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The Importance of Climate Change for Future Wildfire Scenarios in the Western United States

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Excerpted from the full report,
Regional Impacts of Climate Change: Four Case Studies in the United States
Prepared for the Pew Center on Global Climate Change

by

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

In 2007, the science of climate change achieved an unfortunate milestone: the Intergovernmental Panel on Climate Change reached a consensus position that human-induced global warming is already causing physical and biological impacts worldwide. The most recent scientific work demonstrates that changes in the climate system are occurring in the patterns that scientists had predicted, but the observed changes are happening earlier and faster than expected—again, unfortunate. Although serious reductions in manmade greenhouse gas emissions must be undertaken to reduce the extent of future impacts, climate change is already here and some impacts are clearly unavoidable. It is imperative, therefore, that we take stock of current and projected impacts so that we may begin to prepare for a future unlike the past we have known.

The Pew Center has published a dozen previous reports on the environmental effects of climate change in various sectors across the United States. However, because climate impacts occur locally and can take many different forms in different places, *Regional Impacts of Climate Change: Four Case Studies in the United States* examines impacts of particular interest to different regions of the country. This paper is an excerpt from the full report. Although sections of the full report examine different aspects of current and projected impacts, a look across the sections reveals common issues that decision makers and planners are likely to face in learning to cope with climate change.

Kristie Ebi and Gerald Meehl find that Midwestern cities are very likely to experience more frequent, longer, and hotter heatwaves. According to Dominique Bachelet and her coauthors, wildfires are likely to increase in the West, continuing a dramatic trend already in progress. Robert Twilley explains that Gulf Coast wetlands provide critical ecosystems services to humanity, but sustaining these already fragile ecosystems will be increasingly difficult in the face of climate change. Finally, Donald Boesch and his colleagues warn that the Chesapeake Bay may respond to climate change with more frequent and larger low-oxygen "dead zone" events that damage fisheries and diminish tourist appeal. These authors are leading thinkers and practitioners in their respective fields and provide authoritative views on what must be done to adapt to climate change and diminish the threats to our environmental support systems.

A key theme emerges from these four case studies: pre-existing problems caused by human activities are exacerbated by climate change, itself mostly a human-induced phenomenon. Fortunately, manmade problems are amenable to manmade solutions. Climate change cannot be stopped entirely, but it can be limited significantly through national and international action to reduce the amount of greenhouse gases emitted to the atmosphere over the next several decades and thereafter, thus limiting climate change impacts. Managing those impacts requires that we adapt other human activities so that crucial resources, such as Gulf Coast wetlands or public emergency systems, continue to function effectively. The papers in this volume offer insights into how we can adapt to a variety of major impacts that we can expect to face now and in decades to come.

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The Importance of Climate Change for Future Wildfire Scenarios in the Western United States

A. Introduction

Fire has always been an integral part of the ecology of the western United States and has contributed to the diversity of its ecosystems, influencing their carbon and nutrient cycling. Will a warmer future climate increase fires in western forests? If so, how will this change affect the ecosystems and the carbon cycle in the western United States?

To answer these questions, we should first examine the past (Veblen, 2003). During droughts in the 19th century and earlier, fires were as severe as they have been in the last decade. Effective fire suppression since the 1950s has reduced the extent of wildfires in the United States by a factor of eight since the beginning of the 20th century, according to model simulations (Lenihan et al., forthcoming). However, in the past decade, while the number of fires continued to decrease, the size of the fires increased. Recent large fires have captured the headlines in western states—Arizona (Rodeo-Chediski fire in 2000 more than 468,638 acres), Oregon (Biscuit fire in 2002 almost 500,000 acres), and Alaska (6.38 million acres burned in 2004).

Fire suppression leading to the accumulation of vegetation, which fuels fires, was identified as the major culprit leading to larger wildfires, and forest thinning and logging to reduce available fuel was touted as a reliable mitigation option to reduce fires in the West. However, the direct role of humans in causing the current increase in fire activity may have been greatly overstated, as forests in which fire has not been suppressed have seen increases in fire comparable to managed forests. Since 1986, the combination of earlier snowmelt due to warmer springs (resulting in a longer fire season), and warmer summers (resulting in lower soil moisture) have been the major contributors to the increase in fire activity in managed and unmanaged forests, alike (Westerling et al., 2006). Western forests are responding clearly to a strong climate signal rather than simply to mismanagement.

What can we expect from western U.S. forest fires in the 21st century? Projections of future climate change from general circulation models simulate significant increases in temperature across the western United States during the 21st century. Projections of precipitation are more variable, but they generally suggest drier summer conditions in the West (Running, 2006). In fact, a transition to persistently drier conditions has already begun in the Southwest, and mountain snowpack has already declined throughout the West (Mote et al., 2005; Seager et al., 2007). These projections, combined with an increase in population density and the continued expansion of the urban–wildland interface, indicate that fires will continue to be a concern in the West.

An important question now is whether fires will increase across all western forests in the future, or whether more frequent droughts will decrease fuel production and ultimately starve future fires in certain areas. Another question is whether managers can target more sensitive areas for intensive control? This chapter summarizes projections for the 21st century from vegetation models that integrate knowledge of past fire occurrence to simulate changes in fire patterns and their effect on carbon sequestration in western states.

B. Terminology

Some specialized terminology is required to discuss fire trends and their implications for natural and human systems.

- ***Fuel*** is potentially combustible material, and *fuel load* is the amount of fuel available for ignition. Wind, topography, and fire history are among the many local factors that affect fuel load and, in turn, fire frequency and intensity. *Surface fuels* include grasses, dead leaves, and needles; *ladder fuels* include dead branches, mosses, and lichens that carry the fire up into the canopy. *Fine fuels* (such as dead leaves) respond quickly (within hours) to changes in air moisture, while *coarse fuels* (such as tree trunks) respond much more slowly (weeks).

- ***Fire intensity*** describes the amount of energy released by a fire, usually characterized by the maximum temperature of a fire and the height of the flames. It depends on the type and availability of fuel and on weather conditions.

- ***Fire severity*** refers to the degree to which a site has been altered by fire—for example, the amount of fuel burned and the degree of tree mortality. Severity depends on both fire intensity and duration. High-severity or *stand-replacing* fires typically kill trees by burning the tree tops or through very hot surface fires.

- ***Fire return interval*** is the average number of years between consecutive fires at a given location.

- ***Fire frequency*** is the number of fires during a given unit of time and depends on the type of ecosystem, the type of weather and its duration, and the source of ignition.

- ***Fire regime*** refers to fire patterns over long periods of time and their effects on ecosystems. Fire regimes are a function of the frequency of fire occurrence, fire intensity and the amount of fuel consumed. Frequent fires tend to maintain fire-tolerant species such as ponderosa pine, while sporadic fires promote shade-tolerant conifer species such as Douglas firs. Low-severity fires support fire-resistant (thick-barked) vegetation, while high-severity areas are usually dominated by faster-growing, thin-barked trees.

Low-severity fire regimes are characterized by frequent small fires with low intensity. They often occur in lightning-prone areas that are fuel limited, such as most Southwest low-elevation ponderosa pine forests with abundant fine fuels, including grasses and long needles that dry easily. In these forests, average fire return intervals have historically ranged from 4 to 36 years, and fire suppression has been effective in reducing the number of fires, leading to a build-up of fuel (Schoennagel et al., 2004). Due to their accessibility, these forests have also been extensively managed for timber production and livestock grazing (thereby reducing the amount of grass fuel), which has altered tree density and forest composition (Smith and Fischer, 1997). Management activities have often caused widely spaced old-growth trees to be replaced by stands of dense, small-diameter trees that tend to fuel high-intensity fire when fires do occur in these dry ecosystems.

Moderate or mixed-severity fire regimes consist of a combination of frequent low-intensity surface fires and infrequent stand-replacing fires of intermediate size. Middle and lower mountain forests are more likely affected by both mixed- and low-severity fire regimes. Both climate and fuels vary considerably in these forests and fire return intervals vary accordingly, ranging from 25 years to more than 250 years. Forest management activities (primarily logging) and fire exclusion have also affected fire regimes, particularly on sites that once supported open woodlands (Schoennagel et al., 2004).

High-severity fires, typically infrequent fires of high intensity and large size (Agee, 1998), generally affect high-elevation dense forests, where ladder fuels abound. At these cold and wet elevations, fire occurrence is mostly limited by fuel moisture. Fires are often caused by weather events such as droughts accompanied by high winds (Agee, 1997). They typically burn infrequently (50–300 years), although often at a much higher intensity compared with low-elevation drier forests. Because of the paucity of needles and grasses in these forests, only prolonged dry weather conditions create optimal conditions for fires (Schoennagel et al., 2004). However, substantial natural variability exists within each forest type due to both climate and topography (Heyerdahl et al., 2001). The 1988 Yellowstone fire was a good example of a high-severity fire facilitated by a 12-year drought, a low winter snowpack, and a dry, hot, and windy summer (Schoennagel et al., 2004).

C. Fire and Natural Climate Variability in the West

Fire in western ecosystems is determined by climatic variability, local topography, and human intervention. Managers have associated an average fire return interval to the forest types, but these averages mask large year-to-year variability in fire occurrence. When climate alters fuel loads and fuel moisture, forest susceptibility to wildfires changes and contributes to this natural variability (Whitlock et al., 2003). Drought has a major influence on fire in the United States (Siebold and Veblen, 2006; Enfield et al., 2001). Historically, drought patterns in the West are related to large-scale climate patterns in the Pacific and Atlantic oceans (Table 1). In the Pacific, the El Niño–Southern Oscillation (ENSO) varies on a 5–7 year cycle. In the Southwest and Colorado, La Niña years are dry and drought-induced fires are frequent, whereas El Niño years are wet and promote fuel accumulation. Conversely, in the Pacific Northwest El Niño years bring drier conditions and more fires (Swetnam and Baisan, 2003; Westerling and Swetnam, 2003). The Pacific Decadal Oscillation (PDO) varies on a 20–30 year cycle and the Atlantic Multidecadal Oscillation (AMO) varies on a 65–80 year cycle (McCabe et al., 2003; Schoennagel et al., 2004). The 1930s Dust Bowl in the Southwest occurred when both the PDO and AMO were in their warm phases.

As these large-scale ocean climate patterns vary in relation to each other, drought conditions shift from region to region in the United States (Table 1).

Mountainous terrain and the resulting small-scale climatic variation across the landscape also contribute to a mosaic of diverse types of vegetation in the western United States. Plants are well adapted to their environments, and fire has contributed strongly to their distribution. Historically, naturally occurring fire regimes have preserved the boundaries between prairies and forests, and sustained savannas and open forests. Thunderstorms and frequent lightning strikes—common occurrences during summers in the Great Plains, the slopes of the Sierras, and the Rockies, and during the monsoon season in the Southwest—allowed wildfires to maintain natural vegetation boundaries.

Cognizant of the natural relationship between climate, topography, and fire, Native Americans used fire to sustain grazing grounds for buffalo, for hunting and gathering food, and for controlling pests. Pyne (1982) observed that "the general consequence of the Indian occupation of the New World

Table 1

Historic Drought Patterns in Rocky Mountain Subalpine Forests and in the United States

Rocky Mountain subalpine forests	PDO positive phase (1913-1943, 1977–present)	PDO negative phase (1944-1976)
La Niña (NINO3 negative phase) (e.g., 1890, 1924, 1947, 1976, 2006)	High frequency (36–54%) of extreme drought in southern California and parts of the Southwest	Highest frequency (52–68 percent) of extreme drought in the Southwest
El Niño (NINO3 positive phase) (e.g., 1925, 1946, 1977, 1998, 2005) (Greater precipitation during all seasons in the central and southern Rockies)	high frequency (26–38%) extreme drought in the Pacific Northwest and Northern Rockies,	Least influence on drought

Schoennagel et al., 2005

United States	PDO positive phase (1913-1943, 1977-present)	PDO negative phase (1944-1976)
AMO positive phase (1926-1963, 1995-present)	1926–1943, 1995-present (e.g., 1930s drought; did not affect the Southwest)	1944–1963 (e.g., 1950s drought; mostly in the Midwest, Southwest, Rockies, and Great Basin)
AMO negative phase (1964-1994)	1977–1994 (e.g., Pacific Northwest and Maine drought)	1964–1976 (e.g., Southern California and central High Plains drought)

McCabe et al., 2003.

Historic drought patterns in Rocky Mountain subalpine forests and across the United States are related to large-scale climate patterns in the Pacific and Atlantic Oceans (Schoennagel et al., 2005; McCabe et al., 2003). For each mode of climate variability, the "positive phase" corresponds to the warm period of the oscillation and the "negative phase" corresponds to the cool period. See text for further explanation.

was to replace forested land with grassland or savannah, or, where the forest persisted, to open it up and free it from underbrush." Similarly, European descendants used fires to clear the land they settled during the western migration. They also introduced livestock and grazing, which disrupted fire regimes dramatically in the Southwest and the Sierras. These human activities led to extensive changes in land cover, including considerable shrub expansion (Swetnam and Baisan, 2003).

In the past few decades, the western United States has experienced droughts as severe as any on record (NOAA, 2002 as cited by Whitlock et al., 2003). Drought-killed trees have made forests more vulnerable to fires. Sustained drought conditions will make those forests less likely to recover, favoring replacement by grass-dominated semi-arid systems in the future. For example, large-scale drought-related dieback of pinyon pines has been observed recently in the Southwest and could bring large fires to the area in the near future. In the past, similar events caused by natural climate variability promoted vegetation shifts. They may become more prevalent again in a warmer future (Tebaldi et al., 2006; Seager et al., 2007) and will require human adaptation and changes in land use in the more arid parts of the western states.

The close relationship between climate and fire regime and its consequences for ecosystem structure are well recognized. Future changes in the climate, especially with regard to precipitation and drought, are likely to alter fire regimes in the western United States.

D. Fire and Humans

Human activities have added complexity to the western landscape. Fire suppression and prescribed burning, urban expansion, cattle production and grazing, and introduction of exotic plant species, have all conspired to artificially modify the fire regimes of western ecosystems and add another layer of uncertainty to the projections of the future of western forests.

1. Fire suppression

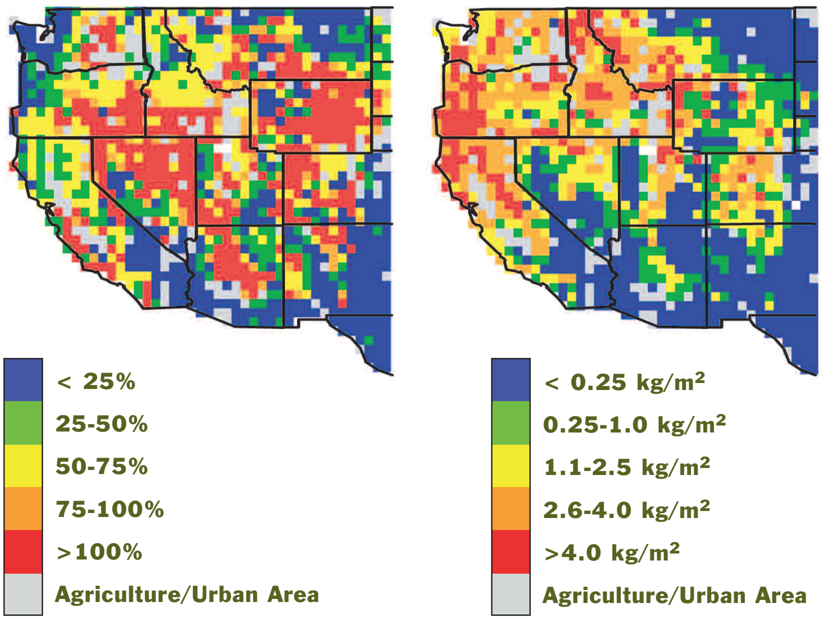
Fires were actively suppressed in the West during the 20th century. Increased government support for fire suppression and rapid mechanization of fire control after World War II contributed to an abrupt decline in the annual area burned after 1950. Fire suppression altered the ecology of plants and animals that depend on fire, sometimes with economic or aesthetic consequences. For example, some commercial tree species need fire to reproduce—lodgepole pine cones only release their seeds after intense heat has melted the waxy resin that keeps their scales closed. Similarly, giant sequoia seeds need bare soil, free from dead plant remains, to germinate. If current fire suppression practices were to continue for centuries, fire would not clean the forest floor, and sequoia groves would be in danger of disappearing as the old trees die and seedlings fail to establish.

Fire suppression in the Sierra Nevada and in the Southwest has resulted in denser forests with high fuel loads, allowing for catastrophic fires in low-elevation dry forests where high-intensity fires were rare historically. Land managers use prescribed burning to mitigate fuel build-up near population centers, but many forests in wilderness areas have accumulated so much fuel that run-away fires have become more common and remain a real danger in dry environments. Past forest management sought to eliminate wildfires but only succeeded in diminishing their extent, as climatic influences have overridden control efforts (Agee, 2003).

In contrast to the dry forests, subalpine forests at higher elevations are considerably wetter and colder. They often have historic fire-return intervals (50–300 years) longer than the period of time in which the current fire-exclusion policies have been in effect. So in general, they have not yet missed fire cycles as the dry forests have, and increased fire in these systems results from a climate signal rather than human intervention.

Figure 1

Simulated Increase in Plant Biomass as a Result of Fire Suppression



Simulated increase in total aboveground plant biomass (percent change on the left; absolute change on the right) due to post-1950 fire suppression by the end of year 2003 (Lenihan et al., forthcoming). Model results are displayed using the VEMAP (Schimel et al., 2000) agricultural and urban mask.

Fire suppression affects the role of forests in carbon sequestration. Scientists have shown that temperate forests of North America have been sequestering carbon over the past several decades. Sequestration in eastern states is thought to be primarily a result of regrowth since forest harvest and agricultural abandonment. In contrast, sequestration in the West is thought to be due primarily to decades of fire suppression coupled with a beneficial climate for growth and possible growth enhancement due to the anthropogenic increase in atmospheric carbon dioxide (CO_2; Caspersen et al., 2000). Several studies calculate the amount of carbon stored due to fire suppression (Table 2). Simulation results using a dynamic vegetation model (Lenihan et al., forthcoming) show the wide-ranging carbon gains across the continental United States (Figure 1). It also illustrates the importance of suppression in the West for total national carbon sequestered. However, future fires enhanced by the accumulation of fuels and climate change could eliminate much of the carbon gains due to suppression.

Table 2

Historical **Effects of Fire Suppression** on Ecosystems and Carbon Sequestration in the United States

Reference	**Method**	**Fire Supression Impacts**	**Carbon Gains and Losses in the 1980s (Pg C year^{-1})**
Houghton (1999, 2003)	Land use statistics	Emissions from wildfire	-0.081
	Bookkeeping model	Re-growth from wildfire	+0.144
		Enhanced growth in western pines due to fire suppression	+0.026 (0.0052)
		Woody encroachment in non forest lands due to grazing and fire suppression	+0.061 (0.122)
Pacala et al. (2001)	Inventory Land Use Change	Woody encroachment in non-forest lands (grazing and fire suppression)	+0.12 to 0.13
Hurtt et al. (2002)	ED model	Woody encroachment (fire suppression)	+0.13
Sohngen and Haynes (1997)	—	Enhanced growth in U.S. forests	+0.0005
Lenihan et al. (forthcoming)	MC1 DGVM	Emissions from wildfires (with suppression)	+0.02 (0.003)
	(USA+Canada)	Enhanced growth due to fire suppression	+0.12
		Enhanced soil respiration due to suppression	-0.07
		Carbon sequestration due to suppression	+0.098

2. Effects of development

Most of the human settlements in the western United States are near dry woodlands and dry forests. As more people have moved into forested areas, public pressure for fire prevention has increased. As a result, the rapidly expanding wildland–urban interface, which was once subject to frequent, low-intensity surface fires, has now become prone to mixed- or high-severity fire regimes and thus more difficult to control, while population pressure and poor zoning regulations heighten the risk of fire damage.

The 20th century population explosion along the West Coast contributed to significant changes to natural fire regimes. Sources of fire ignition in fire-prone but lightning-poor environments, such as the California chaparral (Swetnam and Baisan, 2003), increased as population density rose. Jones (1995) and Stephens (2005) document a significant increase in human-caused ignitions in California. Smokers, campers, and arsonists are likely agents responsible for the high frequency of fires along roadways in southern California (Stephens, 2005).

3. Indirect human impacts

The indirect effects of population growth have also significantly affected fire regimes. Livestock grazing has reduced the amount of fine fuels, thus decreasing ignition potential. Logging has decreased the extent of old-growth forests and the amount of large dead wood critical to fire intensity. However, road cuts and timber harvest sites fragment forests, warming the air below the canopy and leading to the drying of fuels. Timber production has also promoted extensive plantations of even-age trees of the same species, which can easily propagate disturbances, such as fire or insect infestations.

In some areas, the combination of land use and fire exclusion has exacerbated the accumulation of dead fuels resulting from insect and disease outbreaks (Baker, 2003). Spruce budworm in Alaska is now able to successfully complete its life cycle in one year rather than two (Volney and Fleming, 2000). Multi-year droughts reduce tree growth and the production of defensive chemicals by the trees to fend off insect attacks (Logan et al., 2003). The resulting increase in dead fuels from extensive insect damage enhanced by fire suppression is often thought to greatly enhance the probability of catastrophic fires. The extent to which increased insect damage may affect fire regimes remains unclear. Despite an increase in dead fine fuels resulting from a spruce beetle outbreak in high elevation coniferous forests in Colorado, fire susceptibility did not increase (Bebi et al., 2003). Moreover, Bigler et al. (2005) found that the 2002 fires in mountain forests of northern Colorado were attributable primarily to extreme drought conditions rather than to insect damage or past management practices (Veblen, 2003). However, data on insect damage and fire is limited, and land managers would be prudent to perceive large-scale insect damage as a potential fire threat.

People also introduce non-native plant species that can change the fire regime and contribute to the disappearance of native systems. Invasive grasses such as cheatgrass can fill the gaps between native bunchgrass and sparse woody desert vegetation with a dense, continuous vegetation cover that, when dry, presents a major fuel source for brushfires. Frequent fires then allow the displacement of native vegetation by fire-tolerant invasive species, causing a shift from native shrubland to grassland. This invasion process is enhanced by urban development in desert areas, which introduces potential fire hazards and accelerates the invasion of grasses (Brooks et al., 2004). Alternatively, D'Antonio and Mahall (1991) show that ice plants from South Africa successfully compete with native shrubs in coastal California chaparral for critical surface water provided by winter rain or summer fog. The ice plants induce changes in the native shrub rooting profiles and can cause a decline in shrub biomass, lifespan, and reproduction. The conversion from a fire-prone coastal chaparral to a mixture of shrub and succulents with high live fuel moisture reduces fire intensity and fire spread, altering ecosystem properties and reducing the recruitment of native shrub species. By modifying the natural fire regime, exotic species are fostering changes that have not been observed before in these areas, making management of vegetation more difficult.

E. Fire in the 21st Century

Projections of future climate change suggest an increase in growing season length with earlier snowmelt periods as winters become milder and minimum temperatures increase (Mote et al., 2005). These changes will likely cause late-summer drought stress and increase plant susceptibility to pests and pathogens. At the same time, warmer conditions tend to speed up the life cycles of pests and pathogens and allow them to extend their ranges to vulnerable populations thus far protected by colder habitats (Berg et al., 2006). While pest damage can increase the amount of dead fuels in forests, drought stress can slow forest growth and reduce live fuels. These complex interactions make projections of future fire regimes and consequent impacts difficult. Consequently, researchers have designed models that can synthesize current knowledge about ecosystem structure and change and test hypotheses to project possible outcomes following changes in local or regional climate.

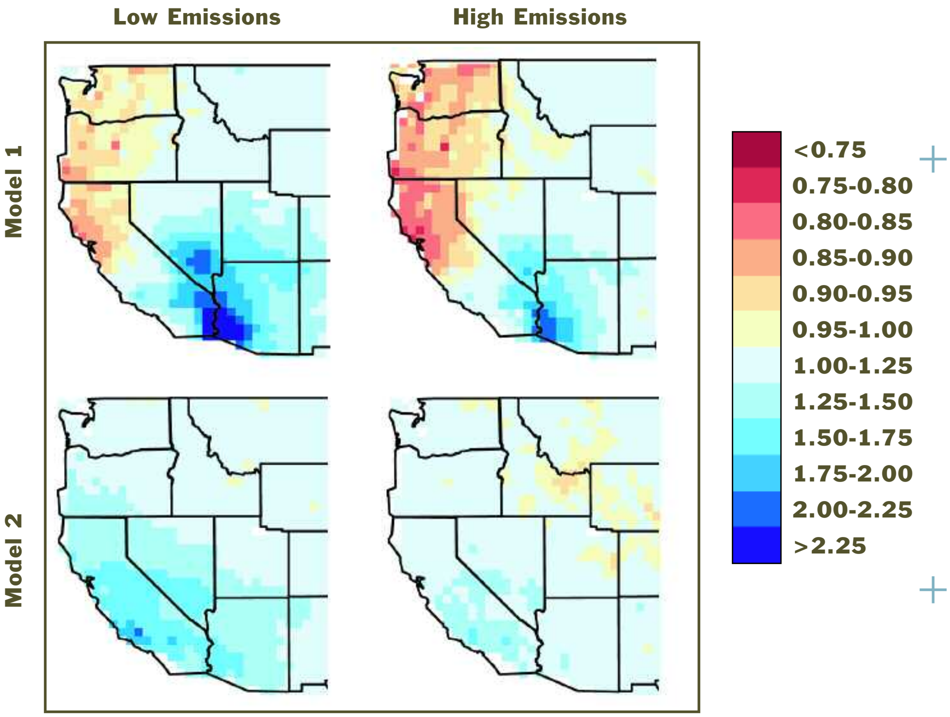
1. Future climate change scenarios

On average, climate models project drying of the western United States as a result of climate change, although the Northwest may be drier only during the summer when fire hazards are greatest (IPCC, 2007; Seager et al., 2007). However, western fire regimes vary on spatial scales smaller than those on which most climate models operate (see Wigley, 1999) and projections vary among individual models (Price et al., 2004), with some predicting wetter conditions in certain parts of the Southwest (e.g., Figure 2).

In particular, general circulation models may disagree in simulating the North American monsoon system, a seasonal precipitation pattern that brings moisture to parts of the southwestern United States during the summer (Collier & Zhang, 2007). Similarly, some climate models project an increase in annual average precipitation in California (Price et al., 2004). Moreover, global climate models have not been designed to simulate regional climate variability

Figure 2

Alternative Projections of **Precipitation Change** in the Western United States



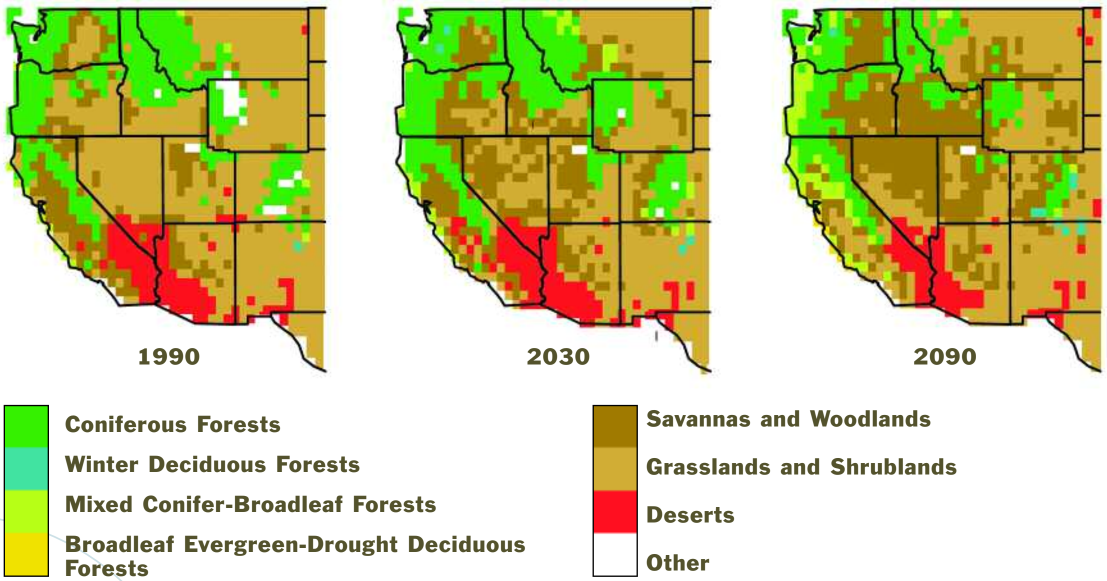
Alternative projections of precipitation change relative to the average for 1961–1990 in the western United States under different climate change scenarios. Two global climate models (Model 1 = HadCM3; Model 2 = CGCM2) and high (SRES A2) and low (SRES B2) greenhouse gas emission scenarios are compared. Values are fractions compared to the present. Values greater than 1.00 are increases; values less than 1.00 are decreases.

and extremes. Consequently, even though models agree on a general drying of the western United States, considerable uncertainty persists about seasonal and regional changes in precipitation patterns on the spatial scales needed to predict wildfires. Therefore, vegetation and fire models need to be driven by a variety of climate scenarios (e.g., Figure 2) to examine how fire is likely to respond to alternative possible climate outcomes (e.g., Figure 3).

When coupled with higher atmospheric CO_2 concentrations and longer growing seasons, wetter conditions promote the expansion of woody vegetation (Figure 3). The build-up of fuels combined with natural climate variability, and the likely occurrence of longer and more intense periodic droughts in the future, increases the likelihood of wildfires (Bachelet et al., 2001). While fuel loads are building, lightning and fire season length are expected to increase (Price and Rind, 1994). Increased use of wildlands by people is also likely to increase human-caused ignitions. Ironically, more frequent human-induced fires could reduce the fuel build-up that has resulted from fire suppression in dry forests, and it could therefore reduce fire danger in the long run. Of course, inadvertent burning is a poor means of land management and increased property damage is likely to result from an increase in accidental fires.

Figure 3

Simulation of **Past and Future Vegetation** Across the Western United States



Simulation of Past and Future Vegetation across the western United States with the CGCM2 global climate model and a high (SRES A2) greenhouse gas emission scenario (Lenihan et al., forthcoming).

The seasonal pattern of future climate change is also important. In general, climate models project higher average winter temperatures with increased winter rainfall (instead of snow) and decreased summer precipitation. Observations of a dwindling snowpack have confirmed that winter and spring temperatures are already getting warmer (Mote et al., 2005). In areas where winters are wet, this increase will not greatly affect fire danger. However, a change in summer moisture could greatly affect the spread of fire. The positive (in terms of carbon sequestration) outcome of a longer growing season resulting from earlier snowmelt could be cancelled out by the early build-up of fuels followed by late-summer droughts; such seasonal changes have already been linked to an increase in wildfires across the West (Westerling et al., 2006).

2. Fire effects on competitive interactions

Fire effects also include conversion of one type of vegetation cover to another as shown by Lenihan et al., (2003). Because of the uncertainty in future precipitation regimes, two types of vegetation changes are possible. A reduction in precipitation would allow drought-tolerant grasses to invade native shrublands and eventually shift the vegetation dominance to grassland. The flammability of grasses promotes greater rates of fire spread. Consequently, more extensive fires would progressively lead to higher fire frequencies, thereby depressing tree or shrub recovery and promoting the dominance of easily ignited grasses (Lenihan et al., 2003).

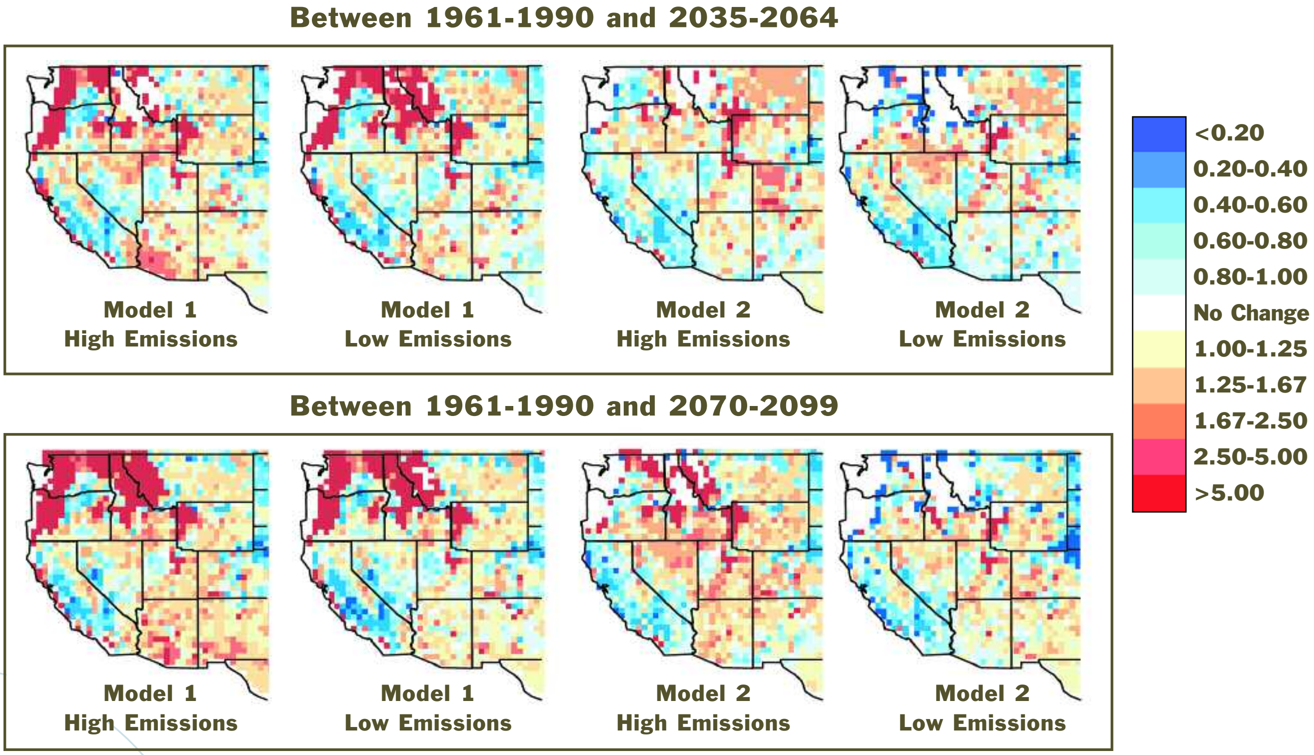
On the other hand, an increase in precipitation would enhance woody plant expansion. Trees and shrubs could provide cool moist shade and create “islands of fertility” unlikely to carry extensive fires because of their patchiness. However, because fire intensity depends on the properties of the total fuel load, a general increase in woody biomass and expansion of dense woodlands could promote more intense fires and more biomass consumption and mortality in the wake of a drought, thus ultimately reducing total tree biomass (Lenihan et al., 2003). In either wetter or drier conditions, models therefore indicate that fire could reduce forest and woody vegetation cover in the West in a future warmer world.

3. Projections

Biomass consumed by wildfire is estimated to at least double in the western United States during the 21st century, when simulated by a dynamic vegetation model under several future climate scenarios (Bachelet et al., 2001). The model shows that global warming may cause significant changes in regional vegetation patterns that would significantly alter the occurrence and distribution of wildfires in forest and grassland areas. Similarly, the average annual acreage and biomass burned across the United States during the 21st century is estimated to increase in comparison with the 20th century average, regardless of whether precipitation increases or decreases (Figure 4 and Table 3; Bachelet et al., 2003). For instance, some climate models project an increase in annual average precipitation in California (Figure 3; Price et al., 2004). Under these circumstances, the vegetation model simulates increased fire intensity and area burned because increased precipitation reduces fire and promotes fuel buildup during relatively wet years, setting the stage for larger, more intense fires during inevitable dry years (Lenihan et al., 2003). This interaction between fuels and year-to-year variability in precipitation produces the somewhat counter-intuitive result of more severe fire years simulated under wetter future climate scenarios.

Figure 4

Projected Change in **Plant Biomass Burned** by Wildfires



Projected change in biomass burned by wildfires from historical conditions based on two different climate models (Model 1 = HADCM3; Model 2 = CGCM2) and using high (SRES A2) and low (SRES B2) greenhouse gas emission scenarios. Values are fractions compared to the present. Values greater than 1.00 are increases; values less than 1.00 are decreases.

Different fire management regimes result in a variety of responses among the western vegetation types (Lenihan et al., forthcoming). For example, the biomass of both maritime conifer forests (that extend from Canada down to northern California) and Southwest temperate arid shrublands decrease under most future climate change scenarios when their natural fire regime is simulated, but they increase under most scenarios when fire suppression is simulated (Lenihan et al., forthcoming).

Several possible future climates and associated ecological responses can be simulated for regional studies (Figures 2 and 4). However, a general warming across the country is consistently projected by the models. Rainfall projections are more variable but point to a general decrease of up to 15 percent from 2040 to 2070 (Running, 2006). Regional droughts and resulting wildfires could significantly distress ecological systems, while wetter climates would benefit most of them. Under the drier scenario (HADCM3), a large increase in biomass consumed by wildfires is simulated for the

Table 3

Impacts of Future Climate Change on Fire and Carbon Sequestration

	Years	United States	Oregon	California
Live vegetation carbon	1901–2000	38 Pg C	2.43 Pg C	1.8 Pg C
	2001–2100	–0.20	–0.08	–0.18
	2031–2060	–0.12	+0.68	–0.23
	2071–2090	–0.37	–0.14	–0.12
Soil carbon	1901–2000	114 Pg C	6.20 Pg C	6.8 Pg C
	2001–2100	–0.01	–0.04	–0.07
	2031–2060	–0.01	–0.05	–0.07
	2071–2090	–0.02	–0.04	–0.08
Area burned by wildfires	1901–2000	104,019 km^2	3,299 km^2	7,352 km^2
	2001–2100	+1.10	+0.21	+0.19
	2031–2060	+1.08	+0.19	+0.14
	2071–2090	+2.61	+0.57	+0.19
Biomass burned by wildfires	1901–2000	140.661 Tg C	13.39 Tg C	22.39 Tg C
	2001–2100	+1.18	+0.08	–0.23
	2031–2060	+3.74	+0.01	–0.26
	2071–2090	+1.39	+0.52	–0.25

Impacts of future climate change on fire and carbon sequestration simulated by vegetation model MC1 (Lenihan et al., 2003; Bachelet et al., 2001). Results are shown for the conterminous United States as a whole and for the individual western states of Oregon and California. Reported are average annual carbon stocks in Pg (billion tons) C, biomass burned in Tg (million tons) C and area burned (km^2), averaged over the historical period, and future fractional changes for the entire 21st century (2001–2100) and the middle (2031–2060) and late (2071–2090) 21st century in the CGCM2 climate model and the SRES A2 greenhouse gas emission scenario.

Pacific Northwest region while a decrease occurs in southern California (Figure 4). It is possible that some areas will see initial gains in carbon sequestration in plant biomass, followed by net losses later in this century as climate change progresses (Table 3).

Given the uncertainty among future scenarios of rainfall, managers should develop contingency plans for alternative futures with specific regional emphases. Monitoring of ecosystem indicators could be configured to provide early warning of changing conditions.

F. Conclusions

Despite imprecise knowledge of future climate and human behavior, it is reasonable to conclude that fires will likely increase in the West. Future climate scenarios project summer temperature increases between 2 and 5°C and precipitation decreases of up to 15 percent (Running, 2006). Such conditions would exacerbate summer drought (Seager et al., 2007) and further promote high-elevation forest fires, releasing stores of carbon and further contributing to the buildup of greenhouse gases. Forest response to increased atmospheric CO_2 concentration—the so-called "fertilization effect"—could also contribute to more tree growth and thus more fuel for future fires, but the effects of CO_2 on mature forests are still largely unknown (Körner et al., 2005). However, high CO_2 should enhance tree recovery after fire and young forest regrowth, as long as sufficient nutrients and soil moisture are available, although the latter is in question for many parts of the western United States because of climate change.

Fire is a natural component of ecosystems in western North America, and its occurrence is strongly correlated with climate variability (Table 1). Paleoclimatic records and future climate scenarios show that regional climate can also shift within centuries and even decades. In addition, fuel conditions may change within years or a few months of major disturbances such as insect infestations, drought, windstorms, or forest thinning. Finally, population expansion and land-use changes can dramatically affect fire regimes. These complex interactions between natural and human pressures on natural systems present a challenge for projecting future fire regimes.

Woody expansion in the western United States may continue under future warming because of natural climate variability, ongoing increases in atmospheric CO_2, and continuing grazing restrictions and fire suppression. This expansion would allow for greater carbon sequestration. However, it would also allow for an increase in coarse fuels likely to carry catastrophic fires if droughts were to occur more frequently in the future. On the other hand, future droughts may also limit tree growth, thus ultimately reducing fuel production and allowing for more open forests with lower fire danger.

Fire suppression has allowed a build-up of fuels in low-elevation tree-dominated systems in the drier regions of the western United States. The 2002 Rodeo-Chedisky fire was the largest Arizona fire in recorded history with an extent of severe burning unprecedented in ponderosa pine forests. This high-severity fire illustrates the danger of fire suppression, which increases ladder fuels and allows contiguous tree crowns to develop in these dry forests. Historically, mild surface fires occurred every 7 to 10 years in these forests, preventing them from developing to this highly susceptible state. Similarly, the introduction of invasive grasses has allowed the build-up of a continuous source of fuel for wildfires in formerly patchy shrublands. Consequently, both fire exclusion and exotic species have tilted dry woody systems towards a greater sensitivity to drought and increased the likelihood of greater fire intensity and spread in the future.

Concurrently, higher elevation forests, which are not limited by the quantity but by the dryness of fuels and have not been greatly affected by suppression activities, are now subject to increasing drought stress. Between 1970 and 1986, the area of forest burned was six times smaller than in the last two decades as longer fire seasons (78 days longer), earlier snowmelt (1 to 4 weeks earlier), and warmer summers (almost 1°C warmer) combined to increase fire activity in the West (Westerling et al., 2006). Western forests, whether they were affected by past management, as in ponderosa pine forests, or not, as in subalpine spruce and fir forests, are now responding as a whole to an overwhelming climate signal. High-severity fires, such as the 1988 Yellowstone fire and the 2002 Hayman fire, happened in response to extreme climate signals, which could become more dominant in a warmer future (Running, 2006; Seager et al., 2007).

Future population pressure will also contribute to an increase in fire danger in the West as human development expands into increasingly fire-prone environments in a more variable climate. New strategies have been delineated to address this problem (Stephens and Ruth, 2005), but it will constitute an increasing challenge for land managers in the 21st century.

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