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Environmental Research Letters

LETTER

Controls on interannual variability in lightning-caused fire activity in the western US

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Abstract

Lightning-caused wildfires account for a majority of burned area across the western United States (US), yet lightning remains among the more unpredictable spatiotemporal aspects of the fire environment and a challenge for both modeling and managing fire activity. A data synthesis of cloud-to-ground lightning strikes, climate and fire data across the western US from 1992 to 2013 was conducted to better understand geographic variability in lightning-caused wildfire and the factors that influence interannual variability in lightning-caused wildfire at regional scales. Distinct geographic variability occurred in the proportion of fires and area burned attributed to lightning, with a majority of fires in the interior western US attributed to lightning. Lightning ignition efficiency was highest across the western portion of the region due to the concomitance of peak lightning frequency and annual nadir in fuel moisture in mid-to-late summer. For most regions the number of total and dry lightning strikes exhibited strong interannual correlation with the number of lightning-caused fires, yet were a poor predictor of area burned at regional scales. Commonality in climate–fire relationships for regional annual area burned by lightning- versus human-ignited fires suggests climate conditions, rather than lightning activity, are the predominant control of interannual variability in area burned by lightning-caused fire across much of the western US.

1. Introduction

Lightning is a significant contributor to area burned globally, a predominant contributor to area burned in sparsely populated areas such as boreal systems (e.g., Stocks *et al* 2002), and accounts for nearly two-thirds of burned area in the western United States (US) (e.g., Pyne *et al* 1996, Stephens 2005). Unlike the more slow-evolving and predictable environmental contributors to wildfire potential, such as fuel accumulation or drought, the stochastic nature of lightning presents a number of challenges both to fire management seeking to predict lightning-caused fire outbreaks, as well as to researchers seeking to model future wildfire activity under anthropogenic climate change. Regional outbreaks of lightning accompanied by inconsequential precipitation (i.e., dry lightning) that reach a receptive fuel bed can result in widespread concurrent ignitions that compromise fire suppression efforts (Rorig and Ferguson 2002). Although lightning-ignited fires often occur in remote areas and are a natural biophysical process, they are often suppressed due to either secondary fire impacts, such as smoke-related degradation of regional air quality (e.g., McKenzie *et al* 2014), or due to concerns that fire growth will eventually threaten infrastructure. Additionally, differences in fire effects between human-caused and lightning-caused fire (e.g., Miller *et al* 2012, Whitman *et al* 2015) could alter post-fire ecological succession. The unique risks to infrastructure and ecosystems posed by lightning highlights the need to identify and understand patterns of lightning-caused wildfire.

While lightning strikes are a prerequisite for lightning-ignited fire at local scales, lightning density is poorly spatially correlated to area burned at broad spatial scales (e.g., Krawchuk *et al* 2009), suggesting that

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other factors shape regional lightning-caused fire activity. These factors likely include fuel moisture, type and abundance (e.g., Flannigan and Wotton 1991), vapor pressure deficit (VPD) (e.g., Sedano and Randerson 2014), lightning multiplicity and polarity (e.g., Fuquay 1982) and how much precipitation accompanies lightning (Dowdy and Mills 2012). Collectively, these factors influence lightning ignition efficiency (LIE), defined as the percent of lightning strikes that result in an ignition (e.g., Latham and Williams 2001).

Previous studies have attempted to understand how climate, fuels and lightning activity control interannual variability in regional area burned, however a comprehensive analysis examining the relative importance of these factors and how they vary geographically is lacking at the present time. Wildfire regimes are a function of (i) fuel mass, (ii) fuel moisture, and (iii) ignitions. The degree to which wildfires are fuel-limited (e.g., insufficient fuels to carry fire), climate-limited (e.g., fuels are too moist for combustion), ignition-limited (e.g., insufficient lightning strikes in fuel-rich and seasonally dry environments), or some combination thereof is important for understanding seasonal wildfire risk under current and future climate scenarios. Regional studies have shown promising interannual relationships between the frequency of lightning strikes and lightning-caused fire activity (e.g., Hall 2007, Sedano and Randerson 2014) suggesting that lightning frequency may be a limiting factor for area burned at interannual timescales. Variability in regional lightning frequency has been linked to concurrent variability in atmospheric circulation and moisture (e.g., van Wagtendonk and Cayan 2008). By contrast, climatic conditions influence both ignition efficiency (e.g., Krawchuk *et al* 2006) and fire growth (e.g., Abatzoglou and Kolden 2011) suggesting that climate may also be a limiting factor of interannual fire activity.

Empirical models of annual area burned for both contemporary and future periods generally incorporate climate variability do not typically incorporate ignitions as predictors (e.g., Flannigan *et al* 2009, Moritz *et al* 2012, Barbero *et al* 2015). Increased lightning frequency resulting from enhanced convective available potential energy under future climate conditions (e.g., Romps *et al* 2014) may result in increased fire activity in ignition-limited fire regimes. Explicit attempts to account for changes in lightning in modeling future fire activity have rarely been made, largely due to inadequate knowledge of the scale at which lightning is limiting with respective to wildfire activity. In a process-based model, Krause *et al* (2014) found that observed and projected changes in climate were the dominant driver of changing wildfire activity at global scales, but that changes in climate and lightning activity could have comparable influences at regional scales.

Studies that link wildfire and climate have generally not distinguished between human and lightning-caused fires (e.g., Westerling *et al* 2003, Littell *et al* 2009; although see Reineking *et al* 2010, Magnussen and Taylor 2012). Climate–fire relationships for human-caused fires and lightning-caused fires may differ through a number of potential mechanisms. First, differences in the seasonality of human-caused versus lightning-caused fires may alter linkages between fire activity and both antecedent and concurrent climate. Secondly, the higher suppression priority of human-caused fires, given that they are usually closer to infrastructure than lightning fires (e.g., Miller *et al* 2012), may dampen the relationship between climate variability and annual area burned in human-caused fires. While human-caused fires are generally started at a single ignition point, promptly reported, and have higher probability of suppression, lightning-ignited fires can be synchronously ignited across a landscape, go undetected for several days until weather conditions favor combustion and fire spread (e.g., Flannigan and Wotton 1991), and therefore likely have lower probability of suppression. Thirdly, interannual variability in lightning (e.g., potential ignitions) could influence lightning-caused fire activity, particularly in ignition-limited systems.

This study seeks to address knowledge gaps in understanding factors that control interannual variability in lightning-caused fire activity across varied fire regimes in the western US in contrast to human-caused fire activity. The null hypothesis is that there are no distinct differences in climate–fire relationships between ignition types. This hypothesis suggests that interannual variability in fuel abundance and flammability, rather than ignitions, limits area burned (e.g., Knorr *et al* 2014) and infers that there should be interannual coherence in area burned by lightning-caused and human-caused fires. Alternatively, lightning ignitions may be limiting such that interannual variability in fire activity is correlated with lightning activity.

2. Data/methods

We constrain our analysis to the coterminous western US west of 102°W longitude, which included over 470 000 wildfires from 1992 to 2013 that collectively burned over 26 million ha. The western US encompasses a diverse set of ecotypes and associated fire regimes that have experienced abundant fire activity including particularly large fires in recent decades (e.g., Barbero *et al* 2014, Dennison *et al* 2014). We further examined relationships at Baileys ecoprovince levels given the commonality in fire regimes and climate–fire relationships as mediated through similar vegetation assemblages (e.g., Littell *et al* 2009). Although there is some heterogeneity in vegetation, land-use and human footprint at such scales, ecoprovinces represent a compromised scale of analysis, as

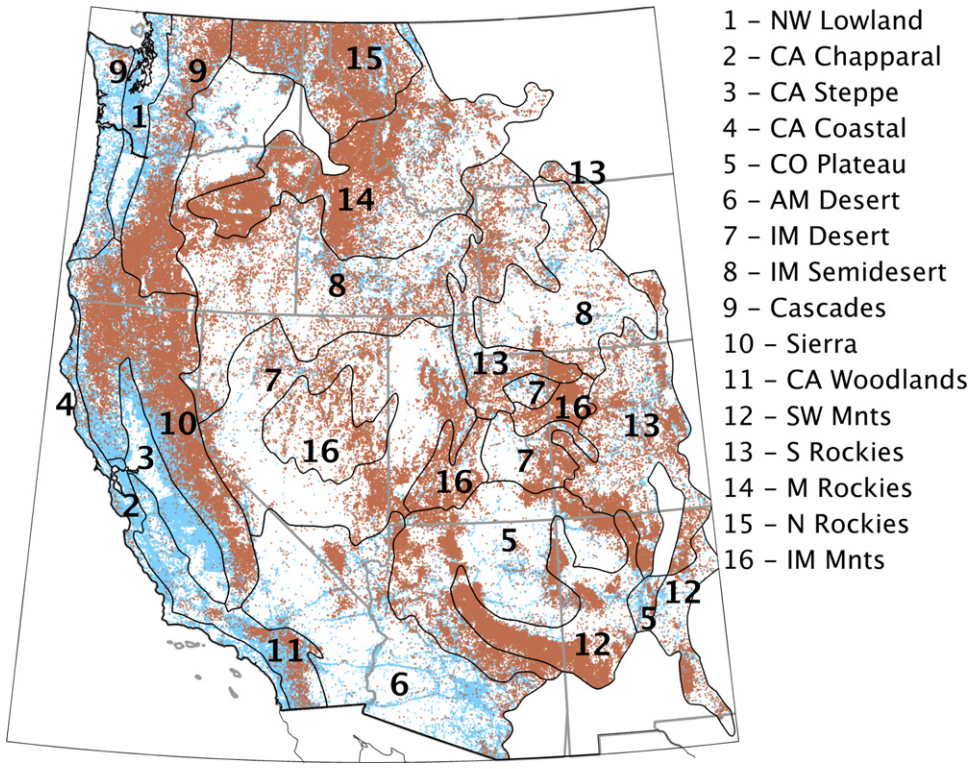

Figure 1. Ecoprovinces of the western United States (see table S1 for full names). The distribution of individual fires attributed to lightning and human ignitions are shown by the brown and blue markers, respectively.

they are broad enough to encompass sufficient information for statistical purposes (i.e., sample sizes). Our analysis focuses on the 16 ecoprovinces completely contained within the western US (figure 1).

2.1. Datasets

Short (2014) compiled a quality-controlled database of geo-referenced fire records from multiple reporting sources with particular effort to minimize redundant reports and inconsistencies in previous fire data collections. These data include fires of all sizes; we examined fires at least 0.04 ha in size. Fires with causes that were missing or undefined were excluded from subsequent analysis, accounting for 6.5% of fires. Human-caused fires were regarded as any fires not ignited by lightning. Prescribed fires were excluded from the database except those reported as escaped burns, and therefore became human-caused wildfires. Individual fires were assigned to ecoprovince based on point of origin.

Daily surface meteorological variables on a 4 km grid were acquired from Abatzoglou (2013). These data were subsequently used to calculate several metrics with demonstrated links to fire activity including energy release component (ERC), VPD, precipitation amount, and Palmer drought severity index (PDSI). ERC, an index of the United States National Fire Danger Rating System, represents the potential daily fire intensity for a given fuel type (here, fuel model G; dense conifer with heavy fuels, as commonly used by regional fire management) exposed to the cumulative drying effect of daily weather conditions. Several studies have documented strong relationships between subseasonal and interannual variability in ERC and fire activity (e.g., Abatzoglou 2013, Barbero *et al* 2014). VPD represents the absolute difference in water vapor content of the air and the water holding capacity of the atmosphere and has established links to water stress of vegetation and rate of fuel drying (e.g., Anderegg *et al* 2012, Williams *et al* 2013) and interannual variability in burned area (e.g., Balch *et al* 2008, Morton *et al* 2013, Sedano and Randerson 2014, Williams *et al* 2015). Finally, we calculated PDSI using reference potential evapotranspiration (ET_o) estimated using the Penman–Montieth protocol (Allen *et al* 1998) and precipitation fields. PDSI has been extensively used as an indicator of longer-term drought (>6 months) and has established links to interannual fire variability (e.g., Westerling *et al* 2003). We also examined monthly mean temperature and ET_o, but do not report results here as the aforementioned variables demonstrated stronger correlations.

Cloud-to-ground (CG) lightning strike data was acquired from two sources: (1) National Lightning Detection Network from 1992 to 2009, and (2) North American Precision Lightning Network from 2010 to 2013. CG lightning data included information on the date, time, location, polarity, peak current and multiplicity (number of strokes per flash). These networks both have reported detection efficiency of 95% and

spatial accuracy typically within 500 m in the western US. Temporal inhomogeneities in lightning data have been noted due to the evolution of the lightning detection network and sensor sensitivity; we removed low intensity positive charges (<10 kA) as they are likely indicative of non-CG lightning strikes (Orville *et al* 2002). This largely removes interannual step-changes in the number of lightning strikes associated with increased detection sensitivity, although additional inhomogeneities in the lightning dataset may exist for parts of the region. Potential inhomogeneities in lightning data across the two datasets (1992–2009; 2010–2013) did not alter our results, as correlation analyses that used lightning frequency from 1992 to 2013 versus 1992 to 2009 were similar.

Lightning strike points were aggregated to 0.01° resolution (~1 km) grid to create a gridded daily lightning density product. We then used co-located fields of daily lightning density (1 km) and daily precipitation (4 km grid) to qualify the occurrence of dry lightning using a threshold of <2.5 mm of daily-accumulated precipitation on the day concurrent to the lightning strike (e.g., Rorig and Ferguson 1999, Dowdy and Mills 2012). While several shortcomings exist with this approach, including lack of knowledge of the timing or duration of precipitation relative to lightning and challenges capturing the heterogeneous nature of convective precipitation with gridded precipitation products, it provides an approach for estimating dry lightning and is consistent with foundational studies (e.g., Rorig and Ferguson 1999).

2.2. Analyses

We conducted four distinct analyses. First, we developed a wildfire atlas stratified by fire-cause across the western US for the primary fire season of May–October for the 22 year period to examine geographic and seasonal variability in lightning-ignited fire activity. This involved characterizing both the percent of fires and the area burned attributed to lightning. We also calculated LIE as the percent of total lightning strikes that resulted in a reported lightning-ignited fire from the Short (2014) database. This approach likely underestimates LIE, as multiple ignitions that merge into individual named fires or complexes count as a single ignition, and ignitions that do not grow large enough to garner attention are not reported. We characterized both the climatology of dry lightning density and the percent of lightning strikes co-occurring with <2.5 mm of precipitation. Statistics were summarized by ecoprovince; however, we also examined statistics at sub-ecoprovince scales by aggregating fires to a 1/8th degree (~12 km) resolution grid, and lightning statistics to a 1/24th degree (~4 km) resolution grid.

Second, we examined interannual relationships between fire data stratified by cause to elucidate any regional commonalities in the number of lightning-caused fires or area burned at regional scales to one another or to human-caused fire activity. We conducted a correlation analysis of the interannual variability in aggregated fire statistics at ecoprovince scales between the (i) number of lightning-caused fires and human-caused fires, (ii) annual area burned in lightning-caused and human-caused fires, and (iii) number of lightning-caused fires and area burned by lightning-caused fires. We used spearman rank correlation for calculations that included the number of fires and Pearson's correlation of base-10 logarithm of area burned for those that did not involve the number of fires. We refer to results as statistically significant where $p < 0.05$.

Third, we examined interannual univariate climate–fire relationships separately for lightning-caused fires and human-caused fires at ecoprovince scales. We constrained this analysis to the 11 of 16 regions that had at least 10% of area burned and number of fires attributed to lightning or human causes. Climate data were spatially aggregated for each ecoregion and temporally aggregated to monthly timescales. Following Abatzoglou and Kolden (2013), we computed Pearson's correlation coefficients between the base-10 log of area burned and the following climate variables averaged over a range of time intervals: (i) monthly averaged ERC and VPD ending in May–October averaged over the previous 1–6 months, (ii) accumulated monthly precipitation ending in January–October averaged over the previous 1–12 months, and (iii) monthly PDSI from January a year prior to the fire season through October the year of the fire season. The maximum absolute correlations were reported for each ecoprovince-climate variable separately for both human-caused fire and lightning-caused fire. Although multivariate and nonlinear statistical approaches have been used to develop climate–fire models (e.g., Balshi *et al* 2009, Littell *et al* 2009, Higuera *et al* 2015), we use simple univariate correlative analysis as it is a widely used and transparent means of assessing relationships and facilitates a straightforward way to compare climate–fire and lightning–fire relationships.

Finally, to test how variability in lightning activity influenced regional lightning-caused fire activity, we examined interannual correlations between May–Oct ecoprovince lightning density and both the number of lightning-caused fires and base-10 logarithm of area burned in lightning-caused fires. This analysis was repeated using dry-lightning density as the response variable instead of lightning density. We also calculated correlations between LIE and summer (JJA) precipitation, ERC, VPD and August PDSI to better examine how climate variability influenced ignition probability.

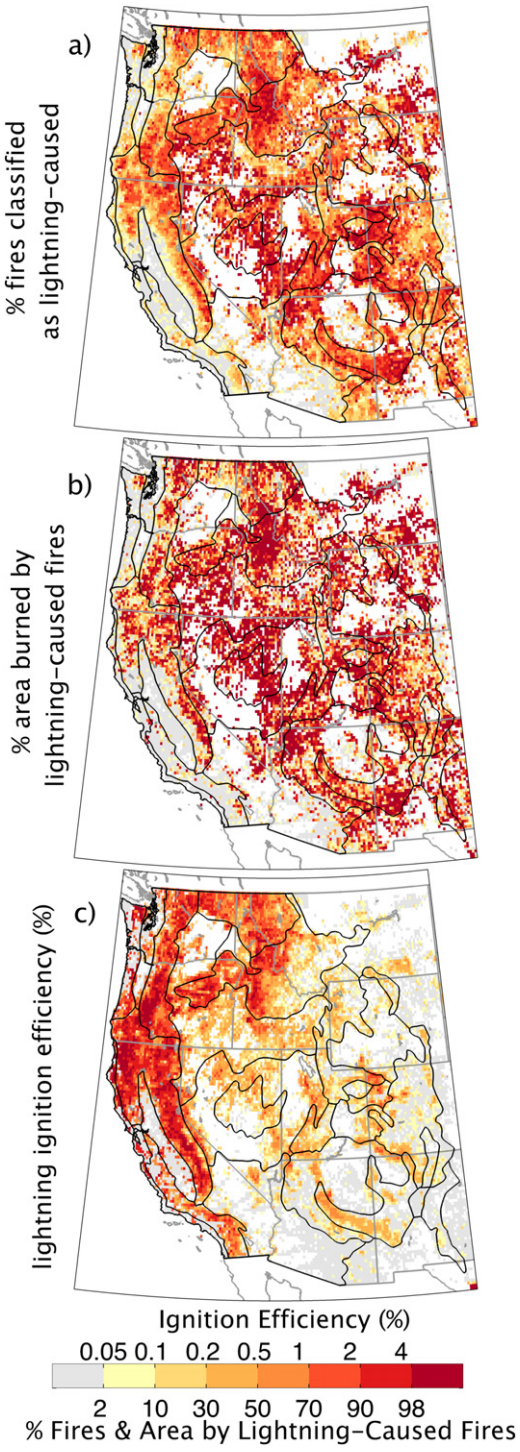

Figure 2. Map of percent of (i) fires and (ii) area burned due to lightning, and (iii) lightning ignition efficiency for all fires May–Oct 1992–2013. Wildfires within each 1/8th degree resolution grid were aggregated. Pixels with fewer than 4 fires over the study period were masked out.

3. Results

3.1. Geographic and seasonal variability

Lightning ignited 40% of the reported wildfires and accounted for approximately 69% of the total area burned across the western US from 1992 to 2013, albeit with distinct geographic variability (figures 2(a) and (b)). Lightning was the dominant source of wildfire in most mountainous regions, and contributed to nearly all (>98%) of the area burned within portions of these ecoprovinces, particularly across remote areas that may be of lower priority for suppression, more difficult to access, or have abundant fuel (table S1). Conversely, lightning-ignitions accounted for less than 15% of all fires in near-coastal and southwestern deserts ecoprovinces. Distinct gradients in the proportion of fires attributed to lightning can be seen across some ecoprovinces, including the Sierra Nevada, where fires in the western foothills were nearly all human-ignited, while fires at higher elevations and along the eastern slopes were primarily lightning-ignited. Seasonal variability in the proportion of fires attributed to lightning was evident (figures 3(a)–(c)) with 54 and 61 percent of all fires over the western US ignited by lightning in July and August fires, respectively, whereas the proportion of fires attributed to lightning declines in the shoulder months (e.g., 19% in April, 35% in May, 40% in September).

Geographic variability in LIE highlights regional differences in the probability of a lightning strike igniting a fire (figure 2(c) and table S1). Ignition efficiency was low (<0.05%) across much of the arid southwestern US where contiguous fuels may be limiting. Conversely, LIE values >1% were common across the Sierra Nevada and Cascade ranges including LIE >3% in coastal California, as well as western portions of the Middle and Northern Rockies where fuels are abundant. A seasonal increase in LIE during mid-summer across most ecoprovinces across the northern and western US (figures 3(d)–(f)) occurs as the percent of lightning occurring as dry lightning is relatively high and lightning seasonality is well synchronized with the annual nadir in fuel moisture. Conversely, LIE wanes across the southern portion of the study area in mid-summer when the arrival of monsoonal moisture increases both fuel moisture and the proportion of lightning strikes accompanied by wetting precipitation (>2.5 mm).

The southwestern US, including Arizona and New Mexico, has the highest dry lightning strike density. Conversely, areas west of the Cascades, Sierra Nevada and coast ranges of southern California that are typically affected by stable maritime air masses in summer experienced the lowest dry lightning strike density (figure 4(a) and table S1). Sharp gradients in lightning density were seen in the lee of the Sierra Nevada and southern Cascades and south of the Snake River Plain in southern Idaho in the Intermountain Semidesert ecoprovince. The percent of lightning strikes that occur as dry lightning was highest over arid portions of the intermountain west including parts of the Intermountain Semidesert, Intermountain desert and American desert ecoprovinces, whereas the ratios were substantially lower across the SW mountains, and Southern Rockies ecoprovinces (figure 4(b) and table S1).

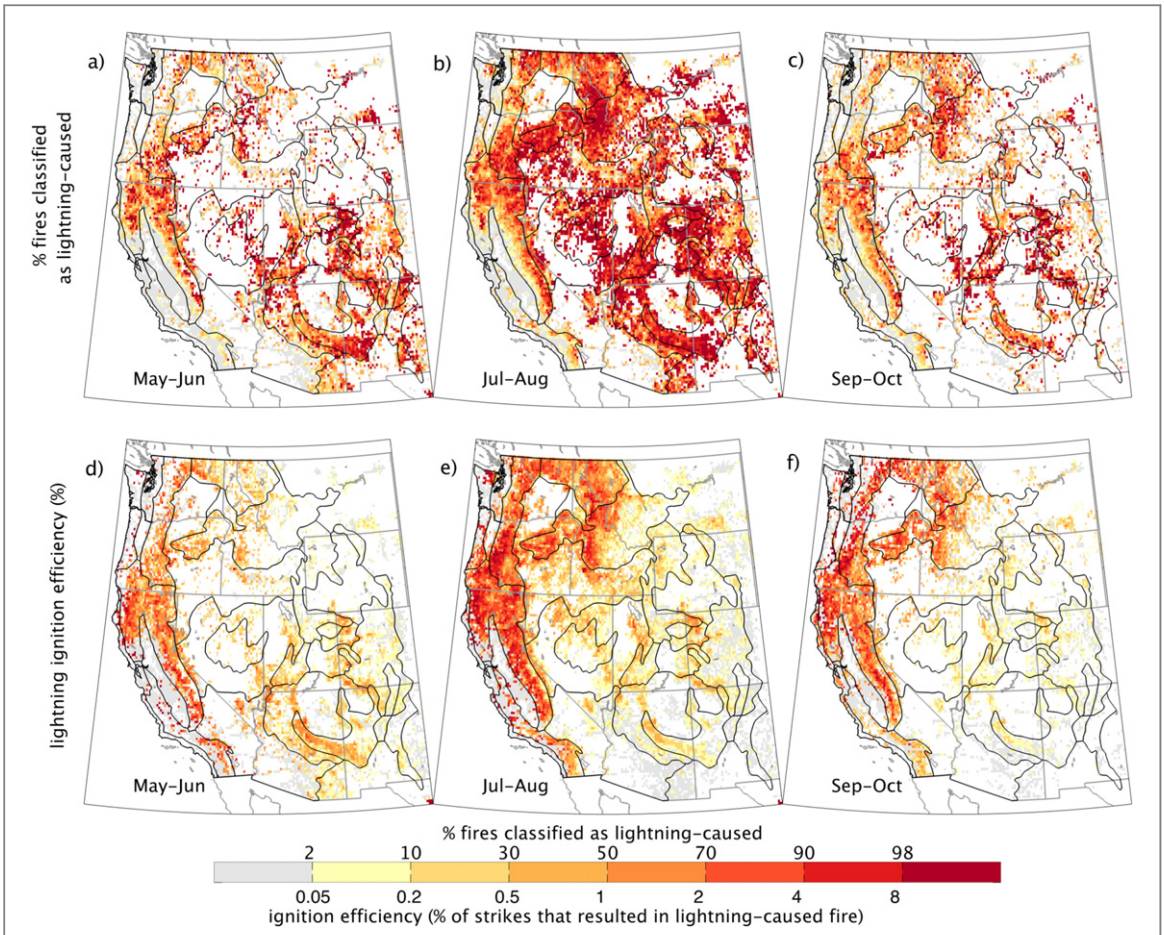

Figure 3. Bimonthly maps of the percent of fires as lightning-caused (top) and lightning ignition efficiency (bottom) for 1992–2013 aggregated to a 1/8th degree grid. Pixels with fewer than 4 fires for a given month over the study period are masked out.

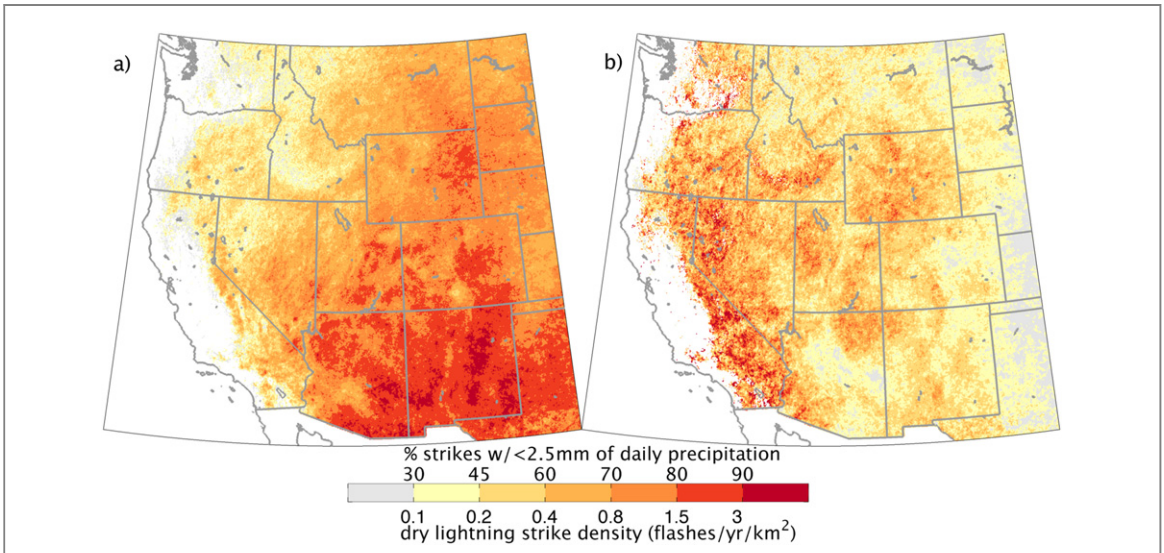

Figure 4. Density of dry lightning (a) and percent of total lightning strikes occurring as dry lightning (b) averaged over May–Oct 1992–2013 aggregated to a 1/24th degree grid. Pixels with fewer than 0.1 combined wet and dry strikes per year per km^2 are masked out.

3.2. Interannual variability: lightning- and human-caused fire

The numbers of human- and lightning-caused fires exhibited significant correlation on interannual timescales in only 6 ecoprovinces (figure 5(a)), with the highest correlation ($r = 0.69$) found for the American Desert ecoprovince. In contrast, significant correlations between annual area burned by lightning-ignited fire and area burned by human-ignited fires were found in all but one ecoprovince (Southwestern

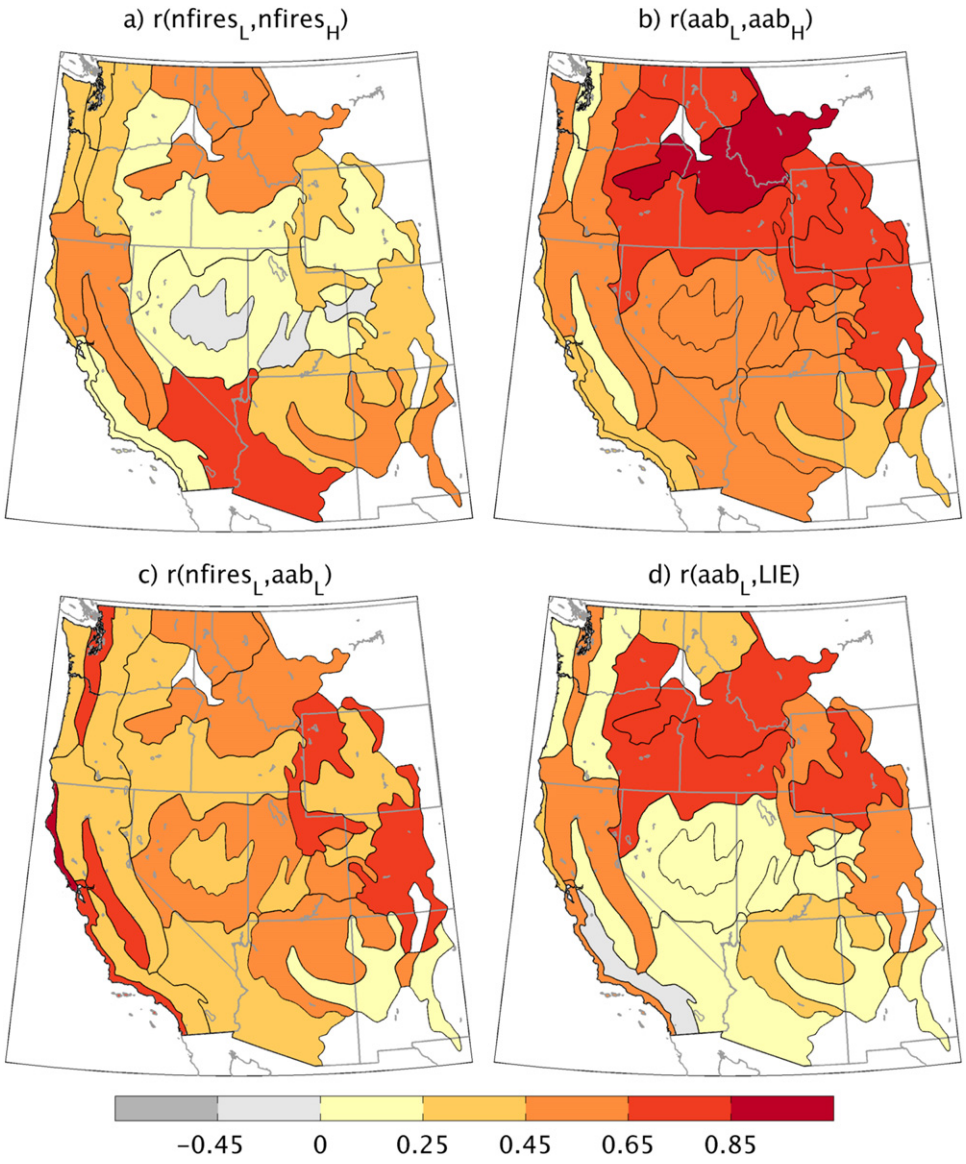

Figure 5. Interannual correlation for 1992–2013 between (a) the number of lightning-caused and human-caused fires, (b) area burned by lightning-caused and human-caused fires, (c) the number of lightning-caused fires and area burned by lightning-caused fires, and (d) area burned by lightning-caused fires and May–Oct lightning ignition efficiency (LIE) for each of the 16 ecoprovinces. Statistically significant correlations ($p < 0.05$) exceed an absolute value of 0.45 and corresponding with discrete transitions on the colormap.

Mountains) where no more than 90% of total area burned was attributed to only one ignition type (figure 5(b)). Finally, the number of lightning-ignited fires and annual area burned exhibited significant correlation across a number of ecoprovinces (figure 5(c)).

3.3. Interannual variability: climate influence on lightning- and human-caused fire

Climate–fire correlations for area burned by lightning-caused and human-caused fires were quite similar (figure 6). Strong correlations ($|r| > 0.5$) were found with ERC, VPD, precipitation and PDSI concurrent to the fire season in strongly climate-limited regimes where variations in fuel moisture can enable or limit ignitions and fire spread. Conversely, PDSI and precipitation antecedent to the fire season exhibited strong positive correlations with area burned in strongly fuel-limited regimes where fuel build-up during wet periods can increase fuel connectivity and enhance fire spread during subsequent fire seasons. On average, climate variables explained around 5% more variance for area burned by lightning-caused fire than area burned by human-caused fire. However, the optimal seasonal windows for correlations did not vary in a consistent way between lightning-caused and human-caused fires.

3.4. Interannual variability: lightning and fire

The number of lightning-ignited fires and both the total number of lightning strikes and dry lightning strikes were correlated in several ecoregions across years (figures 7(a) and (b)). However, while dry lightning strikes were a strong predictor of number of fires,

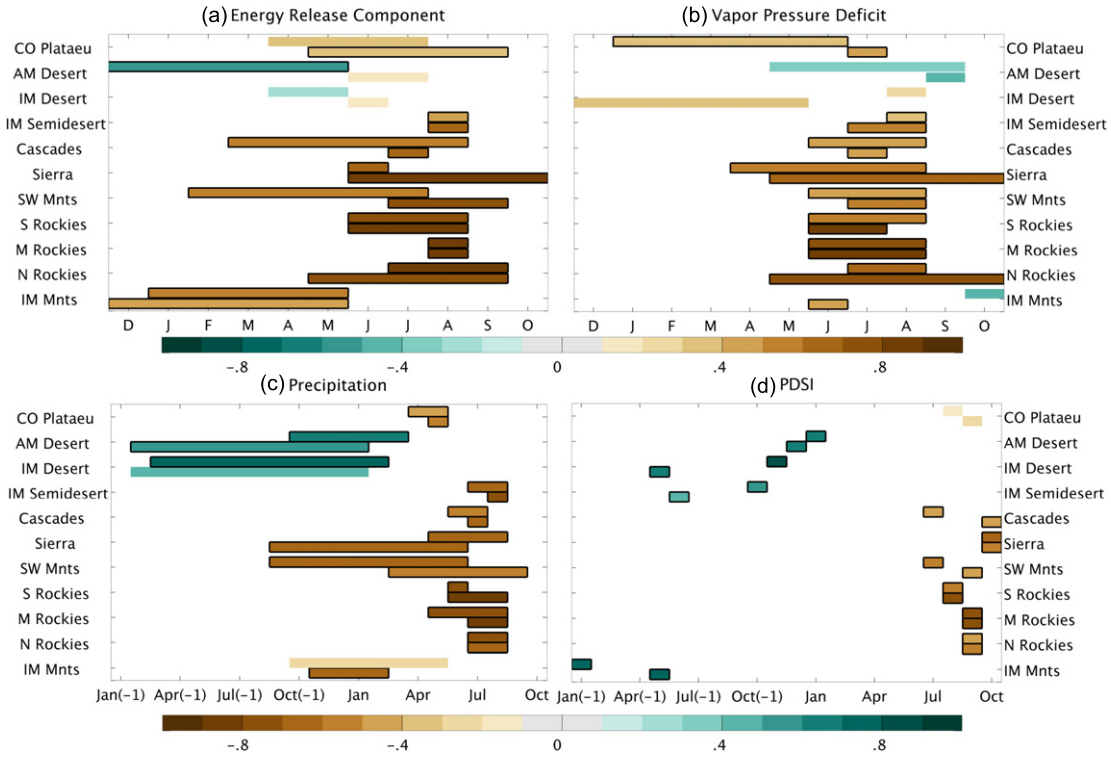

Figure 6. Strongest interannual correlations between the base-10 logarithm of annual area burned and (a) energy release component, (b) vapor pressure deficit, (c) precipitation, and (d) Palmer drought severity index (PDSI). Correlations to annual area burned in human-ignited fires are shown directly above those to annual area burned in lightning-ignited fires for the 11 different ecoprovinces with the colors corresponding to the calculated *r*-values. The seasonal window coinciding with maximum correlation to each variable is represented by the starting and ending points on the *x*-axis. For (c) and (d) the *x*-axis shows data from January the year prior to the fire season to October the year of the fire season. The colormap in panels (c) and (d) is reversed for consistency with panels (a) and (b) such that brown indicates positive correlations with aridity. Statistically significant correlations ($p < 0.05$) are denoted by a black border around each line shown.

they were a poor predictor of area burned (figures 7(c) and (d)). The exceptions were positive correlations with area burned for several ecoprovinces in California and the Cascade ecoprovince that experience limited dry-lightning activity, and a negative correlation for the Intermountain Semidesert ecoprovince.

Significant positive correlations between LIE and area burned by lightning-caused fires were found in 6 ecoprovinces (figure 5(d)). LIE also exhibited strong correlations with summer ERC, precipitation and August PDSI in a number of ecoprovinces (table S2). For example, August PDSI had significant negative correlations ($r = -0.62$ to -0.47) with LIE in 8 of the 11 ecoprovinces with an appreciable amount of lightning-ignited wildfire.

4. Discussion

Lightning is the ignition source for 69% of the area burned and 40% of the total number of wildfires at least 0.04 ha in size across the western US from 1992 to 2013 (figure 2(b)). However, the number of lightning strikes and annual area burned in lightning-ignited fires is poorly correlated regionally on interannual timescales (figure 7(d)). Instead, annual area burned in lightning-ignited fires is strongly correlated to interannual climatic factors related to fuel abundance and flammability. These findings suggest that variability in climate and fuels rather than in lightning strikes is the primary control of regional area burned by lightning-caused fires across much of the western US. Exceptions are evident in ecoprovinces where summer lightning is more rare and not the dominant source of fire activity (e.g., coastal California, figure 7(d)).

Our results reinforce the notion that climate variability shapes the abundance, ignition efficiency and combustibility of fuels that enable fire growth and ultimately annual area burned irrespective of ignition sources. Consistent with prior studies that did not distinguish between lightning- and human-ignited fires, ERC, VPD and precipitation during the fire season were the leading correlates to area burned in climate-limited systems, whereas antecedent moisture was important in fuel-limited systems (figure 6; e.g., Westerling *et al* 2003, Littell *et al* 2009, Abatzoglou and Kolden 2013, Williams *et al* 2015, Williams and Abatzoglou 2016). Slightly stronger correlations between climate and area burned in lightning-ignited fire versus human-caused fire is consistent with Parks *et al* (2014) who showed notably weaker relationships in regions highly influenced by humans and dominated by human-ignited wildfire. While we failed to

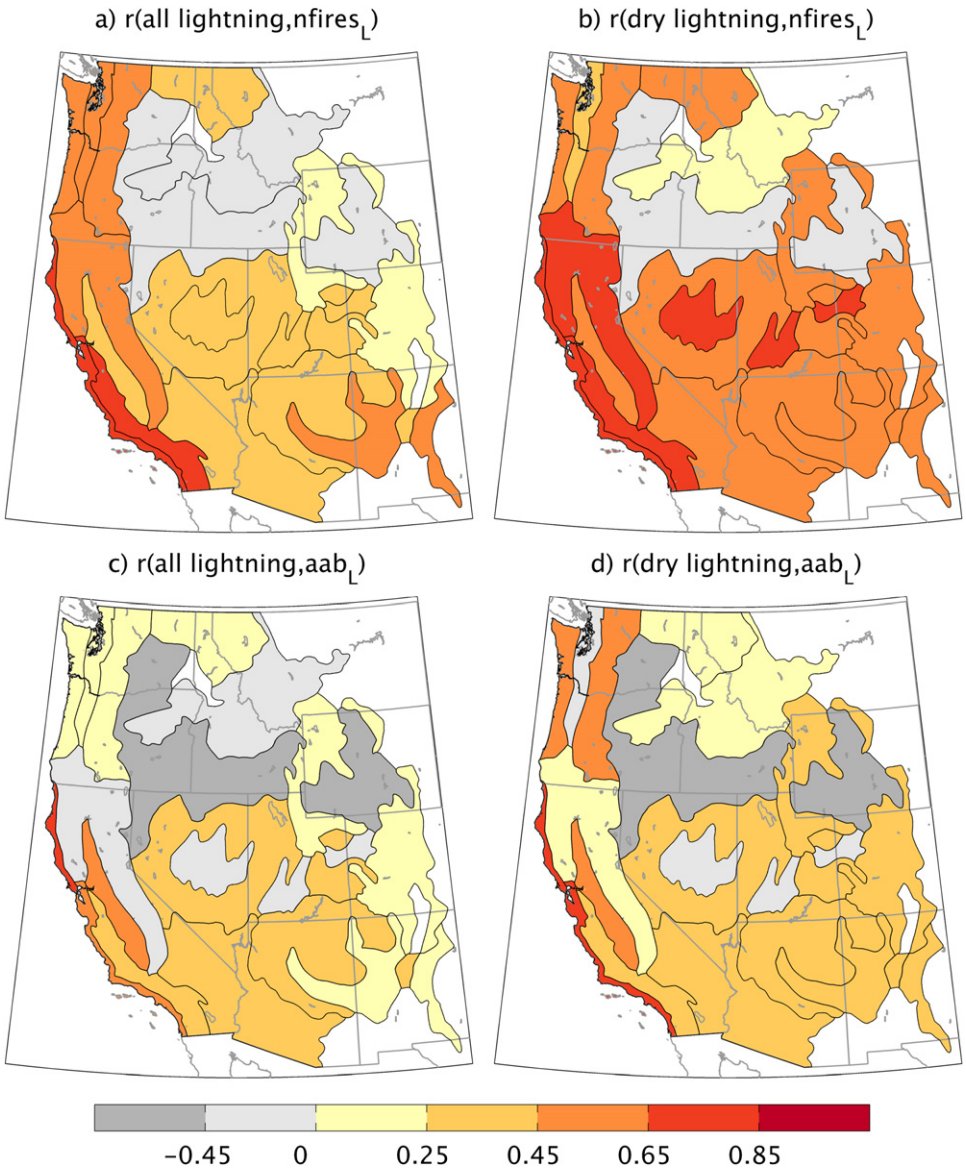

Figure 7. Interannual correlation for 1992–2013 between (a) the number of May–Oct lightning strikes and number of lightning-caused fires, (b) the number of May–Oct dry lightning strikes and number of lightning-caused fires, (c) the number of May–Oct lightning strikes and annual area burned, and (d) the number of May–Oct dry lightning strikes and annual area burned for each of the 16 ecoprovinces. Statistically significant correlations ($p < 0.05$) exceed an absolute value of 0.45 and correspond with discrete transitions on the colormap.

find evidence of substantial differences in climate–fire relationships between human-ignited and lightning-ignited fire at ecoprovince scales, differences could be evident at smaller geographic scales. For example, additional analyses could test for differences in climate–fire relationships when stratified by fire cause where regional policies emphasize fire restrictions during drought periods.

While dry-lightning strikes were a poor predictor of annual area burned, they were strongly correlated with the number of lightning-ignited fires at regional scales. This suggests that lightning strikes are an important limit on interannual fire frequency, but not area burned, at broad scales across the western US. The correlation between the number of fires and annual area burned by lightning-ignited fires for a majority of ecoprovinces is likely mediated by climate variability. For example, in climate-limited systems, a decline in fuel moisture increases LIE (table S2; e.g., Lutz *et al* 2009) and sustained low fuel moistures post-ignition would also enable fire growth (e.g., Flannigan and Wotton 1991, Abatzoglou and Kolden 2011, Barbero *et al* 2014). The approach we used to relate lightning and wildfire activity at interannual timescales fails to incorporate the spatiotemporal distribution of lightning within an ecoprovince. Additional information on the importance of lightning-occurrence on wildfire activity may be gleaned by accounting for fuel aridity concurrent with dry lightning events (e.g., Krawchuk *et al* 2006).

We additionally present the first known regional assessment of the spatial and temporal distribution of

dry lightning strikes, LIE, and percent of fire activity attributed to lightning for the western US. Geographic and seasonal variability in the proportion of fires attributed to lightning was similar to that of Bartlein *et al* (2008). Geographic variability in the proportion of area burned by lightning-caused fire was apparent across the western US, consistent with previous macroscale (e.g., Stephens 2005) and regional (e.g., Hall 2007, Lutz *et al* 2009) analyses. Complementary to macroscale variability, sharp sub-ecoprovince variability is likely a product of gradients in dry lightning strike density, fuel moisture and abundance as well as biophysical factors such as fuel type that influence ignition efficiency. For example, mesic vegetation located in cooler and wetter areas within an ecoprovince may not be flammable until the summer months when lightning activity peaks (e.g., Whitman *et al* 2015). Likewise, invasive annual grasses that contribute to higher and more contiguous fine fuel loads in semi-arid ecosystems may enhance ignition potential in regions they have invaded relative to pre-existing vegetation (e.g., Balch *et al* 2013).

5. Conclusions

Lightning frequency does not appear to be a limiting factor of interannual area burned at regional scales for most of the western US. This finding is consistent with global (Krawchuk *et al* 2009) and continental analyses (Archibald *et al* 2009), which also suggest that ignitions are not a limiting factor for fire activity at large scales. While our study examined these relationships at broad ecoprovince scales, the conclusions are likely scale-dependent as ignitions are hypothesized to be an increasingly important factor at smaller scales while climate variability explains less variance at smaller scales (e.g., Urbieta *et al* 2015).

Our results have implications for both empirical and processed-based modeling of wildfire. Whereas many processed-based fire models are ignition-limited (e.g., Kloster *et al* 2010), regional annual area burned in fire-prone regions of the interior western US do not appear to be limited by interannual variability in lightning. While studies suggest an increase in lightning frequency across the contiguous US due to anthropogenic climate change (Romps *et al* 2014), its impact on future fire activity is unknown outside of a few modeling studies (e.g., Krause *et al* 2014). Our results suggest that changes in lightning activity in parts of the western US where lightning ignitions are not limited on interannual timescales will have minimal impact in modifying empirical or processes based projections of regional area burned that are unable to account for lightning activity.

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