado Rockies, snowmelt now occurs 2–3 weeks earlier than in 1978, and April 1 SWE and maximum SWE have respectively declined 4.1 and 3.6 cm per decade (Clow 2010). Glaciers, which are an iconic component of Western mountains and an important source of water in many locations, have been receding for the past century. Loss of ice has been especially rapid since around 1980 (Hodge et al. 1998; Josberger et al. 2007), with the largest losses of ice mass occurring in Alaska and the Northwest (Granshaw and Fountain 2006).

Concurrent with changes in temperature and the physical environment of forest ecosystems has been an apparent increase in the extent of ecological disturbances. Insect outbreaks have been especially prominent, extending over more land area than any other disturbance (see Chap. 4). Insect-caused mortality causes rapid changes in forest structure, productivity, and hydrology, and provides opportunities for tree regeneration and establishment of invasive species. Current epidemics of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and other beetles in the western United States have increased rapidly over the past decade (Meddens et al. 2012) (Fig. 1.1), mostly in lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson) forests. Over 4 million ha of forest have been killed in the United States, and another 8 million ha in British Columbia. Although most mortality has occurred in older stands that are physiologically stressed, higher temperatures have stimulated the reproductive cycle of beetles and reduced winter beetle mortality, allowing for rapid population increases (see Chap. 4). For the first time, higher temperature has also allowed beetles to attack high-elevation species such as whitebark pine (*Pinus albicaulis* Engelm.) (Gibson et al. 2008; Millar et al. 2012). The largest spruce beetle (*D. rufipennis* Kirby) epidemic ever observed in North America occurred in southern Alaska in the 1990s (Hayes and Lundquist 2009). Pinyon ips (*Ips confusus* LeConte) and other twig beetles have contributed to mortality in drought-stressed pinyon pine (*Pinus edulis* Engelm.) in the Southwest (Shaw et al. 2005), and southern pine beetle (*D. frontalis* Zimmermann) has caused extensive mortality in seven Southern states (Nowak 2004).

After insect outbreaks, wildfire is the second most important ecological disturbance in U.S. forests in terms of area affected and is strongly influenced by climate (see Chaps. 4 and 9). Annual area burned and duration of fire season in the West have increased since the 1980s, including several individual fires larger than 200,000 ha since 2000. This trend has in some cases been attributed to climate change (Westerling et al. 2006), although, a longer term perspective indicates that annual area burned in the past 20 years is not much different than in the early twentieth century (Fig. 1.2), especially for fires larger than 100,000 ha (Morgan et al. 2008). The extent of area burned is correlated with alternating multi-decadal periods of warm and cool climate (associated with phases of the Pacific Decadal Oscillation [PDO]), and it is reasonable to assume that if future climate looks like a warm-phase PDO (or if warm PDOs become more persistent or extreme), then more area will burn. The effect of climate on wildfire is clear and quantifiable (Littell et al. 2009), although fire severity (typically expressed as magnitude of tree mortality) is often modulated by fuel quantities (Miller et al. 2012). We may be entering a cool

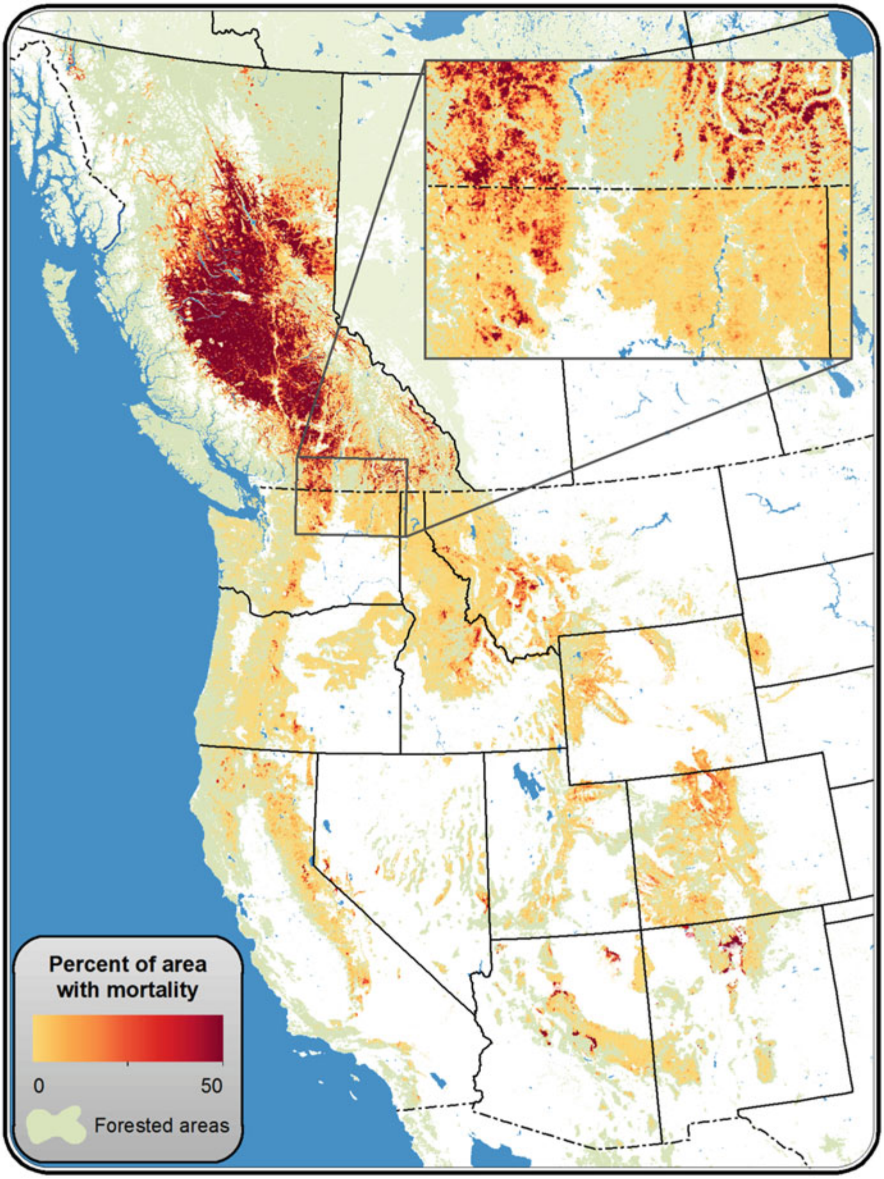

Fig. 1.1 Cumulative mortality area (ha) from 1997 to 2010 for the western conterminous United States and British Columbia for trees killed by bark beetles. Data are adjusted for underestimation (calculated by comparison with classified imagery) (From Meddens et al. (2012), with permission)

phase of the PDO, and if the extent of area burned in the West continues to remain high, then we can confidently infer that the increasing temperature trend associated with climate change is indeed affecting wildfire. A long-term trend of increased area burned, especially if severe, could maintain young forest age classes across

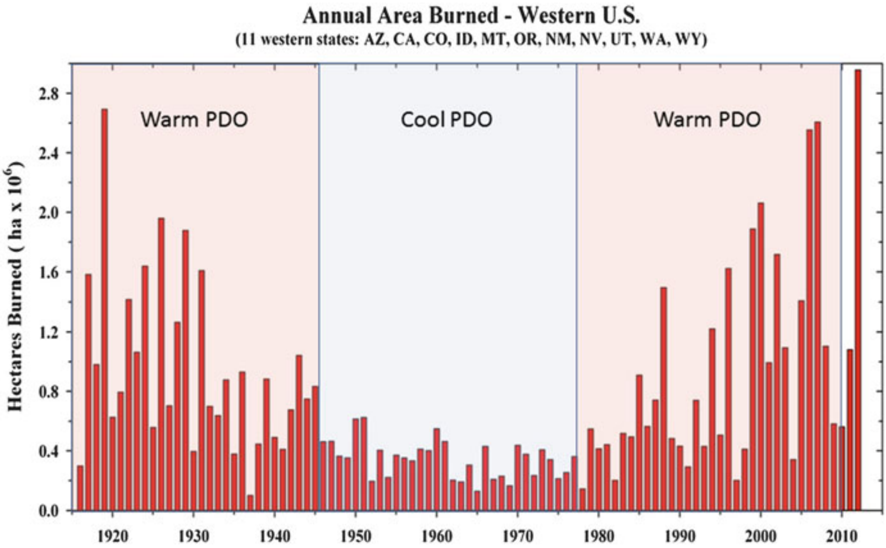

Fig. 1.2 Annual area burned by wildfire on federal lands in the 11 large western states in the conterminous United States, since 1916, including an indication of warm and cool phases of the Pacific Decadal Oscillation (*PDO*) (Based on data from U.S. Forest Service, modified from Littell et al. (2009), with permission)

large landscapes, lead to significant changes in the distribution and abundance of forest species in some locations (see Chap. 4), and cause rapid changes in carbon (C) dynamics (see Chap. 7).

An increase in extreme climatic and biophysical events will be the most important effect of climate change on forest ecosystems in future decades. Analogous to the concept of punctuated equilibrium in evolutionary biology (Gould and Eldredge 1977), we expect that rare but extreme climate-related events will cause faster, more pervasive effects than a gradual increase in temperature over time. For example, large wildfires essentially "clear the slate" across a particular landscape, and postfire biophysical conditions plus climate set the course for species composition, productivity, animal habitat, and many other ecosystem properties over decades to centuries. As a result, ecosystem structure and function can shift rapidly, especially if a big change in species composition occurs. This may already be occurring following large, severe wildfires in the Southwest (from forest and woodland to non-forest) (C. Allen, personal communication) and Alaska (from conifer-dominated forest to hardwood-dominated forest) (Wolken et al. 2011) (see Chap. 6). These shifts in vegetation physiognomy may not be reversible in a permanently warmer climate with more droughts and altered disturbance regimes. Large-scale, "clear the slate" disturbances are not limited to fire. Increased hurricane and storm intensity (Walsh and Ryan 2000), sea level rise, and severe and prolonged drought could have similar effects. Moreover, interactions of multiple disturbances and stressors may result in new combinations of species and ecosystem conditions for which we have no precedent in historical or paleoecological records (Williams and Jackson 2007) (see Chap. 4).

1.3 Resilience of Ecosystems and Institutions

Rapid shifts in climate and disturbance may strain both the resilience of forest ecosystems and the capacity of social systems and management institutions (Moser and Luers 2008) (see Chaps. 5 and 8). During the 1980s and 1990s, public land management in the United States shifted from an emphasis on resource extraction (e.g., timber harvest) to management for multiple resource values. Ecological restoration has become a dominant paradigm on federal forest land, focused on establishment of native species, older forests, and diverse habitat across large landscapes. Restoration targets are often based on "reference conditions" which may in turn be based on "historic range of variation" (HRV) for species and forest structure. In novel climates of the future, static concepts like HRV, plant associations, and potential vegetation types will probably be ineffective in attaining reference conditions. Rather, it will be more effective to recognize that most forests are dynamic, non-equilibrium systems, and to manage them to retain desired functions and processes (e.g., productivity, C retention, hydrologic flow). This approach would shift the management focus from *restoring* systems to *building resilience* in systems.

Current environmental policies and regulations in the United States, most of which were developed before climate change was recognized as an influence on forest resources, may not be flexible enough to accommodate rapidly changing climate and disturbance regimes (Peterson et al. 2011). For example, the capacity (budget and personnel) of agencies to suppress wildfires is already being stretched. Since 2000, the U.S. Forest Service has typically spent $1–2 billion per year on fire suppression, and nearly 50 % of the total agency budget is currently allocated to fire management. If annual area burned doubles during the twenty-first century, a conservative projection in most modeling studies (e.g., McKenzie et al. 2004), then balancing fire suppression versus other management functions will be a critical policy issue in the absence of a large increase in agency budget. Although fuel treatments reduce fire severity and build landscape resilience to wildfire, it will be difficult to offset increasing fire suppression costs without greatly increasing budgets for proactive, strategically placed treatments.

In December 2012, the United Nations Conference of the Parties extended the Kyoto Protocol, a pact that curbs greenhouse gas emissions from industrialized nations but covers only about 15 % of global C output. Failure to make meaningful reductions in emissions ensures that atmospheric CO_2 will continue to increase unabated in the absence of a technological fix or dramatically altered policies in countries that use most of the fossil fuels. In fact, current global emissions appear to exceed the high-end A2 emission scenario (see Chap. 2). This level guarantees that temperature will continue to rise for the next several decades, a trend that will be very difficult to reverse.

Concurrent with increasing temperature, forest ecosystems appear to be nearing important thresholds for the effects of climate change (Fagre et al. 2009). Although physical changes (e.g., temperature, hydrology) are better documented than biological changes, we anticipate that documentation of climate-related changes in U.S. forests will increase in future decades. Modifications of U.S. forest ecosystems will be superimposed on landscapes that have already been greatly altered by timber harvest and other land uses, as well as by the presence of 312 million people (and increasing) and their need for ecosystem services (see Chap. 3). Along with uncertainty in the extent and magnitude of extreme events in a warmer climate, we can expect surprises in how these events will affect the structure and functionality of forest ecosystems at large spatial scales. Responding to known challenges and unanticipated surprises will require shifting the focus of research and management from individual species and forest stands to landscapes that cover millions of hectares (see Chap. 10), while updating policy and regulations to facilitate this shift.

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