# Human presence diminishes the importance of climate in driving fire activity across the United States

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Edited by Janet Franklin, University of California, Riverside, CA, and approved November 3, 2017 (received for review August 6, 2017)

**Growing human and ecological costs due to increasing wildfire are an urgent concern in policy and management, particularly given projections of worsening fire conditions under climate change. Thus, understanding the relationship between climatic variation and fire activity is a critically important scientific question. Different factors limit fire behavior in different places and times, but most fire-climate analyses are conducted across broad spatial extents that mask geographical variation. This could result in overly broad or inappropriate management and policy decisions that neglect to account for regionally specific or other important factors driving fire activity. We developed statistical models relating seasonal temperature and precipitation variables to historical annual fire activity for 37 different regions across the continental United States and asked whether and how fire-climate relationships vary geographically, and why climate is more important in some regions than in others. Climatic variation played a significant role in explaining annual fire activity in some regions, but the relative importance of seasonal temperature or precipitation, in addition to the overall importance of climate, varied substantially depending on geographical context. Human presence was the primary reason that climate explained less fire activity in some regions than in others. That is, where human presence was more prominent, climate was less important. This means that humans may not only influence fire regimes but their presence can actually override, or swamp out, the effect of climate. Thus, geographical context as well as human influence should be considered alongside climate in national wildfire policy and management.**

climate change | wildfire | human influence | land use | fire management

The adverse effects of increasing wildfire on human assets, and altered fire regimes on ecological integrity, are becoming a worldwide concern (1), especially in the wake of recent "megafire" events in some regions (2), which have resulted in enormous loss of human lives and properties (e.g., refs. 3–6). Most of these large fire events are driven by extreme weather conditions combined with prolonged drought; and escalation in fire activity is widely attributed to climatic factors and global warming (7–11). Furthermore, projections suggest that fire extent, frequency, and intensity could skyrocket in upcoming decades due to warmer temperatures and drier fuels (12, 13), although there is inherent variability and regional variation (14).

Climate is often considered the primary factor controlling fire regimes, either directly by controlling weather conditions or indirectly via primary productivity and fuel conditions (15–17). However, evidence of burn patterns over millennia suggests that both climate and human activities have strong controls and that, at times, one control may override the other (18–20). Human influence on fire is also well documented in studies of contemporary fire patterns, where fire management activities and land use change have been implicated (21, 22), as well as the role of humans in changing the pattern, season, and frequency of fires through human-caused ignitions (23–27).

Given the enormity of values at risk, understanding the relative role of climate and other factors driving fire activity, and the potential for fire regimes to change as a result of these drivers, is a critically important scientific question. The issue is complex because different factors limit fire behavior in different places and times, and for different reasons. However, despite recognition that fire-climate relationships vary geographically (28–31), many analyses and future projections are conducted across broad spatial extents (e.g., refs. 32–34).

While broad-scale studies are critical for understanding general patterns, analyses using data that span large environmental or latitudinal gradients may potentially confound spatial and temporal relationships and thus result in overly general conclusions about trends and drivers (11). This masking of regional variation was recently evidenced in a study in California, where statewide analyses of historical fire-climate relationships masked patterns that were only apparent via separate analyses conducted within smaller, climatically homogenous subregions (35). Another information gap in our understanding of fire-climate relationships results from a geographical bias of research conducted in the western United States (e.g., refs. 13, 17, 25, and 30–33), where ecosystems, climate, and fire regimes differ substantially from those in the eastern United States (e.g., ref. 36) or other parts of the world (e.g., ref. 37).

Despite growing recognition that fire-climate relationships and trends vary geographically, the reasons for these differences have never been systematically explored across broad landscapes. One possibility is that landscapes vary in the biophysical characteristics that lead to different fire regimes, resulting in different responses of fire to climatic variation. In northwestern North America, fire activity was highest in areas with moderate-intermediate precipitation and temperature conditions, where fuel abundance and moisture conditions were frequently sufficient to be favorable for fire (25). Pausas and Ribeiro (16) also

## Significance

**Projections of worsening wildfire conditions under climate change are a major concern in policy and management, but there is little understanding of geographical variation in fire-climate relationships. Our analysis relating climate variables to historical fire activity across the United States showed substantial variability in the importance of different seasonal temperature and precipitation variables and of climate overall in explaining fire activity. Climate was significantly less important where humans were more prevalent, suggesting that human influence could override or even exceed the effect of climate change on fire activity. Although climate change may play a significant role in altering future fire regimes, geographical context and human influence should also be accounted for in management and policy decisions.**

Author contributions: A.D.S., J.E.K., and A.H.P. designed research; A.D.S., A.H.P., and K.F. performed research; A.D.S. and J.E.K. analyzed data; and A.D.S. and J.E.K. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1713885114/-/DCSupplemental.

found support for an intermediate fire-productivity relationship globally, which they suggest may result in varying effects of climate change on future fire activity. In another western US study, low precipitation and warm temperatures led to increased area burned in most forested ecoprovinces; however, moist seasons before the fire season were most important in fuel-limited arid provinces because prior-season precipitation facilitated biomass growth (30).

Krawchuk and Moritz (15) distinguished between conditions-limited and resource-limited fire regimes, and this dichotomy was used to explain geographically varying effects of climate change on projected future fire regimes in Mediterranean ecosystems (38). Keeley and Syphard (35) further distinguished ignition-limited systems in which annually both climate and fuel conditions are conducive to large fire events, so that fire events are dependent on timing of anthropogenic ignitions. Although human activities clearly affect the timing, extent, seasonality, and location of fire (27), area burned and ignition frequency are not always correlated (35, 39). Humans also influence fire regimes indirectly—for example, via management or land use decisions that alter the fuel patterns on the landscape—and the effect of fire policy change has been shown to mediate fire-weather relationships over time in southern France (40). Nevertheless, given that a major means by which humans influence fire is via changes in frequency, it has remained unclear whether or where human influence would be strong enough to alter or override the influence of climate.

To better understand the broad-scale nature of fire-climate relationships, and how and why they vary, we developed statistical models relating seasonal temperature and precipitation variables with historical annual fire activity for 37 different regions across the continental United States. By developing separate but parallel models, we were able to then assess geographical variation in the role of climate in explaining fire activity across different land ownership types and climatological regions spanning the entire continent. We stratified historical spatial fire occurrence data for lands administered by three federal agencies, the National Park Service (NPS), US Forest Service (USFS), and Bureau of Land Management (BLM), across 17 National Ecological Observatory Network (NEON) climate regions, known as NEON domains, spanning a period of ∼40 y (Fig. 1). We additionally evaluated fire-climate relationships using a contemporary (∼20 y) dataset [national interagency Fire Program Analysis, Fire-Occurrence Database (FPA FOD)] that included fire records spanning all public and private land ownership types and thus covered a much larger land area than the federal data, albeit for a shorter time span (Fig. 2).

After exploring the independent effects of each climate variable on fire activity, we performed multiple regressions considering all possible variable combinations and calculated the total variance explained for the best-supported fire-climate model in each region. We then related the variance explained, as a metric of the overall importance of climate on fire, to a range of biophysical and human factors that we hypothesized could explain differences in the strength of the fire-climate relationships. The overarching questions were, how do fire-climate relationships vary geographically, and why are these relationships more important in some regions than others?

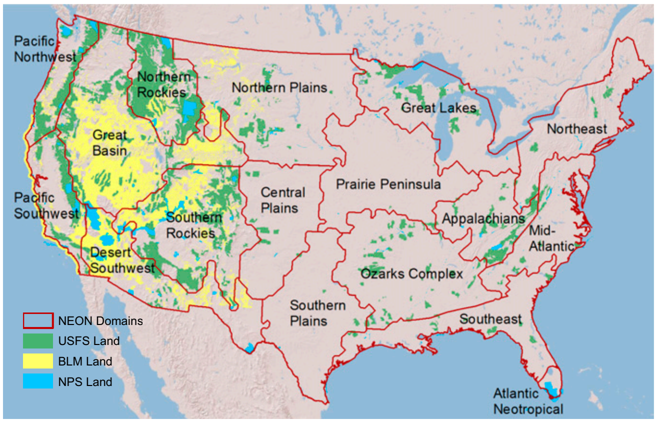

**Fig. 1.** Geographical distribution of federal lands across NEON domains in the continental United States.

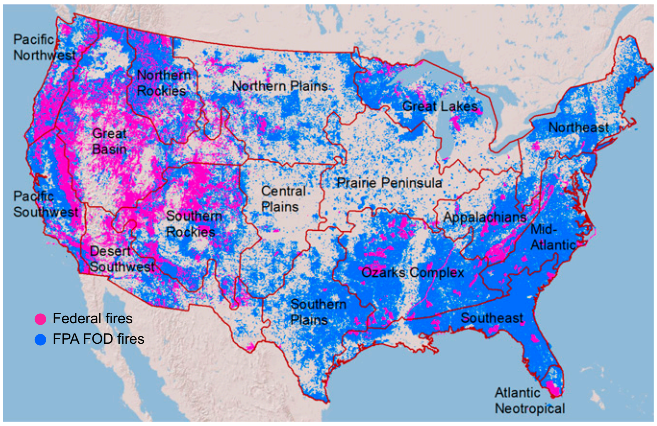

**Fig. 2.** Occurrence locations for fires on federal lands only (1972–2010) and for all fires (1992–2010) across NEON domains in the continental United States.

## Fire-Climate Relationships Varied Geographically in the Importance and Strength of Different Seasonal Climate Variables

There was wide geographical variation in the independent influence of seasonal temperature and precipitation variables on annual fire activity, not only across NEON domains but also across federal agencies (Fig. 3), as well as in comparison with the full-region analyses using FPA FOD data (Fig. 3). There were no strong patterns across latitudinal or longitudinal gradients, but the influence of prior-year precipitation was generally most important in western regions, except for a clear contribution to fire activity in the Appalachian, Mid-Atlantic, and Northeastern regions. Temperature variables were more important than precipitation variables in NPS lands versus USFS lands, but the effect of temperature versus precipitation was more equally, yet unsystematically, distributed across BLM lands and full NEON domains. In terms of seasonal importance, spring and summer temperature and precipitation variables overall explained more independent variation in fire activity than autumn or winter variables.

The results of the multiple-regression analyses showed that the average variance in fire activity explained by climate for the 37 federal regions was 29%. Climatic variables explained ≥50% variation in fire activity in five regions (Table S1), only one of which was located in the eastern United States, the Appalachian region on USFS lands. Here, fire activity was primarily explained by low precipitation in all seasons except for summer, plus high spring temperature. The other four regions with the strongest fire-climate relationships were the Southern Rockies on NPS lands, the Pacific Southwest on USFS lands, and the Great Basin and Northern Rockies on BLM lands. In all four of these regions, prior-year precipitation was among the variables included in the top-supported models, and the relationship was negative for all but the Great Basin where it was positive. Maximum summer temperature was the other variable that was included in all four of the western regions with the strongest fire-climate relationships, and maximum spring temperature was additionally important in the Southern and Northern Rockies.

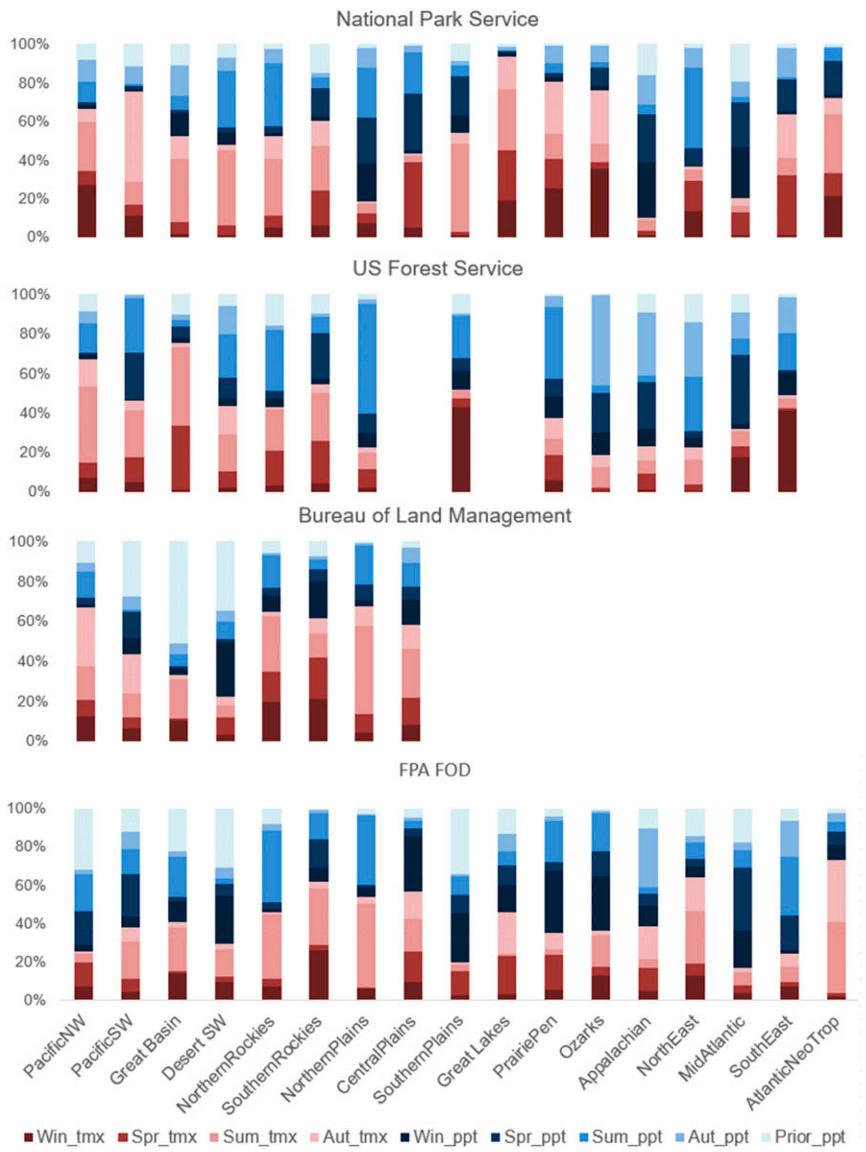

**Fig. 3.** Hierarchical partitioning results showing the percentage of independent variation in fire activity explained by seasonal temperature and precipitation variables for NPS, USFS, and BLM lands and for all public and privately owned lands using the FPA FOD. Aut, autumn; NW, Northwest; ppt, mean precipitation; PrairiePen, Prairie Peninsula; Spr, spring; Sum, summer; SW, Southwest; tmx, mean maximum temperature; Win, winter.

In the multiple-regressions using the FPA FOD data, the average variance in fire activity explained by climate was 42%, and in these data, there were six regions where climate explained >50% of the variation in annual fire activity (Table S2). These regions were either in the Southeast, Midwestern United States (Northern Plains, Prairie Peninsula, Ozarks Complex), or western United States (Northern Rockies, Great Basin). For these regions, high summer or winter temperatures were consistently important in the western regions and the Northern Plains, whereas hot spring and summer maximum temperatures were more important in the Prairie Peninsula or the Southeast. Low spring or summer precipitation was also important in these regions.

## The Importance of Climate Overall Varied Across Regions

The overall strength of fire-climate relationships varied substantially across the continental United States, both in terms of longer-term federal fire records and the shorter-term, more spatially comprehensive FPA FOD fire data (Fig. 4). Although climate variables explained >50% of the variation in fire activity in some regions, as described above, 10 of the 37 regions in the federal analysis and four of the regions in the FPA FOD analysis had adjusted $R^2$ values signifying ≤15% of the variance in fire activity could be explained by climate.

## Human Presence Was the Only Factor to Significantly Explain Differences in the Strength of Fire-Climate Relationships

Of the 10 different variables we explored to explain the variation in the strength of fire-climate relationships, none were statistically significant at $P \leq 0.05$ except for the anthropogenic variables (Table 1 and Figs. S1 and S2). In the federal data, regions in close proximity to either roads or developed areas had weaker fire-climate relationships; and in the FPA FOD data, regions with a higher mean human population and proportion of developed land had weaker fire-climate relationships.

## Discussion

Seasonal climate variation has played a significant role in explaining annual fire activity across the continental United

**Fig. 4.** Proportion of variance explained by top-ranking multiple regression models of seasonal climate influence on annual fire activity for (*A*) federal lands and (*B*) NEON domains in the continental United States.

States, but the relative importance of different variables, in addition to the overall importance of climate, varies substantially depending on geographical context. Why climate explains more fire activity in some regions than others is best explained by human presence. That is, in regions where human presence is more prominent, the importance of climate is lower on average. This suggests that, not only can humans influence fire regimes, as has been documented, but their presence can actually override, or swamp out, the effect of climate. This has serious implications for national fire policy and management as we move forward in this era of rapid global change.

Humans can affect wildfire patterns in a number of ways, from starting fires to managing fires (e.g., prescribed fire or fire suppression) and via changes in the abundance and continuity of fuel through land use decisions. For example, humans alter native vegetation through agriculture, urbanization, and forestry management practices. Although their geographical subdivisions were coarser than those used here, regions where lightning-started fires dominated in a recent nationwide analysis (27) show some alignment with areas here where fire-climate relationships were stronger, largely in the interior, northwestern part of the country. Nevertheless, although human-caused ignitions predominate across most of the country, there are also regions like the interior Southeast where fire-climate relationships were relatively strong but the cause of ignitions was nevertheless dominated by humans.

This suggests that human influence goes beyond just starting fires, and there is some combination of factors that leads to a dampening of the effect of climate on fire activity. This may be due to effective lengthening of the fire season (27), or starting fires in areas where naturally occurring fires are rare. On the other hand, fragmentation of fuels via land use and urban development may interrupt the spread of fires that would otherwise occur in a less human-dominated landscape. In this case, the climatological factors that might otherwise lead to fire spread are overridden by human-created landscape patterns. This dual effect of humans either increasing fire where it would not otherwise occur, or decreasing it where it would occur, may be why the overall amount of fire in a region was not significantly related to the importance of climate. A couple of other studies performed at smaller extents also suggest that human influence [i.e., suppression policy (40) or land use (33)] in addition to fuel quantity or quality (31, 33) can potentially mediate or dampen fire-climate relationships across different temporal scales.

**Table 1. Bivariate regression results for models exploring regional and anthropogenic biophysical characteristics' relation to variance explained by climate on annual fire activity**

| Variable | Coefficient | $R^2$ | $P$ value |
|---|---|---|---|
| Federal data | | | |
| Precipitation | −0.00005 | 0 | 0.35 |
| Temperature range | 0.02 | 0.00 | 0.31 |
| Elevation | 0.00005 | 0.02 | 0.17 |
| Slope | −0.0005 | 0.00 | 0.89 |
| Forest biomass | −0.003 | 0.00 | 0.41 |
| Vegetation | 0.286 | 0.06 | 0.07 |
| Distance to road | 0.00002 | 0.20 | 0.002 |
| Distance to developed | 0.000002 | 0.07 | 0.05 |
| Proportion of area burned | −1.12 | 0.00 | 0.65 |
| Proportion of number of fires | −0.06 | 0.03 | 0.15 |
| FPA FOD data | | | |
| Precipitation | −6 | 0 | 0.96 |
| Temperature range | −0.004 | 0 | 0.69 |
| Elevation | 0.0001 | 0.01 | 0.29 |
| Slope | 0.013 | 0.02 | 0.28 |
| Forest biomass | −0.0005 | 0.00 | 0.68 |
| Vegetation | 0.21 | 0.00 | 0.41 |
| (log) Population | −0.18 | 0.19 | 0.04 |
| Proportion developed | −2.99 | 0.20 | 0.03 |
| Proportion of area burned | 0.72 | 0.00 | 0.51 |
| Proportion of number of fires | 4.4 | 0.00 | 0.91 |

One of the most consistently important variables for explaining strong fire-climate relationships was prior-year precipitation, which is similar to results in other studies (e.g., refs. 28, 30, and 35). This relationship is often found in grasslands and savannahs where fire activity is fuel-limited. High precipitation appears to have a dampening effect on current-year fires but leads to high fuel loads in subsequent years, and the production of fine-fuel biomass that dries by the following year is conducive to fire spread (41). In forested ecosystems, this relationship has been shown to be present in forest types with herbaceous understories and absent in ones with understory fuels comprising litter and other downed material (42).

An important caveat to this study is the fact that the variance explained for the differences in strength of fire-climate relationships was not particularly high, and there was substantial variability in the data (Figs. S1 and S2). Therefore, despite evaluating the role of climatic or topographic variability, or variation in vegetation or forest biomass, differences in strength of fire-climate relationships may be due to additional factors. For example, temperature or precipitation patterns may be less variable in some regions than in others, meaning there is less annual variability in fire activity due to these variables. Another reason may be that the fire-climate models do not include essential factors such as localized fire-weather events, long-term drought, or lightning density, nor do they account for variable interactions or more complex variable combinations.

The record of fire history was only available spatially since the 1970s, and a longer-term history could have provided a more robust analysis. However, fire-climate relationships do vary over long time scales (33, 35, 40), and the findings here are representative of the most current conditions. These results thus provide important insight on contemporary drivers of fire activity across a time when climate has already been changing rapidly (43).

Climate change may indeed be a concern for those areas with strong fire-climate relationships. However, our results suggest that, in some areas, anthropogenic factors diminish the influence of climate on fire activity. Thus, to effectively understand how and where fire regimes may change in the future, anthropogenic factors must become a larger part of the conversation relative to national fire policy and management. In addition to incorporating anthropogenic factors such as land use into future fire projections (44), it will also be important to consider alternative management decisions in the context of human development. For example, land use or conservation planning decisions have the potential to alter fire risk to structures as well as biodiversity outcomes (45, 46). Further work on fire prevention strategies is another important avenue for future fire management and is likely to play very different roles on different landscapes.

## Materials and Methods

To develop our historical fire data, we assembled a comprehensive point-based spatial database of more than a million fires on federal agency lands. The more contemporary database beginning in 1992, the national interagency FPA FOD (47), provides more spatially extensive data that span all public and private lands. (See *SI Text* for additional details on data sources, assembly, and modeling.)

We used monthly PRISM 2.5 arc-minute historical climate data (www.prism.oregonstate.edu/) to derive and extract seasonal climate means to relate to annual fire data for NEON regions and for fire locations within those regions from 1972 to 2010. We defined winter as December through February, spring as March through May, summer as June through August, and autumn as September through November.

To quantify the relative and geographically varying importance of different climate variables in explaining fire activity, we used a hierarchical partitioning algorithm available in R (hier.part package, version 1.0-4 in R) (48, 49). Hierarchical partitioning, via a hierarchy of regression models using all combinations of explanatory variables, calculates the percentage of independent influence of each variable on the response, with or without its joint influence via other variables. Thus, it avoids issues of multicollinearity and provides a discrete quantification of relative variable importance. In addition to quantifying variable importance, we also developed multivariate models for the regions to account for the overall importance of climate in explaining annual fire activity. For every region, we selected the best-supported model, recorded the variables, and calculated the adjusted $R^2$ as a measure of total variance explained by climate.

To identify potential factors explaining the variation in strength of fire-climate relationships, we summarized a range of biophysical and human variables (Table 1) across the geographical extent of each region and related them to the adjusted $R^2$ values described above using bivariate linear regressions.

**ACKNOWLEDGMENTS.** We thank Lou Pitelka for convincing us of the value of utilizing NEON domains in our study. Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the US government.

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