CHAPTER 7

Fire and Drought

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Introduction and Historical Perspective

Historical and presettlement relationships between drought and wildfire have been well documented in much of North America, with forest fire occurrence and area burned clearly increasing in response to drought. Drought interacts with other controls (forest productivity, topography, and fire weather) to affect fire intensity and severity. Fire regime characteristics (area, frequency, severity) are the product of many individual fires, so both weather and climate—including short- and long-term droughts—are important. It is worth noting, however, that the factors controlling fire events and fire regimes are complex and extend beyond drought and climate alone, and so fire regimes and wildfires are affected by other variables from local-to-global scales. Fire history evidence from diverse climate regimes and forest ecosystems suggests that North American forest fire regimes were moderately to strongly controlled by climate prior to Euro-American settlement and subsequent fire exclusion and fire suppression (Flatley and others 2013, Hessl and others 2004, Heyerdahl and others 2002, Heyerdahl and others 2008, Swetnam 1990, Swetnam and Betancourt 1998, Weisberg and Swanson 2003). These presettlement fire histories indicate a relationship between low precipitation anomalies and widespread fire activity, especially in the Western United States. This is consistent with a regional depletion of soil and atmospheric moisture, which leads to low moisture in foliage and surface fuels and ultimately to the potential for widespread fire (Swetnam and Betancourt 1998). Some fire histories in the American Southwest also demonstrate a lagged relationship with above-average antecedent precipitation (Swetnam and Betancourt 1998) and/or cooler temperatures (Veblen and others 2000) in the year(s) prior to years of widespread fire. Most of these records are derived from fire-scarred trees that survived fire events and thus are primarily indicative of low- or mixed-severity fire regimes, although some work has focused also on evidence from high-severity fire regimes (Heyerdahl and others 2002).

In the mid- to late-20th century, relationships between area burned and climate parallel those in the fire history record. From 1980 forward, area burned on Federal lands was related to monthly Palmer Drought Severity Index (PDSI), and the sign and magnitude of the relationships were consistent with reconstructed fire histories (Westerling and others 2003). Littell and others (2009) documented ecologically and geographically variable responses of area burned to year-of-fire climate, with area burned increasing with increased temperature, decreased precipitation, or anomalously low (negative) PDSI in most forests and in some nonforest vegetation. Area burned in nonforested systems is associated with drought, but in some fuel conditions and regions, stronger relationships exist between anomalously *high* antecedent precipitation (or positive PDSI) and area burned (Littell and others 2009). This body of evidence indicates that the role of drought in historical, and likely future, fire regimes is an important contingency that creates anomalously high potential for ignition, fire spread, and large fire events. However, drought is only one aspect of a broader set of controls on fire regimes, and by itself is insufficient to predict fire dynamics or effects. Whereas the relationships between fire occurrence or area burned and drought are well documented, the relationship between drought and fire severity is still emerging. Clear relationships between years with extensive fires and the proportion of area with high severity do not exist (Dillon and others 2011, Holden and others 2012); however, the years with more widespread fires show substantially less landscape and topographic controls on severity (Dillon and others 2011). For example, north-facing slopes might offer some degree of local protection during mild droughts, but even they become dry under extreme conditions, reducing fine-scale heterogeneity in vegetation consequences.

The conditions that affect fires after ignition, from initial spread to eventual extinguishment, exert the strongest control over fire behavior (Rothermel 1972) and thus the ultimate outcomes in terms of area burned and severity. Drought influences the likelihood of ignition and availability of fuels at multiple time scales, and shorter-term weather affects fuel moisture and propagation, but intensity and severity are also determined by other more local factors that interact with drought.

At long time scales (seasons to centuries or longer), moisture availability and drought affect fuel availability via controls on ecosystem characteristics and productivity, and at short time scales (seasons to years) via controls on fuel structure and flammability (Loehman and others 2014). Climate, therefore, acts to facilitate fire by both producing fuels through vegetation growth and making those fuels flammable. The paleoecological record indicates that on time scales of centuries to millennia, the tension between climatic controls on fuel availability and fuel flammability manifests as the fire regime, with fire responding to the limits of available fuels (vegetation) and vegetation responding to the frequency, severity, and extent of fire resulting from changes in flammability (Prichard and others 2009, Whitlock and others 2010).

Climate exerts a strong control over fire, but other factors that affect fuel abundance, frequency of flammability, and propensity for ignition can affect fire regimes. Human management of landscapes and fuels, suppression of fire, and use of fire all exert control in tandem with the effects of climate (Moritz and others 2005). Collectively, the fire regime and how it changes through time are a function of fuels and how other factors affect their availability and flammability. Climate, management, and land use affect availability, flammability, continuity of fuels, and probability of ignition differently in different parts of the World. At the scale of seasons to decades, drought directly affects flammability and thus the frequency of conditions conducive to large fires and possibly the severity of those fires. At the scale of years to millennia, drought directly affects the distribution and abundance of vegetation and indirectly affects disturbances including fire.

Characterizing Drought: Metrics of Fire Risk

Which Drought Metrics Relate to Fire Risk?

Drought is not a necessary or sufficient condition for fire, because fires burn during conditions of normal seasonal aridity (e.g., dry summers that occur annually in California), and drought occurs without wildfires in the absence of ignitions. However, when drought occurs, both live and dead fuels can dry out and become more flammable, and probability of ignition increases along with rate of fire spread (Andrews and others 2003, Scott and Burgan 2005). If drought continues for a long period, the number of days with elevated probability of ignition and fire spread increases, raising the risk of widespread burning. Long droughts are not necessary to increase risk of large wildfires; anomalous aridity of 30 days or more is sufficient to dry fuels substantially in all size classes (Cohen and Deeming 1985, Riley and others 2013) as well as live fuels. Drought can therefore be defined in meteorological terms, or in relative terms with respect to hydrology or ecosystems (chapter 2).

Because drought influences fire both directly via fuel moisture and indirectly through biological and ecological effects on vegetation, fire risk can be quantified by both drought indices and fire behavior metrics. Interpretation of these metrics is complicated by the fact that not all vegetation types respond the same to meteorological drought in terms of fuel availability and flammability, but the probability of ignition increases in most fuels when fuel moisture is low. Although fuels are capable of burning under different conditions in different ecosystems, even short-term drought generally increases wildfire risk through its effects on fuel moisture, and thus on probability of ignition and spread rate.

Palmer Drought Severity Index—Palmer Drought Severity Index (PDSI) (Palmer 1965) is commonly used in fire occurrence research in the United States (Balling and others 1992, Collins and others 2006, Littell and others 2009, Miller and others 2012, Westerling and others 2003). PDSI was designed to capture agricultural drought, using a water-balance method to add precipitation to the top two layers of soil, and a temperature-driven evapotranspiration algorithm to remove moisture (Thornthwaite 1948). PDSI assumes all precipitation falls as rain rather than snow, making its application less reliable where snow comprises a significant proportion of annual precipitation. Because the algorithm does not include some of the important drivers of evapotranspiration (relative humidity, solar radiation, wind speed), its correlation with soil moisture is weak (r = 0.5–0.7; Dai and others 2004). Correlation between PDSI and soil moisture peaks during late summer and autumn, corresponding with fire season in much of the Western United States. PDSI does not have an inherent time scale, but its "memory" varies from 2 to 9 months depending on location (Guttman 1998).

During the past century, PDSI is weakly to moderately associated with fire occurrence in many parts of the Western United States. In Yellowstone National Park (Wyoming, MT), year-of-fire summer PDSI calculated for two adjacent climate divisions had a Spearman's rank correlation of -0.55 to -0.60 (1895–1990), with the correlation decreasing to -0.23 to -0.27 during the previous winter and -0.2 for the previous year (Balling and others 1992). Regional PDSIs for groups of Western States using the average of the PDSI value for each State were r^2 = 0.27–0.43 (1926–2002) for current year PDSI and area burned (Collins and others 2006). Including the PDSI from the two antecedent years increased correlations with area burned to r^2 = 0.44–0.67, indicating that multi-year droughts may increase fire occurrence.

PDSI was a significant predictor, along with precipitation and sometimes temperature, in modeling area burned in 12 of 16 ecoregions in the Western United States for the period 1916–2003 (Littell and others 2009). During the period 1910–1959, summer PDSI explained 37 percent of area burned and number of fires in national forests of northwestern California. However, during the later period of 1987–2008, total summer precipitation was a significant predictor, not PDSI (Miller and others 2012). Among an array of possible drought indices, PDSI values from the previous October showed the strongest correlation with nonforested area burned in the western Great Basin (r^2=0.54 for 1984–2010), indicating that wet conditions during the previous autumn predicted area burned during the next fire season. The index did not perform well in other regions (Abatzoglou and Kolden 2013).

Precipitation totals (monthly, seasonal)—Precipitation totals and anomalies are a measure of meteorological drought. In addition to the study by Miller and others (2012) referenced earlier, monthly and seasonal precipitation anomalies have been used in several studies relating drought to fire occurrence (Balling and others 1992, Littell and others 2009, Morgan and others 2008). Littell and others (2009) further demonstrated that seasonal precipitation was a significant factor in multivariate models predicting area burned in most ecoregions in the Western United States. However, the magnitude and sign of the precipitation term varied; in mountain and forest ecoregions, summer precipitation was generally negatively correlated with area, but in nonforested ecoregions, antecedent (usually winter) precipitation was positively correlated with area burned.

In Yellowstone National Park, total annual precipitation had a Spearman's rank correlation of -0.52 to -0.54 with area burned, which was a stronger correlation than was demonstrated in the same study using PDSI (Balling and others 1992). Summer precipitation had the strongest relationship among drought indices with area burned in nonforested areas of the Pacific Northwest (r^2=0.48) and eastern Great Basin (r^2=0.31; Abatzoglou and Kolden 2013).

Standardized Precipitation Index—The Standardized Precipitation Index (SPI) is a measure of meteorological drought, calculated as the difference of precipitation from the mean for a specified time period divided by the standard deviation (McKee and others 1993). Because the distribution of precipitation amounts is generally right-skewed (Riley and others 2013), it must be normalized before this equation is applied (Lloyd-Hughes and Saunders 2002). One can calculate SPI for any time period, typically ranging from 1 to 24 months. Because SPI is normalized, one can use it to estimate probability of a drought of a certain severity, and the index has a similar meaning across ecosystems (e.g., a value of -1 means that precipitation is one standard deviation below normal). Riley and others (2013) found that 3-month SPI explained 70 percent of the variability in area burned and 83 percent of variability in number of large fires in the Western United States. With increasing time intervals for calculating SPI, correlations decreased until 24-month SPI explained essentially none of the variability. Fernandes and others (2011) also found strong correlations between 3-month SPI and anomalies in fire incidence in the western Amazon.

Energy Release Component—Energy Release Component (ERC) is a fire danger metric used in the National Fire Danger Rating System for the United States and a proxy for fuel moisture or amount of fuel available to burn. The calculation of ERC is based on recent weather (temperature, solar radiation, precipitation duration, and relative humidity). ERC can be calculated for different fuel conditions, but is most commonly used to estimate fire occurrence for larger fuels (>7.5–20 cm diameter) (Andrews and others 2003, Bradshaw and others 1983). ERC approximates dryness (a proxy for amount of fuel available to burn) based on weather during the previous 1.5 months, the amount of time required for fuels 7.5–20 cm diameter (i.e., 1,000-hour fuels) to equilibrate to atmospheric conditions (Fosberg and others 1981). Because ERC varies across different ecosystems, the raw values are commonly converted to percentiles to indicate departure from average conditions (Riley and others 2013).

Over the population of individual wildfires, ERC percentile during the first week of burning is highly correlated with fire occurrence at the scale of the Western United States, explaining over 90 percent of the variability in area burned and number of large fires for the period 1984–2008 (Riley and others 2013). Probability of a large fire ignition can be predicted from ERC (Andrews and Bevins 2003, Andrews and others 2003), although the prediction parameters vary with location because fires are likely to ignite at different ERCs, depending on local fuels and climate. Because of its strong association with fire occurrence, ERC is used operationally as an indicator of heightened fire risk (Calkin and others 2011). It was shown to be correlated with area burned in southern Oregon and northern California (Trouet and others 2009) and the U.S. Northern Rockies (Abatzoglou and Kolden 2013).

Keetch-Byram Drought Index—The Keetch-Byram Drought Index (KBDI) is an indicator of soil moisture deficit and is based on a number of physical assumptions (Keetch and Byram 1968). Soil water transfer to the atmosphere through evapotranspiration is determined by temperature and annual precipitation, which is used as a surrogate for vegetation cover (areas with higher annual rainfall are assumed to support more vegetation). KBDI was developed and evaluated for the Southeastern United States, and has been used for guidelines on expected fire conditions and potential suppression problems for this region (Melton 1989). KBDI has been useful beyond the Southeastern United States, with possible limitations in some cases (Liu and others 2010, Xanthopoulos and others 2006).

Wildfire potential is divided into four levels based on KBDI values (National Interagency Fire Center 1995):

- **Low (KBDI=0–200)**—soil moisture and fuel moistures for large fuels are high and do not contribute much to fire intensity;
- **Moderate (200–400)**—lower litter and duff layers are drying and beginning to contribute to fire intensity;
- **High (400–600)**—lower litter and duff layers contribute to fire intensity and will actively burn; and
- **Extreme (600–800)**—intense, deep burning fires with significant downwind spotting can be expected.

The four KBDI levels are typical of spring dormant season following winter precipitation, late spring and early in the growing season, late summer and early autumn, and severe drought and increased wildfire occurrence, respectively.

The fire hazard measured by KBDI shows large spatial, seasonal, and interannual variability across the continental United States (Liu and others 2013b). In winter, there are high values in the intermountain region, which decrease rapidly towards the east and become <200 (low fire potential) in the Great Plains. This spatial pattern remains during other seasons but with some changes. In summer, KBDI values >300 (moderate fire potential) are observed in the Southern United States. In autumn, KBDI values are higher in both the Western and Southern United States, with values >400 in the latter (high fire potential). Multiple-year trends of seasonal fire hazard measured by the slope of a linear line fitting the normalized KBDI time series show a positive sign in all seasons and regions except three seasons in the Pacific Northwest and two seasons in the Southeast.

Fosberg Fire Weather Index—The Fosberg Fire Weather Index (FFWI) measures fire potential and hazard (Fosberg 1978). It is dependent on temperature, relative humidity, and wind speed, assuming constant grass fuel and equilibrium moisture content (Preisler and others 2008). In order to gauge fire-weather conditions, FFWI combines the equilibrium moisture content (Simard 1968) with Rothermel's (1972) rate of spread calculation (Crimmins 2006). FFWI demonstrated significant skill in explaining monthly fire occurrence in the Western United States (Preisler and others 2008). To further include the effect of precipitation, a modified version of FFWI (mFFWI) was developed by adding KBDI as a factor (Goodrick 2002). One can use the mFFWI as a refinement of KBDI by adding the effects of relative humidity and winds.

Evapotranspiration—Evapotranspiration (ET), the combined evaporation from the surface and transpiration from plant tissues, is affected by meteorological conditions near the surface, plant physiology, and soil characteristics. Summer evapotranspiration had the highest correlations among drought indices with forested area burned in the Southwest and southern California, and with nonforested area burned in the U.S. Northern Rockies and Southwest (r^2=0.44–0.83) (Abatzoglou and Kolden 2013). June through September values of potential evapotranspiration, the evapotranspiration that could occur if plants did not limit water loss through stomata, was a significant predictor (r^2=0.19–0.61) of area burned in forested Pacific Northwest ecoregions during recent decades (1980–2009) (Littell and Gwozdz 2011, Littell and others 2010).

Ecological water deficits: water balance deficit and climatic water deficit—Various algorithms are used to define water deficit, but all approach deficit as the evaporative demand not met by available water. It is estimated as the difference between atmospheric demand for water from plants and the land surface and how much water is available to meet that demand. Like PDSI, water deficit attempts to integrate energy and water balance of some area to describe water availability. Some calculations of water deficit attempt to account for more of the factors in the soil-plant-atmosphere continuum than PDSI (e.g., storage in snow, effects of plant canopy energy balance, albedo, and wind).

Stephenson (1990, 1998) defined water balance deficit (WBD) as the difference between potential evapotranspiration (PET) and actual evapotranspiration (AET), and related it to the coarse distribution of biomes. Littell and Gwozdz (201) showed that PET, AET, and WBD are related (i.e., WBD = PET – AET) with a range of R^2=0.25–0.78 to area burned in ecosystems of the Pacific Northwest. Summer WBD had the highest correlation of several indices with area burned in forested areas of the Pacific Northwest (r^2=0.66) (Abatzoglou and Kolden 2013). Others have used a version closer to Thornthwaite's (1948) approximation and defined deficit as PET – precipitation.

Relationship to Hydrologic Drought

Many of the same factors affecting moisture in vegetation also affect moisture available for streamflow (chapter 2), and both fire and hydrologic drought occur with some lag after meteorological drought begins. Understanding such relationships could be useful for operational fire forecasts based on the same mechanisms that could be built from the substantial infrastructure and capacity for forecasting hydrologic drought. Broad changes and trends in snowpack, streamflow timing, and streamflow volume have been noted in various parts of the Western United States (Luce and Holden 2009, Luce and others 2012, Mote and others 2005, Regonda and others 2005, Stewart 2009), as have recent trends in fire occurrence related to climatic forcings (Dennison and others 2014).

Analysis of wildfire occurrence across the Western United States with streamflow records noted a moderately strong interannual correlation between the first principal component of streamflow center of timing and burned area in forests (Westerling and others 2006). Other work contrasting the correlation with total streamflow volume and center of timing in the Northwestern United States found similar relationship strength between burned area and annual streamflow volumes and between burned area and streamflow timing (Holden and others 2012). In the Pacific Northwest, a decline in streamflow and precipitation, particularly during drought years, suggested that much of the trend in fire in the historic record may be related to precipitation trends (Luce and Holden 2009, Luce and others 2013).

Synthesis of Index Relationships

The time window, over which the drought indices discussed earlier are computed, determines both the mechanistic relationships with fire they capture and their skill in predicting different aspects of fire regimes (fig. 7.1). For example, for fire occurrence at the spatial scale of the Western United States, ERC (calculated based on fuel moistures during the previous 1.5 months) is strongly correlated with both number of large fires and the burned area (Riley and others 2013). Monthly precipitation anomalies were comparably correlated. As the time window for the index increases to longer lags, the correlation with fire occurrence decreases. At finer scales, however, the relationships differ significantly across ecosystems. For example, above-normal precipitation in the year(s) prior to fire is associated with higher area burned in the Southwestern United States (Littell and others 2009, Swetnam and Betancourt 1998, Westerling and others 2003) and Great Basin (Littell and others 2009, Westerling and others 2003). Long-term drought (>4 months) is not necessarily a prerequisite for extensive area burned, and seasonal climate can override the effect of antecedent climate (Abatzoglou and Kolden 2013).

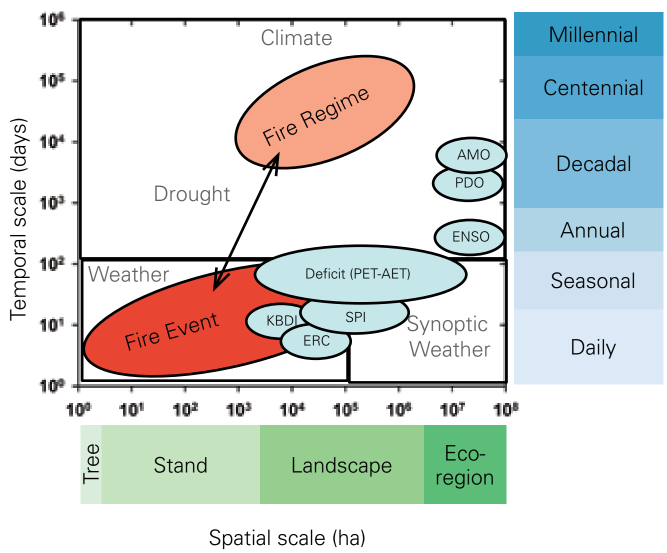

Figure 7.1—Scaling of controls on fire events, fire regimes (top, after climatic scaling of Clark [1985]), drought metrics, and climatic drivers related to their variation. In general, drought metrics are temporally coincident with fire events. The correlation between drought metrics and components of the fire regime in a location varies with time and space. Climatic factors that affect probability of ignitions, spread, area burned, and severity in a location in a given year is the product of multiscale influences of the climate system (top down) on fuel flammability and historical controls on fuel availability. Atlantic Multidecadal Oscillation (AMO), El Niño Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO) refer to modes of climatic variability. AET=actual evapotranspiration; PET=potential evapotranspiration; ERC=Energy Release Component; KBDI=Keetch-Byram Drought Index; and SPI=Standardized Precipitation Index.

Regional Differences in Fire and Interactions With Other Stressors

Drought clearly increases probability of fire occurrence in forest ecosystems, but other disturbances and stressors, both biotic and abiotic, interact with drought and fire in stress complexes that affect the vigor and sustainability of forest ecosystems (McKenzie and others 2009). Although some of these interactions are predictable, they are poorly quantified and complicated by the fact that most ecosystems are rarely in dynamic equilibrium with biophysical processes. In addition, equilibrium rarely occurs even in relatively constant climate, and it is typically punctuated by disturbance episodes that may or may not be associated with climatic variability; these disturbance episodes allow succession to proceed along multiple pathways (Frelich and Reich 1995) and create forest dynamics that are difficult to project accurately. These dynamics and their consequences reflect natural processes in many forest ecosystems. However, the role of climate change in increasing the probability of drought and the simultaneous effects of climate on forest processes that feed back to disturbance bears consideration of interactions that may result in more rapid change than drought alone.

Increasing air temperatures are expected to change the frequency, severity, and extent of wildfires (Littell 2006, McKenzie and others 2004, Moritz and others 2012). Large wildfires that have occurred during a warmer climatic period during the past two decades portend a future in which wildfire is an increasingly dominant feature of western landscapes. Similarly, bark beetles, whose life cycles are accelerated by increased temperatures, are causing extensive mortality across the West (Logan and Powell 2001, Swetnam and Betancourt 1998, Veblen and others 1991).

Tropospheric ozone, a stressor of forest ecosystems, is an indirect product of fossil fuel emissions and is exacerbated by sunlight and high temperature, although most other air pollutants are the direct result of human-caused emissions. Fire and insect disturbance clearly interact, often synergistically, thus compounding rates of change in forest ecosystems (Veblen and others 1994). For example, mountain pine beetles (*Dendroctonus ponderosae*)—which have caused high mortality, mostly in lodgepole pine (*Pinus contort*a subsp. *latifolia*) forests across 20 million ha in western North America—may significantly increase fine fuels and fire hazard for years following outbreaks (see review by Hicke and others 2012), though there is some uncertainty as to whether the probability of severe fires is affected positively or negatively by bark beetle mortality after dead needles have fallen (Lundquist 2007, Pollet and Omi 2002). In addition, fire severity in subalpine forests can be altered by a combination of bark beetles and annual-scale drought (Bigler and others 2005).

To explore the consequences of these interactions for different ecosystems, we extend a pathological model of cumulative stress in trees (Manion 1991, 2003) to forest ecosystems by describing interacting disturbances and stresses as stress complexes that have potentially far-reaching effects. Temperature increases are a predisposing factor causing often lethal stresses on forest ecosystems, acting both directly through increasingly negative water balances (Littell 2006, Milne and others 2002, Stephenson 1998) and indirectly through increased frequency, severity, and extent of disturbances (chiefly fire and insect outbreaks) (Logan and Powell 2001, 2009; McKenzie and others 2004; Skinner and others 2006). Increased disturbances can in turn cause rapid changes in forest structure and function and will be more important than temperature increase alone in altering the distribution and abundance of plant and animal species. We use examples from several forest ecosystems to document the existence of stress complexes and how they may be affected by a warmer climate.

Pinyon-Juniper Woodlands of the American Southwest

Pinyon pine (*Pinus edulis*) and various juniper species (*Juniperus* spp.) are among the most drought-tolerant trees in western North America, and characterize lower treelines across much of the West. Although pinyon-juniper woodlands appear to be expanding in some areas, possibly due to fire suppression or cessation of Native American fuelwood harvesting (Samuels and Betancourt 1982), they are clearly water-limited systems. At fine scales, pinyon-juniper ecotones are affected by local topography and existing canopy structure that may buffer trees against drought to some degree (Milne and others 1996), although severe multi-year droughts periodically cause massive dieback of pinyon pines, overwhelming any local buffering. Dieback of pine species—both ponderosa pine (*Pinus ponderosa*) and pinyon pine—occurred during and before the 20th century (Allen and Breshears 1998, Breshears and others 2005), and the recent (since the early 2000s) dieback is clearly associated with low precipitation and higher temperatures (Breshears and others 2005).

In the stress complex for pinyon-juniper woodlands (fig. 7.2), climate change is a predisposing factor; pinyon pine mortality and fuel accumulations result from warming and can lead to other impacts. Ecosystem change, possibly irreversible, comes from large-scale, severe fires that lead to colonization of invasive species, which further compromise the ability of pines to regenerate. However, it is worth noting that severe fires were historically characteristic of some pinyon pine systems (Floyd and others 2004).

Mixed-Conifer Forests of the Sierra Nevada and Southern California

Dominated by various combinations of ponderosa pine, Jeffrey pine (*Pinus jeffreyi*), sugar pine (*P. lambertiana*), Douglas-fir (*Pseudotsuga menziesii*), incense cedar (*Libocedrus decurrens*), and white fir (*Abies concolor*), these forests experience a Mediterranean climate in which summers are dry and long. Despite increasing temperatures since the early 20th century, fire frequency and extent did not increase in the mid- to late-20th century (McKelvey and others 1996). Rather, 20th century fire frequency and likely area were at lower levels than those present over the rest of the last 2,000 years (Swetnam 1993, Swetnam and Baisan 2003). Stine (1996) attributes this to decreased fuel loads from sheep grazing, decreased Native American fire management, and fire exclusion. Fire exclusion has led to increased fuel loadings and competitive stresses on individual trees as stand densities have increased (Ferrell 1996, van Mantgem and others 2004).

Elevated levels of ambient ozone, derived from vehicular and industrial sources in urban environments upwind, are phytotoxic and reduce net photosynthesis and growth of ponderosa pine, Jeffrey pine, and possibly other species in the Sierra Nevada and the mountains of southern California (Byternowicz and Grulke 1992, Miller 1992, Peterson and Arbaugh 1988, Peterson and others 1991). Sierra Nevada forests support endemic levels of a diverse group of insect defoliators and bark beetles (typically *Dendroctonus* spp.), but bark beetles in particular have reached outbreak levels in recent years, facilitated by protracted droughts. Ferrell (1996) refers to biotic complexes in which bark beetles interact with root diseases and mistletoes. Dense stands, fire suppression, and nonnative pathogens such as white pine blister rust (*Cronartium ribicola*) can exacerbate

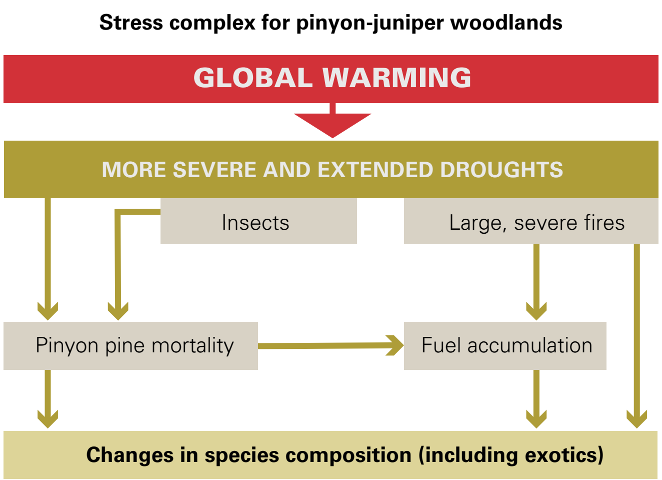

Figure 7.2—Stress complex in pinyon-juniper woodlands of the American Southwest. The effects of disturbance regimes (insects and fire) will be exacerbated by global warming. Stand-replacing fires and drought-induced mortality both contribute to species changes and exotic invasions. (Adapted from McKenzie and others 2009).

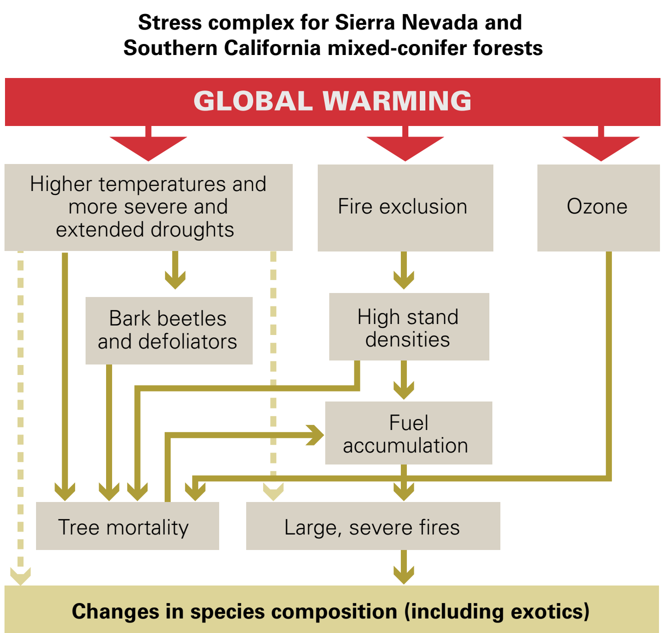

Figure 7.3—Stress complex in Sierra Nevada and southern Californian mixed-conifer forests. The effects of disturbance regimes (insects and fire) and fire exclusion will be exacerbated by global warming. Stand-replacing fires and drought-induced mortality both contribute to species changes and exotic invasions. Dashed lines indicate potential direct effects of higher temperature and drought. (Adapted from McKenzie and others 2009).

both biotic interactions (van Mantgem and others 2004) and drought stress. The stress complex associated with Sierra Nevada forest ecosystems (fig. 7.3) is likely applicable to the mountain ranges east and north of the Los Angeles basin as well.

Interior Lodgepole Pine Forests

Lodgepole pine is widely distributed across western North America and is the dominant species over much of its range, forming nearly monospecific stands that are maintained either because poor soils preclude other species or through adapting to stand-replacing fires via cone serotiny (Burns and Honkala 1990). Lodgepole pine is the principal host of the mountain pine beetle, and older, low-vigor stands are vulnerable to massive mortality during beetle outbreaks. Recent beetle outbreaks have caused extensive mortality across western North America, with large mature cohorts (age 70–80 years) contributing to widespread vulnerability. Warmer temperatures facilitate insect outbreaks by drought stress, making trees more vulnerable to attack and speeding up the reproductive cycles of some insect species (Logan and Bentz 1999, Logan and Powell 2001). Scientists accept that warming temperatures will exacerbate these outbreaks northward and into higher elevations (Hicke and others 2006, Logan and Powell 2009), but lodgepole pine ecosystems are poised for significant changes even at current levels of mortality.

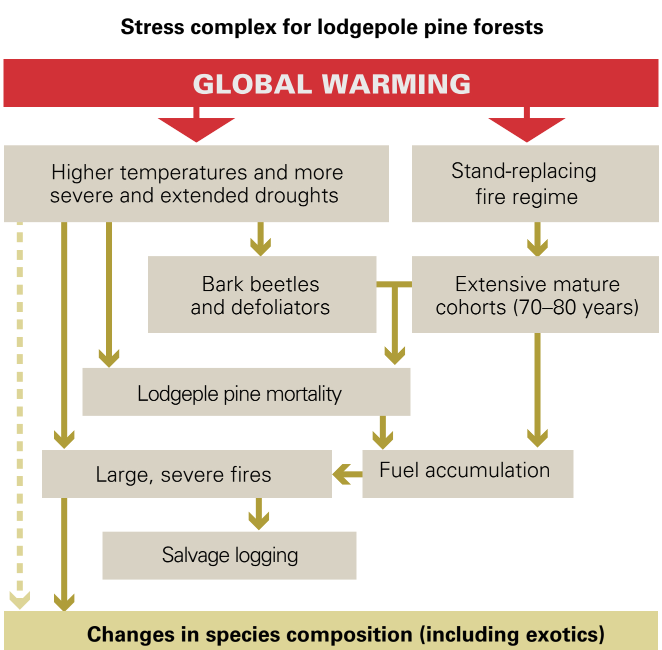

Figure 7.4—Stress complex in interior lodgepole pine forests. The effects of disturbance regimes (insects and fire) will be exacerbated by global warming. Stand-replacing fires, beetle mortality, and other stressors contribute to species changes. Dashed lines indicate potential direct effects of higher temperature and drought. (Adapted from McKenzie and others 2009).

In the stress complex for lodgepole pine forests (fig. 7.4), warmer temperatures combine with the highly flammable dead biomass (associated with beetle-induced mortality), and this combination exacerbates the natural potential for severe crown fires for roughly 5 years. Then, after fine fuels decompose and become compressed, the fire hazard may be lessened considerably.

Interior Alaskan Forests

A combination of large crown fires and outbreaks of spruce bark beetle (*Dendroctonus rufipennis*) in south-central Alaska has affected millions of hectares of boreal forest during the past 20 years (Berg and others 2006). Although periodic beetle outbreaks have occurred in southern Alaska and the southwestern Yukon throughout the historical record, the recent outbreaks are unprecedented in extent and percentage mortality (over 90 percent in many places) (Berg and others 2006, Ross and others 2001). Summer temperatures in the Arctic have risen 0.3–0.4 °C per decade since 1961 (Chapin and others 2005), and wildfire and beetle outbreaks are both likely associated with this temperature increase (Berg and others 2006, Duffy and others 2005, Werner and others 2006). Although fire-season length in interior Alaska is associated with the timing of onset of the late-summer precipitation, the principal driver of annual area burned is early summer temperature (Duffy and others 2005).

White spruce (*Picea glauca*) and black spruce (*P. mariana*) are more flammable than co-occurring deciduous species [chiefly paper birch (*Betula papyrifera*)]. Similarly, conifers are a target of bark beetles, so spruce in south-central Alaska will be disadvantaged compared to deciduous species, most of which respond to fire by sprouting. The stress complex for Alaskan boreal forests (fig. 7.5) projects a significant transition to deciduous species via more frequent and extensive disturbance associated with warmer temperatures. Scientists contend that this transition is unlikely without changes in disturbance regimes, because both empirical data and modeling suggest that warmer temperatures alone will not favor a life-form transition (Bachelet and others 2005, Boucher and Mead 2006, Johnstone and others 2004).

Southern Pine Forests

Much of the forested landscape in the Southeastern United States is adapted to frequent fire, and unlike most of the rest of the country, prescribed fire is a mainstay of ecosystem management. Fire-adapted inland forests overlap geographically with coastal areas affected by hurricanes and potentially by sea-level rise (Ross and others 2009); therefore, interactions between wildfires and hurricanes are synergistic (fig. 7.6). For example, dry-season (prescribed) fires may have actually been more severe than wet-season (lightning) fires in some areas, causing structural damage via cambium kill and subsequent increased vulnerability to hurricane damage (Platt and others 2002). The stress complex for Southern pine forests is represented conceptually in figure 7.6, where different disturbances "meet" in the outcomes for forest ecosystems.

Increasing frequency and magnitude of drought is expected to increase the flammability of both live and dead fine fuels in upland forests and pine plantations (Mitchell and others 2014). This may increase the frequency and intensity of some wildfires, and it may also reduce opportunities for safe implementation of prescribed burning. Both drought and increased fire may lead to greater dominance by invasive species [e.g., cogongrass (*Imperata cylindrical*)], which can in turn alter the flammability of fuels (Mitchell and others 2014). Proactive fuel reduction through prescribed burning, a common practice in Southern pine forests, will be even more important in a warmer climate.

Discussion

Rapid climate change and qualitative changes in disturbance regimes may send ecosystems across thresholds into dominance by different life forms and cause significant changes in productivity and capacity for carbon storage. For example, in the Southwest, stand-replacing fires are becoming common in what were historically low-severity fire regimes (Allen and

Stress complex for Alaskan boreal forests

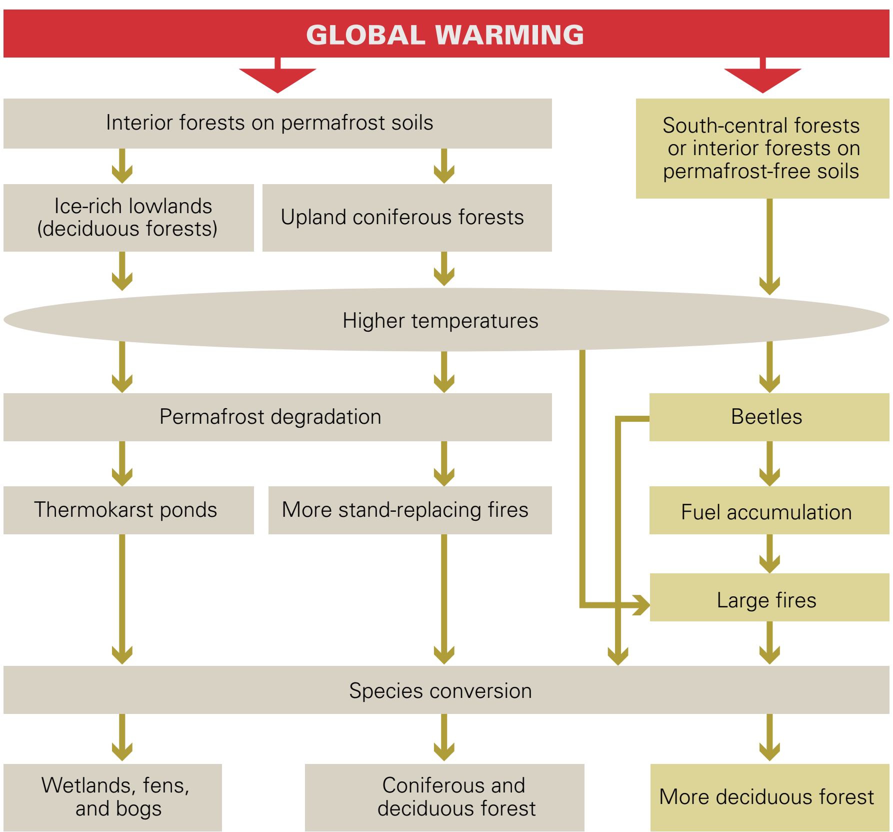

Figure 7.5—Stress complex in interior and coastal forests of Alaska. Rapid increases in the severity of disturbance regimes (insects and fire) will likely be triggered by global warming. Stand-replacing fires, mortality from insects, and stress-induced dieback contribute to species changes and conversion to deciduous species. (Adapted from McKenzie and others 2009).

others 2002), and protracted drought is killing species (ponderosa pine) that are adapted to low-severity fire (Allen and Breshears 1998). If these trends continue, ponderosa pine may be lost from some of its current range in the Southwest, and productivity of these systems will decline. In contrast, if warming temperatures accelerate mountain pine beetle reproductive cycles (Logan and Powell 2001) such that outbreaks are more frequent and more prolonged, lodgepole pine might be replaced by a more productive species such as Douglas-fir, at least on mesic sites where conditions for establishment are favorable.

As the climate warms, we expect that more ecosystems will become water limited (Albright and Peterson 2013, Littell 2006, Milne and others 2002), more sensitive to variability in temperature (due to its controls on both phenological and ecophysiological processes), and prone to more frequent disturbance. Consequently, productivity may decline across much of the West (Hicke and others 2002), and long-term carbon sequestration may be limited by a continuous mosaic of disturbances of various severities. Species and ecosystems will be affected in various ways and not all undesirable changes will be preventable by management intervention (McKenzie and others 2004).

There is no historical or current analog for the combination of climate, disturbance regimes, and land-use changes expected by the end of the 21st century. For example, tempering the idea of "desired future conditions" with "achievable future conditions" will facilitate more effective adaptive management and more efficient allocation of resources to maintain forest resilience. Conceptual models of stress complexes improve our understanding of disturbance interactions in forest ecosystems affected by climate change. Quantitative models of stress complexes are now needed to characterize alternative future states for a broad range of forest ecosystems across North America.

Stress complex for Southern U.S. pine forests

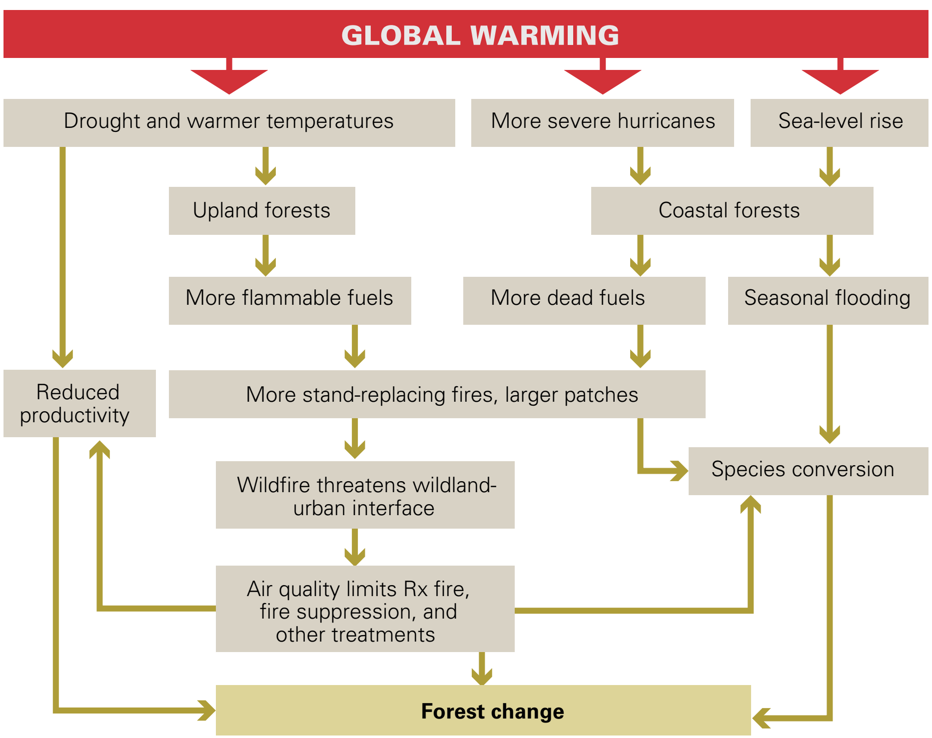

Figure 7.6—Stress complex in interior and coastal forests of the southeastern United States. Increases in the severity of hurricanes are triggered by global warming. Warmer and drier climate in uplands leads to longer periods with flammable fuels. Changes in fire and hydrologic regimes, and responses to them, lead to species change and altered carbon dynamics.

Quantifying and Projecting Drought Effects on Wildfire: Biological and Physical Factors

In chapter 2 of this publication, drought is defined as an area-specific anomalous lack of water. Here, we expand this definition to an uncharacteristic lack of water, specific to an ecosystem and a time scale. Risk is often defined as the product of the probability of an event and its consequences. Wildland fire researchers calculate fire risk as the probability of fire of a certain intensity times the effect on resource values (Bratten 1982, Calkin and others 2011, Mills and Bratten 1982). Wildfire probability increases as the moisture stored in fuels (live and dead vegetation) declines. Wildfire risk therefore responds to meteorological drought, and fire occurrence and area are correlated with metrics that measure precipitation delivery, relative humidity, and/or fuel moisture, reflecting both supply of water and demand for it (Abatzoglou and Kolden 2013, Littell and others 2009, Littell and Gwozdz 2011, Riley and others 2013). Drought is related to fire risk because it increases fuel dryness (in both live and dead fuels), which is correlated with probability of ignition and increases rate of spread. Drought may also increase the number of days with heightened probability of ignition.

Wildfire risk differs across the continental United States (Finney and others 2011, Preisler and Westerling 2007, Radeloff and others 2005) as a function of probability of burning and values at risk (buildings, municipal watersheds, endangered species habitat, etc.). Fire probability is generally related to the inverse of fire return interval, with longer fire return intervals having a lower annual probability of burning; for example, annual probability of burning in forests that burn infrequently is lower than that of chaparral which burns frequently (Agee 1993, Frost 1998). Probability of burning is also affected by quantity and distribution of fuels, land management, fire suppression, and invasive plants. Because many ecosystems in the United States were structured by fire until effective suppression, some consider wildfire to be a regulating ecosystem service through periodic reduction of fuels, which would otherwise require costly treatment. Cessation of Native American burning combined with fire suppression may have reduced area burned annually in the United States by an order of magnitude (Leenhouts 1998, Marlon and others 2012). If that burning takes place preferentially under extreme drought conditions when it cannot be suppressed, it is more likely to be of uncharacteristically high severity than if it took place under more moderate conditions.

Tree-ring evidence of North American "megadroughts" indicates that droughts of severity and duration not yet encountered by modern societies occurred on a widespread basis in the past (Cook and others 2007). Currently, only thin consensus exists regarding the effect of climate change on drought occurrence (Maloney and others 2014; chapter 2). High confidence exists for projected temperature increases across most of the planet in future decades, whereas altered precipitation and relative humidity are uncertain (Blöschl and Montanari 2010, Walsh and others 2014), and that uncertainty varies geographically. As temperatures continue to warm, all else being equal, droughts of given magnitude and low fuel moistures may become more likely in summer-dry climates even if precipitation increases, because potential evapotranspiration will also increase.

Seasonal timing of increases or decreases in precipitation would have important effects on risk, leading to geographic heterogeneity driven by historical fire regimes, ecological responses to climate change, and management. Regardless of specific climatic mechanisms, fire risk may increase or decrease depending on temporal scale and factors influencing probability and consequences of fires. Fire occurrence probabilities could be affected both through fuel production (frequency or severity of drought, affecting species assemblages and thus fire regime through fuels) or through flammability (fire frequency responds to flammability and drives changes in species assemblages). As noted in chapter 2, leaf area of some forests may decrease in response to prolonged drought, which could increase the water available for understory plants. In this case, understory plants could contribute to the intensity of surface fires.

Expected Changes in Drought and Consequences for Wildfire

It is important to account for physical, hydrological, ecological, and human dimensions in translating projected climate into future fire risk. However, in the near term (e.g., the first half of the 21st century) it can be argued that changes in fire risk will occur on landscapes and within management strategies that already exist. Given that expected physical and hydrologic changes can be quantified, we present projections of two fire-related drought indicators discussed earlier: an ecohydrological indicator (define as PET – AET) (fig. 7.7) and the hydrologic indicator 7Q10 (the lowest 7-day average flow that occurs on average once every 10 years) (fig. 7.8). A composite of 10 General Circulation Models shows that summer

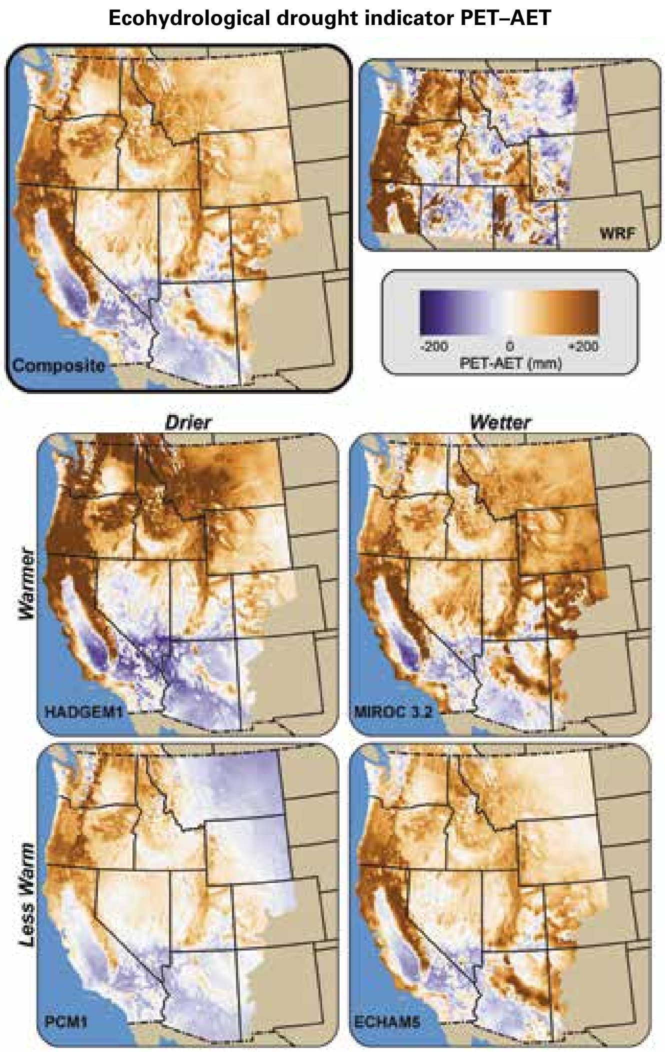

Figure 7.7—Downscaled change (2030–2059) in summer (June through August) water-balance deficit from historical (1916–2006): potential evapotranspiration (PET) – actual evapotranspiration (AET), measured in total mm water. Water-balance deficit (WBD) is well correlated with many climate effects on vegetation. In this representation, positive responses reflect an increase in deficit (less water availability and brown shaded), while negative responses reflect a decrease (more water availability and blue shaded). Ten-model composite (upper left) and output from the Weather Research and Forecasting (WRF) model (upper right) is followed by four bracketing General Circulation Model (GCM) scenarios [Coupled Model Inter-comparison Program (CMIP3)/AR4, after Littell and others 2011 and Elsner and others 2010] (Figure: Robert Norheim. Data source: U.S. Geological Survey, Western U.S. Hydroclimate Scenarios Project Datasets.)

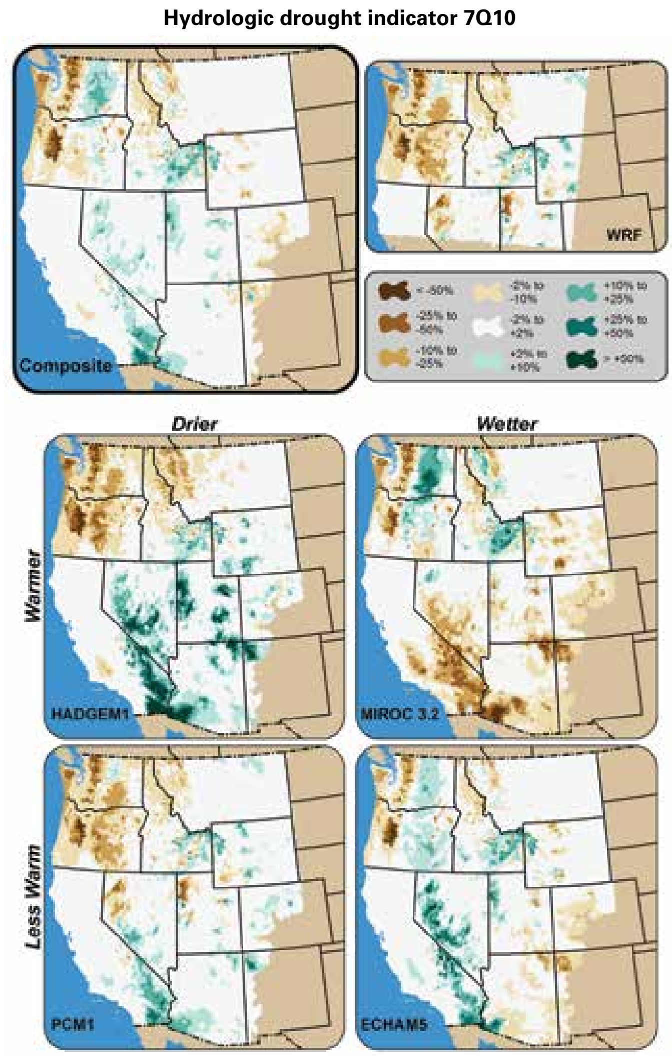

Figure 7.8—Changes (2030–2059) from historical (1916–2006) in 7Q10 (the lowest weekly average flow that occurs on average once every 10 years)—a measure of extreme low-flow periods in streams. The climate-change driven variation in low flows depends on characteristics unique to watersheds, regions, and future climate. Upper left: composite of statistically downscaled changes from 10 climate models. Upper right: dynamically downscaled changes from a single climate model (ECHAM5). Lower four panels illustrate bracketing General Circulation Models (warmer drier, warmer wetter, less warming drier, less warming wetter). (Figure: Robert Norheim. Data source: U.S. Geological Survey, Western U.S. Hydroclimate Scenarios Project Datasets.)

(June through August) water-balance deficit is projected to increase in much of the West except in portions of the Southwest that have significant monsoon precipitation and in some mountainous areas in the Pacific Northwest. The geographic distribution and magnitude of projected changes differ among climate models. Four climate models that bracket the range of projected changes in temperature and precipitation suggest that extreme low streamflows would be more frequently exceeded in the Cascades than in other areas of the West. Model output suggests that the Columbia Basin, upper Snake River, and southeastern California/southwestern Oregon may exceed extreme low flows less frequently than they did historically. Given the historical relationships between fire occurrence and drought indicators such as water-balance deficit and streamflow, climate change can be expected to have significant effects on fire risk.

Similarly, future fire hazards as measured by KBDI are projected to increase in most seasons and regions of the continental United States in the 21st century (Liu and others 2013b). The largest increases in fire hazard are in the Southwest, Rocky Mountains, northern Great Plains, and Southeast and Pacific Coasts, mainly caused by future temperature increase. The most pronounced increases occur in summer and autumn, including an extended fire season in several regions.

Fire Feedbacks to Drought

Drought is caused by changes in one or more of three atmospheric properties: thermal instability, water vapor supply, and dynamic systems creating upward motion. Wildfires can contribute to these properties from local to global scales by emitting particles and gases that affect atmospheric dynamics and by modifying land cover, feedbacks that were not systematically investigated until recently (Liu and others 2013a).

Smoke Particles

Fires emit particles including organic carbon (OC), which is bound in various compounds derived from plant tissue, and black carbon (BC), which is a pure carbon component of fine particulate matter [<2.5 μm (micrometers)] formed through incomplete combustion as soot. BC emissions from biomass (forest and savanna) burning account for 5–10 percent of fire smoke particles and about 40 percent of total global BC emissions (Bond and others 2004). These smoke particles can affect atmospheric radiative budgets by scattering and absorbing solar radiation (direct radiative forcing). This can further affect cloud cover and precipitation at regional scales. Koren and others (2004) analyzed Moderate Resolution Imaging Spectroradiometer (MODIS) satellite measurements during biomass burning in the Amazon region and found that cloud cover was reduced from 38 percent in clean conditions to nearly 0 percent for heavy smoke.

The radiative forcing of smoke can affect regional precipitation in many ways (fig. 7.9), but especially by modifying atmospheric thermal stability. The land surface and the atmosphere below the smoke layer are cooled by scattering and absorption of solar radiation by smoke particles. During a wildfire near Boulder, CO, in 2010, the surface under the smoke plume was cooled 2–5 °C (Stone and others 2011). Meanwhile, the upper air with smoke particles was warmed by solar radiation absorption. These changes in the vertical temperature profile stabilize the atmosphere and suppress cloud development.

Air relative humidity of the smoke layer is reduced from the warming effect of solar radiation absorption by BC, and cloud formation is inhibited. Relatively low cloud cover over the ocean has been documented due to the large concentration of soot aerosols, which leads to higher air temperature and lower relative humidity that help to “burn out” clouds (Ackerman and others 2000). Clouds and precipitation are reduced during the burning season over the Amazon because water vapor transport from the ground is low, and the planetary boundary layer to clouds is weakened from lower turbulent activity (Liu 2005a).

Atmospheric horizontal airflow convergence and vertical ascending in the lower troposphere favor cloud and precipitation formation. The radiative forcing of smoke particles leads to cooling on the ground and in the lower troposphere, despite possible warming at some elevations due to solar radiation absorption by BC. In a simulation study of the 1988 Yellowstone National Park wildfires that occurred during a drought (Liu 2005b), absorption of solar radiation by smoke particles over the fire area released heat in the upper smoke layer. This phenomenon altered westerly airflows, transporting warmer air downwind and converging in the trough area over the Midwest. The trough weakened, reducing clouds and rainfall, which suggests that feedbacks from wildfires may enhance drought.

Greenhouse Gases

Carbon dioxide is the largest fire emission component, accounting for 87–92 percent of total carbon burned

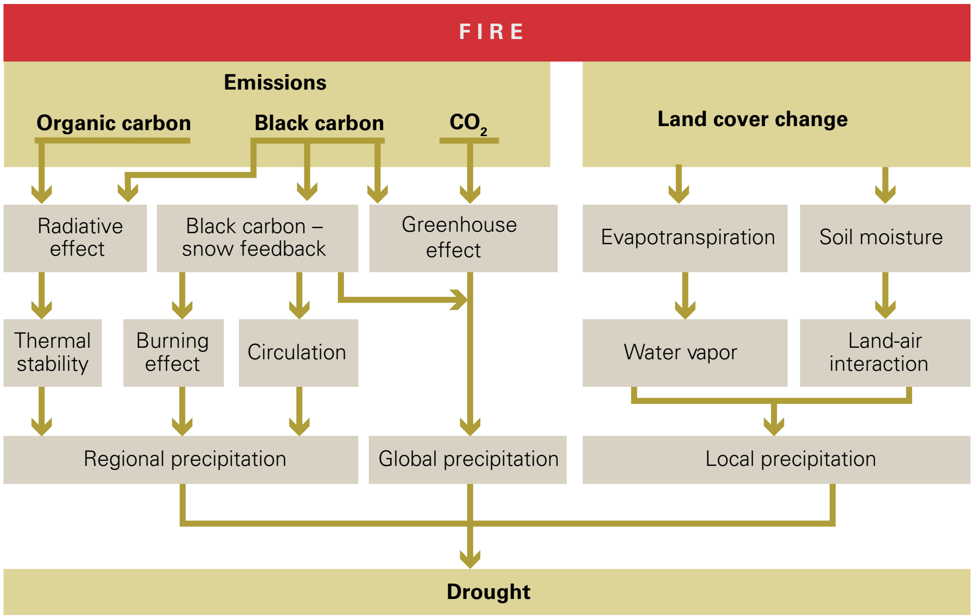

Figure 7.9—Physical processes for feedbacks of wildfires to drought.

(Urbanski and others 2008). Average annual global fire carbon emissions were about 2 picograms (Pg) in the recent decade, about one-third of total carbon emissions. BC emissions enhance the greenhouse effect in the atmosphere, and deposition of BC emissions on snow and ice at high latitudes reduces albedo and increases solar radiation absorbed by the surface, which in turn accelerates snow melting (Hansen and Nazarenko 2004). Boreal fires contribute more BC to the Arctic than human sources in summer based on multi-year averages (Stohl and others 2006). As a major source of atmospheric carbon dioxide and BC, wildfire emissions contribute significantly to atmospheric carbon dynamics and radiation absorption. Analyses of the Coupled Model Inter-comparison Program phase 3 (CMIP3) and phase 5 (CMIP5) indicate that future drought occurrence, duration, and severity will likely increase in response to the greenhouse effect globally and in many mid-latitude areas including the United States (Maloney and others 2014). Increasing drought amplifies the warming effect over decades to centuries.

Land Cover Change

Water transfer from the land surface, a local water vapor source for precipitation, is much higher on vegetated lands through evapotranspiration than unvegetated lands through evaporation. Leaf area after stand-replacing fires decreases greatly from pre-fire conditions, and evapotranspiration is temporarily reduced, leading to reduced water transfer through transpiration. The Bowen ratio (a ratio of sensible to latent heat flux) increases after burning, meaning that more solar energy absorbed on the surface is converted to sensible heat instead of being used as latent energy for water-phase change. After fire, the capacity of soil to store water is reduced, canopy and understory interception is decreased, and evapotranspiration from live vegetation is decreased, with a net effect of increased runoff and reduced soil water available for transfer to the atmosphere despite the reduction in evapotranspiration. As a result, the atmosphere will receive more heat energy and more intense convective activities, but less water from the ground for a long post-fire period.

During the 2004 Alaska fire season, wildfires altered land cover over large areas, leading to changes in dynamic, radiative, vegetative, thermal, and hydrological surface characteristics (Möldersa and Kramma 2007). A simulation to quantify the effects of fire-caused land cover changes indicated that sensible heat fluxes into the atmosphere increased by up to 225 Watts per square meter (W/m^2) over burned areas. There was enough enhanced lifting in the areas with large burns to produce areas of increased clouds followed by an area of decreased clouds downwind of them. Precipitation increased significantly in the lee of burned areas, but decreased slightly a few days after large fires.

Management and Social Implications

To the extent that drought affects fire directly, management implications mirror those associated with changes in fire regimes stemming from climate change (Littell and others 2009). In regions where area burned has historically been higher with high temperature and low precipitation anomalies (most of the Western United States), area burned will likely increase with temperature and possibly the frequency of drought (Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, National Research Council 2011). Fire severity and frequency may also increase, but blanket statements about these phenomena are strongly affected by local conditions and therefore differ considerably. However, larger fires and higher area burned will continue to challenge fire suppression efforts and budgets, and may require rethinking historical approaches to fire management on landscapes. If annual area burned increases >200 percent in most of the Western United States as projected for the mid-21st century (Peterson and Littell 2014), the proportion of landscapes recently burned would also increase. Combined with the effects of increasing temperature on climatic suitability for regeneration, ecosystem function and structure may change rapidly (Littell and others 2010), thus altering the landscapes for which land management agencies have responsibility.

In some regions of the United States, a longer season during which fuels are highly flammable may affect management activities intended to reduce the quantity of those fuels. Even if there is minimal change in probability of historically extreme droughts, effective or "ecological" drought due to increased water demand may decrease favorable conditions for prescribed fire. However, the duration of time when burning can be conducted (relative to fuel conditions, regulatory compliance, and social acceptance) could simply move to earlier in spring and later in autumn. If drought-caused wildfire activity increases, wildland-urban interface areas will face increased fire risk, thus increasing suppression costs and potentially altering social perceptions of management and risk in fire-prone human communities.

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