

Article

Human-Related Ignitions Increase the Number of Large Wildfires across U.S. Ecoregions

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Abstract: Large fires account for the majority of burned area and are an important focus of fire management. However, ‘large’ is typically defined by a fire size threshold, minimizing the importance of proportionally large fires in less fire-prone ecoregions. Here, we defined ‘large fires’ as the largest 10% of wildfires by ecoregion ($n = 175,222$ wildfires from 1992 to 2015) across the United States (U.S.). Across ecoregions, we compared fire size, seasonality, and environmental conditions (e.g., wind speed, fuel moisture, biomass, vegetation type) of large human- and lightning-started fires that required a suppression response. Mean large fire size varied by three orders of magnitude: from 1 to 10 ha in the Northeast vs. >1000 ha in the West. Humans ignited four times as many large fires as lightning, and were the dominant source of large fires in the eastern and western U.S. (starting 92% and 65% of fires, respectively). Humans started 80,896 large fires in seasons when lightning-ignited fires were rare. Large human-started fires occurred in locations and months of significantly higher fuel moisture and wind speed than large lightning-started fires. National-scale fire policy should consider risks to ecosystems and economies by these proportionally large fires and include human drivers in large fire risk assessment.

Keywords: large wildfire; anthropogenic wildfire; fire regime; ecoregion; fire season; fire program analysis fire occurrence dataset

1. Introduction

Large wildfires have important economic, societal, and ecological costs and threaten infrastructure, ecosystems, and human life. As recent examples in the U.S., the Chimney Tops 2 fire in Tennessee in November–December 2016 burned ~6900 ha and led to the loss of 700 structures and 13 fatalities, while the Soberanes fire in California in 2016 burned over 53,000 ha and was the most expensive fire in U.S. history to suppress, costing over \$250 million U.S. dollars [1]. The frequency of large wildfires has increased over the last several decades in the U.S. [2–7], boreal forests of North America [8], central Asia and Russia [9], and in the western Mediterranean [10] (but decreased across the whole Mediterranean [11]). Additionally, more large fires are expected in the future with more severe fire danger in the U.S. [7,12], Canada and Russia [13], the Mediterranean [11], and Australia [14,15]. As a result, it is critical to understand the conditions that promote large fires on the landscape.

Wildfires burned an estimated 36 million ha in the continental U.S. from 1992 to 2012 and, of the total burned area, just over half was concentrated in desert and forested ecosystems of the western U.S. [5]. However, when large wildfires are delineated by a fire size threshold (e.g., 100,000 acres or

40,468 ha [16]; 20,000 ha [17]; <5000 and >404 ha [18]; 404 ha [19]) the resulting large fires are located almost exclusively in the western U.S. [16]. This focus on large fires neglects a considerable amount of burned area. For example, the inclusion of smaller fires in a Landsat satellite-based product increased total burned area by 116% in the U.S. relative to the Monitoring Trends in Burn Severity (MTBS) product [20], and by 35% globally, when smaller, thermally-detected Moderate Resolution Imaging Spectroradiometer (MODIS) active fires were compared with MODIS burned area products [21]. As a result, a fire size threshold approach neglects large amounts of burned area and reduces the importance of fires in some areas when considering the important question of what causes large fires.

Not all large western U.S. wildfires are problematic [22], however, the focus on large fires in the West is well justified because these fires have a clear potential for severe ecological and economic impacts [23,24]. Nonetheless, a wildfire that might fall below a national fixed fire size threshold could still be significant, particularly in areas with lower fire frequency and ecosystems with low resilience to fire [25], or if co-located with human settlements. The use of a national threshold could also skew our understanding of the drivers of large fires. For example, in western ecoregions such as Northwest Forested Mountains and North American Deserts, lightning is the primary source of fire, constituting 75–79% of burned area [5], thus suggesting that human ignitions are relatively unimportant. Moving away from a singular fixed fire size threshold towards thresholds designed for local fire regimes relative to the ecoregion would enable additional insight into the causes of large fires across U.S. ecoregions.

The alignment of biomass and biophysical conditions is necessary for wildfires of all sizes [26], but is perhaps most important for large wildfires [17]. Large wildfires require not only an ignition source, but also sufficient fuels to carry fire coupled with hot, dry, and often windy conditions that promote spread [17,27,28]. In the western U.S., increases in temperature, vapor pressure deficit, and subsequently fuel aridity related directly to anthropogenic climate change (ACC) resulted in the doubling of burned forest area over the past three decades [29]. The influence of ACC on wildfires in other U.S. ecoregions is unknown. Identifying both ignition sources and environmental conditions that promote large wildfires across the U.S. is critical for fire management against a backdrop of changing climate [7].

Here, we identify large fires proportionally as the largest 10% of fires occurring within Level III U.S. ecoregions [30], which divides the U.S. based on areas of similar geology, vegetation, climate, land use, and hydrology. We ask how human ignitions contribute to the spatial extents, seasonality, and numbers of these proportionally large fires. Additionally, we ask whether large, human-started fires occurred under different environmental and biophysical conditions relative to large, lightning-started fires. This analysis provides a first comparison of ignition source and the interactions with key environmental variables (i.e., wind speed, fuel moisture, biomass, and vegetation type) for large fires across the continental U.S.

2. Materials and Methods

To identify wildfires in the contiguous U.S., we used the 4th edition of the Fire Program Analysis fire occurrence database [31]. This dataset identifies the location of over 1.83 million wildfires that required a local, state, or federal agency response from 1992 to 2015. This database does not include intentionally set prescribed burns or agricultural fires, unless they escaped into wildfires. The fire occurrence database attributes a cause to each fire (lightning, missing/undefined, and numerous categories associated with humans: equipment use, smoking, campfire, debris burning, railroad, arson, children, miscellaneous, fireworks, powerline, and structure). The fire occurrence database also includes the fire size, which we used to designate large wildfires.

We identified large wildfires within each of the 84 Level III ecological regions defined by the Commission for Environmental Cooperation (Figure S1; [30]) in the continental U.S. We used ecoregions as the scale for this analysis because ecoregions represent areas of common vegetation and hence fuels, which are an important determinate of fire regimes. We also used the Level I ecoregions [30]

to visualize general ecoregion trends in fire characteristics (e.g., fire size). For discussion purposes, we also grouped ecoregions broadly into the ‘eastern’ and ‘western’ U.S. (Figure S2).

We define large fires here as the largest 10 percent of all fires within an ecoregion. Wildfires whose burned area exceeded the ecoregion threshold for fire size are hereafter referred to as ‘large fires’ in the manuscript. We excluded large wildfires with a missing/undefined cause. These constituted a small portion of the database (8% of all large fires from 1992 to 2015): the percent of undefined fires varied by year from 2.0% in 2000 to 14.8% in 1994. Fires listed as having a lightning cause were classified as lightning, and the remaining fires were classified as human-started. In addition to the top 10 percent, we also tested thresholds of 5% and 20% to see how choosing a smaller or larger threshold for large fires might change the results.

Our classification of ‘large’ depends on the distribution of fire sizes within each ecoregion, rather than a fixed value across the continental U.S. Although previous analyses have defined large fires as those burning more than a fixed area (Table 1), we argue that defining large fire size thresholds on ecologically meaningful scales allows for a more flexible definition of a ‘large’ fire that varies based on the fundamental fuel and climate constraints that limit fire size and enables us to consider the importance of smaller (relative to commonly used thresholds) large fires within ecoregions that have historically had lower fire probability.

Table 1. Definitions of a large fire in previous studies vary substantially by region/country/agency. MODIS: Moderate Resolution Imaging Spectroradiometer.

| Study | Location | Large Fire Threshold (ha) |
|-------|---------------------------------------|---|
| [32] | Northern Arizona, U.S. | >20 |
| [33] | Western U.S. | >40; largest wildfires > 400 |
| [2] | Western U.S. | >400 |
| [34] | Continental U.S. | ≥1300 (or 13 contiguous MODIS active fire pixels) |
| [35] | Entire U.S. (Forest Service) | ≥121.4 |
| [36] | Continental U.S. | >10,000 |
| [8] | Alaska, U.S. and Canada boreal forest | >100,000 |
| [37] | Rocky Mountain forest, U.S. | >1000 |
| [38] | Intermountain West, U.S. | >2008 |
| [39] | California, U.S. | ≥200 |
| [19] | Eastern U.S. | >202 |
| | Western U.S. | >404 |
| [3] | Western U.S. | >405 |
| [40] | Western U.S. | >405 |
| [41] | Alaska, U.S. | >405 (from 1950 to 1987); >40.5 (from 1988 to 2005) |
| | Canada boreal forest | >200 |
| [42] | Canada | >200 |
| [15] | Greater Sydney, Australia | ≥1000 |
| [43] | Russia | >200 |
| [44] | Southern France | >100 |
| [11] | Mediterranean Europe | >500 |
| [45] | Europe | >1000 |

To assess the recent (1992–2015) human contribution to large wildfires across U.S. ecoregions, we calculated the percentage of large wildfires attributed to human vs. lightning causes by ecoregion. We compared the mean and median fire sizes and total area burned of large human-started vs. large lightning-started wildfires by ecoregion. Secondly, we compared the seasonality of large fires associated with human-ignitions with those associated with lightning-ignitions. This was done separately for human-caused and lightning-caused fires following [5], by calculating the median (and interquartile range) Julian date of discovery days for large fires, and classifying the fire season as the middle 95% of Julian dates. By comparing the seasonal range for large human-caused wildfires to large lightning-caused wildfires, we can quantify the degree to which the large fire season attributed exclusively to lightning ignitions differs from the human-caused fire season. To understand if and where human ignition pressure has driven large fires, we ran Pearson correlations on the number of

large human-caused fires by day of year vs. the number of human-caused fires of all sizes by day of year for all ecoregions.

To understand the environmental conditions where large wildfires occurred in different ecoregions, we explored the fuel moisture, wind speed, vegetation type/biophysical setting, and biomass conditions of large human- and lightning-started wildfires. We obtained monthly climatological (1992–2015 average) dead 100-h fuel moisture (%) and wind speed (m s^{-1}) data from the gridded surface meteorological dataset [46] at a spatial resolution of 4 km. We chose 100-h fuel moisture because it integrates the effects of seasonal patterns of temperature, humidity, and precipitation, yet has similar climatological patterns as seen for 1-h to 1000-h fuels. We obtained information on vegetation classes (e.g., savanna, hardwood, conifer) across the U.S. from LANDFIRE biophysical setting (BPS 130, GROUPVEG) data at a spatial resolution of 30 m (Figure S3; [47]), and biomass (g m^{-2}) data from the National Biomass and Carbon Dataset 2000 [48] at a spatial resolution of 240 m.

We extracted the vegetation class, biomass, and monthly climatological fuel moisture and wind speed that corresponded to each large fire event. We expected that average monthly data would capture seasonal drivers of wildfire, acknowledging that climate variability may foster opportunities for large fire activity in seasons and locations where environmental conditions may not be climatologically favorable. While the spatial resolution of the vegetation class, biomass, and wind speed and fuel moisture datasets vary, due to spatial autocorrelation amongst these environmental variables, we assumed that the ignition location of each fire record was representative of the primary region that burned. We used paired t-tests to compare the mean fuel moisture and wind speed of large lightning- and human-started wildfires by ecoregion. For visualization, we also subtracted the mean fuel moisture of large human wildfires from the mean fuel moisture of large lightning wildfires to identify any ecoregions where large human-started fires occur under higher or lower average fuel moisture. Analogously, we subtracted the mean wind speed of large human wildfires from the mean wind speed of large lightning wildfires to identify any ecoregions where large human-started fires occur under higher or lower average wind speeds. We calculated the number of human- and lightning-started large wildfires by biophysical setting or vegetation class (e.g., savanna, conifer, sparsely vegetated) to assess whether human-started fires occurred disproportionately in certain vegetation classes at the ecoregion level. We also used linear regression to compare the mean large fire size (ha) to the mean biomass, fuel moisture, and wind speed by ecoregion to understand the relationship of these variables in driving fire size in the eastern and western U.S.

3. Results

There were a total of 1,698,835 fire records from 1992 to 2015 with an attributed cause: of these, 1,424,630 were human-caused and 274,205 were lightning-caused. There were 175,222 large fires across the U.S. from 1992 to 2015. Humans ignited four times as many large wildfires as lightning across U.S. ecoregions (142,276 human vs. 32,946 lightning) and were the primary source of large wildfires in ecoregions of the eastern U.S. and the west coast (Figure 1). By contrast, lightning was responsible for a majority of large fires across much of the interior western U.S. Spatial patterns were similar when different thresholds were used to define large fires (Figure S4), with the eastern U.S. and west coast dominated by human-ignited fires.

The number of large fires (of all causes) per ecoregion during the study period ranged from 10 to 24,471. Four ecoregions had <100 large wildfires (of all causes) during the study period: Chihuahuan Deserts, Eastern Corn Belt Plains, Huron/Erie Lake Plains, and Erie Drift Plain, and Flint Hills. Two ecoregions had zero lightning-caused large wildfires during the study period: Huron/Erie Lake Plains and Eastern Corn Belt Plains.

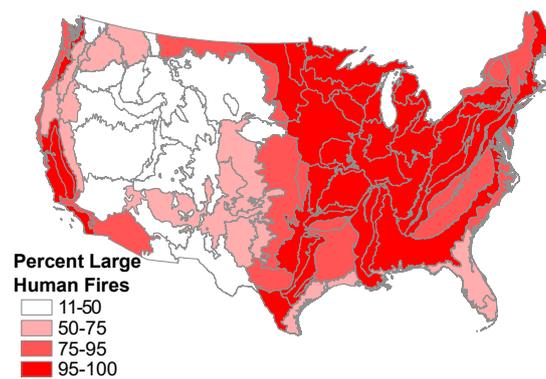


Figure 1. The percent of large fires (defined as the largest 10 percent of fires by ecoregion) caused by humans: humans are the dominant source of large fires in ecoregions of the eastern U.S. and the west coast.

3.1. Large Fire Size and Total Burned Area

The mean size of a large fire varied across ecoregions by three orders of magnitude, from 1 to 10 ha in the Northeast to >1000 ha in the western U.S. (Figure 2a). For example, the two largest mean fire sizes were 4611 ha and 2933 ha in the Northern Basin and Range and the Snake River Plain ecoregions, respectively, while the smallest of the large mean fire sizes were 1.5 ha and 2.3 ha in the Eastern Great Lakes Lowlands and the Northeastern Coastal Zone ecoregions, respectively. The median size of large wildfires followed roughly the same pattern, with larger wildfires in the western than eastern U.S. (Table S1). Maximum fire size also varied by 3–4 orders of magnitude; the smallest maximum fire size for any ecoregion was 60 ha in the Northern Allegheny Plateau, whereas the largest fire across the entire record was 225,895 ha in the Northern Basin and Range. The maximum large fire size was similar for human- and lightning-caused fires (Figure 2b).

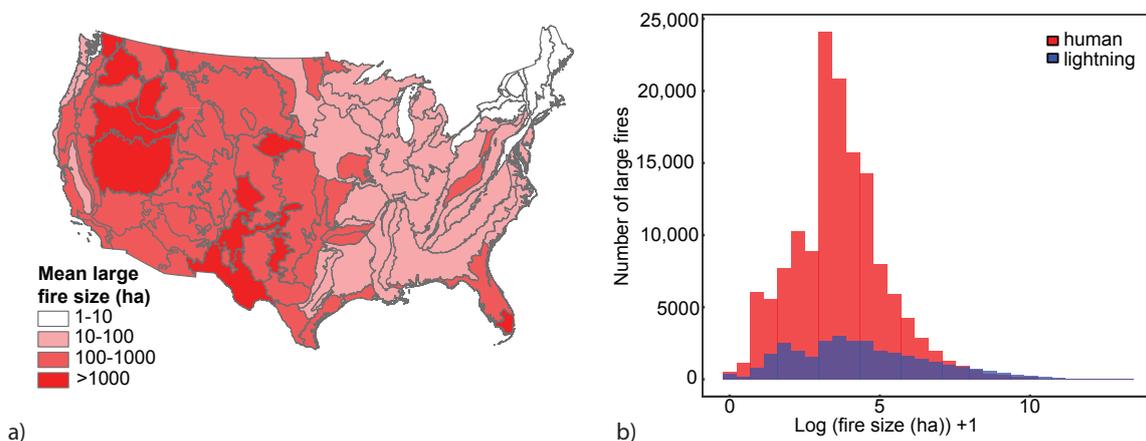


Figure 2. Large fire size and relative sizes of human vs. lightning fires across ecoregions of the continental U.S. (a) The mean size of a large fire (top 10% of largest fires relative to the ecoregion) varies by three orders of magnitude across the continental U.S.; (b) Histogram of $\log(\text{fire size (ha)} + 1)$ for large human- and lightning-started wildfires shows a shorter tail for large human-caused fires compared to large lightning-caused fires and many more large human-caused fires of moderate sizes compared to lightning-caused fires of similar sizes.

Total burned area of large human-caused fires (normalized by the area of the ecoregion) was highest in southern Florida and California, and generally higher in southern and western ecoregions than in northern ecoregions (Figure S5).

3.2. Large Fire Seasonality

The human-caused large fire season is much longer than the lightning-caused large fire season in both the East and the West, and in ecoregions with high (e.g., Central California Valley) and low (e.g., lightning-dominated Idaho Batholith) percentages of human-started wildfires (Figure 3).

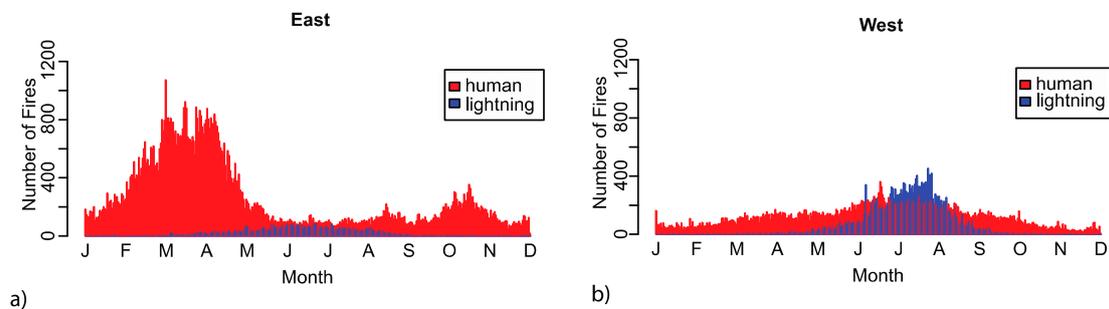


Figure 3. Seasonality of large human- vs. lightning-caused wildfires. (a) Humans ignited many fires in the spring and fall in the eastern U.S.; (b) Humans ignited large fires fairly evenly across seasons in the western U.S.

The median Julian day of year for large human-started wildfires was 118 (28 May), compared to 205 (24 July) for large lightning-started wildfires (interquartile range of 75 to 221 (16 March to 9 August) and 178 to 226 (27 June to 14 August) for large human- and lightning-started wildfires, respectively). In 52 of 84 ecoregions, the median Julian day of year for large human-caused wildfires was >20 days earlier than for large lightning-caused wildfires, with the greatest difference between large human-caused fires and large lightning-caused in the southeastern U.S. (Figure S6). By contrast, in only 2 of 84 ecoregions, the median Julian day of year for large human-caused wildfires was >20 days later than for large lightning-caused wildfires (Figure S6). When lightning fires were rare (i.e., before the 2.5th or after the 97.5th percentiles; 13 April and 24 September, respectively), humans ignited 80,896 large wildfires—in other words, nearly half of all large fires occurred during the off-season for lightning, particularly in eastern and southeastern U.S. ecoregions (Figure S7). Many of these large fires outside of the lightning-fire season were started in the spring in the eastern U.S. (Figure 3a). The number of large human-caused fires by day of year was highly correlated with the number of human-caused fires of all sizes by day of year in the eastern ($r = 0.99$) and the western U.S. ($r = 0.94$). This high correlation held across most eastern ecoregions ($r > 0.80$), but was lower in northwestern ecoregions ($r < 0.50$; Figure 4).

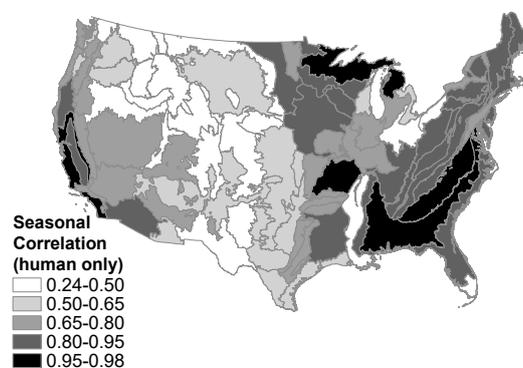


Figure 4. The correlation coefficient between the number of large fires by day of year and the number of fires of all sizes by day of year by ecoregion for human-ignited fires only: the seasonality of large human-started fires is highly correlated with the seasonality of human-started fires of all sizes in the East (>0.81) while the correlation is lower (<0.66) in the northwest and central U.S.

3.3. Large Fire Conditions

When compared across the entire continental U.S., large human started-wildfires occurred in places and months of significantly higher climatological mean fuel moisture ($p < 0.0001$) and higher mean wind speed ($p < 0.0001$) than large lightning-started wildfires (Figure 5).

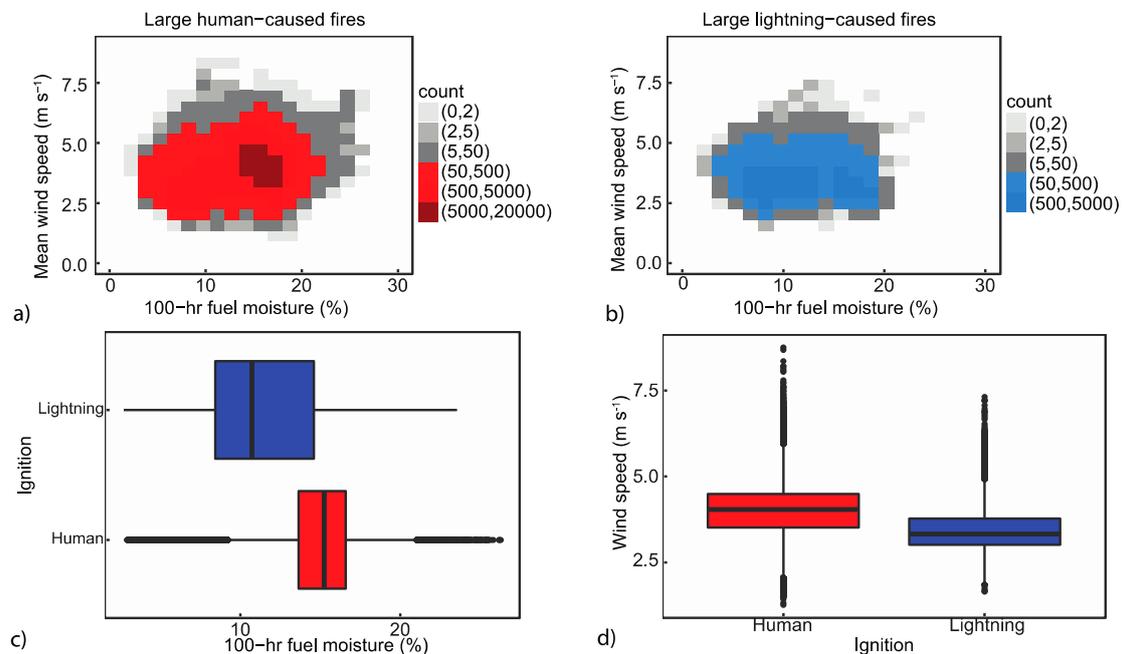


Figure 5. Number of large (a) human- and (b) lightning-started wildfires in bins of monthly mean climatological (1992–2015 average) 100-h fuel moisture (%) vs. monthly mean wind speed (m s^{-1}). Boxplots of (c) 100-h fuel moisture (%) and (d) wind speed (m s^{-1}) for large fires by ignition source. Together, (a–d) show that large human-caused fires occurred in wetter and windier conditions than large lightning-caused fires.

Across all ecoregions, mean 100-h fuel moisture was $14.5\% \pm 0.0\%$ vs $11.4\% \pm 0.0\%$ and mean wind speed was $4.0 \pm 0.0 \text{ m s}^{-1}$ vs. $3.4 \pm 0.0 \text{ m s}^{-1}$ for large human- and lightning-started wildfires, respectively. Large differences in climatological mean fuel moistures and wind speeds for human-caused and lightning-caused fires were also seen at the scale of individual ecoregions (Figure 6). Human-ignited large fires occurred with higher mean fuel moisture across much of the western U.S. (e.g., Coast Range, Blue Mountains, Strait of Georgia/Puget Lowland; Figure 6a and Figure S8). In contrast, in the eastern U.S., human ignitions occurred in areas and seasons with similar or lower mean fuel moisture than lightning ignitions (e.g., Middle Atlantic Coastal Plain, Northern Minnesota Wetlands, Southern Florida Coastal Plain; Figure 6a and Figure S8). Large human-started wildfires also tended to occur in areas and seasons with higher mean wind speed, particularly in the southeastern U.S. (e.g., Mississippi Valley Loess Plains, Southwestern Appalachians, Blue Ridge) and New England (Figure 6b and Figure S8).

Humans caused more wildfires (including all fire sizes) than lightning across all vegetation classes (grassland, conifer, hardwood, riparian, savanna, shrub, hardwood/conifer, sparsely vegetated, and other) (Table 2a). Human ignitions were particularly dominant in savanna, hardwood, and mixed hardwood/conifer vegetation types (Table 2a; Figure S3). For large fires specifically, the proportion of human-caused fires across vegetation types was similar to the pattern of fires of all sizes (Table 2b).

Mean large fire size by ecoregion was significantly, negatively ($p = 0.005$) related to annual average fuel moisture in the West, but was not significantly related ($p = 0.487$) to annual average fuel moisture in the East (Figure 7a). Mean large fire size by ecoregion was not significantly related to annual average

wind speed in the East ($p = 0.91$) or the West ($p = 0.60$) (Figure 7b). Mean large fire size by ecoregion was significantly negatively ($p = 0.004$) related to mean ecoregion biomass in the East, but was not related ($p = 0.11$) to mean ecoregion biomass in the West (data not shown). Within Level I ecoregions of the U.S., there was generally a negative relationship between biomass and large wildfire size (only significant in the Great Plains Level I ecoregion), with the opposite pattern observed in Mediterranean California and Marine West Coast Forests (Figure 7c).

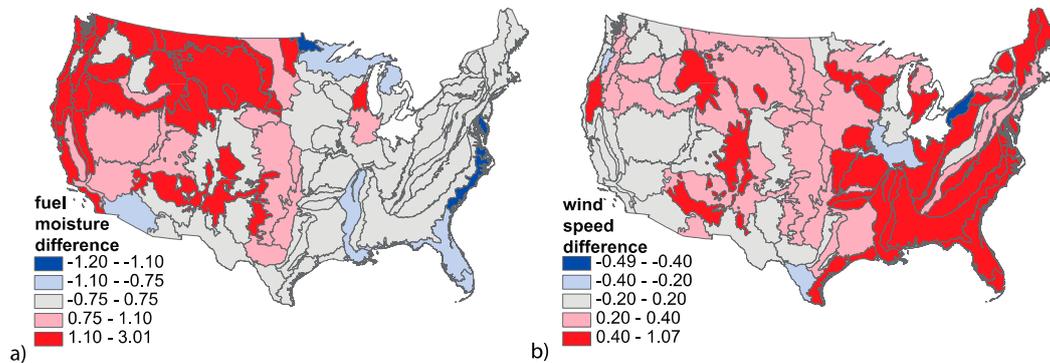


Figure 6. Difference in mean ecoregion (a) fuel moisture (%) and (b) wind speed ($m\ s^{-1}$) of large human-minus large lightning-caused wildfires. (a) Large human-caused fires in the northwestern U.S. occurred in conditions with climatologically higher fuel moisture (red) compared to large lightning-caused fires in the same ecoregion. (b) Large human-caused fires in the southeastern U.S. and New England occurred in conditions of climatologically higher wind speed (red) compared to large lightning-caused fires in the same ecoregion.

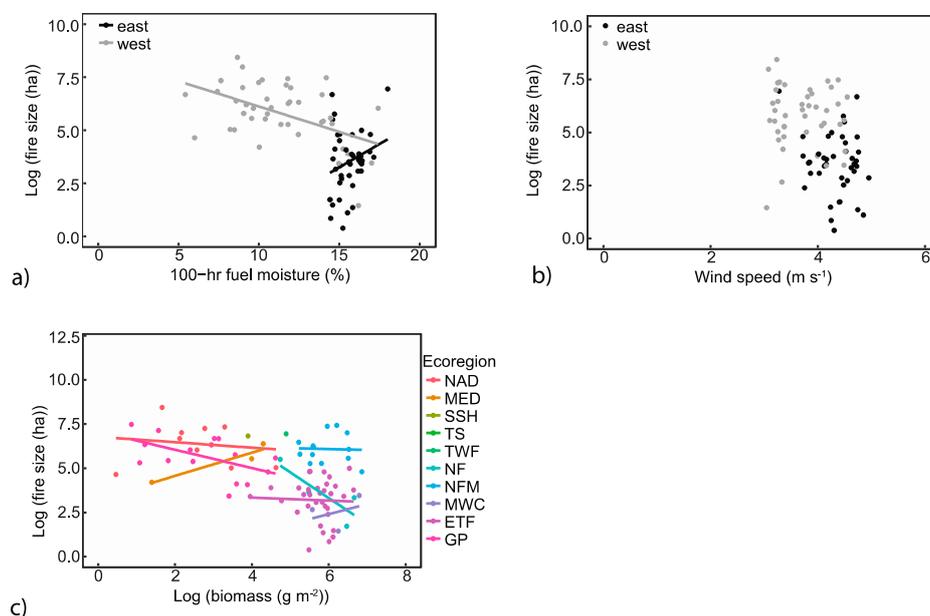


Figure 7. Linear regression between the log of mean large fire size (ha) vs. (a) mean 100-h fuel moisture (%) for the eastern and western U.S.; and (b) mean wind speed ($m\ s^{-1}$) for the eastern and western U.S.; and (c) log of mean biomass ($g\ m^{-2}$) by ecoregion. In (c), Level III ecoregion points are colored by the Level I ecoregion code where NAD = North American Deserts, MED = Mediterranean California, SSH = Southern Semi-Arid Highlands, TS = Temperate Sierras, TWF = Tropical Wet Forests, NF = Northern Forests, NFM = Northwestern Forested Mountains, MWC = Marine West Coast Forests, ETF = Eastern Temperate Forests, GP = Great Plains. In (a,b) regression lines are shown where regression relationships were significant ($p < 0.05$).

Table 2. Number of human- and lightning-started wildfires in different biophysical settings (grassland, conifer, hardwood, riparian, savanna, shrub, hardwood/conifer, sparsely vegetated, and other) and the ratio of human (H):lightning (L)-started wildfires in these classes for (a) wildfires of all sizes and (b) large wildfires only, defined as the largest 10% of wildfires by ecoregion.

| (a) | | | | | | | | | | |
|-------------|-----------|---------|----------|----------|---------|---------|------------------|--------|--------|-----------|
| Ignition | Grassland | Conifer | Hardwood | Riparian | Savanna | Shrub | Hardwood/Conifer | Sparse | Other | Total |
| Human | 143,980 | 318,168 | 386,804 | 259,006 | 3248 | 114,002 | 172,056 | 3265 | 24,101 | 1,424,630 |
| Lightning | 19,253 | 142,802 | 13,697 | 33,620 | 76 | 51,065 | 9800 | 1042 | 2850 | 274,205 |
| Ratio (H:L) | 7.5 | 2.2 | 28.2 | 7.7 | 42.7 | 2.2 | 17.6 | 3.1 | 8.5 | 5.2 |
| (b) | | | | | | | | | | |
| Ignition | Grassland | Conifer | Hardwood | Riparian | Savanna | Shrub | Hardwood/Conifer | Sparse | Other | Total |
| Human | 13,574 | 28,357 | 39,624 | 27,963 | 566 | 12,541 | 17,322 | 210 | 2119 | 142,276 |
| Lightning | 3792 | 13,574 | 1728 | 4967 | 12 | 6899 | 1327 | 130 | 354 | 32,946 |
| Ratio (H:L) | 3.6 | 2.1 | 22.9 | 5.6 | 47.2 | 1.8 | 13.1 | 1.6 | 6.0 | 4.3 |

4. Discussion

Large wildfire events can be economically costly and often have pronounced negative consequences for ecosystems and societies, including losses of structures and even lives [18,49]. In recent decades, the size and number of large wildfires has increased [2,3,5], and extreme fires (termed “mega-fires”) are becoming more common [11,50,51]. Moreover, climate projections suggest that large wildfires will become increasingly common in the future, with warming and drying trends increasing the probability of large fires and fires of greater severity [49,52,53]. Although large wildfires are a natural and needed part of some ecosystems, there is great concern that the frequency and size of wildfires is increasing across many ecoregions, beyond historical ranges of variability. This highlights a strong need to understand the spatial patterns and processes that promote large fires.

4.1. Defining Large Fires Based on Ecoregions

Globally, large fires have been defined in many different ways, often by absolute thresholds (Table 1). What is considered a large fire in Australia may be much bigger (in absolute size) than what is considered a large fire in southern France (Table 1). However, large fires can also be defined by relative thresholds as a percentage of area burned [54] and fundamentally should reflect the climate and fuel constraints that vary by ecoregion. The usefulness of these different criteria for defining ‘large fires’ varies by context [54].

Defining a large fire within the U.S. by a set size threshold [34–36] emphasizes the role of lightning, because lightning-started fires are more common in mountainous regions of the western U.S., where the largest fires occur ([5]; Figures 1 and 2a). However, when large fires are defined based on the ecoregion they occur in, human ignitions are a much more prominent driver of large fires (Figure 1). We assert that defining large fires by ecoregion is important because variation in fuel load and structure, climatic conditions, and current and historical land use constrain the absolute size of fires within a given ecoregion. Thus, a single absolute size threshold is unlikely to provide a consistent indicator of ecological and economic risk across all U.S. ecoregions. Using a threshold relative to each ecoregion, our analysis shows that human ignitions were responsible for four times as many large fires as lightning during the study period (Figure 2b).

At the ecoregion level, what constituted a large fire varied considerably; large wildfires were three orders of magnitude larger on average in the western compared to the eastern U.S. (Figure 2a; Table S1). Thus, the importance of large wildfires should be placed in a regional context: large fires in the West dominated total land area burned, but large fires in the East can still be costly to ecosystems and infrastructure. As an example, the Alpine Lake fire in Minnesota in 2005 burned only 540 ha but cost \$2,780,000 U.S. dollars to suppress [55]. Additionally, not all large western wildfires are problematic [22], as large fires can promote ecosystem health in certain regions. Large wildfires can be ecologically beneficial by reducing fuel loads and regenerating vegetation [36], while causing minimal societal damage.

4.2. Large Fire Seasonality

The seasonal expansion of large wildfires in the spring in the eastern U.S. (Figure 3a) was similar to the pattern of fires of all sizes [5], with many large human-caused fires occurring earlier in the year than large lightning-caused fires (Figure S6) and outside of the lightning fire season (Figure S7). Given the strong correlations previously identified between large fires and climate [3,18,34,49,56], we expected large fires across the U.S. to be more likely during dry, hot summer months in the western U.S. In the eastern U.S., the seasonality of large human-caused fires was highly correlated with the seasonality of human-caused fires of all sizes across most eastern ecoregions (Figure 4). These results suggest that seasonal climate does not play an important role in facilitating large fires in the East. Instead, ignition pressure is the primary driver of large fires in these ecoregions. This finding is consistent with [57], who showed that human ignitions are a more important driver of fire than climate in the eastern U.S. In the northwestern U.S., the seasonal correlation between large fires and all fires was lower (Figure 4), suggesting that climate conditions may play a more important role in facilitating large fires here. Nonetheless, even in ecoregions of the intermountain west where climate is known to influence large fires [2,12,56], human ignitions explained a substantial portion of the seasonal pattern of large fires ($r > 0.66$; Figure 4). This finding suggests that ignition pressure, and human expansion of ignitions [5], plays a much larger role in influencing large fires than previously thought.

4.3. Environmental Controls on Large Fire Size

Studies have shown that large fires are driven by antecedent climatic factors that promote fuel abundance plus extreme fire weather and climatic factors (e.g., wind, drought, high temperatures) at the time of fire ignition [3,18,26,34,49,56]. However, our results suggest that the pattern between fire size and biomass varied substantially within and across U.S. ecoregions. Ecoregions with relatively low biomass but an abundance of fine fuels from grasses sustained some of the largest mean fire sizes, including North American Deserts and Great Plains (Figure 2a, Figure 7c and Figure S3). Large lightning-caused wildfires were common in the historical record of prominent shrubland ecosystems including Rocky Mountain sagebrush communities [36]; large fires occur here when dry summers follow wet winters/springs, which allows fuels to build up and then dry out [18,36,58]. Within the Mediterranean California and Marine West Coast Forests ecoregions, as biomass increased, large fire size increased (Figure 7c), perhaps as a product of fuel continuity. Within Eastern Temperate Forests, lower biomass pine forests in the Southeast may be more flammable than higher biomass hardwood forests in New England.

The relationship between fuel moisture and ecoregion specific large fire size showed a threshold effect, with the largest fire sizes occurring in western ecoregions where annual average fuel moisture was below 14% whereas large fires of a similar size were less likely in eastern ecoregions where fuel moisture was higher (Figure 7a). This is consistent with studies that have shown that fuel aridity is related to burned area in western forests [29]. In the Southeast, long, wet growing seasons interspersed with periodic drought (and coupled with windy conditions) may promote situations conducive for fire spread [59,60].

Although greater wind speeds have been linked to larger fire events [28], we did not find a link between mean large fire size and mean wind speed at the ecoregion scale (Figure 7b). The aggregation of environmental conditions to an ecoregion average, and to climatological averages, may mask patterns observable at the level of individual fire events that are wind-driven, and further exploration of the environmental correlates to large fires at the fire event level is needed.

4.4. Human Controls on Large Fires

Of the large wildfires, a greater percentage were started by humans in the eastern U.S. (Figure 1) compared to the western U.S. and this was likely tied to population density, infrastructure, and the wildland-urban interface (WUI) [34,61–64]. This pattern for large fires mirrored the human contribution

to overall numbers of ignitions [5]. While suppression efforts are high within urban and suburban areas themselves, ignition pressure increases with population density, at least to a certain point [65,66]. However, while human population density, housing/structure density, distance to roads and railroads, and percent of WUI may be good predictors of ignitions [67–70], they are only proxies for ignition pressure and a better understanding of the human behaviors driving ignitions is critical for understanding large fire risk. In areas of the eastern U.S. where humans are responsible for a greater proportion of fires (e.g., hardwood, mixed hardwood/conifer, and savanna vegetation areas; Table 2) ignition pressure from various human behaviors (e.g., arson and debris burning) is coinciding with climate and fuel conditions that promote large fires.

5. Conclusions

In summary, this study adds a comprehensive review of large human- and lightning-caused wildfires by ecoregion in the U.S. There was a strong regional difference in mean fire size of large wildfires by ecoregion, which varied by three orders of magnitude. Humans ignited four times as many large wildfires as lightning across U.S. ecoregions and human ignitions of large wildfires dominated the eastern U.S. The fire season of large human-caused fires spanned the entire year with a large pulse of spring wildfires in the eastern U.S., while the fire season of large lightning-caused fires was constrained to mainly May–September. Large human started-wildfires occurred in areas of significantly higher fuel moisture (particularly in the northwestern U.S.) and higher wind speed (particularly in the eastern U.S.) than large lightning-started wildfires. We assert that when assessing fire risk in the U.S., fire management and policy should acknowledge how human ignitions start many of our nation’s large wildfires.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2571-6255/1/1/4/s1>, Table S1. Summary statistics of large fires by Level III ecoregion; Figure S1. Map and key of Level III U.S. Ecoregions from the Center for Environmental Cooperation (2006); Figure S2. Grouping of U.S. Level III ecoregions into the ‘eastern’ and ‘western’ U.S.; Figure S3. LANDFIRE Biophysical Settings (vegetation classes) of the continental U.S.; Figure S4. Percent of large fires caused by humans defined as the (a) top 5 percent and (b) top 20 percent of largest fires by ecoregion: Humans are the dominant source of large fires in ecoregions of the eastern U.S. and the west coast. Figure S5. Total burned area of large human-caused wildfires of each ecoregion divided by the area of the ecoregion; Figure S6. The difference in median Julian day of year for large human-caused wildfires vs. large lightning-caused wildfires by ecoregion; Figure S7. The number of large wildfires that occurred outside of the fire season for large lightning-caused wildfires by ecoregion; Figure S8. Number of large wildfires by ecoregion in bins of annual 100-h fuel moisture vs. wind speed data.

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