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Chapter 12: Climate Change Impacts on Wildfire

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Introduction

There is a perception that large and severe wildfires have increased in many parts of the world in recent decades, and these increases are often attributed to anthropogenic climate change. Actually documenting increases in large wildfire frequency in many parts of the world is, however, very difficult. This is because, on the one hand, the incidence of wildfire naturally varies greatly on interannual to decadal timescales, necessitating a long record in order to detect significant trends in wildfire activity. On the other hand, long records that document wildfire activity are often not readily available. Where they are available, they tend to be affected by several problems. Older records are less comprehensive than recent records, meaning fires can appear to be increasing merely because of improved reporting. Changes in strategies and resources for managing wildfires over time may also affect apparent trends in wildfire as the comprehensiveness and effectiveness of suppression varies. Changes in population and land use can have immediate and dramatic effects on the number and sources of ignitions and on the availability and flammability of fuels. Over the long term, fire management and land uses that suppress surface fires can lead to changes in the density and structure of the vegetation that fuels wildfires, changing the likelihood of a large or severe fire occurring.

Consequently, while there are good reasons to expect that climate change will lead to changes in wildfire, detecting a climate change signal in historical wildfire records is usually not possible.

While comprehensive long-term (i.e. century-scale) wildfire histories are often unavailable, we can still use the available records to infer the impact on wildfire of climate change scenarios. Where they can be compiled, accurate, comprehensive short-term documentary wildfire histories for recent decades analyzed in conjunction with climate and vegetation data provide insight into how wildfire responds to variations in climate.

Similarly, reconstructions of past wildfire from fire scars preserved in trees and from charcoal records from sedimentary cores, combined with reconstructions of past climate from tree rings, ice cores, corals and other natural recorders, can also give us insights into how wildfire responds to climate variability. Reconstructions can span long time periods, but usually can't give a clear indication of climate-related long-term trends through recent decades for a variety of reasons, including the effects of land use changes and fire suppression. However, from relationships observed between climate, vegetation and wildfire in recent documentary records and fire reconstructions, we can infer how wildfire in diverse locations will respond to a warmer climate.

Climate—primarily temperature and precipitation—influences the occurrence of large wildfires on multiple time scales through its effects on the availability and flammability of fuels. On seasonal to decadal time scales, climatic averages and variability around those averages largely shape the type, amount, and structure of the live and dead vegetation that comprises the fuel available to burn in a given location

(Stephenson 1998). On seasonal to interannual time scales, climatic averages and variability determine the flammability of these fuels (Westerling et al 2003).

On interannual and shorter time scales, the relative importance of climatic influences on fuel availability versus flammability can vary greatly by ecosystem and wildfire regime type (Westerling et al 2003). Fuel availability effects are most important in arid, sparsely vegetated ecosystems, while flammability effects are most important in moist, densely vegetated ecosystems. Consequently, climate scenarios' changes in precipitation can have very different implications than do changes in temperature in terms of the characteristics and spatial location of wildfire regime responses.

While climate models across a range of plausible emissions scenarios generally agree that temperatures will increase over time, changes in precipitation under climate change tend to be much more uncertain. Consequently, future changes in wildfire regimes in ecosystems where wildfire risks are strongly affected by precipitation are more uncertain. Conversely, in ecosystems where wildfire risks are strongly driven by temperature, climate change is likely to lead to substantial increases in wildfire. Finally, as changes in climate lead to changes in the potential spatial distribution of vegetation types, vegetation and associated fire regimes will be transformed synergistically.

While policies to mitigate climate change could help to limit changes in fire regimes, some level of additional warming is going to occur regardless, requiring adaptation. Fire suppression, fuels management, and development policies (zoning and building codes) are the primary means by which wildfire risks are managed, in descending order of prominence. As means to adapting to a warmer climate, however, their priority may need to be reversed, with development policies and fuels management

showing more promise than intensified fire suppression for reducing some of the economic impacts of increased forest fire risks.

The first section of this chapter uses fire histories and climate records for the western United States to demonstrate some important climate-vegetation-wildfire interactions. Projecting how a warming climate will change wildfire requires an understanding of the climatic controls on both wildfire and the vegetation in which it burns; these will change synergistically as the climate changes. We use western US ecosystems here as examples of climate-vegetation-wildfire interactions, but acknowledge that these ecosystems do not span the full range of possibilities globally. However, they serve to illustrate how climate affects wildfire through its effects on vegetation, and in the second section we extrapolate these relations to some important ecosystems outside the region with a brief review of some recent literature on climate-wildfire relationships in boreal forests of Canada, Alaska and Siberia, and tropical forests in the Amazon. Section three discusses implications of these climate-vegetation-wildfire interactions for plausible climate change scenarios. Section four concludes with a summary of policy implications.

Climate-Vegetation-Wildfire Interactions in western North America

The type of 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 types is strongly correlated with

long-term average precipitation and temperature.

For a western U.S. example, we consider four coarse vegetation types: Forests, Woodlands, Shrublands, and Grasslands (Figure 1).[1] Instead of representing the location of vegetation types spatially—by longitude and latitude (as in Figure 1)—we can instead plot them climatologically: by their long-term average annual precipitation and long-term average summer temperature (Figure 2). Forests are concentrated in parts of the western U.S. with the highest average annual precipitation and lowest average summer temperatures. Conversely, the highest fractions of shrubland cover are concentrated in locations with the least precipitation and warmest temperatures. In between these extremes there is a gradient from forest to woodland to grassland to shrubland cover types, with evident tradeoffs between temperature and precipitation. This is because higher temperatures produce higher evaporation, reducing the moisture available to plants.[2] Vegetation types that require large amounts of water are consequently sensitive to temperature as well as precipitation. Woodlands, for example, can occur at higher temperatures where precipitation is plentiful, but in regions where precipitation is more moderate, Woodlands tend to be more plentiful in locations with lower summer temperatures (Figure 2b).

The response of fire regimes in each location to interannual variability in climate varies in a manner consistent with a set of commonly employed hypotheses about the relative importance of fuel availability versus fuel flammability in diverse vegetation types. At their simplest, these hypotheses can be summarized as follows: (1) fuel availability becomes more of a limiting factor for wildfire activity as average moisture availability and biomass decrease; (2) fuel flammability becomes more of a limiting

factor as average moisture availability and biomass increase.[3] 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.

For our western U.S example, we show an index of drought conditions ("moisture deficit") for large wildfires (i.e. fires greater than 200 ha in burned area) during the season they burned (Figure 3a) and one year prior (Figure 3b), again plotting them by their long-term average annual precipitation and long-term average summer temperature.[4] Average moisture deficits at the time of discovery for large wildfires are driest for cool, wet locations with mostly Forest and Woodland vegetation types (Figure 3a). That is, the locations with the highest average moisture availability and biomass have the most fires when conditions are much drier than normal. This is consistent with the hypothesis that fuel flammability is the most important factor determining interannual variability in fire risks in these locations.

Conversely, moisture deficits were somewhat wetter than normal at the time of fire discovery for the warmest, driest locations that were mostly covered with Shrubland vegetation (Figure 3a).   This indicates that fires in the hottest, driest locations tended to occur in relatively wet years. Wet winter conditions in these locations fosters the growth of grasses and forbs that quickly cure out in the very hot summer dry season typical of these locations,[5] providing a load of fine fuels that could foster the ignition and spread of large fires. This pattern is consistent with the hypothesis that the availability of fine fuels is the limiting factor for fire risks in arid locations with less biomass.[6]

Moisture deficits a year prior to the fire (Figure 3b) indicate wetter than normal

conditions for a large part of the western US, particularly for those areas with lower

average annual precipitation that are primarily Shrub and Grassland. Again, the tendency

for fires to follow wet years is consistent with the idea that climate-driven variability in

the availability of fuels drives the risk of large wildfires in more arid, lower biomass

regions.[7] Note that the regions with the wettest conditions on average the year of the fire

(upper left corner of Figure 3a) do not show as strong a wet signal a year prior to the fire

as do regions that are somewhat cooler (upper left versus middle left of Figure 3b). This

may have to do with the effects of summer temperature on the time it takes for vegetation

to dry out sufficiently to burn. Fine fuels grown in very warm locations may be more

likely to burn the same year, while in cooler locations there may be more of a tradeoff

between moisture effects on availability and flammability, resulting in longer lags on

average between the growth, drying out, and burning of vegetation.

Notice also that the average change in moisture a year prior to fires in Forest areas

is negligible (Figure 3b), implying that moisture effects on fuel production are probably

not important on interannual time scales in these locations. The greater biomass available

in these Forest areas (where canopy cover is greater than 60%) means the incremental

effect on fuel load of one years' growth is negligible.

To summarize the discussion thus far, the climatic controls (temperature and

precipitation) on vegetation type (Forest, Woodland, etc.) 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 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 have greater biomass, and fires there

tend to occur in dry years. Warmer, drier areas tend to have less biomass and fires there tend to occur after one or more wet years.

One important consequence, from a global change perspective, of this variability in fire regime response to climate is that wildfire is much more sensitive to variability in temperature in some locations than in others. In the western US, cool, wet, forested locations tend to be at higher elevations and latitudes (Figure 1a) where snow can play an important role in determining summer moisture availability.[8] 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 (Figure 4a). A recent study by Westerling et. al. concluded that this increase is due to earlier Spring snowmelt and a longer Summer dry season in warm years.[9] They found that years with early arrival of Spring account for most of the forest wildfires in the western US (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). This effect of the timing of spring was particularly pronounced in the higher-latitude mid-elevation (1680-2590 m) forests of the U.S. Northern Rocky Mountains,[10] which accounted for 60% of the increase in forest wildfires in the western US since the 1970s and early 1980s. Higher elevation forests in the same general region have been buffered against these effects to some extent by available moisture, while lower elevations have a longer summer dry season on average and are consequently less sensitive to changes in the timing of spring.

Conversely, the number of large wildfires in western US grass and shrublands is not significantly correlated with average Spring and Summer temperatures (Figure 4b).

In the western US these types of vegetation tend to occur at lower elevations and latitudes, and consequently do not have as much snow, nor snow on the ground for as long, 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 with little or no snow on the ground for most of the year, and as we discuss above, 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.

Climate, Vegetation and Wildfire Interactions Outside the Western US

While the examples presented above are derived for the western United States, the climate-vegetation-wildfire linkages they describe are not unique to the region. Climatic influences on wildfire risks everywhere involve tradeoffs between fuel availability and fuel flammability, with characteristics of a locale's vegetation and climate determining the relative importance of availability versus flammability at different time scales. Here we briefly discuss some additional examples from literature on wildfire in boreal forests and tropical forests.

Wildfire in the Boreal forests of Canada is associated with warm temperature anomalies and dry conditions caused by persistent high-pressure systems in the upper atmosphere.[11] Not unlike the Northern Rockies, the Canadian Boreal forests are another example of a flammability-limited, high biomass fire regime, where drought and warm temperatures increase the risk of large wildfires, but antecedent moisture does not have a

significant impact on fuel availability on interannual and shorter time scales. Impacts of earlier spring snowmelt on wildfire in the Canadian Boreal forests have not been documented.

Goldammer and Price (1998) note that temperature is "not necessarily a critical factor influencing forest and savanna fire regimes in the tropical environment, which is characterized by high daytime temperatures anyway." Recent very active fire years with large forest fires in tropical Southeast Asia, Mexico and the Amazon Basin have been associated with El Nino conditions in the Pacific Ocean, which brought reduced precipitation in all three regions.[12] Like the boreal forest and the mountain forests of the western U.S., fuel flammability is an important factor for fire risks in these tropical forests. Unlike in the higher latitudes, however, temperature anomalies are not as important. While reduced precipitation can play a role in promoting fire risks in boreal, tropical, and western U.S. mountain forests, it's effects are probably most immediate in tropical forests due to their higher temperatures.

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 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 boreal forests of Canada, Alaska, and Siberia,[13] as well as in mid-elevation forests of the western U.S. Northern Rocky Mountains,[14] associated with warmer temperatures there in recent years.

Changes in precipitation, combined with increased temperatures, may have very different effects on wildfire in different ecosystems. In tropical forests for example, decreased precipitation would likely result in increased wildfire.[15] Conversely, higher temperatures and decreased precipitation could result in decreased wildfire activity in some dry, fuel-limited fire regimes, as the reduced moisture available to support the growth of fine fuels leads to less biomass and less continuous fuel coverage.[16] 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 changes in precipitation under diverse climate change scenarios varies considerably across simulations and GCMs.[17] 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.[18]

Policy Implications

Effective policies for climate change mitigation are urgently needed at the local, national and international level, and would help to limit the extent and speed of changes in vegetation and wildfire. However, even climate scenarios with rapid reductions in global greenhouse gas emissions project increases in temperature substantially greater

than those observed in recent decades[19] that have been associated with substantial increases in wildfire activity in some ecosystems.[20] Strategies for adapting to a warmer world will need to consider the impacts of climate change on wildfire.

Currently, the primary strategies for managing wildfire risks fall into three general categories: fire suppression, fire prevention, and fireproofing. Suppression involves the active extinguishing of 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). Fireproofing refers to 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, etc.).

Developed countries devote considerable resources to suppressing wildfires, and the technologies employed have developed in sophistication over the last century. However, fire suppression technologies are still not effective under climatic conditions that foster the rapid spread of wildfires. Absent revolutionary technological developments, how likely is it that additional investment in fire suppression will reduce future fire risks in a warmer world? Furthermore, supposing that new technologies to suppress wildfires more effectively could be employed, the ecological consequences of this kind of intervention might turn out to have their own undesirable consequences, reducing fire activity in the short run but increasing risks long term by contributing to the

build up of fuels in otherwise fuel-limited fire 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) over the course of the 20th Century.[21] Conversely, if fires could be effectively suppressed, this might be a desirable course of action in 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, and reducing the severity of wildfires in locations where forests have accumulated biomass due to fire suppression and land use. Thinning forests that are naturally densely vegetated may not actually reduce wildfire risks however. 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.[22]

Fireproofing strategies 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, proofing) have been emphasized to varying degrees around the world. In places like the western US where there is a substantial and rapidly

growing wildland-urban interface in fire prone areas, fireproofing strategies hold out the greatest promise to reduce the economic impact of wildfires in a changed climate, but 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 fuel flammability is the limiting factor in determining fire risks, anthropogenic increases in temperature will lead to more 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 fire 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, increasing for the immediate future 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 now taken 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, societies will need to adapt.

Given that the time frame for climate change extends decades and centuries into the future, it is feasible to consider development strategies that reduce societies' economic vulnerability to wildfire. By putting fewer structures in places where fire risks are high and increasing, and by taking measures to increase the ability of structures to resist fire, capital losses to wildfire can be reduced.

[1] We use the Land Data Assimilation System (LDAS) 1/8 degree gridded vegetation layer using the University of Maryland vegetation classification scheme with fractional vegetation adjustment ("UMDvf") (see Mitchell et al 2004). Four coarse vegetation types were derived from the UMDvf classifications: Forest (Evergreen, Deciduous and Mixed cover types), Woodland (Woodland and Wooded Grass/Shrubland cover types), Shrubland (Closed and Open Shrubland cover types), and Grassland (Grassland cover type) (Figure 1 shows the fraction of vegetated area in each 1/8-degree grid cell composed of these vegetation types) (Mitchell et al 2004).

[2] Stephenson 1998

[3] see e.g. Swetnam and Betancourt 1998, Veblen et al 2000, Westerling et al 2003, Westerling et al 2006.

[4] The index of drought conditions used here is defined as the average, normalized, cumulative water-year moisture deficit. Moisture deficit is the difference between the moisture that could evaporate from soils and vegetation based on the observed temperature (Potential Evapotranspiration) and the actual evaporation constrained by the available moisture (Actual Evapotranspiration). It is a more reliable indicator of drought stress in plants than many other hydrologic measures, and neatly incorporates the tradeoffs between temperature and precipitation that determine the moisture available to plants (see Stephenson 1998).

We use cumulative water-year (October through September) moisture deficits here to represent the cumulative drought stress on vegetation during the fire season, which is usually in the summer in this region. For much of the western US, most precipitation occurs in fall, winter and spring, rather than the summer, so the water year starting in October is used to capture the effect of variations in the years' water supply. By normalizing the moisture deficit, we get a measure of the deviation from average conditions that can be compared across locations.

[5] Osmond et al 1990

[6] A complicating factor is that in locations with an active summer monsoon, fires are ignited by dry lightning in the early summer and extinguished by monsoon rains later in the season. Greater fire activity can be associated with more lighting strikes, which in turn may be associated with subsequent precipitation. In this case, moist conditions could also indicate fires associated with an active summer monsoon rather than with just a wet winter immediately preceding the fire season.

[7] In this case, associations between lightning ignitions and precipitation do not play a role because of the long lag time (one year) between the above-average moisture and the occurrence of a large fire.

[8] Sheffield et al 2004

[9] Westerling et al 2006

[10] "Northern" from a U.S. – centric viewpoint of course. The Canadian Rockies lie further to the north.

[11] see Girardin et al in press for a summary citing Newark 1975, Johnson and Wowchuk 1993, Bessie and Johnson 1995, Skinner et al 1999 and 2002; see also Flannigan and Harrington 1988.

[12] Roman-Cuesta, Gracia and Retana 2002, Schimel and Baker 2002, Nepstad et al 2004.

[13] Gillett et al 2004, Soja et al 2007

[14] Westerling et al 2006

[15] Goldammer and Price 1998

[16] Westerling and Bryant 2007

[17] e.g. Dettinger 2006

[18] Westerling and Bryant 2007

[19] Fourth Assessment

[20] Gillett et al 2004, Westerling et al 2006, Soja et al 2007

[21] C. D. Allen *et al*., *Ecol. Appl.* **12,** 1418 (2002).

[22] W.F. Laurance, et al (2002), Cochrane 2003 Nature 421:913-919.

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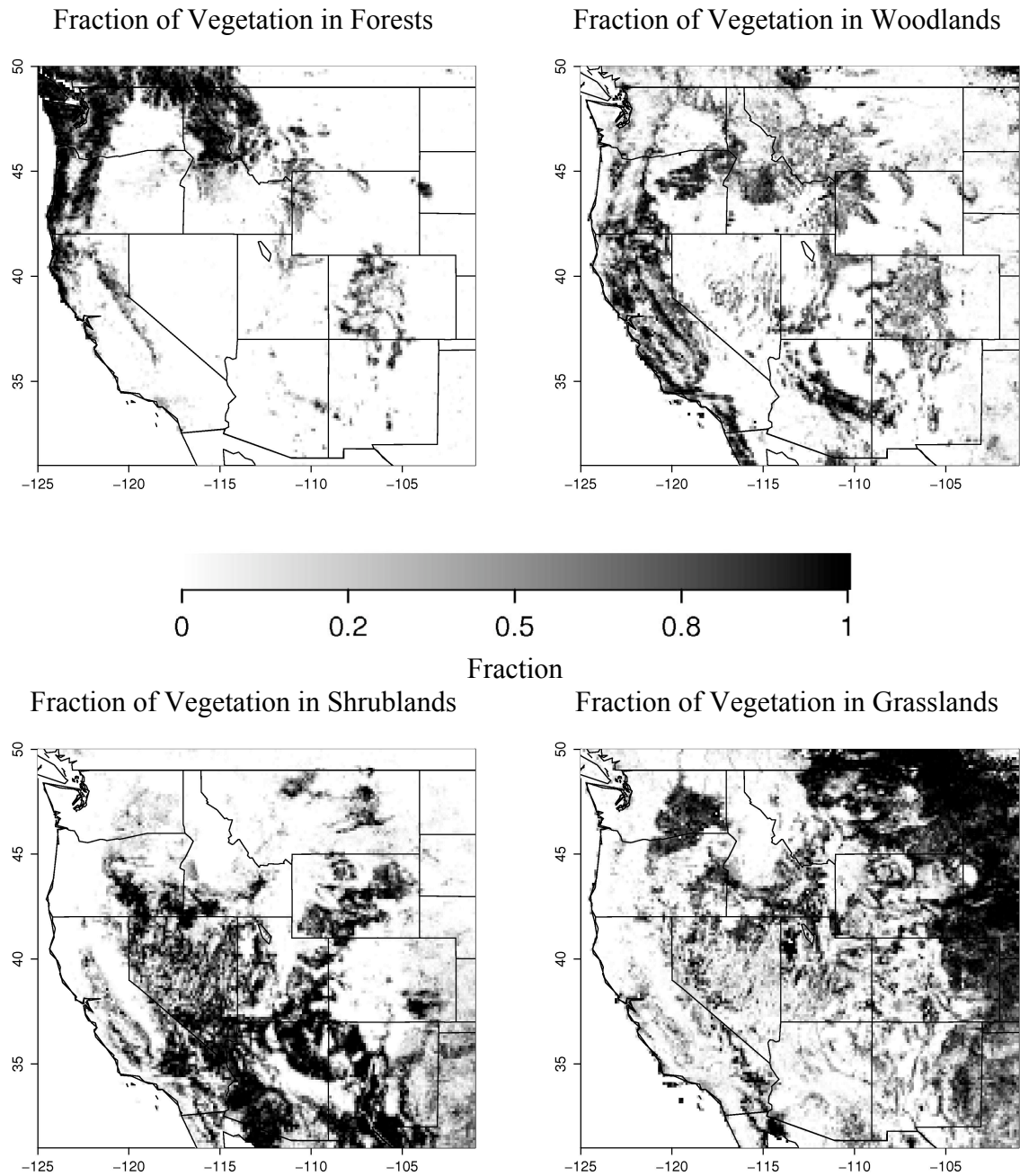
Figure 1. Fraction of vegetated area in the western U.S. covered with each of four vegetation types on a 1/8-degree grid, using University of Maryland vegetation classifications with fractional vegetation adjustment, from the North American Land Data Assimilation System. Upper left: Forest (Evergreen, Deciduous and Mixed cover types),. Upper right: Woodland (Woodland and Wooded Grass/Shrubland cover types). Lower left: Shrubland (Closed and Open Shrubland cover types). Lower right: Grassland (Grassland cover type). (Mitchell et al 2004)

The Climatology of Coarse Vegetation Types
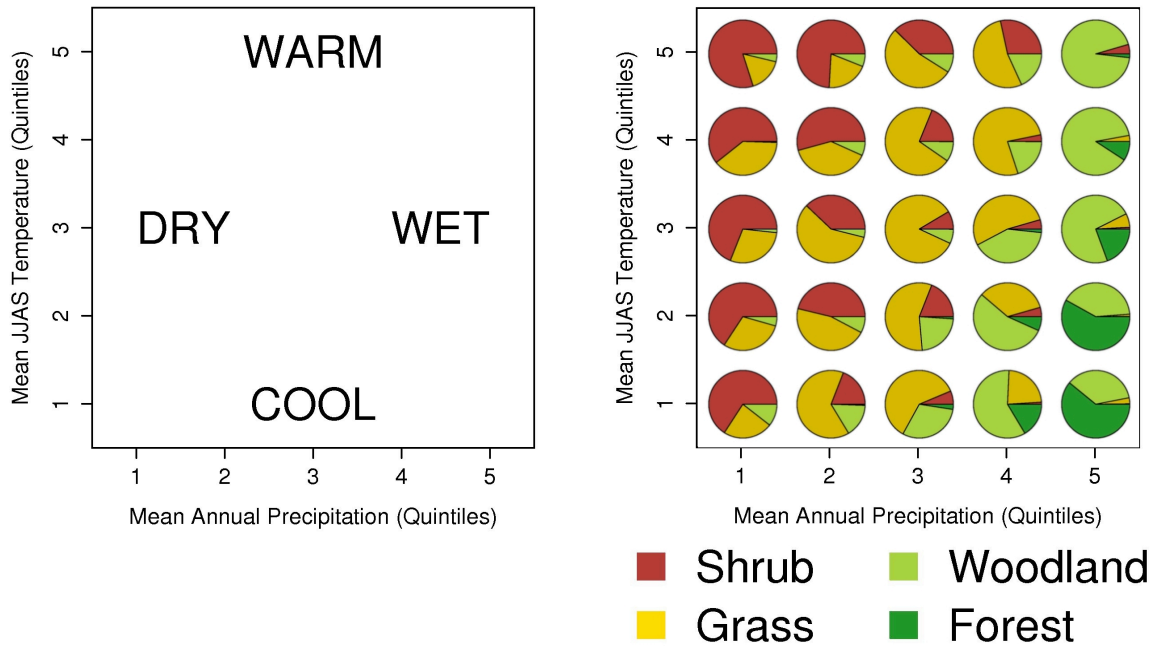
Figure 2. Average vegetation fractions for Forest, Woodland, Shrubland and Grassland vegetation classifications are plotted for all the 1/8-degree grid cells in each quintile of annual precipitation and summer temperature for the contiguous western United States. Forests and Woodlands are concentrated 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.
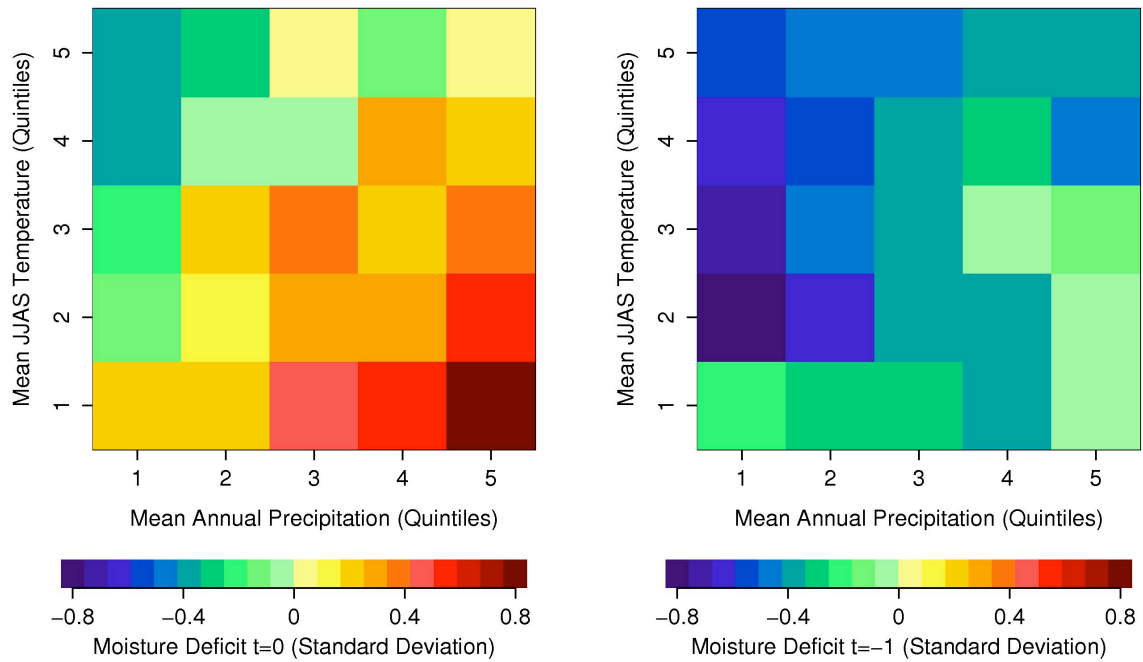
Figure 3. Deviations from average drought conditions for the year of fire discovery (left) and one year prior (right) for over 8000 western US wildfires. Drought conditions are represented by normalized cumulative water-year moisture deficits, averaged for fires in locations whose long term average annual 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.
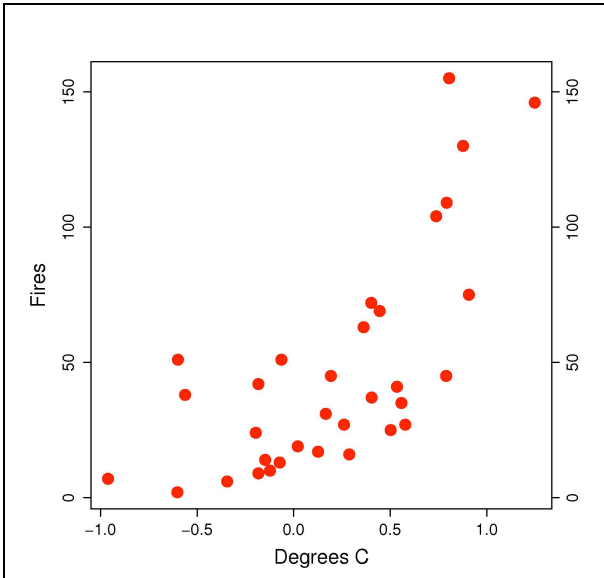
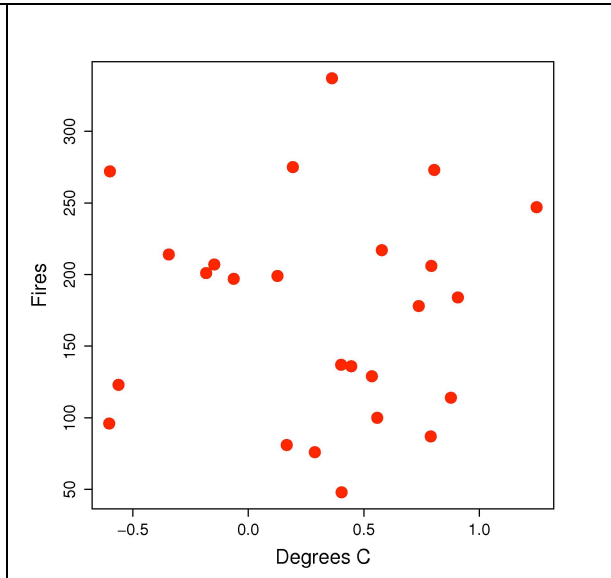| Figure 4a scatter plot of annual number of large (> 200 ha) forest wildfires versus average spring and summer temperature for the western United States. Forest Service, Park Service, and Bureau of Indian Affairs management units reporting 1972 - 2004. Fires reported as igniting in forested areas only. | 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. |