THE ECOLOGICAL IMPORTANCE OF MIXED-SEVERITY FIRES
NATURE'S PHOENIX

Edited by Dominick A. DellaSala and Chad T. Hanson

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Nature's Phoenix

Dedication

A special dedication is in order: To Ariela Fay DellaSala, Dr. DellaSala's ten-year-old daughter, who on hikes to the Grizzly Peak high-severity burn in southwest Oregon was especially excited to see the woodpeckers, butterflies, and kaleidoscope of flowering plants thriving in the snag forest. We are encouraged by the thought that if a ten-year-old can see beauty in a post-fire landscape, then maybe someday others will look twice before declaring these areas a wasteland. Also to Rachel Fazio, Dr. Hanson's wife, for her perspective, support, and patience throughout the writing of this book.

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Chapter 9

Climate Change: Uncertainties, Shifting Baselines, and Fire Management

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9.1 TOP-DOWN CLIMATE FORCING FIRE BEHAVIOR

There is no doubt that today's climate is changing, primarily from increased greenhouse gases from fossil fuel emissions (Romero-Lankao et al., 2014). The combination of rising temperatures and changes in seasonal and annual precipitation affects the size, severity, and occurrence of fires around the world (e.g., Krawchuk et al., 2009; Bowman et al., 2009; Flannigan et al., 2009). Because climate will increasingly dominate fire behavior in the future (Figure 9.1), it is important to draw on as broad a base of knowledge as possible to understand fire-climate interactions and identify appropriate management strategies.

In this chapter, we argue that the period chosen for comparison to current or future conditions is critical for understanding fire trends. Too short a period can overlook the influence of legacy conditions, the importance of extreme fire weather conditions, and the long-term climate conditions that have shaped fire activity in particular biomes. A suitable historical baseline or reference period must thus capture a long-enough span of time (reviewed by Papworth et al. (2008) and DellaSala et al. (2013)) to adequately reflect the dynamics of the disturbance and postfire recovery, as well as fire-climate variability. Selecting the wrong baseline, or one that is too short, can actually lead to poor management decisions and novel ecosystems (see DellaSala et al., 2013).

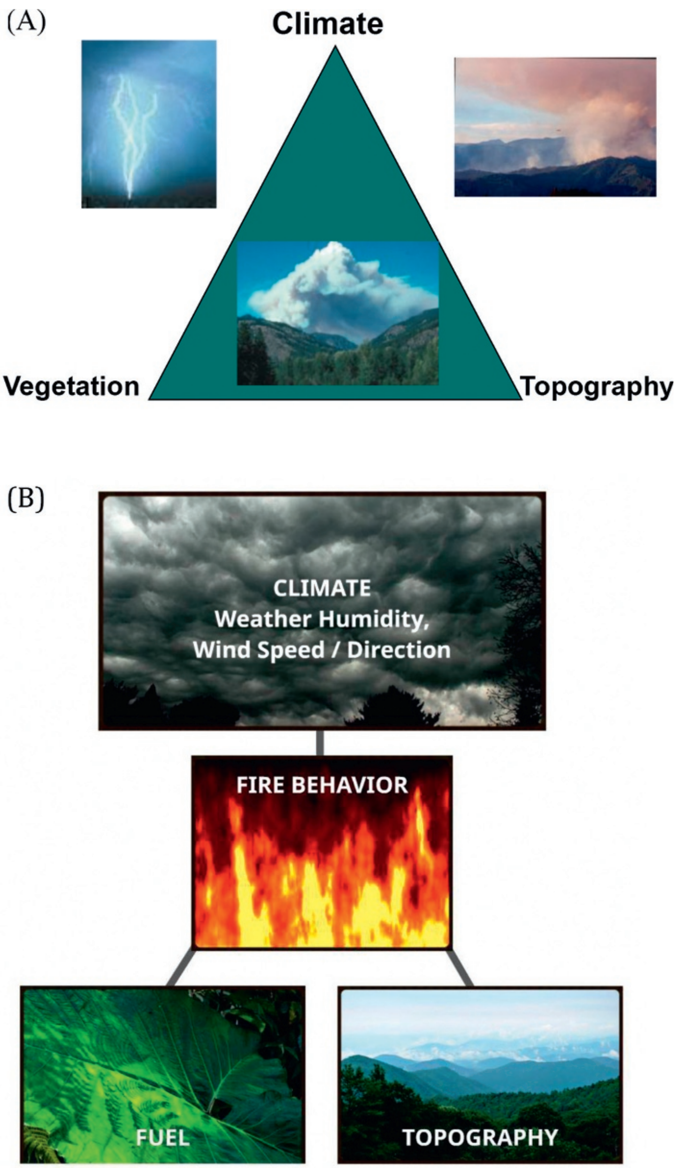

FIGURE 9.1 (A) Fuel-limited fire regimes depicting the interaction of climate, vegetation/fuels, and topography as generally equivalent influences of fire behavior. (B) Climate-limited fire regime depicting the top-down influence of climate on fire behavior. Many fire regimes are shifting from A to B as climate increasingly becomes the limiting factor of fire behavior. *(Also see Littell et al. (2009))*.

9.2 USING THE PALEO-RECORD TO CONSTRUCT A FIRE ENVELOPE

Fire history for any given location is a unique body of knowledge for establishing fire baselines because it describes fire causes and consequences over a wide range of climate conditions, land-use activities, and vegetation types. By providing a long-term perspective on fire regimes, historical data make us mindful of the short time span that serves as a reference condition for many forest management decisions, as well as the potential role of fire ahead with future climate and land-use changes. To effectively utilize historical fire information requires some level of understanding of the data sets that are available, as well as the time domains at which they describe fire. It also requires an appreciation of human influences on fire, including the degree to which people have altered past fire regimes through deliberate burning, land-use change, and the introduction of new species. Finally, fire history should be viewed not as irrelevant storytelling, but rather as vital information that describes the range of possible fire conditions under a broader array of spatial and temporal scales than we can observe at present.

9.3 RECONSTRUCTING PAST FIRE REGIMES

Multiple data sets are available to describe fire activity at different spatial and temporal scales (Gavin et al., 2007; Kehrwald et al., 2013) (Figure 9.2). On time scales of days to decades, remotely sensed data and historical documents register fire occurrence and are used to estimate global area burned (also see the Preface). On longer time scales of decades to centuries, tree-ring records, both fire scars on living trees and forest stand structures, provide information on prehistoric fire occurrence, fire frequency, and fire severity. Studies of tree rings in the western United States have been instrumental in describing low- and mixed-severity fire regimes (e.g., Brown et al., 1999), the character of postfire vegetation development following high-severity fires (Romme, 1982; Sherriff et al., 2001; Odion et al., 2014), and modes of climate variability that lead to years and decades of large fires (Swetnam and Betancourt, 1990; Heyerdahl et al., 2008; Trouet et al., 2010). Fire-scar tree-ring records can produce a reconstruction of fire history with yearly and sometimes seasonal precision and extend our knowledge of past fires back centuries and in some cases millennia, but they are less useful in understanding the history of forests that experience high-severity stand-replacing fires. In these settings, analysis of stand ages and postfire age structure provides information on past fire events as well as postfire vegetation development. In mixed fire regimes, a combination of stand age and fire scars has been effectively used to reveal the mosaic of burned and unburned vegetation patterns (Taylor and Skinner, 2003; Schoennagel et al., 2011; Odion et al., 2014).

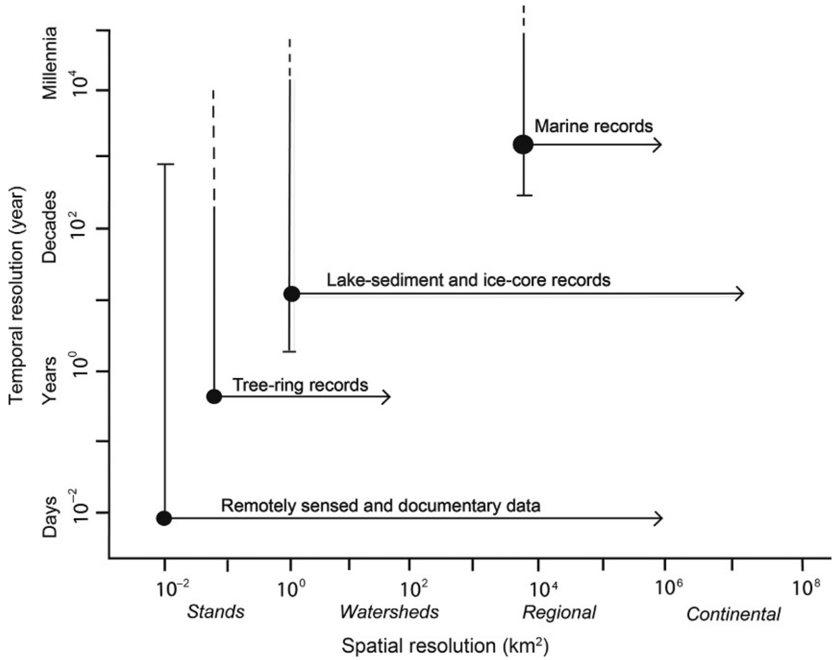

FIGURE 9.2 Types of data and models used to reconstruct past fire on different temporal and spatial scales. *(After Gavin et al. (2007).)*

Sedimentary Charcoal Analysis

On time scales of centuries to millennia, sedimentary records from lakes and natural wetlands provide information about fire history, and particulate charcoal is often a primary proxy. Charcoal records are less spatially resolved and temporally less precise in comparison to tree-ring data, but they have the advantage of examining fire response to a broader range of climate conditions and vegetation types than exist in the recent past. Evidence of fire in the form of black carbon, charcoal particles, and chemical signatures also is available in marine and ice cores that span several millennia (Daniau et al., 2013; Kehrwald et al., 2013).

Fire-history research based on sedimentary charcoal records has undergone a renaissance in recent decades, in part motivated by interest in understanding recent large, severe fires that seem to have little precedence in historic time. Whether such conflagrations occurred in the more distant past and the extent to which they were caused by unusual climate conditions or human activities are topics of both scientific and public concern. Charcoal analysis is based on the premise that charred particles are carried aloft during the fire and travel some distance in the atmosphere before settling on the ground and lake surface. The charcoal particles that fall on lakes and wetlands eventually become sequestered in sediment, and changes in particle abundance at different depths in sediment cores provide a proxy of past fire activity (Whitlock and Larsen, 2001). A suite of radiocarbon dates or other chronologic markers establishes an independent chronology in most fire-history studies. The primary data are presented as charcoal accumulation rates (CHAR particles per cm^2 per year), although several metrics have been used (Conedera et al., 2009). High-resolution charcoal investigations from lake sediments refer to the examination of large charcoal particles (>125 microns in diameter) in contiguous thin slices of the core. Because large particles are transported relatively short distances, they provide a record of local fires, and continuous sampling allows reconstructions with decadal precision (Figure 9.3).

The CHAR time-series data from a particular site are decomposed statistically to reconstruct the fire history (Marlon et al., 2006; Higuera et al., 2009). The long-term trend in the data is attributed to slowly varying changes in biomass burning, which is a function of both fuel composition and distribution

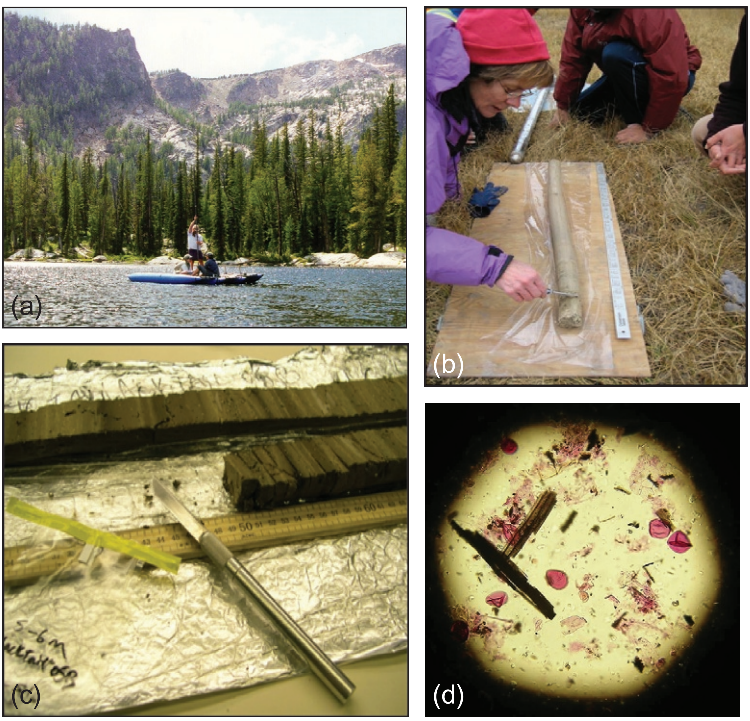

FIGURE 9.3 Fire-history analysis from lake sediments involves collecting a suite of cores from small lakes from an anchored platform (A); extruding and describing each sediment core in the field (B); slicing the core into contiguous 0.5-cm intervals and washing the material through sieves (C); and tallying black charcoal particles under the microscope for each sample (D). *(Photo 9.3D courtesy of Janet Wilmshurst, Landcare Research, Lincoln NZ.)*

(vegetation) and fire severity. Calibration studies and process-based models of charcoal transport suggest that CHAR trends are a good proxy of area burned within a <30 km radius of small lakes being studied, and the source area often matches that of pollen records from the same core used to reconstruct the vegetation history (Higuera et al., 2011; Kelly et al., 2013). Statistically significant CHAR peaks above a prescribed threshold are attributed to individual fire episodes (i.e., one or more fires occurring in the time span of the sample). Peak detection is used to identify fire episodes and describe variations in the frequency as well as the magnitude of fire episodes. Some studies make efforts to identify and separate grass and wood charcoal at each stratigraphic level as a tool to discriminate between surface and crown fires (Whitlock et al., 2006; Walsh et al., 2008). Additional precision also comes when the charcoal particles are themselves identified, a technique that comes from archeology (Carcaillet and Thinon, 1996; Marguerie and Hunot, 2007).

9.4 FIRE HISTORY ACROSS A MOISTURE GRADIENT

The goals of fire-history research are to distinguish the drivers of fire activity, be they climate, fuel, or anthropogenic factors; understand the extent and nature of past fire activity; and assess fire's long-term ecological effects. These objectives require (1) examining multiple charcoal records to separate local from regional patterns; (2) modeling studies to examine fire-ecosystem feedbacks; and (3) data-model comparisons (Henne et al., 2011; Marlon et al., 2013; Pfeiffer et al., 2013). One way to understand fire's role in different ecosystems is to examine its importance across a moisture gradient (Figure 9.4). At the dry end, deserts experience frequent ignitions and low fuel and soil moisture, but discontinuous fuel often prohibits fire spread, and fires of any significant size are infrequent. At the wet end, fuels are abundant in rainforests, but the dry

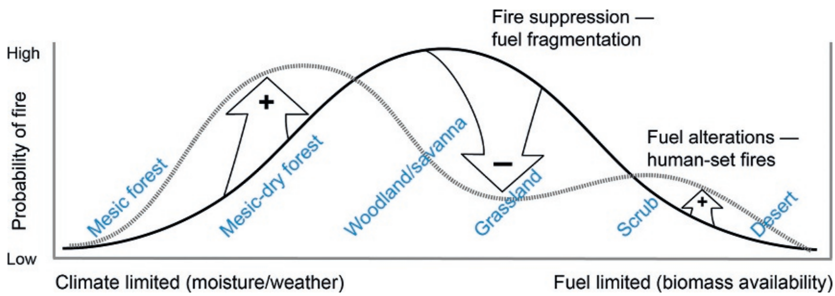

FIGURE 9.4 The magnitude of human influences on natural fire regimes varies along a broad moisture gradient of vegetation types. Climate exerts strong control over fire activity at the extreme wet and dry ends of the moisture gradient as a result of low combustion potential of fuels in mesic settings and the scarcity and disconnected arrangement of fuels in arid regions. Humans have the potential to alter fire regimes (shown by positive and negative arrows) by changing ignition frequency, fuel composition, and pattern as well as by suppressing fires (dashed line). *(After Whitlock et al. (2014)).*

season is short and natural ignitions are infrequent or do not coincide with the period of dry fuels. In such wet settings fires are also infrequent, although they can be severe when ignition and drought coincide. At the intermediate scale, temperate dry forests and savanna meet both requirements of sufficient amount and dryness of fuel and frequency of ignition, and these vegetation types support frequent low- and mixed-severity fires (Williams and Baker, 2012; Odion et al., 2014). Thus fires are infrequent at wet and dry ends of the moisture spectrum, and severe fires tend to characterize ignition-limited systems (Whitlock et al., 2010; Archibald et al., 2013; McWethy et al., 2013). Of course, these relationships are compromised by human activities, including where people alter the natural ignition frequency (e.g., the arrival of people on the Pacific Islands; McWethy et al., 2010; Chapter 7), introduce nonnative species that affect flammability (Brooks et al., 2004), or fragment natural landscape patterns (e.g., through logging and fire suppression; Odion et al., 2014).

9.5 CASE STUDIES OF LONG-TERM FIRE HISTORY IN THE WESTERN UNITED STATES

Tree-ring and charcoal data from middle- and high-elevation forests in the western United States indicate that past variations in fire activity are strongly linked to a changing climate. On long time scales, a primary driver of past fire activity has been slow variations in the seasonal cycle of insolation. In the early Holocene (~12,000-6000 calendar years before present (cal year BP), with "present" set at 1950 AD), summer insolation (generally, the degree of sun exposure) was 8% higher than at present, and winter insolation was lower by the same amount. Higher summer insolation led directly to higher-than-present summer temperatures and effectively decreased moisture; it indirectly produced a strengthened northeastern Pacific subtropical high-pressure system, which further suppressed summer moisture in the northwestern United States. Most parts of the northwestern United States show higher fire activity in the early Holocene compared with the late Holocene (Whitlock et al., 2008). At the same time, stronger-than-present monsoonal circulation, also driven by the summer insolation maximum, may have led to wet summer conditions and fewer fires in the southwestern United States (Bartlein et al., 1998; Anderson et al., 2008). On decadal to century time scales, ocean-atmosphere interactions (El Niño Southern Oscillation, Pacific Decadal Oscillation, American Multidecadal Oscillation) may contribute to fire occurrence and severity through atmospheric configurations that create persistent drought (Kitzberger et al., 2007; Trouet et al., 2010), although the strength of the these short-term relationships varies greatly from region to region.

Greater Yellowstone Region

In the greater Yellowstone ecosystem, regional analysis of charcoal records describe broad trends in climate, fire, and vegetation change over the past

15,000 years (Iglesias et al., 2015). These data indicate that highest fire activity in the region occurred between 12,000 and 10,000 cal year BP, when summers were warmer than today, winters were colder, and winter precipitation was generally high. The high-fire period was associated with decline in fire-vulnerable Engelmann spruce (*Picea engelmannii*) and an increase in whitebark pine (*Pinus albicaulis*) at all elevations.

On the rhyolite (a type of silica-rich volcanic rock) plateaus of central Yellowstone, charcoal data highlight the direct connections between fire and climate through time (Millspaugh et al., 2000). This area has supported lodgepole pine (*Pinus contorta*) forest for the past 11,000 years because of the strong edaphic (relating to the soil) controls on vegetation composition. By contrast, past fire activity was more dynamic than the vegetation history, showing the highest occurrence between 11,000 and 7,000 cal year BP during the summer insolation maximum and decreasing frequencies to the present day. Most prehistoric fires were likely mixed- or high-severity events, given the persistence of lodgepole pine. Other studies of Yellowstone show the occurrence of infrequent large fires during the Little Ice Age (1600-1900 AD), and fewer and likely small fire events during the Medieval Climate Anomaly (800-1200 AD) (Meyer et al., 1995; Pierce et al., 2004; Whitlock et al., 2012). By contrast, an analysis of postfire sediment deposits in alluvial fans in ponderosa pine (*Pinus ponderosa*) forests in southern Idaho revealed large, severe-fire events well above recent levels during a warm period from 1050 to 650 cal year BP (Pierce et al., 2004).

Pacific Northwest

The fire history of the Pacific Northwest region also was strongly influenced by shifts in the duration and severity of summer drought and the composition of the forest. Between 9500 and 5000 cal year BP, drier-than-present summers supported forests with abundant Douglas-fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), and bracken fern (*Pteridium*). This forest composition resembled current early seral forest stages, and—not surprisingly—fires were more frequent than today. In valley floors, woodland, prairie, and savanna habitats were expanded in the early Holocene compared with their present distribution, again in association with more fires. As summer insolation decreased in the late Holocene, summers became cooler and wetter than before, and forests of mesophytic (referring to plants adapted to moderate levels of moisture) conifers (e.g., western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), fir (*Abies* spp.), and Sitka spruce (*Picea sitchensis*)) prevailed. In association with this cooling trend, fires were less frequent, but, given the vegetation composition, they were likely more severe than in earlier times (Walsh et al., 2008; Whitlock et al., 2008; Gavin et al., 2013).

The temperate wet forests of the Pacific Northwest do not seem to have been particularly vulnerable to prehistoric human activities, even though people lived in the region throughout the Holocene and the population density at the time of European arrival was relatively high (Boyd, 1990). Several ecological and cultural factors may account for the limited influence of people in shaping Pacific Northwest fire regimes, but among them is the pyrogenicity of the dominant tree species in wet temperate forests: Douglas-fir. This conifer has evolved with fire and displays several life-history traits that allow it to persist across a wide range of fire frequencies and severities (Tepley et al., 2013). Its rapid establishment and growth of seedlings after mixed-severity fires and its ability to establish beneath and above competing shrubs promote rapid recovery of Douglas-fir canopy, often within decades after fire (Tepley et al., 2014). The presence of partially intact forest within most burned areas also enables Douglas-fir to rapidly colonize adjacent high-severity patches. Given these factors, it seems highly unlikely that a targeted ignition strategy by prehistoric peoples in the Pacific Northwest would have resulted in large-scale forest conversion, as occurred, for example, in the temperate wet forests of New Zealand (Whitlock et al., 2015).

Further south in the Pacific Northwest, the fire history is more complex in terms of spatial and temporal variability, particularly in the Klamath-Siskiyou region of southwestern Oregon and northern California (Taylor and Skinner, 2003; Colombaroli and Gavin, 2010; Odion et al., 2010; Briles et al., 2011). A study of Bolan Lake showed infrequent fires in the early postglacial period (17,000-14,500 cal year BP), when the climate was cooler than present and subalpine parklands of lodgepole pine, spruce, and mountain hemlock (*Tsuga mertensiana*) were present (Briles et al., 2005). Warming after 14,500 cal year BP was associated with forest closure and increased fire activity. After 11,000 cal year BP, open xerothermic (pertaining to plants adapted to relatively hotter, drier conditions) forests of pine, oak (*Quercus*), incense cedar (*Calocedrus decurrens*), and *Ceanothus* developed, and fires became more frequent than during the late-glacial period. During the middle Holocene (7000-4500 cal year BP), a closed forest of fir, Douglas-fir, red alder, and oak became established, and the frequency of fire episodes reached its highest levels. In the past 4000 years, fir-dominated forests have developed at middle elevations, and mountain hemlock has expanded at high elevations. At most sites, fire frequency has declined in the late Holocene, with the exception of elevated fire activity during the Medieval Climate Anomaly (Briles et al., 2011).

Colorado Rocky Mountains

The fire history of subalpine forests in the Colorado Rocky Mountains shows the importance of changes in forest composition and density on fire behavior (Higuera et al., 2014). Tree-ring records indicate that subalpine forests of Engelmann spruce, subalpine fir (*Abies lasiocarpa*), and lodgepole pine have supported low-frequency, stand-replacing fires in recent centuries (Buechling and Baker, 2004; Sibold and Veblen, 2006). The vegetation and fire frequency have shown little variation over the past 6000 years, despite long-term trends toward lower summer temperatures and less effective moisture (where effective moisture = precipitation − evaporation) (see Figure 9.5). Mean fire return intervals have ranged between 150 and 250 years during the past 6000 years, although the variability around the long-term fire return interval mean correlated well with shifts in summer moisture (i.e., more fires during drier summers). Levels of biomass

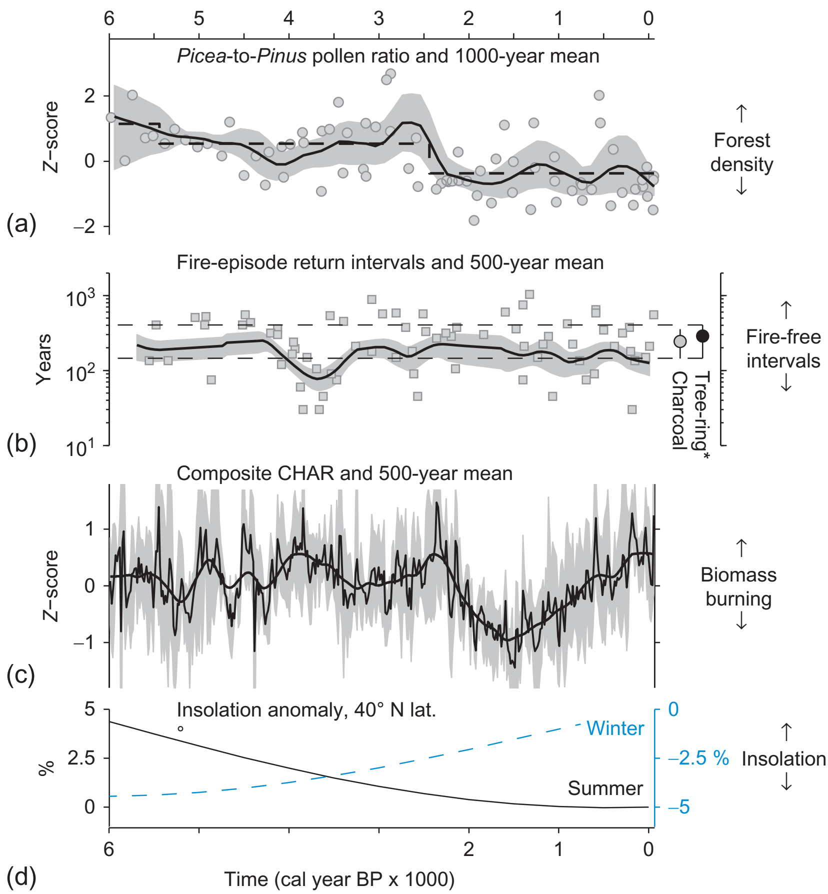

FIGURE 9.5 Millennial-scale vegetation, fire, and climate history from subalpine forests in Rocky Mountain National Park. (A) The *Picea*-to-*Pinus* pollen ratio (points) is a composite from three pollen records (black curves and grey envelopes represent the 95% confidence intervals). The ratio shifts to lower values (more pine) at 5400 and 2400 cal yr BP (calendar years before present). (B) Individual fire return intervals (FRIs) from each site (squares) and the composite mean FRI averaged and smoothed over 500-year periods (gray shading). Mean FRI from the charcoal record for the past 300 years (circa 1650-1950) compares well with estimated fire rotations from tree-ring records over the same period (Buechling and Baker, 2004; Sibold and Veblen, 2006) (grey and black circles on right). (C) Composite CHAR record at 15-year intervals (with 95% confidence intervals) and smoothed to 500 years. (D) Holocene insolation for the summer and winter solstice at 40° N latitude. *(From Higuera et al. (2014)).*

burned (inferred from CHAR trends) decreased significantly at 2400 cal year BP, despite little change in vegetation or fire frequency. This shift is interpreted as evidence of less biomass burned per fire and a decrease in crown fire severity. In the past 1500 years fire severity has steadily increased in these forests. Higuera et al. (2014) suggest that in Rocky Mountain subalpine forests (1) fire severity is likely more responsive to climate change than is fire frequency, and (2) the indirect influence of climate on vegetation and fuels is as important as the direct effects of climate on fire activity.

9.6 HISTORICAL RECORD AND THE FIRE ENVELOPE

Most studies describing current and projected trends in fire activity draw on a short baseline of historical data for comparison. In the conifer forests of North America a variety of methodological approaches have been used to establish historical reference conditions, including analysis of spatially explicit historical records of high-severity fire, reconstructions of past fire severity using aerial photographs to determine the number of emergent (surviving) trees in a particular study area, age analyses of stands in current unlogged forests, and analyses of stand structure based on historical field plot data (Baker, 2012; Williams and Baker, 2012; Baker, 2014; Odion et al., 2014; Hanson and Odion, 2015a; see also Chapter 1 for more detailed descriptions). An examination of historical data relative to current estimates of high-severity fire rates highlights the problem of using a baseline that is too short (and recent) to fully capture the historical variability of particular fire regimes. We focus, in particular, on areas where there is a tendency for recent trends in high-severity fire—whether increases or decreases—to be erroneously considered outside of the context of historical baseline variability. In such cases, land managers and policymakers assume that current fires exceed natural levels, despite historical data (pertaining, in this section, to the past few centuries) that indicate a substantial decline in fire activity (Baker, 2014; Odion et al., 2014; Hanson and Odion, 2015a). As a result, current conditions are misinterpreted in the development of management prescriptions.

For example, while area burned has increased in the boreal forests of Canada in recent decades (1959-1999) (Kasischke and Turetsky, 2006; Chapter 8), the pattern is not uniform when placed in a longer-term context and does not hold for high-severity fire ("stand-initiating" fire). Overall, high-severity fire and rotation intervals have decreased (i.e., less high-severity fire, on average, per year or decade) by two- to threefold in the boreal forests of eastern and western Canada. Based on stand-age analyses, high-severity fire rotations are much longer (i.e., less high-severity fire) currently than they were before the mid-1800s (Bergeron et al., 2001, 2004a,b). Studies analyzing longer time periods also report decreases in fire activity in many regions of western Canada. Wallenius et al. (2011) indicate a significant decrease in burned area in northwestern Canada (northeast British Columbia, northwest Alberta, southeast Yukon Territory, and southwest Northwest Territories) from 1800 to 2000, and the findings are consistent with other long-term studies that describe decreases in boreal fire activity since 1850 (see Girardin et al., 2009). This decline has been attributed mainly to long-term shifts toward warmer, wetter conditions (with some fluctuations in the opposite direction in the early twentieth century) since the mid-1800s (Larsen, 1996; Bergeron et al., 2001, 2004a, b). For example, Meyn et al. (2013) report a significant decrease in burned area in British Columbia from 1920 to 2000 that was linked to increased precipitation, which outweighed the effects of rising temperatures and drought severity.

In mixed-conifer and ponderosa pine forests of western North America, historical high-severity fire rotation intervals typically ranged from about 150 to 400 years before the effects of fire suppression and logging (Leiberg, 1900, 1902; Bekker and Taylor, 2001; Baker, 2012, 2014; Williams and Baker, 2012; Hanson and Odion, 2015a). Since the early twentieth century, high-severity fire has declined by approximately two- to fourfold in most forests, and current high-severity fire rotations are generally 600-1000 years across broad regions (Odion and Hanson, 2013; Odion et al., 2014). This decline in fire is likely a result of fire suppression, long-term climate change, or both. Because many species in these forests benefit from and depend on the unique habitat created by high-severity fires (Chapters 3-6), alteration of fire frequency or severity threatens biodiversity and ecosystem dynamics. Increases or decreases in fire occurrence in the past few decades, and those projected in the future, must be understood within an ecological context informed by long-term fire regimes and high-severity fire rotation intervals.

9.7 UNDERSTANDING THE INFLUENCE OF ANTHROPOGENIC CLIMATE CHANGE ON FIRE

Given the strong influence of climate on fire activity, anthropogenic climate change is likely to alter fire activity around the globe (Bowman et al., 2009; Flannigan et al., 2009; Krawchuk et al., 2009). Because climate change is placing stress on ecosystems (Parmesan 2006), a common assumption is that anthropogenic climate change will increase fire activity to levels that will be deleterious to forests. As illustrated in previous chapters, however, wildfire, including high-severity fire, provides important ecological benefits to forest ecosystems, and these types of fires have become uncommon in many regions of western North America (Odion et al., 2014). Therefore, analyses linking fire and climate change should also consider fire's ecological benefits and the degree to which fire has been removed from the ecosystem (the fire deficit). Assessment of fire-climate trends should be based on a sufficiently long-term baseline to capture the historical range of fire variability of the ecosystem and should also account for the role of other anthropogenic factors, such as changes in wildfire management policies. Most current studies of fire and climate change do not consider all of these components.

Using a historical baseline for detecting and interpreting the effects of climate change on fire activity is particularly important in western US forests where fire activity trends of the past century have been altered by land-use and management practices. Stringent policies on fire suppression on US federal lands throughout most of the twentieth century profoundly and abruptly decreased the area burned in many western forests (Mouillot and Field, 2005; Stephens et al., 2007; Marlon et al., 2012; Odion et al., 2014). These studies indicate that a baseline that at least considers fire variability before 1900 is needed to understand fire variability under a range of climate and fuel conditions. A long-term baseline also clarifies the relative influences of nonclimate drivers in shaping current fire conditions. The invasion of nonnative plants, introduction of nonnative grazers, land-use change, and changes in forest management practices, for example, have caused abrupt changes in fire regimes globally, independent of climate change (Pausas and Keeley, 2014).

Using the appropriate spatial scale is also important for understanding the relationships between climate change and fire activity. Many studies have documented spatial variability in fire-climate relationships among western ecoregions (Westerling et al., 2006; Littell et al., 2009; Parisien et al., 2011, 2012) and in the ways that climate change will affect temperature, precipitation timing and extent, drought severity, and other key drivers of fire activity (Hartmann et al., 2013; Melillo et al., 2014). Depending on the interplay between rising temperature and changing precipitation timing and amounts, climate change will affect fire activity differentially across regions and vegetation types (Krawchuk and Moritz, 2011). For example, in many northern and mountainous regions of the western United States, low precipitation and warmer temperatures in the seasons leading up to and including the fire season are strongly associated with increased burned area (Littell et al., 2009), whereas increased precipitation in summer suppresses fire (Moritz et al., 2012). By contrast, in the more fuel-limited arid ecosystems of the southwestern United States, increased precipitation before the fire season is strongly associated with increased burned area (Littell et al., 2009), but lower precipitation before the fire season suppresses fire activity by decreasing fuel biomass (Moritz et al., 2012).

9.8 OBSERVED TRENDS IN FIRE ACTIVITY LINKED TO CLIMATE CHANGE

Studies of fire trends in western North America in relation to recent climate change report a range of patterns depending on the fire activity metric (e.g., burned area, occurrence, severity), regional scale, and time period analyzed. Most studies have examined trends only over recent decades (e.g., 1970s/1980s to 2000s) rather than longer periods that would encompass a greater range of variability. Although some studies report increases in burned area linked to increased temperature and precipitation change in recent decades (e.g., Westerling et al., 2006), others indicate patterns of decrease (e.g., Meyn et al., 2013) and areas of relative fire stability (e.g., Dennison et al., 2014). Most current research has not detected a trend in fire severity in recent decades.

Westerling et al. (2006) is the most highly cited study linking wildfire activity with recent climate change in western North America. Using a study period from 1970-2003 and averaging across forested regions in the western United States, the study reported a marked shift during the mid-1980s toward a higher frequency of large fires, a greater average annual area burned, and a longer fire season, which the authors associated with increased spring and summer temperatures and an earlier spring snowmelt. However, trends since the mid-1980s are less clear (Westerling et al., 2006).

Most subsequent studies have examined fire-activity trends on an ecoregional level and have found differing geographic patterns over short time periods. Dillon et al. (2011) analyzed trends across six ecoregions in the southwestern and northwestern United States from 1984 to 2006 and detected no trends in annual area burned or proportion burned severely in the northwestern ecoregions (Pacific, Inland Northwest, and Northern Rockies). The study did report a significant increase in burned area and high-severity burned area in the three southwestern ecoregions (Southern Rockies, Colorado Plateau, and Mogollon Rim) and a significant upward trend in fire severity (proportion of high-severity fire) in one southwestern ecoregion (Southern Rockies). Topography (i.e., elevation, aspect/slope) was identified as the most important variable in determining severe fire occurrence, followed by climate conditions.

Dennison et al. (2014) examined trends in fire activity from 1984 to 2011 in nine ecoregions in the western United States. This study detected significant increases in annual fire area in three of nine ecoregions (Southern Plains, warm deserts, and Arizona-New Mexico Mountains) and significant increases in the number of large fires in four of nine ecoregions (Southern Plains, Arizona-New Mexico Mountains, Rocky Mountains, Sierra Nevada/Cascades). In contrast to Westerling et al. (2006), this study did not detect a significant trend toward an earlier fire season in any ecoregion. Dennison et al. (2014) caution against directly attributing increases in fire activity to climate change but note that ecoregions with increasing trends in the number of large fires and total fire area also experienced increasing drought severity over that period.

The few studies that have examined trends in fire severity also use short time periods and indicate that fire severity has not increased in recent decades in most forested regions in the western United States: Pacific Northwest and California (Schwind, 2008), Pacific Northwest and Southwest except the Southern Rockies (Dillon et al., 2011), northwestern California (Miller et al., 2012), the Klamath/Siskiyou region and Eastern Cascades (Hanson et al., 2009), and Sierra Nevada and Southern Cascades (Collins et al., 2009; Hanson and Odion, 2014; however, see Miller et al., 2009; Miller and Safford, 2012). Hanson and Odion (2014) found that use of a vegetation data set that postdates the time series being analyzed tends to result in a statistically significant bias toward reporting an increasing trend in severity. For example, conifer forest that experiences high-severity fire in the earlier years of the time series is disproportionately reclassified later as nonconifer vegetation, thus creating the false appearance of increasing severity. Safford et al. (2015) hypothesized that an increasing trend would be found if analysis focused solely on wildland fires in mixed-conifer and ponderosa/Jeffrey pine forests on national forest lands. Hanson and Odion (2015b) tested this hypothesis and again found no trend in increasing fire severity.

9.9 PROJECTED CHANGES IN FIRE ACTIVITY IN RESPONSE TO CLIMATE CHANGE

Studies projecting how climate change will affect future fire activity typically use one of three modeling approaches, each with its own limitations: statistical models, changes in fire activity indices, and dynamic global vegetation models (DGVMs) (see Yue et al., 2013). Statistical models correlate empirical observations of fire activity (e.g., area burned, fire occurrence, fire probability) with environmental variables expected to affect fire. The models are used to project fire activity under future climate conditions derived from a global or regional climate model. This approach is similar to species distribution models that forecast shifts in species ranges under climate change, and they have similar limitations (e.g., Guisan and Thuiller, 2005). A second approach projects changes in a fire activity index, such as a drought index, severity rating, or energy release component, to estimate future fire potential as a result of climate change; a primary limitation is the accuracy of the index in representing fire activity. A third approach is to incorporate a fire module into a DGVM, which is a process-based biogeochemical model that simulates vegetation dynamics in response to climate change driven by climate data from global climate models (GCMs). Modeling fire in DGVMs can be challenging because it requires a mechanistic understanding of how climate and fire interact, and this approach is often limited by the accuracy of representing historical fire activity patterns.

Fire projection studies differ not only in their modeling approaches but also in the number and choice of GCMs, emissions scenarios, climate variables, spatial scale (i.e., global or regional), and the historic baseline for deriving fire-climate relationships and for comparing projected versus historic fire activity, all of which can create significant variation among study results and interpretations. One important source of uncertainty is the large differences across GCMs in the projected change in precipitation timing and amount in western North America (Roy et al., 2012; Peterson et al., 2013). The choice of GCMs has the potential to create divergent projections of future fire activity depending on whether selected models forecast wetter or drier futures.

Modeling studies have projected a range of responses in future fire activity across the globe and in western North America, including areas of decrease, increase, and relative stability in wildfire probability, occurrence, and biomass burned (Scholze et al., 2006; Krawchuk et al., 2009; Gonzalez et al., 2010; Liu et al., 2010; Pechony and Shindell, 2010; Moritz et al., 2012). These global studies show a general lack of spatial concordance in their projections, likely because of differences in modeling approaches, climate variables used, and the number and selection of GCMs (see Moritz et al., 2012). For example, using changes in drought index to measure fire potential, Liu et al. (2010) projected future global fire patterns nearly opposite those of Moritz et al. (2012) that employed a statistical modeling approach.

Analyses of the western United States and Canada have primarily projected increases in fire activity (e.g., area burned and fire potential) in response to climate change, although there is significant variability among studies and ecoregions, in particular forested ones. Using one GCM in a statistical modeling approach, Spracklen et al. (2009) projected an average increase in burned area of 54% across the western United States overall by midcentury, although significant increases occurred in only three of six western ecoregions (Pacific Northwest forests, desert Southwest, Rocky Mountains forests). Yue et al. (2013), using 15 GCMs, projected an average increase in burned area of 61% across the western United States by midcentury, but increases in ecoregions varied substantially depending on whether a statistical or process-based modeling approach was used. Fire projection studies at smaller regional scales have suggested increases in fire activity for some regions—the Pacific Northwest (Rogers et al., 2011) and Southern Rockies (Litschert et al., 2012)—and conflicting patterns of increases and decreases for others: California, Nevada, southern Oregon, southwestern Idaho, western Utah, and western Arizona (Westerling and Bryant, 2008, Krawchuk and Moritz, 2012). Projection studies typically have not examined changes in fire severity (but see Rogers et al., 2011), but focus on occurrence, probability, and area burned.

Most fire projection studies use a short historical baseline spanning the past few decades, which does not provide a useful context for determining whether projected changes fall within the range of historical variability. Illustrating important exceptions, Bergeron et al. (2010) projected a 125% increase in burn rate in the eastern Canadian boreal forest by the end of the century compared with the recent period from 1961 to 1999, but they determined that the increase fell well within the long-term variability for this region during the past 7000 years, as well as a shorter baseline of the past 300 years. By contrast, Westerling et al. (2011) suggest enormous increases in area burned in the forests of the greater Yellowstone ecosystem, projecting a nearly 10-fold (900%) increase by midcentury and a 1000-fold (100,000%) increase by the end of the century. If true, this level of burning would lie well outside the range of variability of the past 10,000 years. Some studies have projected increases in total annual area burned in California ranging from 9% and 11% to 15% by the end of the century compared with that in 1895-2003 (Lenihan et al., 2008), and increases in the number of large fires ranging from 12%, 23%, and 34% to 53% by the end of the century compared with that during 1961-1990 (Westerling and Bryant, 2008). Given that the average annual burned area in

California in the past several decades (1950-2009) was at least several times lower than the burned area before 1800 (Stephens et al., 2007; Odion et al., 2014), these projected increases in fire activity in California would likely remain within the historical range of the past several centuries.

9.10 CONCLUSIONS

Understanding the causes and effects of wildland fire in forest ecosystems depends on the temporal and spatial scale of interest. In this regard, fire triangles are a common starting point for conceptualizing the suite of biophysical factors operating at particular scales as well as cross-scale interactions (Figures 9.1 and 9.6). Taken together, the fire envelope is defined by a hierarchy of temporal

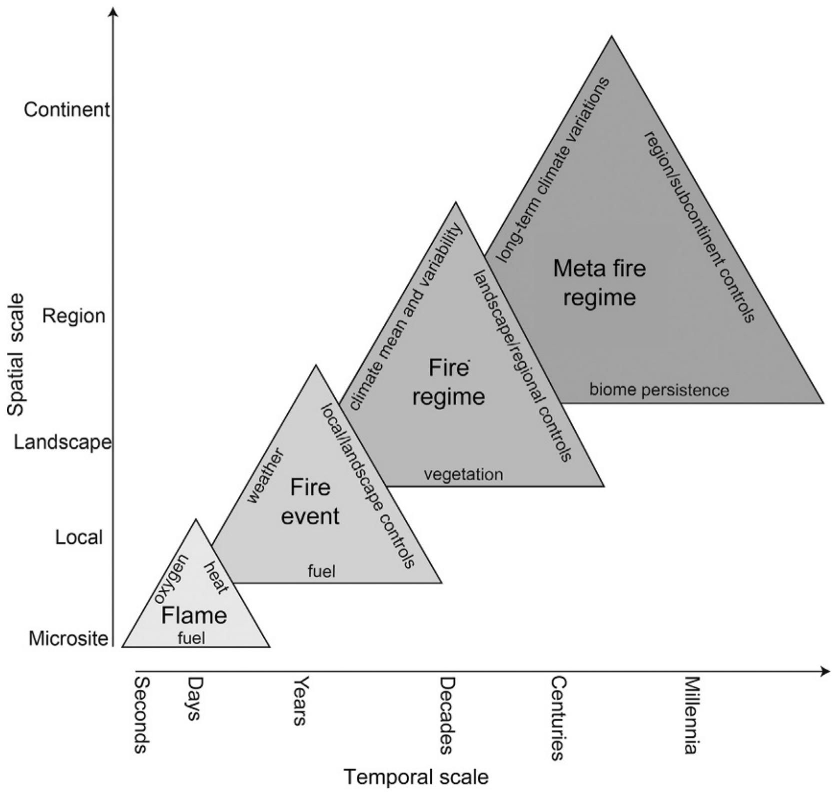

FIGURE 9.6 Controls of fire at multiple temporal and spatial scales conceptualized as fire triangles (modified from Parisien and Moritz, 2009). The side of each triangle indicates the dominant drivers at different temporal and spatial scales, and the overlap of triangles shows their nested nature. Paleoecological data suggest the need for a broader conceptualization of fire regimes that considers the variability of fire characteristics over the lifespan and spatial extent of a biome. *(From Whitlock et al. (2010)).*

and spatial conditions (or triangles) that shape biomass burning over time and space. At the smallest scale, the fire fundamentals triangle links oxygen, heat, and fuel at time scales of hours to years. At the next temporal and spatial scale, the fire event triangle links weather, fuels, and topography as factors that influence ignition probability, rate of fire spread, and fire intensity over seasons and years (Rothermel, 1972; Bowman et al., 2009). On decadal-to-millennial time scales, the fire regime triangle describes variables that determine the characteristic pattern, frequency, and intensity of fire at landscape and broader scales, reflecting the linkages between vegetation as a determinant of fuel, climate conditions as creators of fire weather, and ignition sources, be they human or natural (Parisien and Moritz, 2009; Krawchuk and Moritz, 2011). Our understanding of the paleofire record suggests that a larger and longer scale should also be considered in the fire envelope. A meta-fire regime triangle describes insights gained from the range of conditions that govern fire history over the duration of a vegetation type at time scales of centuries to millennia and fire variability at the scale of regions.

Understanding past human-vegetation-climate linkages of fire regimes has gained wider attention and appreciation in the face of projected future climate change. Although many definitions of a fire baseline implicitly consider time, historical data are rarely used to define a fire envelope. More often, baselines rest on recent fire statistics that are at best imprecise and at worst inaccurate in capturing fire activity over long time scales. What may seem like a stationary response on short time scales is often nonstationary when viewed on longer time scales and over a broader range of bioclimatic forces (Swetnam, 1993). In many parts of the western United States, for example, current levels of fire are considerably less than what climate would predict based on long-term linkages. This notion of a present-day fire deficit in many forest types implies that current fire management is decoupling the natural relationship between area burned and climate (Marlon et al., 2012).

We recommend that observed and projected changes in fire-climate linkages be understood in terms of (1) fire's ecological benefits, (2) the current fire deficit in most forested regions of North America, and (3) a sufficiently long baseline to capture the historical range of fire variability within the particular biome. Detecting and interpreting the significance of climate-driven fire patterns requires information on the magnitude and direction of change in comparison to the long-term fire occurrence within the ecosystem as well as the relative influences of climatic and nonclimatic drivers. Ideally, a fire regime should describe the size, severity, and frequency of fires at different stages of forest development and consider the climate, fuel properties, and human influences that have influenced fire history. This broad temporal and spatial context is essential if we are to accurately project and understand the consequences and benefits of fires in the future.

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