Briefing: Climate and Wildfire in Western U.S. Forests

Anthony Westerling

Associate Professor, Environmental Engineering and Geography, Sierra Nevada Research Institute, University of California, Merced

Tim Brown

Director, Western Regional Climate Center, Division of Atmospheric Sciences, Desert Research Institute, University of Nevada, Reno

Tania Schoennagel

Research Scientist and Adjunct Assistant Professor Institute of Arctic and Alpine Studies, Department of Geography, University of Colorado, Boulder

Thomas Swetnam

Regents' Professor of Dendrochronology, Director, Laboratory of Tree-Ring Research, University of Arizona

Monica Turner

Eugene P. Odum Professor of Ecology, Department of Zoology, University of Wisconsin

Thomas Veblen

Professor of Distinction, Department of Geography, University of Colorado, Boulder

Abstract: *Wildfire in western U.S. federally managed forests has increased substantially in recent decades, with large (>1000 acre) fires in the decade through 2012 over five times as frequent (450 percent increase) and burned area over ten times as great (930 percent increase) as the 1970s and early 1980s. These changes are closely linked to increased temperatures and a greater frequency and intensity of drought. Projected additional future warming implies that wildfire activity may continue to increase in western forests. However, the interaction of changes in climate, fire and other disturbances, vegetation and land management may eventually transform some forest ecosystems and fire regimes, with changes in the spatial extent of forest and fire regime types. In particular, forests characterized by infrequent, high-severity stand replacing fire may be highly sensitive to warming. Increased wildfire combined with warming may transform these ecosystems such that fuel availability, rather than flammability, becomes the dominant constraint on fire activity. Climate will continue to warm for some time regardless of future greenhouse gas emissions, requiring adaptation to warmer temperatures. Changes in forest location, extent and type will result in substantial changes in ecosystem services.*

INTRODUCTION

Climate change is generating higher temperatures and more frequent and intense drought (Cayan and others 2010; Peterson and others 2013). Globally, the last three decades (1980s, 1990s, and 2000s) have each in turn been the warmest in history (Arndt and others 2011). In the United States, 2012 was the warmest year on record (Blunden and Arndt 2013), and drought has become more widespread across the western United States since the 1970s (Peterson and others 2013). Climate projections suggest increased likelihood of heat waves in the western United States and droughts in the Southwest (Wuebbles and others 2013). Concomitantly, the fire season and area burned are expected to increase substantially by mid-century across the western United States due to expected climate change (Yue and others 2013).

Climate—primarily temperature and precipitation—influences the occurrence of large wildfires through its effects on the availability and flammability of fuels. Climatic averages and variability over long (seasonal to decadal) time scales influence the type, amount, and structure of the live and dead vegetation that comprises the fuel available to burn in a given location (Stephenson 1998). Climatic averages and variability over short (seasonal to interannual) time scales determine the flammability of these fuels (Westerling and others 2003).

The relative importance of climatic influences on fuel availability versus flammability can vary greatly by ecosystem and wildfire regime type (Westerling and others 2003; Littell and others 2009; Krawchuck and Moritz 2011). Fuel availability effects are most important in arid, sparsely vegetated ecosystems, while flammability effects are most important in moist, densely vegetated ecosystems. Climate scenarios' changes in precipitation can have very different implications than changes in temperature in terms of the characteristics and spatial location of wildfire regime responses (namely, changes in fire frequency, average area burned, and fire severity).

While climate change models generally agree that temperatures will increase over time, changes in precipitation tend to be more uncertain, especially in arid midlatitude regions (Dai 2011; Moritz and others 2012; Gershunov and others 2013). Therefore, in ecosystems where wildfire risks have been strongly affected by variations in precipitation, there is less certainty about how these wildfire regimes may change. However, in ecosystems where wildfire risks have been sensitive to observed changes in temperature, climate change is likely to lead to substantial increases in wildfires. Also, as climate change alters the potential spatial distribution of vegetation types, ecosystems and their associated wildfire regimes will be transformed synergistically. In the following sections, we give an overview of climate-vegetation-wildfire interactions in western U.S. forests, and summarize recent scientific literature on the subject for several subregions.

While policies to mitigate climate change can help to limit changes in wildfire regimes, some level of additional warming is going to occur regardless, requiring adaptation. Despite ongoing progress in describing climate-wildfire relationships and their implications for western U.S. forest resources under a changing climate, significant challenges remain in incorporating this science into land management planning and policy for climate change adaptation and mitigation. Federal land management agencies have recently formulated extensive guidelines for this process, which we review in the concluding section below.

Climate-Vegetation-Wildfire Interactions in the Western United States

The type of vegetation (i.e., fuels) that can grow in a given place is governed by moisture availability, which is a function of both precipitation (via its effect on the supply of water) and temperature (via its effect on evaporative demand for water) (Stephenson 1998). As a result, the spatial distribution of vegetation types and their associated fire regimes is strongly correlated with long-term average precipitation and temperature (e.g., Westerling 2009). Climatic controls (temperature and precipitation) on vegetation type along with successional stage largely determine the biomass loading in a given location, as well as the sensitivity of vegetation in that location to interannual variability in the available moisture. These factors in turn shape the response of the wildfire regime in each location to interannual variability in the moisture available for the growth and wetting of fuels. Cooler, wetter areas (forests, woodlands) have greater biomass, and wildfires there tend to occur in dry years. Warmer, drier areas (grasslands, shrublands, pine savannas) tend to have less biomass and wildfires there tend to occur after one or more wet

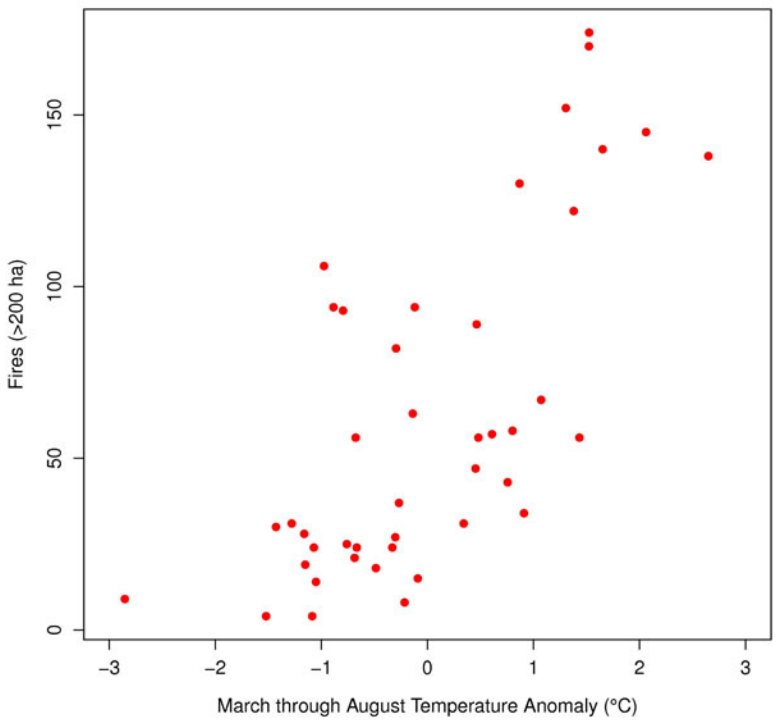

Figure 1. Scatter plot of annual number of large (> 200 ha) forest wildfires versus average spring and summer temperature for the western United States. Forest Service, Park Service, and Bureau of Indian Affairs management units reporting 1972-2004. Fires reported as igniting in forested areas only. Source: Westerling 2009.

seasons or years (Swetnam and Betancourt 1998; Westerling and others 2003; Crimmins and Comrie 2004).

Consequently, wildfire is much more sensitive to variability in temperature in some locations than in others. In the western United States, cool, wet, forested locations tend to be at higher elevations and latitudes where snow can play an important role in determining summer moisture availability (Sheffield and others 2004). Above-average spring and summer temperatures in these forests can have a dramatic impact on wildfire, with a highly nonlinear increase in the number of large wildfires above a certain temperature threshold (Figure 1). Westerling and others (2006) concluded that this increase is due to earlier spring snowmelt and a longer summer dry season in warm years. They found that years with early arrival of spring account for most of the forest wildfires in the western United States (56 percent of forest wildfires and 72 percent of area burned, as opposed to 11 percent of wildfires and 4 percent of area burned occurring in years with a late spring).

Fire severity tends to be highest, with large infrequent stand-replacing fires that burn in the forest canopy, in cooler, more moist forests at generally higher elevations and/or latitudes, such as the lodgepole pine forests in the northern and central Rocky mountains (Baker 2009). Prior to the era of extensive/intensive livestock grazing (post 1850s) and active fire suppression by government agencies (post 1900s), warmer, drier forests tended to have mixed or low severity, more frequent fire with more of the fire concentrated in surface fuels (grass, shrub, forest litter) and less tree mortality (Allen and others 2002). However, increased fuel loads due to historic fire suppression and land use changes, combined with more extreme climatic conditions, have resulted in high severity fire in some forests where it was rare prior to the 20th century (Miller and others 2009).

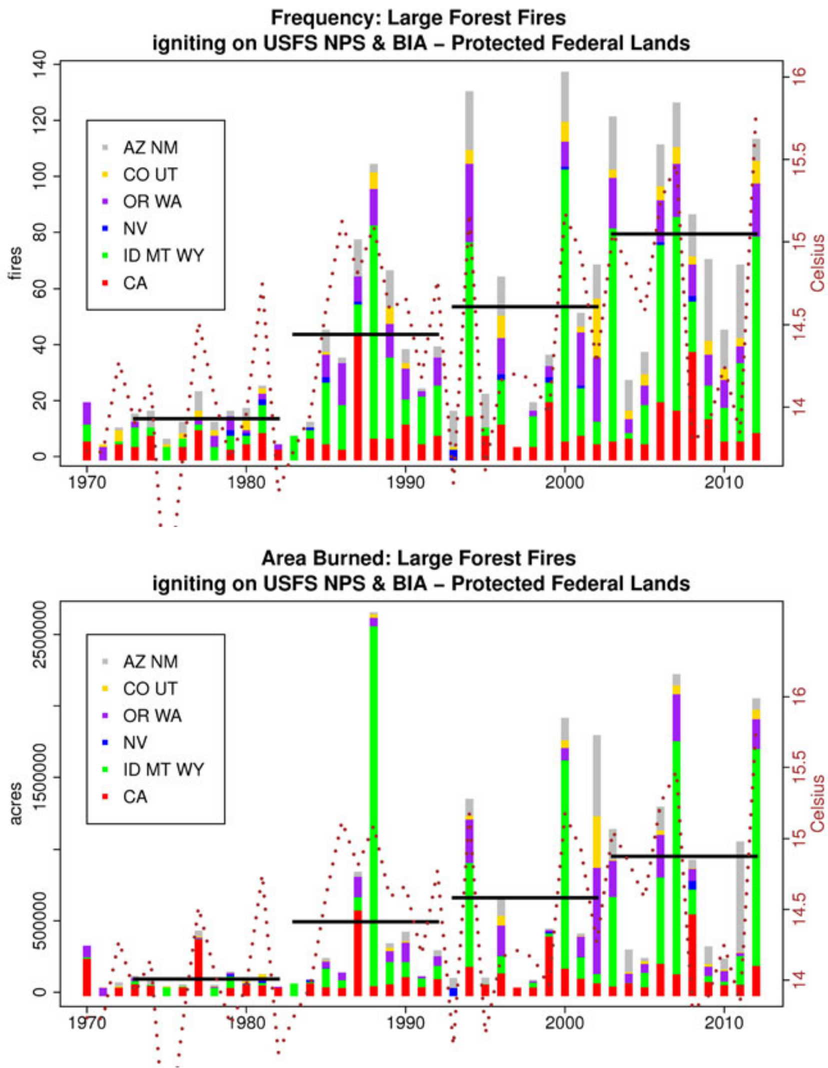

Figure 2. Frequency of (top panel) and area burned in (bottom panel) large (>1000 acre) forest fires. Fires are action fires for which suppression was attempted, reported by USFS, NPS and BIA as burning on federal lands in primarily forest vegetation. Fires are grouped by states (colored bar sections) with average regional spring and summer temperature overlayed (dashed line). Horizontal solid lines indicate averages for the last four decades. Large fires in the last decade are over 480% more frequent and burn 930% more area than fires in the first decade. Average annual area burned on these lands has increased by over 285,000 acres per decade for the last three decades, to just under 1 million acres per year at present.

The frequency of large (>1000 acre) forest fires and the area burned in those fires has continued to increase steadily over the last three decades as temperatures have risen throughout the region (Figure 2). Forests of the northern and central Rocky mountains where fire typically burned with high severity but was infrequent, have been the most sensitive to changes in temperature, accounting for the largest share of the increase in burnt forest area (Figure 2, Westerling and others 2006). As discussed below, projections of additional increases in future temperatures imply further increases in fire activity. However, warming and fire frequency may increase past critical thresholds, with some forests no longer able to sustain large high-severity fires. That is, fuel availability may become a limiting condition on fire in areas where climatic controls on fuel flammability were recently the dominant constraint on fire.

REGIONAL SUMMARIES[1]

Regional Summary: Idaho, Montana, Wyoming Rockies

Climate is generally semiarid with summer-dry conditions to the northwest, and summer-wet to the southeast (Bailey 1996), and generally moister and cooler conditions relative to regions at lower latitudes. Elevation ranges from 3000 to 7000 ft in the southern and central portions, and 3000 to over 9000 ft in the northern portion. Mixed evergreen-deciduous forests dominate montane and subalpine elevations in the north, with strong topographic controls on moisture fostering diverse forest vegetation zones to the south (Bailey 1996; Cleveland 2012). Forests with characteristically infrequent high-severity, stand-replacing fires account for the largest area (mixed spruce-fir, lodgepole pine), with significant forest area characterized by mixed- (e.g., Douglas-fir) and low- (e.g., ponderosa pine) severity fire regimes prior to the historical fire suppression era (Schoennagel and others 2004).

Notably, some northern Rockies ponderosa pine forests, usually associated with low-severity surface fire regimes in the literature, may have experienced occasional high-severity, stand-replacing fires during extended droughts of past millennia, as inferred from sedimentary charcoal studies (Pierce and others 2004). However, the patch sizes of these ancient high severity fires within ponderosa pine-dominant or mixed forests are unknown for almost all forests of these types, and it is possible that current large, high-severity patch sizes and subsequent geomorphic responses may be unique over the late Holocene, as similar sedimentary charcoal studies in Colorado pine and mixed-conifer forested watersheds suggest (Bigio and others 2010). In the only detailed, highly systematic study of tree age structures and fire scar evidence at stand to landscape scales in northern stands of ponderosa pine (i.e., in the Black Hills of South Dakota), Brown and others (2008) found that only about 3 percent of the landscape experienced high-severity fires during the three and one-half centuries prior to 1893, and overall, frequent, low-severity surface regimes dominated those landscapes.

In northern forests where infrequent, large high-severity fires occurred, these events likely were driven by extended drought associated with high pressure atmospheric blocking patterns (Romme and Despain 1989; Renkin and Despain 1992; Bessie and Johnson 1995; Nash and Johnson 1996; Baker 2009). Paleo studies support a strong influence of climate on fire-return interval (e.g., Whitlock and others 2003, 2008; Milspaugh and others 2004), with fuel controls playing a much lesser role (Higuera and others 2010).

Historically, burned area is concentrated in a relatively small number of very large fire events (Balling and others 1992; Schoennagel and others 2004; Baker 2009). From 1972-1999, 66 percent of burned area in the ID - MT - WY Rockies occurred in only two years (1988 and 1994), and 96 percent of burned area in the Greater Yellowstone area occurred in one fire year (1988) (Westerling and others 2011a). This pattern is consistent with climatic controls on the flammability of plentiful fuels being the dominant constraint on the occurrence and spread of large wildfires (Littell and others 2009); namely, large areas burn in rare dry years.

[1] Note that the scientific studies available to draw upon for each regional summary vary somewhat in focus. Consequently, the types of information incorporated into a survey like this vary more than would be the case for a summary of a research project that treats each region in a unified way.

The effect of changes in the timing of spring on wildfire has been particularly pronounced in the higher-latitude (> 42° North), mid-elevation (1680-2590 m) forests of the Rocky Mountains, which account for 60 percent of the increase in forest wildfires in the western United States (Westerling and others 2006). Higher elevation forests in the same region had been buffered against these effects by available moisture, while lower elevations have a longer summer dry season on average and were consequently less sensitive to changes in the timing of spring.

The frequency and extent wildfire is projected to continue to increase in coming decades until fuel availability and continuity becomes limited and supplants climatic controls on flammability as the dominant constraint on the spread of large wildfires by mid-century in the Greater Yellowstone region (Westerling and others 2011a) and in the Rockies more generally (Westerling in preparation). Increased burned area of similar magnitude has been projected by the National Research Council (2011), applying models from Littell and others (2009) (see also Climate Central 2012).

Regional Summary: Utah and Colorado

Colorado and Utah also experience high geographic and interannual variability in temperature and precipitation due to elevation, topography, and latitude. In general, the region is characterized by summer-dry areas northwest of the Rocky Mountains under the influence of the subtropical high, and summer-wet areas southeast of Rocky Mountains and in southern portions of Colorado and Utah, due to monsoons from the Gulf of Mexico and Gulf of California (McWethy and others 2010).

A number of low-elevation forests (e.g., below 2100 m in the central Colorado Front Range; Sherriff and Veblen 2008) with grass or other fine-fuels in the understory record regional fires during dry summers when preceded by increased spring-summer moisture availability up to 4 years prior, that enhance fine-fuel accumulation and contribute to fire spread when subsequently cured (Donnegan and others 2001; Grissino-Mayer and others 2004; Brown and others 2008; Sherriff and Veblen 2008; Gartner and others 2012). Moister, higher-elevation forests lacking grass understories do not record this wet-dry signature in the fire record (Sibold and Veblen 2006; Brown and others 2008; Schoennagel and others 2011). Documentary records of area burned in ecoregions encompassing Colorado and Utah showed that moist antecedent conditions are associated with greater area burned (and were more important than warmer temperatures or drought conditions in the year of fire) in grasslands, shrublands and arid low-elevation woodlands with grass or shrub understories, but only fire-year conditions were significant in moister high-elevation and/or west-slope forests (Knapp 1995; Westerling and others 2003; Collins and others 2006; Littell and others 2009).

Littell and others (2009) found that area burned in the S. Rockies (1977-2003) was positively related to winter temperature, and negatively related to spring temperature, along with spring and summer precipitation and lagged drought;($r^2 = 0.77$; Littell and others 2009). Predictions for Utah and Nevada Mountains were linked to lagged spring temperature, but were much less robust ($r^2 = 0.33$). The Southern Rockies only accounted for <1 percent of recent increase in wildfire activity since 1985, in contrast to the Northern Rockies, which accounted for 60 percent, primarily related longer fire seasons and snowpack reduction (Westerling and others 2006).

Average annual summer and winter temperatures are expected to increase dramatically in Colorado and Utah by 2050, yet models show low agreement for precipitation (Fig. 5.1 in Ray and others 2010). However, Seager and others (2007) predict that the Southwest (125°W-95°W, 25°N-40°N, which includes most of Colorado and Utah) will become more arid during the next century as annual mean precipitation minus evaporation becomes more negative. Similarly, Gutzler and Robbins (2011) predict that higher evaporation rates due to positive temperature trends will exacerbate the severity and extent of drought in the semi-arid West.

Brown and others (2004) predict that reduced relative humidity will increase the number of days of high fire danger at least through the year 2089 compared to the base period, however, the Colorado Rockies and Front Range showed no change in predicted fire risk thresholds, suggesting little change in wildfire activity. This contrasts with a Spacklen and others (2009) study that predicts higher temperature will increase annual mean area burned by 54 percent by 2050s relative to the 1980-2004 period, with the entire Rocky Mountains showing large increases (78 percent) and high interannual variability.

The National Research Council (2011) predicts that burn area in parts of western North America may increase by 200 to 400 percent for each degree (°C) of global warming relative to 1950-2003, adapting methods developed by Littell and others (2009) to use temperature and precipitation as the predictor variables. Across Colorado and Utah, the southern Rocky Mountain Steppe Forest is predicted to experience the greatest increase in mean annual area burned (>600 percent), with the least in the Nevada-Utah Mountains (only 73 percent).

Regional Summary: Arizona and New Mexico

The Southwestern United States (Arizona and New Mexico) is generally a semi-arid region. Considerable topographic relief, however, results in a very diverse biotic landscape and consequent differences in vegetation and wildfire. These differences are often expressed along relatively short distances (10s of kilometers) and elevational gradients from desert basins to forested mountains. Natural fire regimes along these gradients vary from essentially no spreading wildfires in the pre-21st century historical record (e.g., lower Sonoran desert), to frequent, low-severity surface fires (e.g., mid-elevation ponderosa pine forests, with intervals between widespread fires ranging from 2 to 20 years), to low-frequency, high-severity, stand-replacing fires (high-elevation spruce-fir forests, with intervals between large crown fires ranging from 150 to 300+ years) (Swetnam and Baisan 1996, 2003; Margolis and others 2007, 2009).

Seasonal climate of the Southwest is characterized by bimodal precipitation, with winter-cool season and summer-warm season maxima, with a pronounced dry season during most years in late spring to early summer. The peak of fire activity tends to occur in this warm/dry season (May through June), with a maximum area burned in the driest weeks of June, and the maximum number of fire ignitions in July when monsoonal moisture and convective activity generates large numbers of lightning strikes (Crimmins 2006; Keeley and others 2009). Human-set fires are also important in Southwestern landscapes, both in the distant past (i.e., by Native Americans), and in the modern era. During some seasons and years human-set fires exceed areas burned by lightning set fires, especially during some recent years when extraordinarily large fires were set accidentally or purposely during spring-summer droughts. Paleo and modern records of fire and climate show the strong importance of both prior cool-season and current spring-through-summer moisture indices to fire activity in this region (especially regionally synchronized fire events in the paleorecord and total area burned per fire season/year in the modern record; Swetnam and Betancourt 1998; Westerling and others 2002; McKenzie and others 2004; Crimmins and Comrie 2004; Crimmins 2006; Holden and others 2007; Littell and others 2009; Williams and others 2013).

Because comprehensive documentaries of wildfire only go back a few decades, paleo proxy records of past fire and climate activity have been developed to provide annual to millenial scale perspectives on fire, vegetation and inferred climate variability (Swetnam and Baisan 1996; Swetnam and Brown 2010; Falk and others 2011; International Multiproxy Paleofire Database; Anderson and others 2008; Frechette and others 2009; Bigio and others 2010).

These paleorecords demonstrate the follow specific findings:

(1) Widespread surface fires were ubiquitous in ponderosa pine forests and mixed-conifer forests across the region before the advent of extensive livestock grazing in the late nineteenth century and active fire suppression by government agencies beginning about 1910. High-severity, stand-replacing crown fire occurred in some dense pinyon-juniper woodlands (Romme and others 2009), shrublands, and higher elevation spruce-fir forests (Margolis and others 2007; Margolis and Balmat 2009) in the pre-1900 period, but large, high-severity fires were rare in ponderosa pine forests. Although some evidence of high-severity fire in ponderosa pine and mixed-conifer forests has been found in charcoal sediments (e.g., Frechette and others 2009; Bigio and others 2010), and small patch size (<200 ha) high-severity fires have been reconstructed in a few tree-ring studies (Swetnam and others 2001; Iniquez and others 2009), we lack any clear evidence at this time that large patch size (>200 ha) high-severity fires occurred in ponderosa pine-dominant forests in the past were as extensive as those occurring today (Cooper 1960; Allen and others 2002).

(2) Extreme droughts and regional fire activity are highly correlated over the past four centuries in the available tree-ring record. Lagging patterns are evident in lower elevation forests and woodlands, with wet conditions in prior 1 to 3 years, coupled with dry conditions during current year often leading to extensive regional fire years in the past (Swetnam and Betancourt 1998).

(3) Decadal-scale variation in past fire activity is evident in parts of the Southwest, with occasional periods of 1 to 2 decades of either decreased or increased local to regional fire activity (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Brown and Wu 2005; Margolis and Balmat 2010; Roos and Swetnam 2011). Many studies have shown some association between these annual-to-decadal-scale patterns and climatic variations (e.g., Swetnam and Betancourt 1990, 1998; Kitzberger and others 2007; Brown and Wu 2005).

(4) There are relatively few long-term, sedimentary charcoal-based records of fire activity in the Southwest compared to other more mesic regions with more lakes and bogs. The available records do show, however, decadal-to-centennial-scale variations in fire and vegetation that are likely associated with climatic variations on those time scales (e.g., Anderson and others 2008). One striking finding in a comparison of tree-ring and charcoal-based fire histories is the unprecedented lack of fire in the most recent century (due to livestock grazing and fire suppression) in a record of more than 7,000 years (Allen and others 2008).

The longest modern records for the Southwest show a similar pattern to that observed in some other forests across the western United States during the 20th-21st centuries, namely, some large fires occurred during early decades of the 20th century, there were lower levels of fire activity during the mid-20th century (but with several large events, > 5000 ha during the 1950s drought), and after the late 1970s a rather sharp rise in numbers of large fires and area burned occurred (e.g., Rollins and others 2001; Holden and others 2007)

The post-2000 period includes several fires in forested landscapes that exceed in area any other wildfire in this two state region over at least the past 100 years (e.g., most notably, the 189,651 ha [468,640 acre] Rodeo-Chediski Fire in central Arizona in 2002, and the 217,741 ha [538,049 acre] Wallow Fire in east-central Arizona and west-central New Mexico in 2011 and the 63,000 ha [156,593 acre] Las Conchas Fire in New Mexico in 2011). Nearly simultaneously, over the past two decades large areas of forest and woodland have experienced extensive tree mortality due to a combination of direct drought-induced physiological stress and mortality, and attacks by phloem-feeding bark beetles (Allen and Breshears 1998; Breshears and others 2005). Williams and others (2010) summarize the mortality extent across the Southwest by these agents (drought, fire, bark beetles) and they estimate that nearly 20 percent of forested areas experienced high levels of tree mortality between 1984 and 2010.

Both the recent large fires and the extensive bark beetle outbreaks are unprecedented in the historical documentary record of the past century. There are older documentary records (e.g., newspaper accounts) from the late nineteenth century that refer to fires covering more than 400,000 ha (988,421 acre) (e.g., Bahre 1986). These reported large events, however, tended to be at lower elevations (i.e., in grasslands) as well as in some higher elevations. There are no known burn scars ("bald" mountain areas lacking trees because of past fires, or recovering forests) at the scales and extent (patch sizes) of recent high-severity burns (Cooper 1960; Allen and others 2002).

The importance of changed conditions (e.g., increase tree densities, dead fuel accumulations, understory species changes including invasive grasses) has commonly been identified as a major factor in unusual fire sizes and severity in recent decades in Southwestern ponderosa pine forests (e.g., Fule and others 1997; Allen and others 2002). It is interesting to note, however, that high forest densities in many Southwestern forests were already established by the middle of the 20th century. Cooper (1960), for example, noted in his comparisons of forest stands in central Arizona that about one-quarter of the stands had stem densities exceeding 12,000 trees/ha, and he described at length the increasing fire severity problems being observed at that time in these forests as a consequence of these changes. Harold Weaver described similar patterns of extensive pine thickets in Southwestern forests a decade earlier (1951). The extreme 1950s drought, which exceeds the current Southwest drought in total or maximum precipitation deficits in some parts of the Southwest, did result in a number of large fires (e.g., the Escudilla Fire and McKnight Fire of 1951, and the Dudley Lake Fire of 1956). But these fires were much smaller (<22,000 ha / 54,360 acre), and an order of magnitude smaller than some recent very large fires (e.g., 2002 Rodeo-Chediski and 2011 Wallow Fires). Moreover, the rates of spread observed on fires in recent years are truly extraordinary, and far outside the experience of modern wildland fire fighters. There were multiple days during both the Rodeo-Chediski Fire, Wallow Fire, and Las Conchas Fire (2011, in Jemez Mountains) when, for example, wind-driven, fast moving crown fires burned areas exceeding 16,000 ha in less than 24 hours, and in some cases, in less than 12 hours.

It is not possible at this time to precisely parse the relative importance of causes of these extraordinary recent fire behaviors and drought/bark beetle-induced forest mortality events among the various probable contributing variables (forest and fuel changes, invasive species, management and policy changes, and climate trends and variations). Interpreting from results of multiple types of analyses of broad-scale, best available data, however, it has been suggested that warming temperatures, in combination with extreme drought, are the likely key variables that are unusual in the context of the past century (Westerling and others 2006; Breshears and others 2005; Williams and others 2010, 2013). In a recent assessment of climate variables from the Southwest, Weiss and others (2009) confirm that the current drought has been "hotter" than previous major droughts of the twentieth century (e.g., the 1930s and 1950s droughts). Again, a telling line of evidence in support of this interpretation is the difference in "large fires" during the 1950s in central Arizona pine forests, which already had dense forest conditions in many places (Cooper 1960). No Southwestern forest fires exceeding about 22,000 ha (54,360 acre) occurred during that relatively "cooler" drought, as compared to the largest fire in Arizona state history—the Wallow Fire of 2011 (217,741 ha), which occurred in the exceptionally warm and dry June of 2011.

Regional Summary: California

About 13 percent of California's forest area is composed of forest types with naturally high-severity (30 percent-80 percent crown-burned) fire regimes with mean fire return intervals (MFRI) of 15-100 yr (predominately cedar/hemlock/Douglas-fir, red fir), while nearly 70 percent is comprised of forest types that experienced frequent, low-severity prehistoric fire regimes (MFRI $\leq$ 10 yr, crown burned $\leq$ 5 percent; predominately mixed conifer, mixed California evergreen, redwood and ponderosa pine) (Stephens and others 2007). A policy of fire suppression and land use changes reduced the annual burned area in California forests from pre-settlement levels by more than 90 percent in the 20th century (Stephens and others 2007). Miller and others (2009) document trends toward increasing fire severity in the Sierra Nevada, and hypothesize that both fire suppression and increased precipitation over the 20th century increased fuel densities, contributing to increased fire severity. The frequency of large fires, total area burned, mean fire size and fire severity have all increased in northern California forests since the mid-1980s (Westerling and others 2006; Miller and others 2009) (Figure 1). Because a large portion of the interannual variability in northern California forest wildfire burned area is due to variability in ignitions from clustered lightning strikes, only a modest fraction of observed interannual variability in burned area can be explained by climate alone (Preisler and others 2011; Westerling and others 2011b).

Wildfire is predicted to increase substantially in northern California forests in the Sierra Nevada, Southern Cascades and Coast Ranges under some climate change scenarios. Westerling and Bryant (2008) project 100 percent-400 percent increases in the probability of large fire occurrence over much of the Sierra Nevada, Coast Ranges and Southern Cascades under a relatively warm, dry climate scenario (GFDL SRES A2). A study by the National Research Council (2011), applying regression methods from Littell and others (2009) for fire aggregated by ecosystem provinces similarly found increases exceeding 300 percent for a 1°C temperature increase. Westerling and others (2011b) find increases in burned area ranging from 100 percent to over 300 percent for much of northern California's forests across a range of climate and growth and development scenarios using three climate models (NCAR PCM1, CNRM CM3, GFDL CM 3.1) for the SRES A2 emissions scenario. Spracklen and others (2009) find increases in burned area on the order of 78 percent by midcentury for the GISS GCM under the SRES A1b emissions scenario, which is similar in magnitude to Westerling and others (2011b) for midcentury for northern California forests under GFDL SRES A2 scenarios. Conversely, increases in California forest wildfire frequency and burned area are more modest under a lower (SRES B1) emissions scenario, with end of century burned area roughly the same as midcentury (Westerling and Bryant 2009; Westerling and others 2011b; Yue and others 2013).

DISCUSSION: CLIMATE-WILDFIRE-VEGETATION INTERACTIONS

The direct effects of anthropogenic climate change on wildfire are likely to vary considerably according to current vegetation types and whether fire activity is currently more limited by fuel availability or flammability. In the long run, climate change is likely to lead to changes in the spatial distribution of vegetation types, implying that transitions to different fire regimes will occur in locations with substantial changes in vegetation. At present, most long-term projections of changing wildfire activity have not successfully incorporated dynamic changes in vegetation types and fuels characteristics in response to climate and disturbance. This is an ongoing challenge for wildfire and climate science that is the subject of ongoing research. On the other hand, we can use existing fire-climate-vegetation interactions to understand the likely direction and magnitude of climate-driven changes in fire activity over the next few decades. Beyond that, we may be able to use these models and our understanding of current ecosystems to assess when changes in climate and disturbance regimes will begin to lead to qualitative changes in ecosystems. Given the lack of analogues to projected climate changes—especially the substantial changes in that latter half of the 21st Century that are projected to result from continued high emissions of greenhouse gases—precise modeling of future changes in vegetation and disturbances like wildfire becomes significantly more challenging for later in this century and beyond.

Climate change will result in higher temperatures and more frequent and intense drought (Cayan and others 2010), with the fire season and area burned expected to increase substantially by mid-century across the western United States (Yue and others 2013). In forests where wildfire is very sensitive to variations in temperature, the short-term result is likely to be an increase in the frequency of very active fire seasons and an increase in the number of large wildfires. There have been substantial increases documented in the frequency of large wildfires in forests of the Rocky Mountains of the western United States (Westerling and others 2006; Figure 2). These increases have been associated with warmer temperatures there in recent years. As climate continues to change later in this century, changes in vegetation types and amounts in these forests may lead to qualitative changes in fire-climate-vegetation interactions, as fuel availability may start to become a limiting factor in some places where forest wildfire regimes were historically limited by climatic controls on fuel flammability.

Conversely, higher temperatures and decreased precipitation could result in decreased wildfire activity in some dry, fuel-limited wildfire regimes, as the reduced moisture available to support the growth of fine fuels leads to less biomass and less continuous fuel coverage (Dettinger 2006). Any increases in precipitation might be counterbalanced to some extent by increased evaporative demand from higher temperatures.

The overall direction and spatial pattern of changes in precipitation under diverse climate change scenarios varies considerably across both future greenhouse gas emissions scenarios and global climate models (Dettinger 2006). In ecosystems where climatic influences on fire risks are dominated by precipitation effects, this implies greater uncertainty about climate change impacts on wildfire in those locations (Westerling and Bryant 2007). Overall, however, greater warming will lead to more evaporation of moisture from soils and the live and dead vegetation that fuels forest wildfires. Given the substantial interannual variability in precipitation characteristic of western U.S. climate, it is likely that fire activity will at least increase in drought years in coming decades, across a broad range of future climate scenarios.

Climate scenarios (even those with rapid reductions in global greenhouse gas emissions) project increases in temperature substantially greater than those observed in recent decades (IPCC 2007), which have been associated with substantial increases in wildfire activity in western U.S. forests (Gillett and others 2004; Westerling and others 2006; Soja and others 2007; Williams and others 2013; Figures 1&2). Strategies for adapting to a warmer world will therefore need to consider the impacts of climate change on wildfire.

Climate change implications for land management

Changes in climate, nitrogen deposition, and disturbance regimes (fire, insects, floods, etc.) will likely lead to changes in ecosystem services in the coming decades, with losses in some areas and possibly improvements and expansion of services in others (Vose and others 2012; Turner and others 2013). Because of the speed of anticipated changes in climate, disturbance regimes and ecosystems, ecosystem changes in coming decades may be highly uncertain, with near-term changes dominated by transition effects. For example, parts of the Greater Yellowstone area may become unsuitable to sustain forest types that are currently dominant, but might be suitable for tree species that are currently not present (Westerling and others 2011a). Future ecosystem services will thus depend in part on the speed with which species ranges can shift on the landscape. Land management choices can both resist (e.g., fire suppression) and facilitate (e.g., assisted migration) changes in ecosystem and disturbance regime characteristics, and either or both types of approaches may be appropriate depending on management priorities for a given resource.

To address adaptation in management planning and policy, a number of guides relevant to the forest sector have been produced since 2007 (Table 1). One important component to help managers consider developing adaptation plans is providing examples. Miller and others (2011) provide examples for two generalized wilderness fire management objectives: Restore or maintain—restore fire to ecosystems that have been altered by fire suppression or other land use change, or maintain process of fire in ecosystems that have not been altered. Protect—protect ecosystems that are threatened by fires that are too frequent. Specific responses to climate change that might achieve restore or maintain objectives: revise fire and land management plans to reflect climate-mediated changes to fire regimes; modify fuel treatment specifications to ensure they will moderate fire behavior and effects under more extreme fire weather conditions. Specific responses to climate change for protect objectives would be: emphasize preparedness and revise preparedness plans to reflect longer fire seasons and higher fire danger; modify fuel treatment specifications to ensure they will moderate fire behavior and effects under more extreme fire weather conditions; revise fire use prescriptions to reflect higher fire danger and longer fire seasons.

Table 1. Climate change adaptation guide list from Millar and others (2012; Table 4.3)		
Category	**Emphasis**	**Reference**
Adaptation Framework	General options for wildlands	Millar and others 2007
	Options for protected lands	Baron and others 2008, 2009
	Adaptation guidebooks	Peterson and others 2012; Snover and others 2007; Swanston and Janowiak 2012
Vulnerability Analysis	Climate change scenarios	Cayan and others 2008
	Scenario exercises	Weeks and others 2011
	Forest ecosystems	Aubry and others 2011; Littell and others 2010
	Watershed analysis	Furniss and others 2010
Genetic management	Seed transfer guidelines	McKenney and others 2009
	Risk assessment	Potter and Crane 2010
Assisted migration	Framework for translocation	McLachlan and others 2007; Riccardi and Simberloff 2008
Decisionmaking	Silvicultural practices	Janowiak and others 2011b
	Climate adaptation workbook	Janowiak and others 2011a
Priority setting	Climate project screening tool	Morelli and others 2011b

Land management agencies face significant challenges incorporating recent scientific findings on fire-climate interactions into land management practices. First, differences between a researcher's "useful" result and the usability of that result by a manager must be bridged (Dilling and Lemos 2011). Human capacity is needed to translate research information into management planning and policy, and to understand the limits of scientific results in this context. Connecting environmental problems to policy is inherently difficult given complex biological, physical and social interactions, and the dependence on collaboration among scientists, policymakers and the public (Lemos and Morehouse 2005). Second, climate change projections include varying degrees of uncertainty depending upon factors such as emissions, input parameters, and the modeling system used. Climate model uncertainty can be quantified in a fairly straightforward manner, but uncertainty in outcomes of ecosystem response or management actions is much more difficult to quantify. Scenario planning is one means to address this uncertainty by considering alternative futures and impacts, identifying key vulnerabilities, and gauging adaptation and mitigation capacities (Weeks and others 2011; Cross and others 2012). A related challenge is that, while the cost of producing large numbers of scenarios has been greatly reduced by the spread of low-cost, high-performance computers and software, development of methods for extracting and communicating useful information from large scenario data sets for policymaking and management applications has lagged. Third, adverse impacts of management activities on protected species and other protected resources must be avoided or mitigated as provided for under applicable laws.

The capacity for communities to adapt to changes in ecosystem services they rely on is determined in part by the extent of the changes they are exposed to, the extent to which existing infrastructure and systems for resource extraction can be adapted to changing conditions, and the diversity of their economies (Vose and others 2012). Notably, the majority of existing forest resources in the western United States is on federal lands managed by federal resource agencies. Characteristics of existing infrastructure for resource use and extraction on these lands are strongly influenced by policymaking at the national level, and the capacity for adapting forest resource management to changing conditions depends on federal priorities and a diverse national economy.

For communities in the wildland-urban interface exposed to risk of property destruction due to wildfire, the primary strategies for managing wildfire risks fall into three general categories: fire suppression, fire prevention, and development policies. Suppression involves actively extinguishing wildfires. Prevention measures seek to reduce the number, size and severity of large fires and their economic and ecological impacts, primarily through vegetation management (e.g., mechanical thinning, managed fires, cleared buffers) and ignition reduction (e.g., burn controls, park closures, warnings and educational campaigns). Development strategies include measures designed to reduce the impact of wildfires on structures, and of structures on the ability to manage wildfires safely and effectively. Measures include zoning ordinances to reduce the spread of development in fire-prone wild areas, and regulations to enhance the ability of structures to resist fire (e.g., fire proof materials, thermal barriers, cleared perimeters, fire-resistant landscaping; Caulkin and others 2014). A particularly challenging problem is the disconnect between state and local authority over land-use decisions affecting development in fire-prone areas versus federal responsibility for most of the fire suppression costs. Potential remedies include federal incentives to encourage greater state and local responsibility to use zoning ordinances, building codes, and wildfire insurance requirements to reduce risk in the wildland urban interfaces near federal lands (Gorte and others 2013).

Despite the considerable resources devoted to fire suppression, it is often ineffective under climatic conditions that foster the rapid spread of wildfires. Furthermore, the ecological consequences of this kind of intervention might turn out to have their own undesirable consequences. Reducing fire activity in the short run may increase risks in the long term by contributing to the build-up of fuels in otherwise fuel-limited wildfire regimes. This has already become a major problem in ponderosa pine forests in the Sierra Nevada and the southwestern United States due to fire suppression and land uses (such as grazing livestock) (Allen and others 2002). Conversely, if fires could be effectively suppressed, this might be a desirable course of action in some naturally dense forest ecosystems where very long return times between fires was previously the norm, if the result of climate change is that these forests would not regenerate post-fire and a substantial portion of the carbon stored in them would be released into the atmosphere.

Among prevention strategies, fuels management is likely to continue to be an important tool for building buffers around communities at risk from wildfire. It may also reduce the severity of wildfires in locations where forests have accumulated biomass due to fire suppression and land use. However, thinning forests that are naturally densely vegetated constitutes an unnatural disturbance in itself, and may not always reduce wildfire risks. Development policies could make a substantial difference in the economic impact of wildfire in a warmer world by reducing the capital losses associated with catastrophic wildfires. By reducing the need to actively protect structures during a wildfire, these measures could also free up suppression resources that could be better employed protecting resources with cultural and natural conservation values, or restoring forests through the use of prescribed fire (Caulkin and others 2014). All of these measures (suppression, prevention, development) have been emphasized to varying degrees around the world. In places like the western United States, where there is a substantial and rapidly growing wildland-urban interface in fire prone areas (Gude and others 2008), development strategies hold out the greatest promise to reduce the economic impact of wildfires in a changed climate (Gorte and others 2013). However, they have only limited applicability to preserving ecosystem and resource values.

CONCLUSION

The effects of climatic change on wildfire will depend on how past and present climates have combined with human actions to shape extant ecosystems. Climate controls the spatial distribution of vegetation, and the interaction of that vegetation and climate variability largely determines the availability and flammability of the live and dead vegetation that fuels wildfires. In moist forest ecosystems where snow plays an important role in the hydrologic cycle and fuel flammability is the limiting factor in determining fire risks, anthropogenic increases in temperature may lead to substantial increases in fire activity.

In dry ecosystems where fire risks are limited by fuel availability, warmer temperatures may not increase fire activity significantly. Warmer temperatures and greater evaporation in some places could actually reduce fire risks over time if the result is reduced growth of grasses and other surface vegetation that provide the continuous fuel cover necessary for large fires to spread. The effect of climate change on precipitation is also a major source of uncertainty for fuel-limited wildfire regimes. However, in some places these are the same ecosystems where fire suppression and land uses that reduce fire activity in the short run have led to increased fuel loads today as formerly open woodlands have become dense forests. For the immediate future, this increases the risk of large, difficult-to-control fires with ecologically severe impacts.

Thus, the combined long-term impact of diverse human activities has been to increase the risks of large wildfires in many places in ways that cannot be easily reversed. Even if prompt action is taken now to reduce future emissions of greenhouse gases, the legacy of increased atmospheric concentrations of these gases means that the risk of large fires will remain high and will continue to increase in many forests. Consequently, communities will need to adapt. The capacity for adaptation is strongly influenced by the size and diversity of the economy a community can draw upon.

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