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Supporting Online Material for

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

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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.

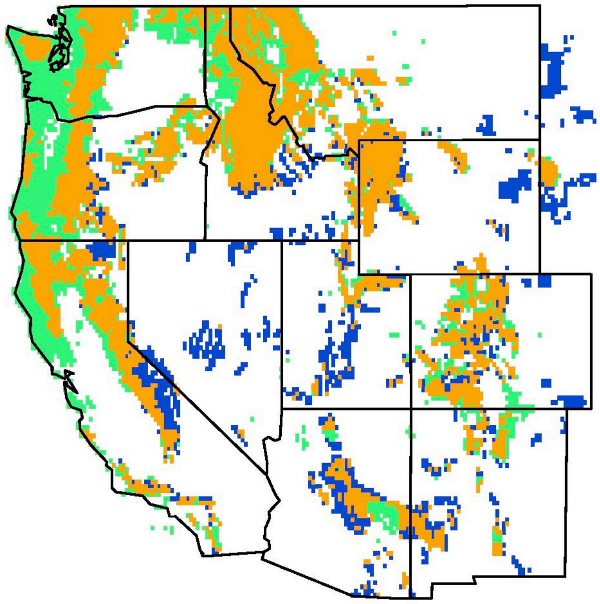

Figure S1. *Orange*: western U.S. forested area managed by federal agencies reporting wildfires from 1970-present. *Green*: non-federal forested area. *Blue*: primarily non-forested federal area.

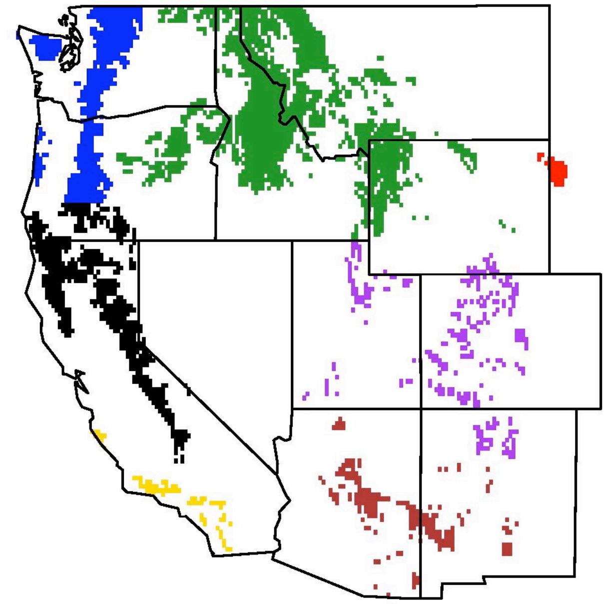

Figure S2. Western forest areas within federal land management units reporting forest wildfires since 1970. Clockwise from top left: Northwest (*blue*), Northern Rockies (*green*), Black Hills (*red*), Southern Rockies (*purple*), Southwest (*brown*), Southern California (*gold*), Sierra Nevada and Southern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

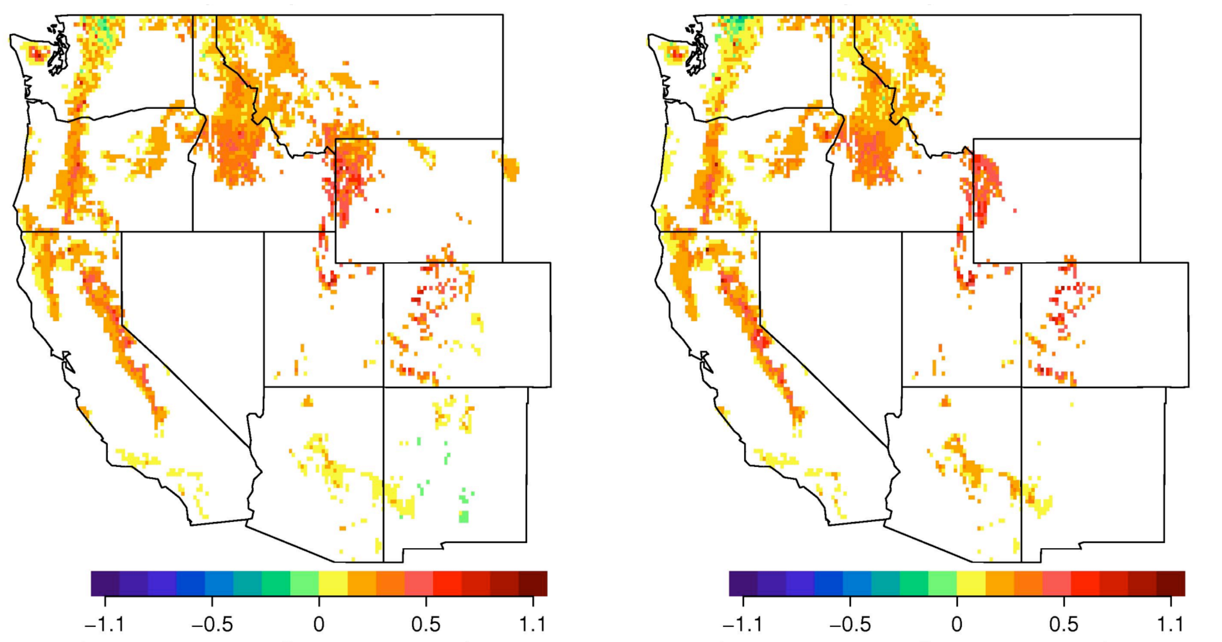

Figure S3. Index of forest vulnerability to changes in the timing of spring: the percentage difference in Early versus Late snowmelt years' cumulative October-to-August moisture deficit (δ) at each gridpoint, scaled by the forest-type vegetation fraction (F) at each gridpoint. (*left*) 1970-1999. (*right*)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

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