Climate and Wildfire in the Western United States

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Climatology of Wildfire during Recent Decades

The number and extent of wildfires in the western United States each season are driven by natural factors such as fuel availability, temperature, precipitation, wind, humidity, and the location of lightning strikes, as well as anthropogenic factors. It is well known that climate fluctuations significantly affect these natural factors, and thus the severity of the western wildfire season, at a variety of temporal and spatial scales. Large-scale climate patterns in conjunction with El Niño affect the frequency and extent of wildfires that occur in particular regions of the United States (Simard *et al.*1985, Swetnam and Betancourt 1990, Jones *et al*. 1999). Swetnam and Betancourt (1998) and Balling *et al* (1992) have found relationships between the Palmer Drought Severity Index (PDSI) and fire season severity. Westerling et al (2003) demonstrate large scale, coherent patterns in wildfire driven by moisture available to grow and wet fuels, and Westerling et al (2006) show that spring and summer temperatures and the timing of spring drive large forest wildfire occurrence in the western US.
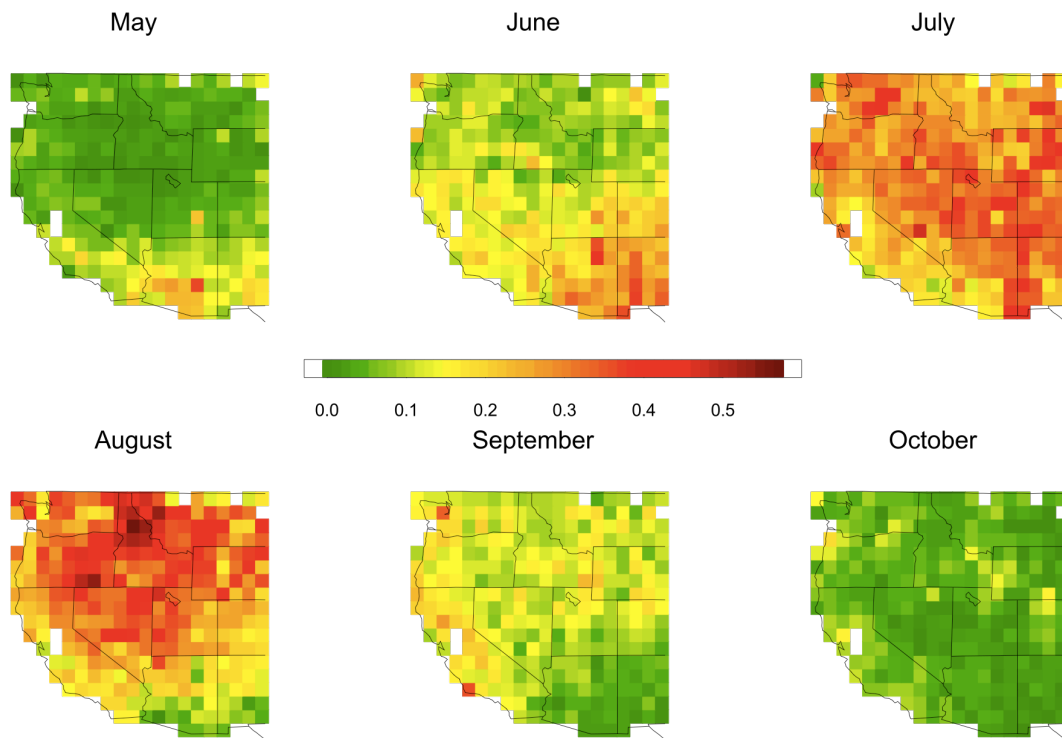
Figure 1: Seasonal cycle in fire ignitions, BLM, BIA, NPS and USFS fires 1980-1999. *Westerling et al 2003.*

Seasonality of Wildfire

Wildfire in the West is strongly seasonal, with 94% of fires and 98% of area burned occurring between May and October (Westerling et al 2003). Wildfire seasonality closely follows the mid-latitude annual cycle of temperature, yielding a peak of fire starts and acres burned when temperatures are warmest, during July and August. It should be reminded that, depending on location, most of the western U.S. is characterized by summer dryness, with 50 to 80% of annual precipitation occurring between October and March. Therefore, it is not surprising that the peak of the fire season occurs during the hottest and driest portion of the climatological annual cycle.

Within the general tendency for peak fire activity in summer, there is a noteworthy regional progression in the locus of fire activity. Fire start activity begins its seasonal increase somewhat

sooner in Arizona and New Mexico than elsewhere, commencing as early as May and June, when precipitation and mountain snowpack there diminish considerably, and ends earliest there as well, in August. This pattern is consistent with the dry spring and early summer that precedes the heaviest monsoon rains in July and August. Monsoonal lightning strikes produce numerous fire starts in June and July, before the height of the monsoon rains wets the fuels (Swetnam and Betancourt, 1998). The start of the fire season spreads north and west through July and August. To the north, in northern Idaho and western Montana, the fire season is more concentrated toward the later part of the summer, with roughly 50 percent of annual fire starts occurring in the warmest month, August. In many parts of California the fire season peaks in August and September, aggravated by hot, dry conditions that build through the summer season before rains begin in fall.

The greatest number of reported wildfires occurs in July and August in central Arizona and in the Sierras, Cascades and Rocky Mountains. In conjunction with the hottest and driest time of year, monthly mean acres burned also peak in July and August, but show somewhat different spatial features than do fire starts. Areas with the largest number of acres burned tend to be in regions of finer fuel types (*e.g.*, grasses, shrubs, chaparral), though not exclusively. Finer fuels typically lose moisture more rapidly than heavier fuels, increasing their fire consumption potential. In addition, predominately fine-fueled regions climatologically tend to be windy areas, such that once a fire starts, the combination of fuel factors and wind cause rapid spread. Moreover, the presence of fine fuels within a region may also give rise to higher monthly mean acres burned, because fine fuels—grasses especially—regenerate faster than heavy fuels,

shortening the interval between burns.   Finally, the tendency for area burned to be greater in areas characterized by fine fuel types is strongest early in the fire season (June), and may simply reflect the earlier arrival of warm, dry summer conditions at lower elevations. Forested areas in the western U.S. tend to be at higher elevations.

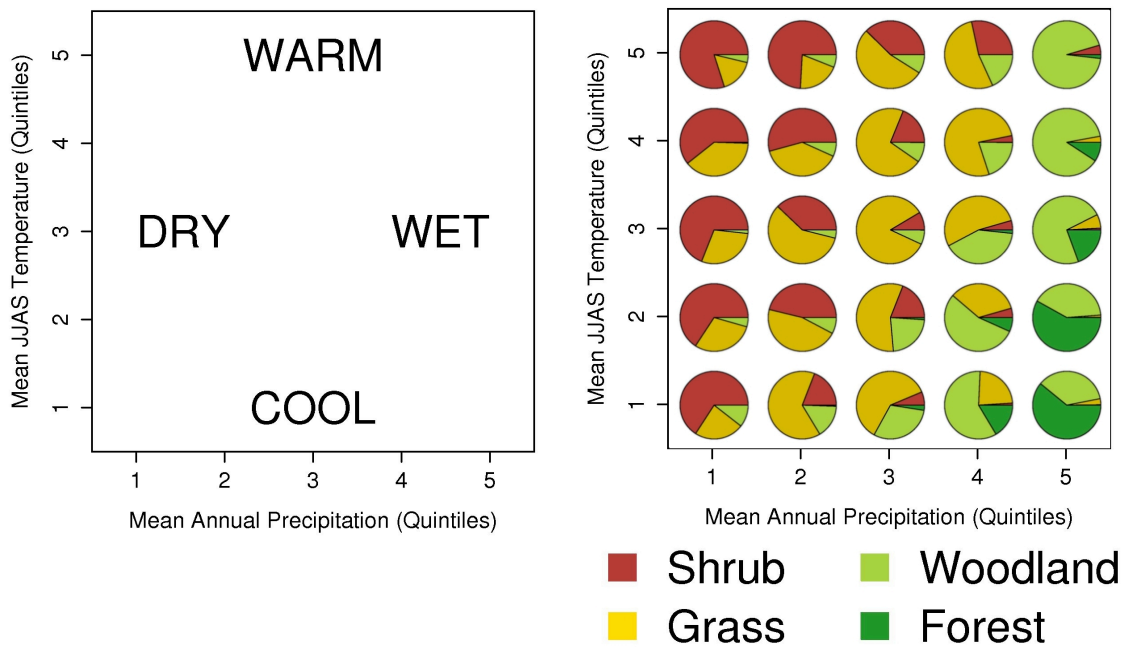The Climatology of Coarse Vegetation Types

Figure 2. Average vegetation fractions for Forest, Woodland, Shrubland and Grassland vegetation classifications are plotted for all the 1/8-degree grid cells in each quintile of annual precipitation and summer temperature for the contiguous western United States. Forests and Woodlands are concentrated in cooler and/or wetter locations, while Grasslands and Shrublands tend to be in drier, warmer climates. *Left:* Quintiles of summer Temperatue (y-axis) and annual Precipitation (x-axis) for the western U.S. *Right:* each pie chart shows the fractional vegetation coverage for lands corresponding to a pair of temperature and precipitation quintiles.

Interannual variability

Climate—primarily temperature and precipitation—influences the occurrence of large wildfires by affecting the availability and flammability of fuels. The relative importance of climatic influences on fuel availability versus flammability can vary greatly by ecosystem and

wildfire regime type. Fuel availability effects are most important in arid, sparsely vegetated

ecosystems, while flammability effects are most important in moist, densely vegetated

ecosystems.   The vegetation 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 and fire regime types is strongly correlated with long-term average
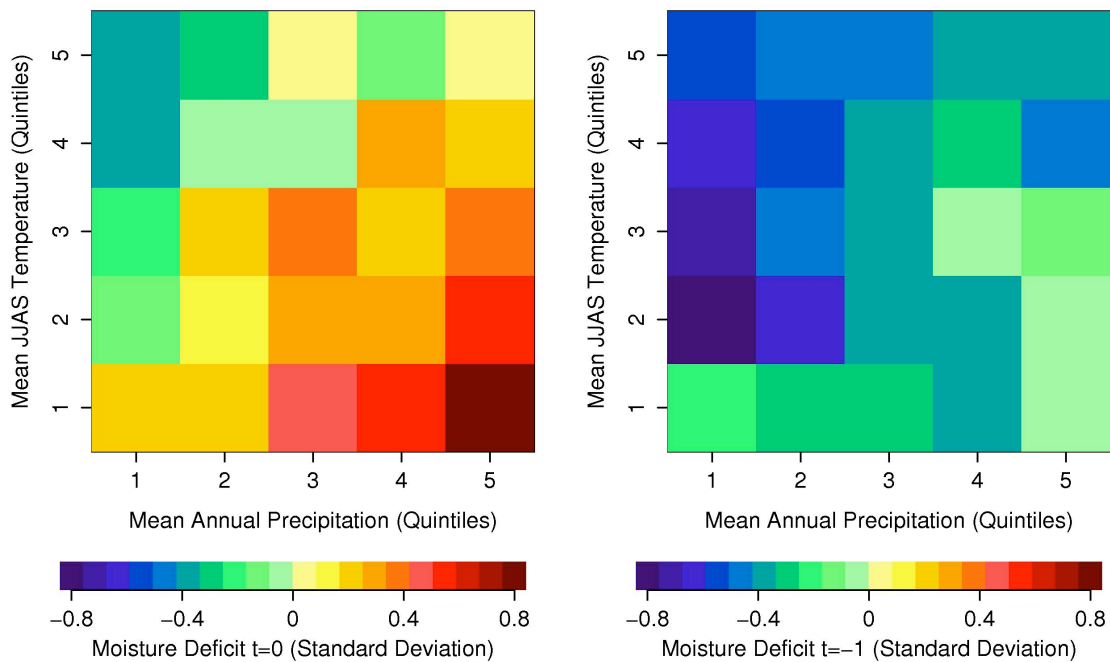
precipitation and temperature.

Figure 3. Deviations from average drought conditions for the year of fire discovery (left)
and one year prior (right) for over 8000 western US wildfires. Drought conditions are
represented by normalized cumulative water-year moisture deficits, averaged for fires in
locations whose long term average annual precipitation and long term average summer
temperature correspond to quintiles in western U.S. precipitation and summer
temperature. Normalized moisture deficits are shown in standard deviations from the
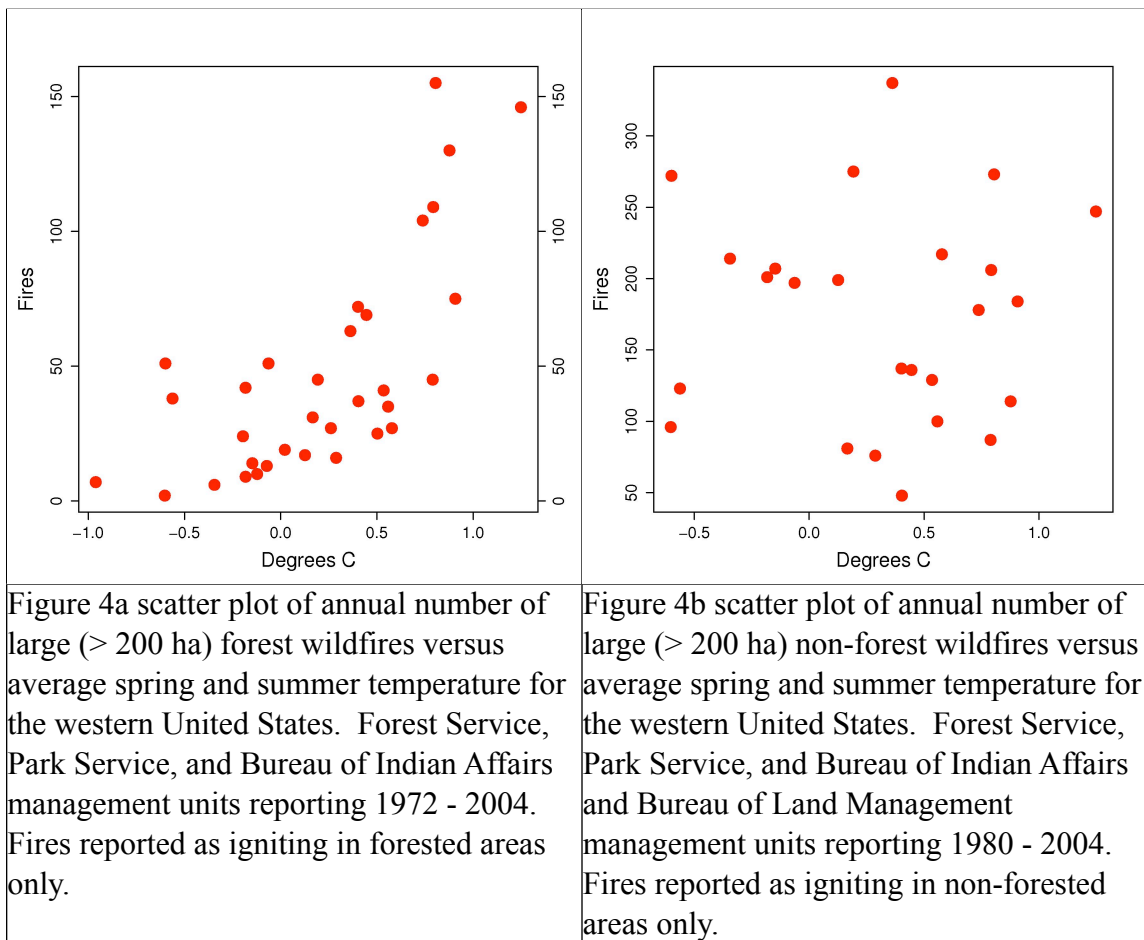mean.

The response of wildfire regimes is expected to be limited more by (1) fuel availability

as average moisture availability and biomass decrease; or (2) fuel flammability as average

moisture availability and biomass increase (e.g. Swetnam and Betancourt 1998, Veblen et al 2000, Westerling et al 2003, Gedalof, Peterson and Mantua 2005, Westerling et al 2006). These hypotheses make intuitive sense: the moist conditions that foster high biomass on average also tend to reduce fuel flammability, while the dry conditions that foster low average biomass imply high flammability in most years.

Western United States locations with the highest average moisture availability and biomass have the most fires when conditions are much drier than normal, consistent with the hypothesis that fuel flammability is the most important factor determining interannual variability in their fire risks. Conversely, fires in the hottest, driest locations comprised of shrubland vegetation tended to occur in relatively wet years. Wet winter conditions in these locations foster the growth of grasses and forbs that quickly cure out in the very hot summer dry season typical of these locations, providing a load of fine fuels that can foster the ignition and spread of large wildfires. Moisture deficits a year prior to wildfire occurrences also indicate wetter than normal conditions for a large part of the western United States, particularly for those areas with lower average annual precipitation that are primarily shrub and grassland. These patterns are both consistent with the availability of fine fuels as the limiting factor for wildfire risks in arid locations with less biomass.

An important consequence of this variability in wildfire regime response to climate is that 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. Above-average spring and summer temperatures in these forests have a dramatic impact on

wildfire, with a highly nonlinear increase in the number of large wildfires above a certain

temperature threshold. A recent study by Westerling et al. (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% of forest wildfires and 72% of area burned, as opposed to 11% of wildfires and 4%

of area burned occurring in years with a late spring).

Figure 4a 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.	Figure 4b scatter plot of annual number of large (> 200 ha) non-forest wildfires versus average spring and summer temperature for the western United States. Forest Service, Park Service, and Bureau of Indian Affairs and Bureau of Land Management management units reporting 1980 - 2004. Fires reported as igniting in non-forested areas only.

The number of large wildfires in western U.S. grass and shrublands is not significantly

correlated with average spring and summer temperatures. In the western United States these

types of vegetation tend to occur at lower elevations and latitudes, and consequently do not have

as much snowfall or snowpack, as do the forests of the Northern Rockies or forests at higher

elevations in the Sierra Nevada or Colorado Rocky Mountains. The incremental effect of

warmer temperatures on the duration and intensity of summer drought is less pronounced in

areas of the western U.S. with little or no snow on the ground for most of the year, and wildfire

in these vegetation types appears to be limited more by fuel availability than by flammability.

Given the importance of fuel availability, the moisture available during the growing season is an

important consideration, but it is probably less affected by spring and summer temperatures than
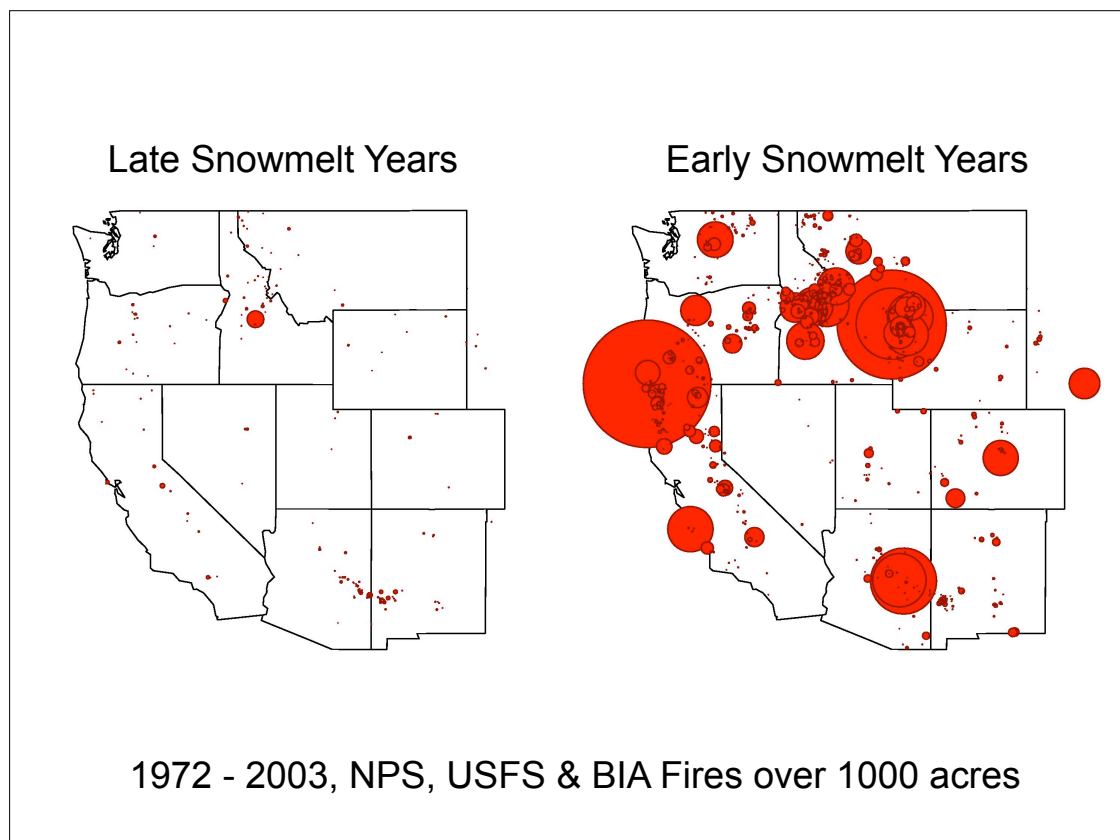
by variability in precipitation.

Figure 5: Forest Service, Park Service and Bureau of Indian Affairs large forest wildfires (>1000 acres) for the 1/3 of years with early (left) or late (right) spring snowmelt. *Westerling et al 2006.*
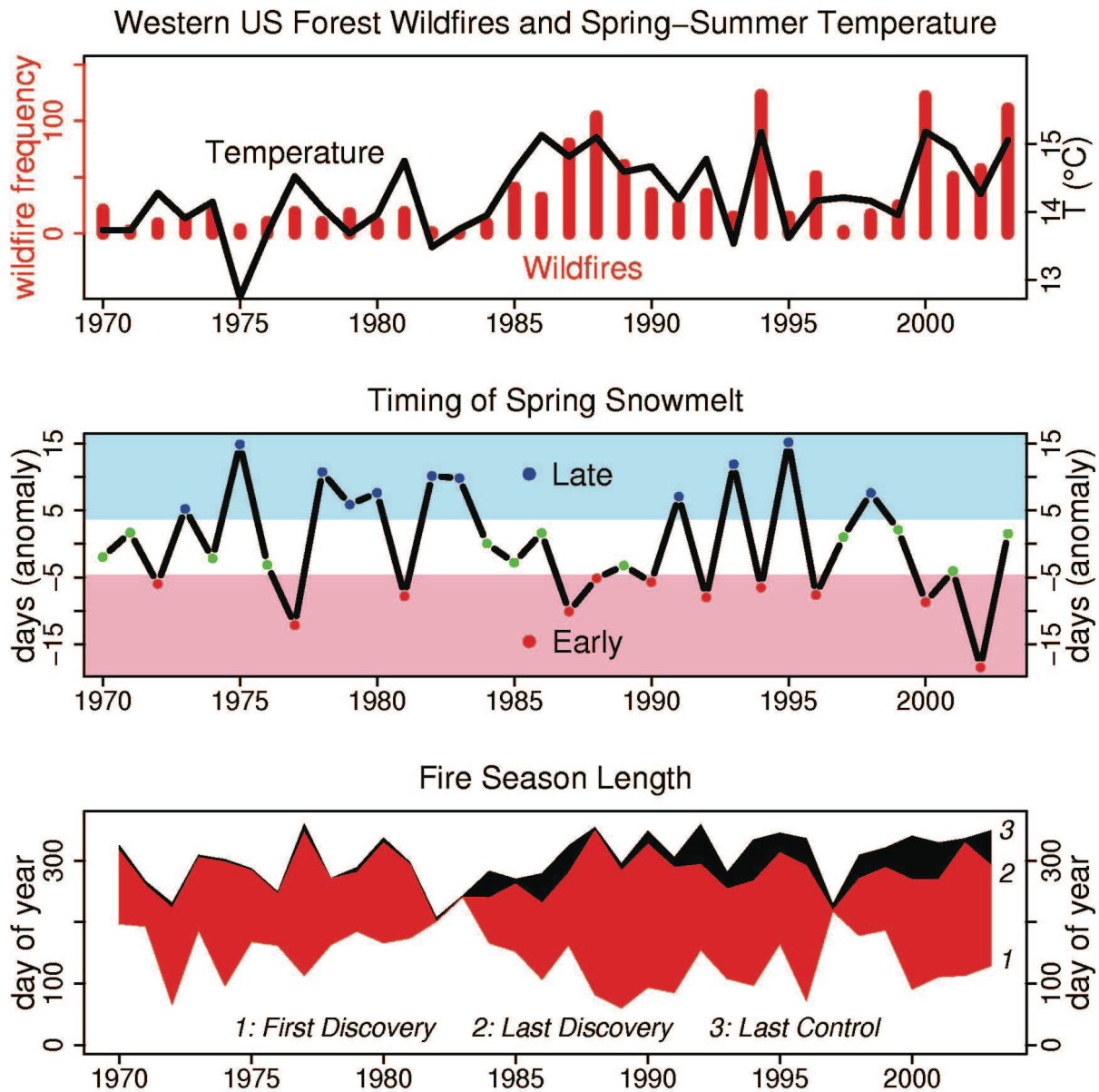
Figure 6: *(top)* Annual frequency of large (> 400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western US (line) *(26, 30)*. Spearman's rank correlation between the two series is 0.76 (p < 0.001). Wilcoxon test for change in mean large forest fire frequency after 1987 was highly significant (W = 42 (p < 0.001)). *(middle)* 1st principle component of center timing of streamflow in snowmelt dominated streams (line). Low (*pink shading*), middle (*no shading*) and high (*light blue shading*) tercile values indicate Early, Mid, and Late timing of spring snowmelt. *(bottom)* Annual time between first and last large fire ignition, and last large fire control.

Climate-driven Trends in Forest Wildfire

The incidence of large wildfires in western U.S. forests increased in the mid-1980s. Subsequently, forest wildfire frequency was nearly four times the average of 1970-1986, and total area burned by these fires was more than six and a half times its previous level (Westerling et al 2006). Interannual variability in forest wildfire frequency is strongly associated with regional spring and summer temperature (Spearman's correlation of 0.76, p<0.001, n=34). A 2nd-order polynomial fit to the regional temperature signal alone explains 66% of variance in the annual incidence of these fires, with many more wildfires burning in hotter than in cooler years.

The length of the wildfire season also increased in the 1980s. The average season-length (the time between the reported first wildfire discovery date and the last wildfire control date) increased by 78 days (64%), comparing 1970-86 to 1987-03. Roughly half that increase was due to earlier ignitions, and half to later control (48% versus 52%, respectively). While later control dates were no doubt partly due to later ignition dates, with the date of the last reported wildfire ignition increasing by 15 days, a substantial increase in the length of time the average wildfire burned also played a role. The average time between discovery and control for a wildfire increased from 7.5 days in 1970-86 to 37.1 days in 1987-2003. The annual length of the fire season, and the average time each fire burned, were also moderately correlated with the regional spring and summer temperature (Spearman's correlations of 0.61 and 0.55, (p<0.001 and p<0.001), respectively).

The greatest increase in wildfire frequency has been in the Northern Rockies, which accounts for 60% of the increase in large fires. Much of the remaining increase (18%) occurred in the

Sierra Nevada, southern Cascades, and Coast Ranges of northern California and southern Oregon. The Pacific Southwest, the Southern Rockies, the Northwest, coastal central and southern California, and the Black Hills each account for 11%, 5%, 5%, <1%, and <1%, respectively. Interestingly, the Northern Rockies and the Southwest show the same trend in wildfire frequency relative to their respective forested areas. However, the Southwest's absolute contribution to the western regional total is limited by it's smaller forested area relative to higher latitudes.

Increased wildfire frequency since the mid-1980s has been concentrated between 1,680m and 2,690m in elevation, with the greatest increase centered around 2,130m. Wildfire activity at these elevations has been episodic, coming in pulses during warm years, with relatively little activity in cool years, and is strongly associated with changes in Spring snowmelt timing, which in turn is sensitive to changes in temperature.

Implications for Climate Change

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 also 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.

Climate change will result in higher temperatures and more frequent and intense drought. In forests where wildfire is very sensitive to variations in temperature, the result is a likely increase in the frequency of very active fire seasons and in the number of large wildfires.

Associated with warmer temperatures in recent years, there have been substantial increases documented in the frequency of large wildfires in the boreal forests of Canada, Alaska, and Siberia (Gillett et al 2004, Soja et al 2007), as well as in forests of the western United States--particularly in mid-elevation forests of the Northern Rocky Mountains (Westerling et al 2006).

Changes in precipitation, combined with increased temperatures, may have very different effects on wildfire in different ecosystems. In tropical forests for example, decreased precipitation will likely result in increased wildfire. 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. In both cases, any increases in precipitation might be counterbalanced to some extent by increased evaporative demand from higher temperatures.

The overall direction and spatial pattern of precipitation changes varies considerably across both future greenhouse gas emissions scenarios and global climate models. 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.

Policy Implications

Climate scenarios (even with rapid reductions in global greenhouse gas emissions) project increases in temperature substantially greater than those observed in recent decades, which have been associated with substantial increases in wildfire activity in some ecosystems. Strategies for adapting to a warmer world will therefore need to consider the impacts of climate change on wildfire.

Currently, strategies for managing wildfire risks fall into three general categories: fire suppression, fire prevention, and development policies in descending order of prominence. As means to adapting to a warmer climate, however, their priority may need to be reversed. Development policies and fuels management show more promise than intensified fire suppression for reducing some of the economic impacts of increased wildfire risks.

Suppression involves actively extinguishing wildfires. Prevention measures seek to reduce the number 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 sprawling 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).

Developed countries devote considerable resources to suppressing wildfires, and the technologies employed have increased in sophistication over the last century. However, fire suppression technologies are least effective under climatic conditions that foster the rapid spread of wildfires. Absent revolutionary technological developments, it seems unlikely that additional investment in fire suppression will significantly reduce future wildfire risks in a warmer world. Furthermore, the ecological consequences of this kind of intervention might turn out to have their own undesirable consequences. Reducing wildfire 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). Conversely, if wildfires could be effectively suppressed, this might be a desirable course of action in naturally dense forest ecosystems where very long return times between wildfires 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 may not actually reduce wildfire risks. In the Amazon Basin, for example, thinning and clearing forests makes the remaining vegetation drier, and increases the risk of wildfire and of forest conversion.

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. 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, development strategies hold out the greatest promise to reduce the economic impact of wildfires in a changed climate. However, they have only limited applicability to preserving ecosystem and resource values.

Seasonal Forecasting

Wildland managers have long desired to know the risks of severe fire events in advance of their occurrence. A number of actions are available to improve the efficiency of wildfire suppression efforts during severe fire seasons, including reallocating resources from other activities to fire suppression, reallocating suppression resources from low-risk to high-risk regions, public education campaigns to reduce ignitions, curtailment of fire use for vegetation management, and changing the number and timing of temporary hires. Because the annual expenditure on wildfire suppression is so high—averaging more than $1.3 billion/year for federal land management agencies since the year 2000 after adjusting for inflation—even marginal improvements in suppression efficiency have the potential to save significant sums of money through either reduced suppression costs or reduced losses due to wildfire. However, contingency actions have associated costs and timeliness issues. For example, temporary hires for fire suppression require training before they can be put to work suppressing wildland fires, but may be retained for only a limited time period (six months). Hiring them too early or too late incurs the risk that they will not be available when they are most needed. Another need for fire danger forecasting is for planning prescribed fires. Making effective decisions in light of these issues requires information about the likelihood of large fire events.

Managers relay on a variety of fire danger indicators to make their forecasts of likelihoods of large fire events at various lead times. For example, the NFDR system (Bradshaw et al. 1984) produces fire danger maps for one-day-ahead forecasts. Seasonal (three to six month ahead) fire risk forecast maps are produced by the MAPPS team. Fire danger indicators are useful for describing burning conditions at a particular location and time. However, their utility may be enhanced if their relationship with actual fire occurrence and spread is quantified. Specifically, a useful tool to managers will be a system whereby it is possible to forecast probability of a large fire event given a particular value of a fire danger index or a list of values of various fire danger predictors.

Correlations between patterns of observed antecedent climatic anomalies and subsequent fire occurrence provide a basis for predicting fire season severity, as measured by the frequency of large fires or the level of the total burned area in a region. Several climatic factors with apparent demonstrated effects on wildfire occurrence and size can be used as predictors for wildfire, depending on the desired lead time of the forecast and the availability of climate observations or forecasts.

Numerous authors have reported relationships between wildfire and moisture anomalies concurrent with and antecedent to the fire season (see, e.g., Balling et al 1992, Swetnam and Betancourt 1998, Kipfmueller and Swetnam 2000, Veblen et al 2000, Donnegan et al 2001, Heyerdahl et al. 2001, Westerling et al 2003b). Swetnam and Betancourt (1990, 1998) and Westerling and Swetnam (2003) discuss the use of indices of Pacific sea surface temperatures (El Nino/Southern Oscillation and Pacific Decadal Oscillation) as predictors for wildfire activity.

Westerling et al. (2002, 2003a & b) demonstrate the utility of the Palmer Drought Severity Index (PDSI) in forecasting wildfire area burned for wildfires in a variety of vegetation types, and Westerling et al (2005, 2006a & b) have examined the relationship between temperature, seasonal temperature forecasts and forest wildfire.

Westerling et al (2002, 2003, 2004) demonstrate regional seasonal forecasts for the western U.S. of wildfire area burned using drought indices observed prior to the fire season, as well as drought indices combined with North Pacific sea surface temperatures (Westerling *in press*). Preisler and Westerling (2007) demonstrate forecasts of the probability large fires occurring on a 1-degree grid over the western United States at one-month lead times using nonlinear, non-parametric logistic regressions driven by observed drought indices, temperature, and North Pacific sea surface temperature indices. Preisler et al (in press) use the same methodology to assess the skill of various fire weather forecasts to predict large wildfire occurrence, using the Fire Weather Index and National Fire Danger Rating System (NFDRS) indices deduced from RSM 50-km 1-day simulations from the Experimental Climate Prediction Center (ECPC) at Scripps Institution of Oceanography.

August 1995 observed
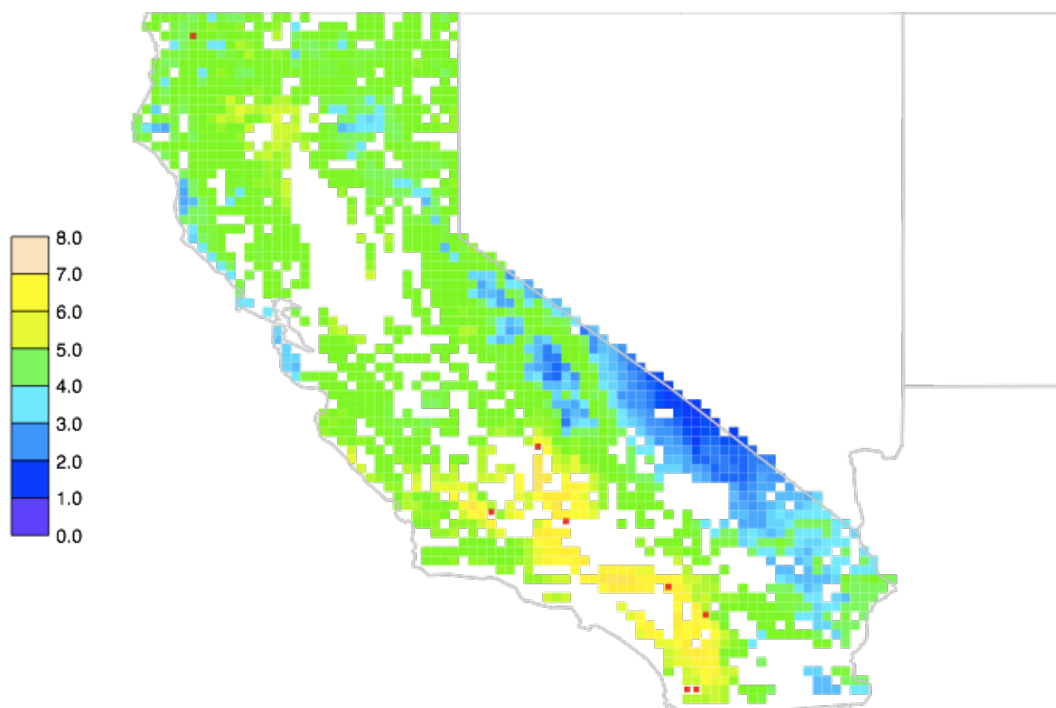
Map of Probabilities (%) of > 200ha burn areas
Red dots are observed pixels with >200ha burns

Figure 7: Example of seasonal fire forecast product for California, showing forecast probabilities of large wildfire occurrence (shading) and observed wildfire incidence (points). Transitioning experimental seasonal wildfire forecasts to an operational product for state and federal land managers is an ongoing effort supported by the California Applications Program (Scripps Institution of Oceanography), the Climate Impacts Group (University of Washington), the Climate Assessment for the Southwest (University of Arizona) and the Pacific Southwest Research Station (U.S. Forest Service). This forecast system makes forecasts of monthly large fire incidence for May - October, starting in April with monthly updates through the fire season.

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