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Warming and Earlier Spring Increases 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, but surprisingly, the extent of recent changes has never been systematically documented. Nor has it been established to what degree climate may be driving regional changes in wildfire. Much of the public and scientific discussion of changes in western United States wildfire has focused rather 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 to hydro-climatic and land-surface data. Here, we show that large wildfire activity increased suddenly and dramatically 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*). Here we investigate 34 years of western United States ("western") wildfire history together with hydro-climatic 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 re-growth 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 [e.g., 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 (e.g., 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 Nino/La Nina events in recent decades, along with severe droughts in 2000 and 2002 may have promoted greater forest wildfire risks in areas like 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 twentieth century.

We describe land-use history versus climate as competing explanations, but in fact they may be complementary in some places. In some forest types, past land-uses have probably increased current forest wildfire regimes' sensitivity 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 over-abundant 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 western forests. Likewise, detailed fire-climate analyses for the region have not been conducted to evaluate what hydro-climatic variations may be associated with recent increased wildfire activity, and the spatial variations in these patterns.

We compiled a comprehensive time series of 1,166 large (> 400 ha) forest wildfires for 1970-2003 from federal land management units containing 61% of western forested areas (and 80% above 1,370m) (*26*) (fig. S1). We compared these data with corresponding hydro-climatic 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 the incidence of large wildfires in western forests increased in the mid-1980s (Fig. 1) [hereafter, "wildfires" refers to large fires events (>400 ha) within forested areas only (*26*)]. Subsequently, 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. 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 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 1970-86 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 ("Northern California", 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 1,680 m and 2,690 m in elevation, with the greatest increase centered around 2,130 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 use Stewart *et al.*'s 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). 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 1,680m and 2,690m elevation (Fig. 2), with a non-linear 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, while just 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 U.S. (Fig. 3). The arrival of spring snowmelt in the mountains of the western U.S., 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 increased with elevation.

Snow carries over a significant 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 1987-2003 were 0.87°C higher than for 1970-1986. 1987-2003 Spring and summer temperatures were the warmest since the start of the record in 1895, with six years in the ninetieth percentile—the most for any 17 year period since the start of the record in 1895 through 2003—while only one year in the preceding 17 years ranked in the ninetieth percentile. Likewise, 73% of Early years since 1970 occurred in 1987-2003 (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 measure 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 use 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 over three quarters of increased wildfire frequency since the mid-1980s. While the trend in temperature over the Northern Rockies increases with elevation, vulnerability in the Northern Rockies is highest around 2130m, 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), while 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 hydro-climate 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 one week) duration to one with much more frequent and longer-burning (five weeks) fires. This transition was 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 (e.g., lodgepole pine and spruce-fir) where fire exclusion has had little impact on natural fire regimes (*1*, *5*), but where we found 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 following 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, while land use history is an important factor for wildfire risks in specific forest types (e.g. 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 hydro-climate and wildfire are the result of greenhouse gas-induced global warming, or only an unusual natural fluctuation, is presently unclear. 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 1.5C to 5.8C projected global surface temperature warming by the end of the 21st Century is considerably larger than the recent warming of less than 0.9ºC 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 U.S., 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 US forests are responsible for 20-40% 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 U.S. 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 shows 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 U.S. is likely to magnify the threats to human communities and ecosystems, and significantly increase the management challenges in restoring forests and reducing greenhouse gas emissions.

References and Notes

1. C. Whitlock, *Nature* **432,** 28 (2004).
2. W. W. Covington, *Nature* **408,** 135 (2000).
3. C. D. Allen *et al.*, *Ecol. Appl.* **12,** 1418 (2002).
4. J. L. Pierce, G. A. Meyer, A. J. T. Jull, *Nature* **432**, 87 (2004).
5. T. Schoennagel, T. T. Veblen, W. H. Romme, *BioSci* **54**, 661 (2004).
6. M. Savage, T. W. Swetnam, *Ecol.* **71**, 2374 (1990).
7. A. J. Belsky, D. M. Blumenthal, *Cons. Biol.* **11**, 315 (1997).
8. S. J. Pyne, P. L. Andrews, R. D. Laven, *Introduction to Wildland Fire* (Wiley, New York, 1996).
9. W. W. Covington, M. M. More, *J. For.* **92**, 39(1994).
10. K.S. McKelvey *et al.*, in *Sierra Nevada Ecosystems Project: Final Report to Congress* (Univ. of California, Davis 1996), vol. 2, chap 37.
11. G. E. Gruell, *Fire in Sierra Nevada forests: A photographic interpretation of ecological change since 1849* (Mountain Press, Missoula, MT, 2001).
12. T. Schoennagel, T. T. Veblen, W.H. Romme, J. S. Sibold, E. R. Cook, *Ecol. Appl.* **15**, 2000 (2005).
13. R. C. Balling, G. A. Meyer, S. G. Wells, *Agric. For. Meteor.* **60**, 285 (1992).
14. E. K. Heyerdahl, L. B. Brubaker, J. K. Agee, *Holocene.* **12**, 597 (2002).
15. K. F. Kipfmueller, T. W. Swetnam, "Fire-Climate Interactions in the Selway-Bitterroot Wilderness Area" (*USDA Forest Service Proceedings* RMRS-P-15-vol-5, 2000).
16. T. W. Swetnam, J. L. Betancourt, *J. Clim.* **11**, 3128 (1998).
17. T. T. Veblen, T. Kitzberger, J. Donnegan, *Ecol. Appl.* **10**, 1178 (2000).
18. A. L. Westerling, T. J. Brown, A. Gershunov, D. R. Cayan, M. D. Dettinger, *Bull. Am. Meteorol. Soc.* **84**, 595 (2003).
19. T. W. Swetnam, J. L. Betancourt, *Science* **249**, 1017 (1990).
20. A. Gershunov, T. P. Barnett, *J. Clim.* **11**, 1575 (1998).
21. A. Gershunov, T. P. Barnett, D. R. Cayan, *EOS* **80**, 25 (1999).
22. A. L. Westerling, T. W. Swetnam, *EOS* **84**, 545 (2003).
23. N. L. Stephenson, *Am. Nat.* **135**, 649(1990).
24. N. L. Stephenson, *J. Biogeog.* **25**, 855 (1998).
25. T.W. Swetnam, *Science* **262**, 885 (1993).

26. Materials and methods are available as supporting material on *Science* Online.
27. K. E. Mitchell et al, *J. Geophys. Res.*, **109**, D07S90 (2004).
28. E. P. Maurer, A. W. Wood, J. C. Adam, D. P. Lettenmaier, B. Nijssen, J. Clim. 15 (2002).
29. A. F. Hamlet, D. P. Lettenmaier, *J. Hydromet.* **6**, 330 (2005).
30. NCDC, "Time Bias Corrected Divisional Temperature-Precipitation-Drought Index" (Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733, 1994).
31. X. Liang, D. P. Lettenmaier, E. F. Wood, S. J. Burges, *J. Geophys. Res.* **99**, D7 (1994).
32. I. T. Stewart, D. R. Cayan, M. D. Dettinger, *J. Clim*. **18**, 1136 (2005).
33. D. R. Cayan, S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, D. H. Peterson, *Bull. Amer. Meteor. Soc.* **82**, 399 (2001).
34. J.R. Slack, J. M. Landwehr, "Hydro-Climatic Data Network (HCDN): A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874–1988" (*U.S. Geological Survey Open-File Rep.* 92-129 1992).
35. J. Sheffield, G. Goteti, F. H. Wen, E. F. Wood, *J. Geophys. Res.* 109, D24108 (2004).
36. National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (US GCRP, Washington DC, 2000).
37. J. T. Houghton et al, Eds., *IPCC Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 2001).
38. S. W. Pacala *et al*., *Science*, **292**, 2316 (2001).
39. D. Schimel, B. H. Braswell, in *Global Change and Mountain Regions: An overview of Current Knowledge*, U.M. Huber, H. K. M. Bugmann, M. A. Reasoner, Eds. (Dordrecht: Springer 2005), Advances in Global Change Research Vol 23.
40. W. Sacks, D. Schimel, R. Monson, *Oecologia*, in review (2006).
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Supporting Online Material
www.sciencemag.org/cgi/content/full/1128834/DC1
Materials and Methods
Figs. S1 to S3
References

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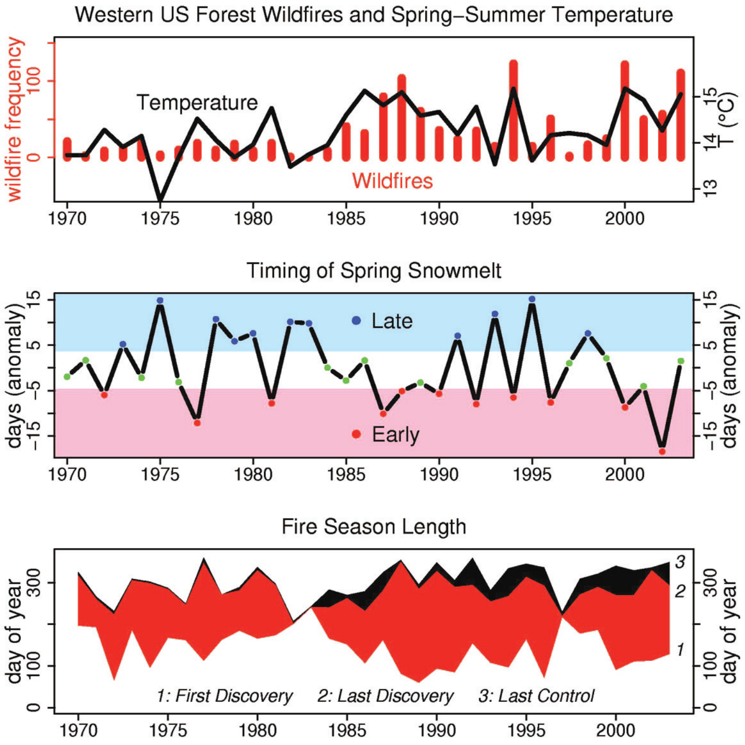
Fig. 1. (**top**) Annual frequency of large (> 400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western US (line) (*26*, *30*). Spearman's rank correlation between the two series is 0.76 ($p < 0.001$). Wilcoxon test for change in mean large forest fire frequency 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.

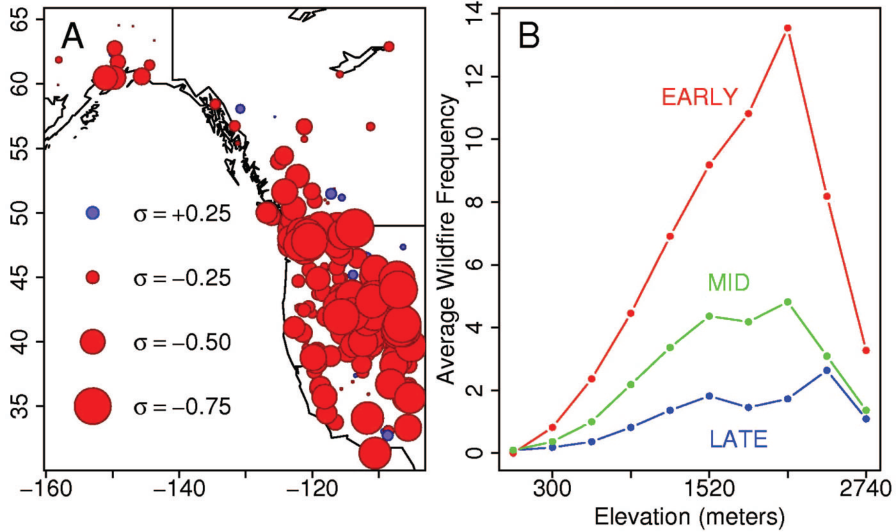
Fig. 2. (**A**) Pearson's rank correlation between annual western U.S. large (> 400 ha) forest wildfire frequency and streamflow center timing. (**B**) Average frequency of western US forest wildfire by elevation and Early, Mid and Late snowmelt years 1970-2002 (see Fig. 1, middle panel and legend, for a definition of Early, Mid and Late snowmelt years).

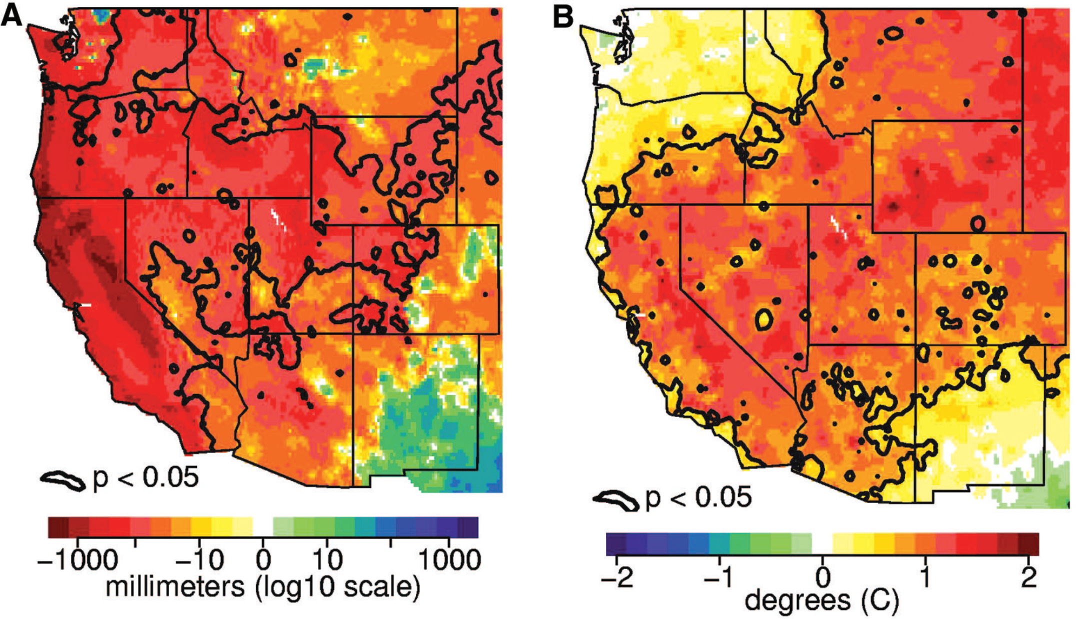
Fig. 3. Average difference between Early and Late snowmelt years' October-through-May average precipitation (**left**) and March-through-August average temperature (**right**). Contours enclose regions where a t-test for the difference in mean between 11 Early and 11 Late years was significant ($p < 0.05$). The null hypothesis that October-through-May precipitation is normally distributed could not be rejected using the Shapiro-Wilk test for normality ($p > 0.05$ for over 95% of 24170 grid cells, $n = 49$ for precipitation; $p > 0.05$ for over 95% of 24170 grid cells, $n = 50$ for temperature). (see Fig. 1, middle panel and legend, 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 Early versus Late snowmelt years' cumulative October-to-August moisture deficit at each grid point, scaled by the forest-type vegetation fraction at each grid point, for 1970-1999 (*26*). (See also fig. S3 for a map of forest vulnerability for 1970-2003 over a smaller spatial domain.) (see Fig. 1, middle panel and legend, for a definition of Early, Mid and Late snowmelt years).

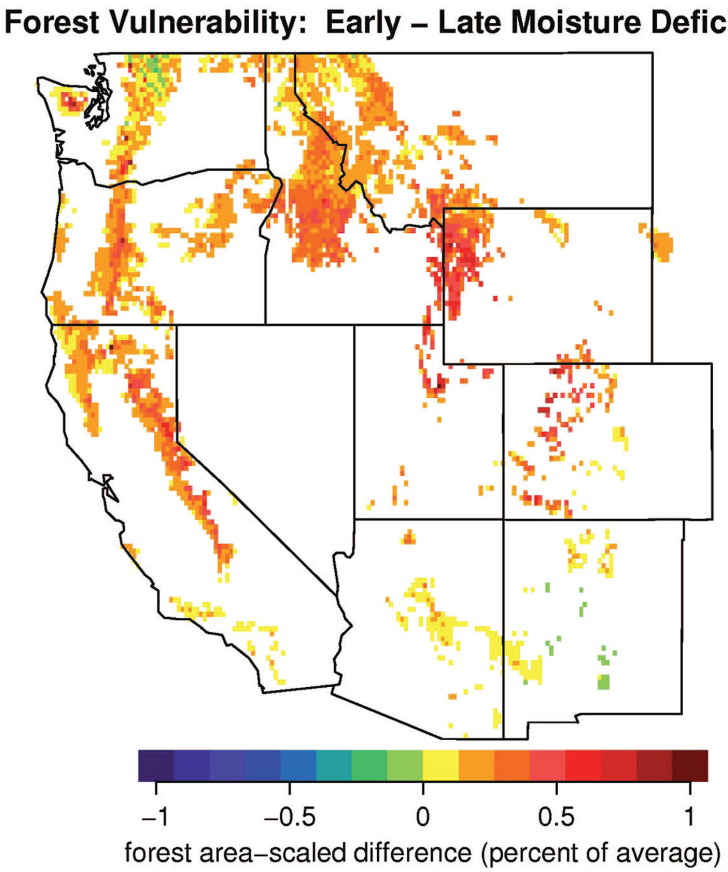

Western US Forest Wildfires and Spring–Summer Temperature
wildfire frequency
0
100
Temperature
Wildfires
T (°C)
13
14
15
1970
1975
1980
1985
1990
1995
2000
Timing of Spring Snowmelt
days (anomaly)
−15
−5
5
15
Late
Early
1970
1975
1980
1985
1990
1995
2000
Fire Season Length
day of year
0
100
300
1
2
3
1: First Discovery
2: Last Discovery
3: Last Control
1970
1975
1980
1985
1990
1995
2000

Forest Wildfire and the Timing of the Spring Snowmelt





A
p < 0.05
−1000
−10
0
10
1000
millimeters (log10 scale)
B
p < 0.05
−2
−1
0
1
2
degrees (C)


Forest Vulnerability: Early – Late Moisture Deficit
–1
–0.5
0
0.5
1
forest area–scaled difference (percent of average)