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Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity

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Western United States forest wildfire activity is widely thought to have increased in recent decades, yet neither the extent of recent changes nor the degree to which climate may be driving regional changes in wildfire has been systematically documented. Much of the public and scientific discussion of changes in western United States wildfire has focused instead on the effects of 19th- and 20th-century land-use history. We compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it with hydroclimatic and land-surface data. Here, we show that large wildfire activity increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

Wildfires have consumed increasing areas of western U.S. forests in recent years, and fire-fighting expenditures by federal land-management agencies now regularly exceed US$1 billion/year (*1*). Hundreds of homes are burned annually by wildfires, and damages to natural resources are sometimes extreme and irreversible. Media reports of recent, very large wildfires (>100,000 ha) burning in western forests have garnered widespread public attention, and a recurrent perception of crisis has galvanized legislative and administrative action (*1*–*3*).

Extensive discussions within the fire-management and scientific communities and the media seek to explain these phenomena, focusing on either land-use history or climate as primary causes. If increased wildfire risks are driven primarily by land-use history, then ecological restoration and fuels management are potential solutions. However, if increased risks are largely due to changes in climate during recent decades, then restoration and fuels treatments may be relatively ineffective in reversing current wildfire trends (*4*, *5*). We investigated 34 years of western U.S. (hereafter, "western") wildfire history together with hydroclimatic data to determine where the largest increases in wildfire have occurred and to evaluate how recent climatic trends may have been important causal factors.

Competing explanations: Climate versus management. Land-use explanations for increased western wildfire note that extensive livestock grazing and increasingly effective fire suppression began in the late 19th and early 20th centuries, reducing the frequency of large surface fires (*6*–*8*). Forest regrowth after extensive logging beginning in the late 19th century, combined with an absence of extensive fires, promoted forest structure changes and biomass accumulation, which now reduce the effectiveness of fire suppression and increase the size of wildfires and total area burned (*3*, *5*, *9*). The effects of land-use history on forest structure and biomass accumulation are, however, highly dependent upon the "natural fire regime" for any particular forest type. For example, the effects of fire exclusion are thought to be profound in forests that previously sustained frequent, low-intensity surface fires [such as Southwestern ponderosa pine and Sierra Nevada mixed conifer (*2*, *3*, *10*, *11*)], but of little or no consequence in forests that previously sustained only very infrequent, high-severity crown fires (such as Northern Rockies lodgepole pine or spruce-fir (*1*, *5*, *12*)].

In contrast, climatic explanations posit that increasing variability in moisture conditions (wet/dry oscillations promoting biomass growth, then burning), and/or a trend of increasing drought frequency, and/or warming temperatures have led to increased wildfire activity (*13*, *14*). Documentary records and proxy reconstructions (primarily from tree rings) of fire history and climate provide evidence that western forest wildfire risks are strongly positively associated with drought concurrent with the summer fire season and (particularly in ponderosa pine–dominant forests) positively associated to a lesser extent with moist conditions in antecedent years (*13*–*18*). Variability in western climate related to the Pacific Decadal Oscillation and intense El Niño/La Niña events in recent decades along with severe droughts in 2000 and 2002 may have promoted greater forest wildfire risks in areas such as the Southwest, where precipitation anomalies are significantly influenced by patterns in Pacific sea surface temperature (*19*–*22*). Although corresponding decadal-scale variations and trends in climate and wildfire have been identified in paleo studies, there is a paucity of evidence for such associations in the 20th century.

We describe land-use history versus climate as competing explanations, but they may be complementary in some ways. In some forest types, past land uses have probably increased the sensitivity of current forest wildfire regimes to climatic variability through effects on the quantity, arrangement, and continuity of fuels. Hence, an increased incidence of large, high-severity fires may be due to a combination of extreme droughts and overabundant fuels in some forests. Climate, however, may still be the primary driver of forest wildfire risks on interannual to decadal scales. On decadal scales, climatic means and variability shape the character of the vegetation [e.g., species populations and their drought tolerance (*23*) and biomass (fuel) continuity (*24*), thus also affecting fire regime responses to shorter term climate variability]. On interannual and shorter time scales, climate variability affects the flammability of live and dead forest vegetation (*13*–*19*, *25*).

High-quality time series are essential for evaluating wildfire risks, but for various reasons (*26*), previous works have not rigorously documented changes in large-wildfire frequency for

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western forests. Likewise, detailed fire-climate analyses for the region have not been conducted to evaluate what hydroclimatic variations may be associated with recent increased wildfire activity, and the spatial variations in these patterns.

We compiled a comprehensive time series of 1166 large (>400 ha) forest wildfires for 1970 to 2003 from federal land-management units containing 61% of western forested areas (and 80% above 1370 m) (*26*) (fig. S1). We compared these data with corresponding hydroclimatic and land surface variables (*26*–*34*) to address where and why the frequency of large forest wildfire has changed.

Increased forest wildfire activity. We found that the incidence of large wildfires in western forests increased in the mid-1980s (Fig. 1) [hereafter, "wildfires" refers to large-fire events (>400 ha) within forested areas only (*26*)]. Subsequently, wildfire frequency was nearly four times the average of 1970 to 1986, and the total area burned by these fires was more than six and a half times its previous level. Interannual variability in wildfire frequency is strongly associated with regional spring and summer temperature (Spearman's correlation of 0.76, $P < 0.001$, $n = 34$). A second-order polynomial fit to the regional temperature signal alone explains 66% of the 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 (Fig. 1). 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 to 1986 with 1987 to 2003. Roughly half of that increase was due to earlier ignitions, and half to later control (48% versus 52%, respectively). Later control dates were no doubt partly due to later ignition dates, given that the date of the last reported wildfire ignition increased by 15 days, but 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 from 1970 to 1986 to 37.1 days from 1987 to 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 ($P < 0.001$) and 0.55 ($P < 0.001$), respectively.

The greatest increase in wildfire frequency has been in the Northern Rockies, which account 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 ("Northern California," in fig. S2). 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 its smaller forested area relative to higher latitudes.

Increased wildfire frequency since the mid-1980s has been concentrated between 1680 and 2590 m in elevation, with the greatest increase centered around 2130 m. 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.

Fire activity and the timing of the spring snowmelt. As a proxy for the timing of the spring snowmelt, we used Stewart and colleagues' dates of the center of mass of annual flow (CT) for snowmelt-dominated streamflow gauge records in western North America (*32*–*34*). The annual wildfire frequency for the region is highly correlated (inversely) with CT at gauges across the U.S. Pacific Northwest and interior West, indicating a coherent regional signal of wildfire sensitivity to snowmelt timing (Fig. 2).

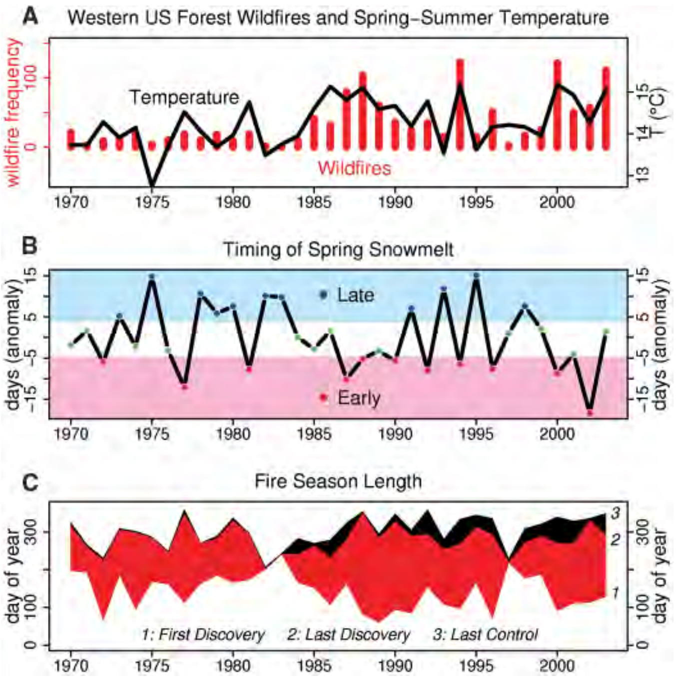

Fig. 1. (**A**) Annual frequency of large (>400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western United States (line) (*26*, *30*). Spearman's rank correlation between the two series is 0.76 ($P < 0.001$). Wilcoxon test for change in mean large–forest fire frequency after 1987 was significant ($W = 42$; $P < 0.001$). (**B**) First 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, respectively. (**C**) Annual time between first and last large-fire ignition, and last large-fire control.

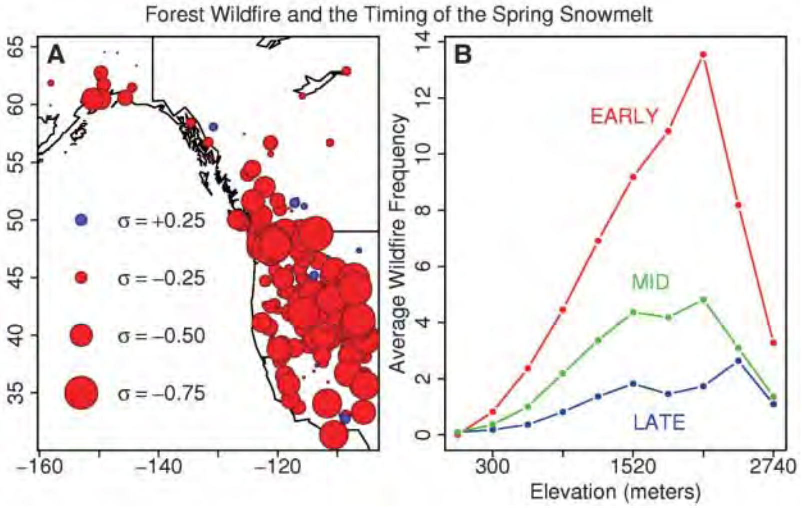

Fig. 2. (**A**) Pearson's rank correlation between annual western U.S. large (>400 ha) forest wildfire frequency and streamflow center timing. *x* axis, longitude; *y* axis, latitude. (**B**) Average frequency of western U.S. forest wildfire by elevation and early, mid-, and late snowmelt years from 1970 to 2002. See Fig. 1B for a definition of early, mid-, and late snowmelt years.

The negative sign of these correlations indicates that earlier snowmelt dates correspond to increased wildfire frequency. Following Stewart *et al*., we used the first principal component (CT1) of CT at western U.S. streamflow gauges as a regional proxy for interannual variability in the arrival of the spring snowmelt (Fig. 1) (*26*, *32*). This signal had its greatest impact on wildfire frequency between elevations of 1680 and 2590 m (Fig. 2), with a nonlinear response at these elevations to variability in snowmelt timing. Overall, 56% of wildfires and 72% of area burned in wildfires occurred in early (i.e., lower tercile CT1) snowmelt years, whereas only 11% of wildfires and 4% of area burned occurred in late (i.e., upper tercile CT1) snowmelt years.

Temperature affects summer drought, and thus flammability of live and dead fuels in forests through its effect on evapotranspiration and, at higher elevations, on snow. Additionally, warm spring and summer temperatures were strongly associated with reduced winter precipitation over much of the western United States (Fig. 3). The arrival of spring snowmelt in the mountains of the western United States, represented here by CT1, is strongly associated with spring temperature (*26*). Average spring and summer temperatures throughout the entire region are significantly higher in early than in late years (Fig. 3), peaking in April. The average difference between early and late April mean monthly temperatures in forested areas was just over 2°C, and it increased with elevation.

Snow carries over a substantial portion of the winter precipitation that falls in western mountains, releasing it more gradually in late spring and early summer, providing an important contribution to spring and summer soil moisture (*35*). An earlier snowmelt can lead to an earlier, longer dry season, providing greater opportunities for large fires due both to the longer period in which ignitions could potentially occur and to the greater drying of soils and vegetation. Consequently, it is not surprising that the incidence of wildfires is strongly associated with snowmelt timing.

Changes in spring and summer temperatures associated with an early spring snowmelt come in the context of a marked trend over the period of analysis. Regionally averaged spring and summer temperatures for 1987 to 2003 were 0.87°C higher than those for 1970 to 1986. Spring and summer temperatures for 1987 to 2003 were the warmest since the start of the record in 1895, with 6 years in the 90th percentile—the most for any 17-year period since the start of the record in 1895 through 2003—whereas only 1 year in the preceding 17 years ranked in the 90th percentile. Likewise, 73% of early years since 1970 occurred in 1987 to 2003 (Fig. 1).

Spatial variability in the wildfire response to an earlier spring. Vulnerability of western U.S. forests to more frequent wildfires due to warmer temperatures is a function of the spatial distribution of forest area and the sensitivity of the local water balance to changes in the timing of spring. We measured this sensitivity using the October-to-September moisture deficit—the cumulative difference between the potential evapotranspiration due to temperature and the actual evapotranspiration constrained by available moisture—which is an important indicator of drought stress in plants (*24*). We used the percentage difference in the moisture deficit for early versus late snowmelt years scaled by the fraction of forest cover in each grid cell to map forests' vulnerability to changes in the timing of spring (Fig. 4) (*26*). The Northern Rockies and Northern California display the greatest vulnerability by this measure—the same forests accounting for more than three-quarters of increased wildfire frequency since the mid-1980s. Although the trend in temperature over the Northern Rockies increases with elevation, vulnerability in the Northern Rockies is highest around 2130 m, where the greatest increase in fires has occurred. At lower elevations, the moisture deficit in early years is increasing from a high average value (i.e., summer drought tends to be longer and more intense at lower elevations), whereas at higher elevations the longer dry season in early years is still relatively short, and vegetation is somewhat buffered from the effects of higher temperatures by the available moisture.

Discussion. Robust statistical associations between wildfire and hydroclimate in western forests indicate that increased wildfire activity over recent decades reflects sub-regional responses to changes in climate. Historical wildfire observations exhibit an abrupt transition in the mid-1980s from a regime of infrequent large wildfires of short (average of 1 week) duration to one with much more frequent and longer burning (5 weeks) fires. This transition was

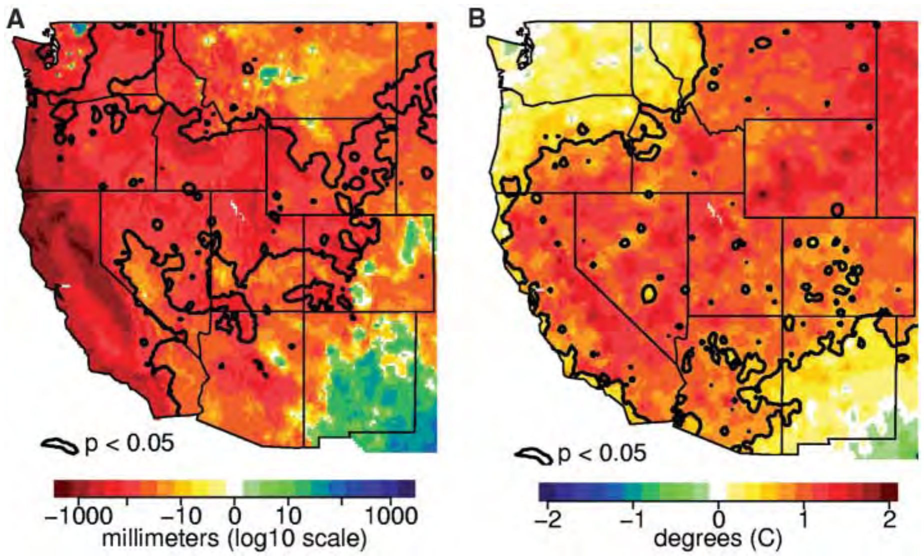

Fig. 3. Average difference between early and late snowmelt years in average precipitation from October through May (**A**) and average temperature from March through August (**B**). Contours enclose regions in which a *t* test for the difference in mean between 11 early and 11 late years was significant ($P < 0.05$). The null hypothesis that precipitation from October through May is normally distributed could not be rejected using the Shapiro-Wilk test for normality ($P > 0.05$ for more than 95% of 24,170 grid cells, $n = 49$ for precipitation; $P > 0.05$ for more than 95% of 24,170 grid cells, $n = 50$ for temperature). See Fig. 1B for a definition of early, mid-, and late snowmelt years.

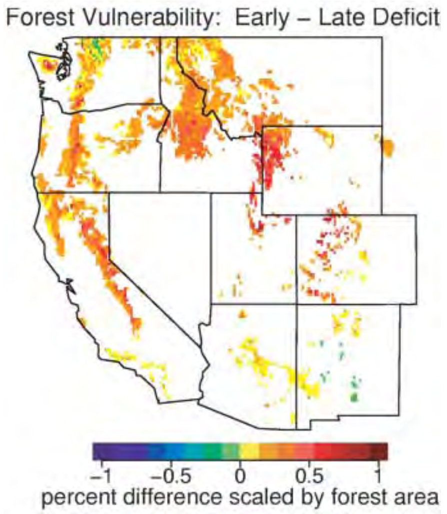

Fig. 4. Index of forest vulnerability to changes in the timing of spring: the percentage difference in cumulative moisture deficit from October to August at each grid point in early versus late snowmelt years, scaled by the forest-type vegetation fraction at each grid point, for 1970 to 1999 (*26*). See fig. S3 for a map of forest vulnerability for 1970 to 2003 over a smaller spatial domain. See Fig. 1B for a definition of early, mid-, and late snowmelt years.

marked by a shift toward unusually warm springs, longer summer dry seasons, drier vegetation (which provoked more and longer burning large wildfires), and longer fire seasons. Reduced winter precipitation and an early spring snowmelt played a role in this shift. Increases in wildfire were particularly strong in mid-elevation forests.

The greatest absolute increase in large wildfires occurred in Northern Rockies forests. This sub-region harbors a relatively large area of mesic, middle and high elevation forest types (such as lodgepole pine and spruce-fir) where fire exclusion has had little impact on natural fire regimes (*1*, *5*), but where we found that an advance in spring produces a relatively large percentage increase in cumulative moisture deficit by midsummer. In contrast, changes in Northern California forests may involve both climate and land-use effects. In these forests, large percentage changes in moisture deficits were strongly associated with advances in the timing of spring, and this area also includes substantial forested area where fire exclusion, timber harvesting, and succession after mining activities have led to increased forest densities and fire risks (*10*, *11*). Northern California forests have had substantially increased wildfire activity, with most wildfires occurring in early years. Southwest forests, where fire exclusion has had the greatest effect on fire risks (*2*, *3*), have also experienced increased numbers of large wildfires, but the relatively small forest area there limits the impact on the regional total, and the trend appears to be less affected by changes in the timing of spring. Most wildfires in the Southern Rockies and Southern California have also occurred in early snowmelt years, but again forest area there is small relative to the Northern Rockies and Northern California. Thus, although land-use history is an important factor for wildfire risks in specific forest types (such as some ponderosa pine and mixed conifer forests), the broad-scale increase in wildfire frequency across the western United States has been driven primarily by sensitivity of fire regimes to recent changes in climate over a relatively large area.

The overall importance of climate in wildfire activity underscores the urgency of ecological restoration and fuels management to reduce wildfire hazards to human communities and to mitigate ecological impacts of climate change in forests that have undergone substantial alterations due to past land uses. At the same time, however, large increases in wildfire driven by increased temperatures and earlier spring snowmelts in forests where land-use history had little impact on fire risks indicates that ecological restoration and fuels management alone will not be sufficient to reverse current wildfire trends.

These results have important regional and global implications. Whether the changes observed in western hydroclimate and wildfire are the result of greenhouse gas–induced global warming or only an unusual natural fluctuation is beyond the scope of this work. Regardless of past trends, virtually all climate-model projections indicate that warmer springs and summers will occur over the region in coming decades. These trends will reinforce the tendency toward early spring snowmelt (*36*, *37*) and longer fire seasons. This will accentuate conditions favorable to the occurrence of large wildfires, amplifying the vulnerability the region has experienced since the mid-1980s. The Intergovernmental Panel on Climate Change's consensus range of 1.5° to 5.8°C projected global surface temperature warming by the end of the 21st century is considerably larger than the recent warming of less than 0.9°C observed in spring and summer during recent decades over the western region (*37*).

If the average length and intensity of summer drought increases in the Northern Rockies and mountains elsewhere in the western United States, an increased frequency of large wildfires will lead to changes in forest composition and reduced tree densities, thus affecting carbon pools. Current estimates indicate that western U.S. forests are responsible for 20 to 40% of total U.S. carbon sequestration (*38*, *39*). If wildfire trends continue, at least initially, this biomass burning will result in carbon release, suggesting that the forests of the western United States may become a source of increased atmospheric carbon dioxide rather than a sink, even under a relatively modest temperature-increase scenario (*38*, *39*). Moreover, a recent study has shown that warmer, longer growing seasons lead to reduced CO_2 uptake in high-elevation forests, particularly during droughts (*40*). Hence, the projected regional warming and consequent increase in wildfire activity in the western United States is likely to magnify the threats to human communities and ecosystems, and substantially increase the management challenges in restoring forests and reducing greenhouse gas emissions.

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Materials and Methods
Figs. S1 to S3
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Increases in Western US Forest Wildfire Associated with Warming and Advances in the Timing of Spring

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Supporting Materials and Methods

Large Forest Wildfire History

A large-fire history for western U.S. forests was compiled from individual fire records for units of the U.S. Department of Agriculture's (USDA) Forest Service (USFS) and the U.S. Department of Interior's (USDI) National Park Service (NPS) west of 102°W Longitude for which data on large fires were available beginning in or before 1970. Together these National Forests and Parks contain most of the montane and sub-alpine forest area in the contiguous western US (Fig. S1). Fire records were obtained from multiple sources, including point fire records from WIMS/NIFMID (*S1*) and large fire perimeter records obtained directly from GIS officers of individual National Forests and Parks. While individual fire records for one unit, the Olympic National Park, were only available from 1972, historical summaries obtained from that Park's website confirmed that there were no large fires in 1970-1971, so these data were included. The sample was arbitrarily restricted to fires larger than 1000 acres (approximately 400 hectares). Standard units were used because the original data sets are entered in these formats. While these large fires represent only one half of one percent of the fires reported since 1970 for the Forests and Parks used here, they account for seventy-three percent of the total area burned in all vegetation types in these locations. The sample was further restricted to include only fires that burned in forested areas (as defined below). The result was a data set of 1166 large forest fires in the western US for 1970 to 2003.

As others have found (*S2, S3*) documentary fire records are often incomplete or contain inaccuracies, but records for relatively large fires are typically much more complete and reliable because these events had greater economic and ecological impacts that required more attention from government agencies. Restricting this analysis to fires over 1000 acres thus produced a relatively complete data set with a manageable size, such that the variables of interest for each fire (location, elevation, coarse vegetation type, and starting and ending dates) could be checked, and omissions and obvious errors corrected as needed and feasible.

Location data for each fire were usually available, either as latitude and longitude, UTM coordinates, or Public Land Survey System coordinates. Wherever geographic coordinates could not otherwise be obtained, fires were assigned the median latitude and longitude recorded for all fires from the same Forest district (an administrative subdivision of a National Forest) or Park. At best, the accuracy of many of the recorded geo-coordinates is not likely to be better than 1/8 of a degree. Consequently, we do not use more finely resolved land surface data sets in the subsequent analysis, and wherever possible use descriptive data from the fire records themselves rather than trying to match individual fire locations to land surface characteristics described in GIS covers.

While USFS fire records contain explicit elevation in feet, NPS fire records report elevations in 1000-foot bands (500 - 1500 feet, 1500 - 2500 feet, etc., upper-bound inclusive). USFS fire elevations were rounded to conform to the NPS standard. In the one percent of records missing fire elevations, they were determined using the nearest Land Data Assimilation System (LDAS) 1/8 degree grid cell's mean elevation, derived from the GTOPO30 Global 30 Arc Second (~1km) Elevation Data Set (*S4*).

Large NPS and USFS wildfires were coarsely characterized by the type of vegetation they burned in: i.e., as either "forest" or "non-forest". "Non-forest" wildfires primarily burned in grass and/or shrub type vegetation. The NPS fire records contained a code indicating whether a fire burned primarily in forested areas or not, while the USFS data were more complicated. Over sixty percent of the USFS fire records contained a description of the vegetation the fire burned in, while ninety-eight percent of the remaining records contained codes for National Fire Danger Rating System (NFDRS) fuel model (*S5*) applicable to the fire. NFDRS fuel models distinguish between several forest, grass, and shrub cover types. For the less than one percent of large fires where both vegetation and fuel model codes were missing, the LDAS 1/8 degree gridded vegetation layer using the University of Maryland vegetation classification scheme with fractional vegetation adjustment ("UMDvf", (*S4)*) was used to determine if forested vegetation types predominated (> 70% of non-agricultural vegetated area, as described in the next section) in the grid cell surrounding the geographic coordinates for each fire. Note that the resulting data set sometimes excludes fires that burned large forested areas if these fires ignited in and/or primarily burned in non-forest vegetation types. A pertinent example is the October 2003 fire siege in southern California: all of these fires started in chaparral, primarily burned in non-forest vegetation types, are excluded from this data set by the definitions of "forest" described above, and yet these fires burned substantial forested areas. This is an issue that deserves further consideration in the future.

While many of the USFS—but none of the NPS—large fire records contain estimated ignition dates, the true ignition dates for many fires in the record are probably unknown. Reasonably, the first reliable available date is usually the date of discovery. While this might often also be the date of ignition, it is not always the case; a fire can sometimes ignite and smolder in the forest duff for days to weeks or longer before flaring up when climatic conditions become favorable to rapid spread. Once an ignition is actively becoming a large fire, it is likely to be discovered.

Similarly, the day each fire is extinguished is often missing as well. What is usually recorded is the day the fire is controlled. A controlled fire is completely contained within a fixed perimeter and excluded from selected unburned areas within that perimeter, with little risk of those perimeters being violated. (*S6*) For large fires, this cessation of fire spread may be more interesting than the ultimate extinction date. Large fires in difficult fire seasons and inaccessible terrain might not be controlled until a season-ending weather event raises relative humidity. It is not unusual to see seasons where many fires that started on different dates in a region are all controlled within a day or so of each other. On the other hand, a fire's ultimate ending date may occur long after control, as a controlled fire can continue to smolder and even flare up in patches within the fire perimeter for a long time.

Given all of these considerations, the discovery and control dates of large fires may be approximately indicative of the start and end of climatic conditions conducive to the spread of wildfires. These are the dates that are recorded for all fires, and that we will use here to demark the start and finish of the wildfire season.

Land Surface Characteristics

The UMDvf vegetation layer from LDAS was used to create a mask defining forested areas around the western U.S. (Fig. S1). For the purposes of compiling composites of climatic and hydrologic variables, "forested" areas were defined as the intersection of three sets of 1/8-degree grid cells:

$$\{ F > S \} \cap \{ F > G \} \cap \{ F > H \} \qquad \text{(Formula S1)}$$

where F is the sum of the vegetation fractions in each grid cell for six UMDvf vegetation categories likely to be associated with forest cover (the Evergreen Needleleaf and Broadleaf Forest categories, the Deciduous Needleleaf and Broadleaf Forest categories, and the Mixed Cover and Woodland categories). The S and G categories were comprised of the aggregate vegetation fractions for shrublands (the Closed Shrubland and Open Shrubland categories) and grasslands (the Wooded Grassland and Grassland categories). The H category was comprised of the fractional areas converted to agriculture and development (the Cropland and Urban and Built-up categories). The net effect was to select as forested all those grid cells where forest and related type categories were the largest single component, as compared to grassland, shrubland, and areas converted for human use. A somewhat more strict definition was used to determine the vegetation type for the less than 1% of wildfire records with no vegetation type, requiring that the forested categories (F) account for more than 70 percent of the total area in natural vegetation ($F + G + S$).

Forested grid cells where the mean elevation derived from GTOPO30 exceeded 9,500 feet were excluded from this analysis. In the 34 years of our fire record, 22 large USFS forest wildfires were reported between 9500 and 10000 feet, and two fires were reported above 10000 feet (ie, 2% of fires were reported above 9500 feet). NPS fire records do not report explicit elevations above 9,500 feet. The alpine tree line in western U.S. forests, while varying considerably with latitude and aspect, roughly coincides with an elevation of about 10,000 ft, although lower in some places. Grid cells with average elevations at or below 9,500 ft still include a substantial area above 9,500 ft.

The USFS and NPS land management unit boundaries were also projected onto the 1/8 degree grid coordinates used by LDAS (*S7*). The intersection between the forest mask for elevations at or below 9500 feet mean elevation and the areas contained within the management unit boundaries formed the domain of analysis for the work reported here (Fig. S1).

Regional Spring and Summer Temperature

Monthly temperature values (1895-2003) for western U.S. Climate Divisions (*S8*) were used to characterize interannual variability in spring and summer temperatures for the west as a whole. A regional annual temperature index was calculated as the average of 110 Climate Divisions in the western contiguous United States for the monthly mean temperatures for March through August.

Timing of Spring

For the timing of the spring snowmelt, we use the dates of the center of mass of annual flow

(CT) for snowmelt-dominated streamflow gauge records provided by the U.S. Geological Survey Hydro-Climatic Data Network and by Environment Canada (*S9–S11*). As a proxy for interannual variability in the arrival of the spring snowmelt for the western U.S. as a region, we use the first principal component (CT1) for 240 stations with at least 30 years of record for 1970-2002 between 32 and 50*N Latitude and 124 and 105*W Longitude. Missing values for each station were replaced with the 1970-2002 mean for that station. CT1 accounts for 21% of total variance in CT, and is essentially the annual average CT value for western U.S. stations. Note that the weights for CT1 produce an index that is broadly representative of the region as a whole, implying a coherent regional signal in snow melt timing (Fig. 4). While the fire history data were available through 2003, at the time of this analysis the stream gauge data were only available through 2002. Since we chose to analyze wildfire and climate variables by snowmelt tercile, and 1970-2002 was conveniently divisible into three 11-year samples, we did not use the 2003 fire data for that part of the analysis. Subsequently, we confirmed with updated CT that 2003 snowmelt timing was not in the Early or Late tercile categories.

Gridded Forest Area-weighted Moisture Deficit and Meteorological Data

Moisture Deficit (*D*, the difference between potential and actual evapotranspiration (*S12, S13*)) was calculated on a 1/8 degree grid using the Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model (*S14*) and the Penman-Monteith equation (*S15, S16*). The VIC model was run in full-energy mode (S14) using as inputs daily meteorological data for the contiguous U.S. (*S17, S18*), along with the LDAS soil and vegetation properties (*S4*). Vulnerability of forests to changes in the timing of spring was mapped on the 1/8 degree grid as the percentage difference in Early versus Late snowmelt years' cumulative October-to-August moisture deficit (δ) at each gridpoint, scaled by the forest-type vegetation fraction (*F*) at each gridpoint*:*

$$\text{Vulnerability} = F \times \delta, \text{ where } \delta = \frac{D^{early} - D^{late}}{D^{all}}. \qquad \text{(Formula S2)}$$

Two versions of the daily meteorological data for the contiguous U.S. were available for this analysis *(S17, S18)*. One version, for 1970-1999, covers the entire spatial domain considered here, but ends four years early, excluding some very large fire years that were early snowmelt years in the western United States. The other version, for 1970-2003, covers the entire time period, but excludes some eastern portions of the spatial domain: the Black Hills sub-region, parts of the Northern Rockies sub-region in Montana and northwest Wyoming, and the easternmost portion of the Southwest sub-region in Montana. Figures 3 and 4 were created using the spatially complete 1970-1999 data. We include duplicate versions of Figure 4 here side by side (Fig. S3) showing F x δ where δ is calculated with both data sets *(S17, S18)*, substituting $D^{1970\text{-}1999}$ for D^{all} as the common denominator (Formula S2). The spatial variability is very similar across both data sets and time periods.

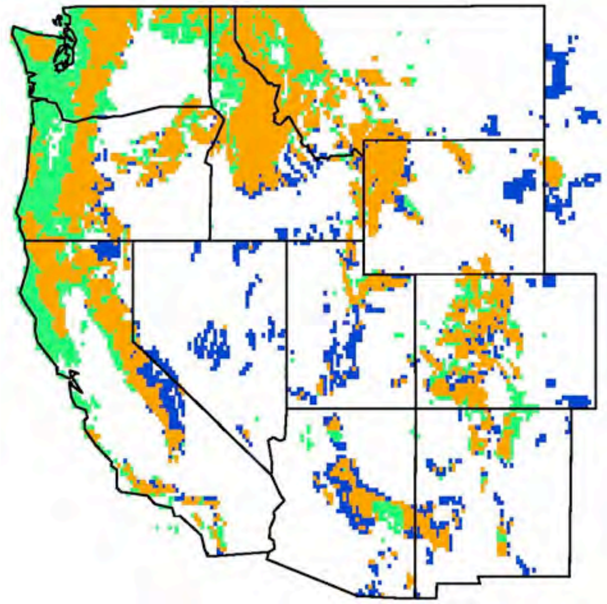

Figure S1. *Orange*: western U.S. forested area managed by federal agencies reporting wildfires from 1970-present. *Green*: non-federal forested area. *Blue*: primarily non-forested federal area.

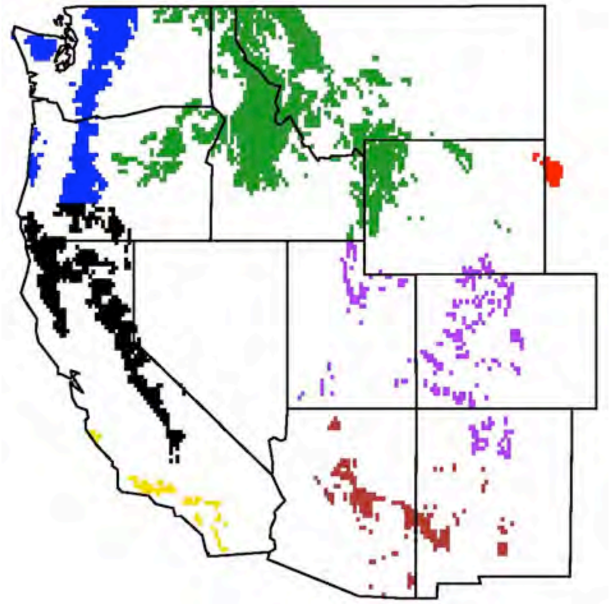

Figure S2. Western forest areas within federal land management units reporting forest wildfires since 1970. Clockwise from top left: Northwest (*blue*), Northern Rockies (*green*), Black Hills (*red*), Southern Rockies (*purple*), Southwest (*brown*), Southern California (*gold*), Sierra Nevada and Southern Cascade and Coast ranges (*black*).

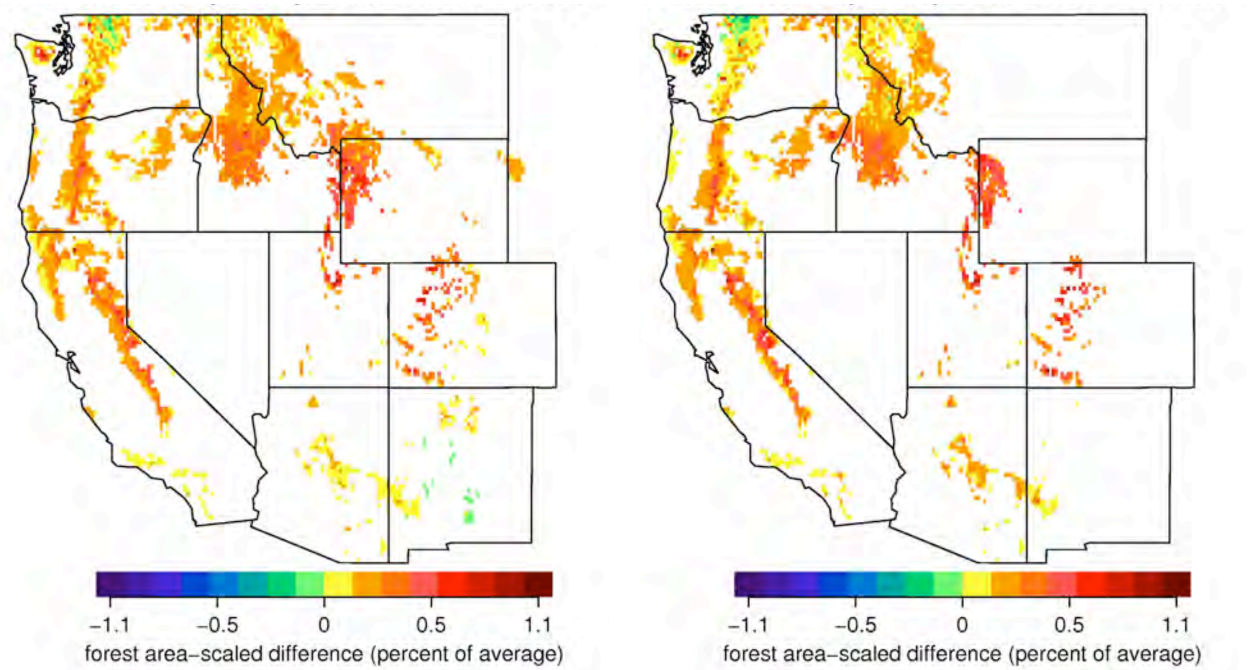

Figure S3. Index of forest vulnerability to changes in the timing of spring: the percentage difference in Early versus Late snowmelt years' cumulative October-to-August moisture deficit (δ) at each gridpoint, scaled by the forest-type vegetation fraction (F) at each gridpoint. (*left*) 1970-1999. (*right*) 1970-2003. F x δ for both periods has been plotted on a common symmetric scale.

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