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Megan E. Cattau
Boise State University

Carol Wessman
University of Colorado

Adam Mahood
University of Colorado

Jennifer K. Balch
University of Colorado

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Anthropogenic and Lightning-Started Fires are Becoming Larger and More Frequent Over a Longer Season Length in the U.S.A.

Megan E. Cattau*
Human-Environment Systems
Boise State University
Boise, ID
megancattau@boisestate.edu

and

Earth Lab
Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado
Boulder, CO

Carol Wessman
Earth Lab
Cooperative Institute for Research in Environmental Sciences (CIRES)

Ecology and Evolutionary Biology

and

Environmental Studies
University of Colorado
Boulder, CO

Adam Mahood
Earth Lab
Cooperative Institute for Research in Environmental Sciences (CIRES)

and

Department of Geography
University of Colorado
Boulder, CO

Jennifer K. Balch
Earth Lab
Cooperative Institute for Research in Environmental Sciences (CIRES)

and

Department of Geography
University of Colorado

Abstract

Aim

Over the past several decades, wildfires have become larger, more frequent, and/or more severe in many areas. Simultaneously, anthropogenic ignitions are steadily growing. We have little understanding of how increasing anthropogenic ignitions are changing modern fire regimes.

Location

Conterminous United States.

Time period

1984–2016.

Major taxa studied

Vegetation.

Methods

We aggregated fire radiative power (FRP)-based fire intensity, event size, burned area, frequency, season length, and ignition type data from > 1.8 million government records and remote sensing data at a 50-km resolution. We evaluated the relationship between fire physical characteristics and ignition type to determine if and how modern U.S.A. fire regimes are changing sensu stricto given increased anthropogenic ignitions, and how those patterns vary over space and time.

Results

At a national scale, wildfires occur over longer fire seasons (17% increase) and have become larger (78%) and more frequent (12%), but not necessarily more intense. Further, human ignitions have increased 9% proportionally. The proportion of human ignitions has a negative relationship with fire size and FRP and a positive relationship with fire frequency and season length. Areas dominated by lightning ignitions experience fires that are 2.4 times more intense and 9.2 times larger. Areas dominated by human ignitions experience fires that are twice as frequent and have a fire season that is 2.4 times longer. The effect of human ignitions on fire characteristics varies regionally. Ecoregions in the eastern U.S.A. and in some parts of the coastal western U.S.A. have no areas dominated by lightning ignitions. For the remaining ecoregions, more intense and larger fires are associated with lightning ignitions, and longer season lengths are associated with human ignitions.

Main conclusions

Increasing anthropogenic ignitions – in tandem with climate and land cover change – are contributing to a ‘new normal’ of fire activity across continental scales.

Keywords: Anthropogenic ignitions, climate, coupled human-environment systems, disturbance ecology, fire regime, satellite data, United States, wildfires

1. Introduction

Scientists (Schoennagel et al., 2017), firefighters (Harball, 2015) and policymakers (Vives, Etehad, & Cosgrove, 2017) have all acknowledged that we may be entering a ‘new normal’ of fire activity. Since national-level reporting began in 1960, the 10 largest fire years have occurred since 2000 (NIFC, 2018). Furthermore, there are increasing trends in the number of large fires – both human- and lightning-caused – in some ecoregions across the United States (Balch et al., 2017; Dennison, Brewer, Arnold, & Moritz, 2014), and fire is expected to increase in frequency and severity in many regions of the U.S.A. over the coming decades (Barbero, Abatzoglou, Larkin, Kolden, & Stocks, 2015; Liu, Goodrick, & Stanturf, 2013; Parks, 2016). The rising economic and societal costs of increased fire activity are of great concern (McCaffrey, Toman, Stidham, & Shindler, 2013; Thompson, Calkin, Finney, Ager, & Gilbertson-Day, 2011), including deflated residential housing prices near burned areas (Loomis, 2004; Stetler, Venn, & Calkin, 2010) and direct costs of $2–3 billion spent annually by federal agencies to fight wildfire (North et al., 2015; Rasker, 2015). Additionally, the ecological consequences of changing wildfire disturbance can be severe, resulting in decreased resistance of vegetation to subsequent disturbance agents (Davis, Hood, & Bentz, 2012; Kulakowski & Jarvis, 2013), changes in regional water resources (Buma & Livneh, 2015) and altered wildlife responses (Kalies, Chambers, & Covington, 2010), especially under prolonged drought events (Keane, Loehman, Clark, Smithwick, & Miller, 2015; Westerling, 2016).

Fire is controlled by fuel, climate and ignitions. Anthropogenic contributions to fire through each of these controls are steadily growing, with increased landscape flammability due to land use change, changing climate and more human-started fires. In modern times in North America, there exist few if any fire regimes that are not impacted by humans (Parisien et al., 2016), either indirectly through changing the underlying conditions so that fire can occur or directly through increased ignitions. For example, human land use, both historical legacies such as logging and current intermixing along the wildland–urban interface (Radeloff et al., 2005; Theobald & Romme, 2007), alters forest structure and dynamics and introduces more anthropogenic ignition sources (Mann et al., 2016). The depth of research evaluating the effects of fuel, climate and ignitions on fire regimes has been variable; the effects of changing fuel and climate on fire regimes in the United States are well established. For example, increasing temperatures and drought have, in part, affected fire activity in the western U.S.A. over the past few decades, including fire season length, frequency, duration, and area (Balch et al., 2018; Dennison et al., 2014; Dillon et al., 2011; Westerling, 2016; Westerling, Hidalgo, Cayan, & Swetnam, 2006). However, if and how increasing anthropogenic ignitions affect contemporary wildfire regimes is less understood, in part because data on ignition type at the national scale have only been made available relatively recently with the Fire Program Analysis fire-occurrence database (FPA-FOD) (Short, 2017) (described below in Materials and Methods).

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Anthropogenic ignitions are fundamentally different phenomena than lightning ignitions. Lightning strikes generally occur over a limited window of time when climatic conditions are conducive to producing thunderstorms. Anthropogenic sources of wildfire ignition do not depend on a specific weather event and sometimes come from sources of heat that can remain smouldering for hours; coals from a campfire or a downed powerline are two prominent examples. Because of these physical differences, anthropogenic ignitions can also occur at any time of year and under a wider range of conditions. It has been established that anthropogenic ignitions extend the wildfire season and expand the fire niche to areas with lower lightning-strike density, higher fuel moisture and higher net primary productivity (NPP) relative to lightning-started fires (Balch et al., 2017; Bartlein, Hostetler, Shafer, Holman, & Solomon, 2008), and that human ignitions may affect spatial patterns of large fire occurrence (Balch et al., 2017; Malamud, Millington, & Perry, 2005; Nagy, Fusco, Bradley, Abatzoglou, & Balch, 2018). Although anthropogenic ignitions may produce separate physical processes with different ecological and social consequences than lightning-ignited fires, if and how the fundamental physical characteristics of modern fires en masse are changing given increasing anthropogenic ignitions is relatively unknown.

The majority of contemporary fires in the United States are human-started; for the period of 1992–2013, 84% of ignitions were anthropogenic (Balch et al., 2017). This is a pivotal time to explore if and how modern U.S.A. fire regimes sensu stricto are changing given increasing anthropogenic ignitions. We ask: (a) how are anthropogenic ignitions and fire physical characteristics changing over time?; (b) do areas under heavy human ignition pressure experience fires with fundamentally different physical characteristics than areas dominated by lightning ignitions and how are these characteristics changing over time?; (c) as anthropogenic ignitions increase, do threshold behaviours in fire physical characteristics exist?; and (d) how do these trends vary among ecoregions? These analyses are important to understanding how increasing human ignitions are shaping our contemporary U.S.A. fire regimes.

2. Materials and Methods

2.1 Data

To capture information embedded in different national-scale fire data products, we compiled a suite of existing fire products, including the Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Product (Giglio, Descloitres, Justice, & Kaufman, 2003), Monitoring Trends in Burn Severity (MTBS) Burned Areas Boundaries Dataset (Eidenshink et al., 2007), and the Fire Program Analysis fire-occurrence database (FPA-FOD) for the contiguous U.S.A. (Short, 2017):

1. MODIS**:** We obtained the MODIS Active Fire Product Version 6 for 2003–2016, processed and quality checked by the University of Maryland (MCD14ML) from the Fire Information for Resource Management System (FIRMS). This product includes, for each fire detected by either the Terra or Aqua MODIS sensor based on emission of mid-infrared radiation, among other information, the location of the centroid for the 1-km resolution pixel in which the fire was detected, the date of detection, and fire radiative power (FRP) of the fire (which we use to represent 'fire intensity'). We exclude MODIS data before 2003 to remove bias, because active fire data derived from the Aqua satellite, with a later overpass time and thus often higher FRP reading than the Terra, were not available until July 2002. We use the term fire intensity to refer to the heat energy released from the fire (Keeley, 2009), which is correlated to combustion and thus related to the fuel amount (Rossi, Chatelon, & Marcelli, 2018; Wooster, Roberts, Perry, & Kaufman, 2005). FRP readings are affected by the location of a pixel within the swath [i.e., at the edge or viewed from nadir, the satellite point spread function (PSF) effect]. However, uncertainty related to view angle is minimal for aggregations at coarser spatio-temporal resolutions (Freeborn, Wooster, Roy, & Cochrane, 2014). Further, no systematic bias exists in view angle as a function of any of the variables evaluated in this paper.

2. MTBS*:* We obtained MTBS burned areas boundaries, a dataset which includes all fires – wildfires and prescribed – over a size threshold (western U.S.A., c. 405 hectares; eastern U.S.A., c. 202 hectares) in the contiguous U.S.A. for 1984–2015. These fire perimeter products were generated by the thematic classification of a Landsat-derived fire index (differenced normalized burn ratio, dNBR) through the MTBS project.

3. FPA-FOD*:* We obtained FPA-FOD fire locations for 1992–2015. These fire locations are based upon wildfire records from federal, state, and local fire organization reports for any fire that required a suppression response, and thus intentional (e.g., prescribed) fires are not included unless they escaped. This product includes information concerning the ignition type in addition to the date and area of the fire. Ignition type was grouped into human (e.g.,

'campfire', 'arson', 'children', 'debris burning') or lightning, and ignition cases that were unspecified or labelled as missing/unidentified (10.5% of all fires) were excluded from further analysis. These data provide the best available national-scale information regarding wildfire ignition source.

To create variables to describe contemporary fires, we derived a suite of 15 variables from the information embedded in these aforementioned satellite sources and government records that describe the average and most extreme fire physical characteristics (e.g., mean and maximum fire event size) across a regular 50-km resolution grid at an annual temporal resolution (Table 1, Supporting Information Figure S1). Fire characteristics from one data source were not assigned to a specific fire in another data source; rather, characteristics from different data sources are associated with one another in each pixel. We derived variables capturing the same fire characteristic from multiple data sources when possible (e.g., the number of fires is derived from MODIS, MTBS and FPA-FOD) in order to integrate the distinctive information embedded in each product (discussed in detail in Discussion). To ensure that these variables are not redundant, we tested that all variables capturing the same characteristic but derived from different data sources have significantly different values, using Wilcoxon rank sum tests (alpha $< .01$) when there are two data sources and Kruskal–Wallis tests ($p < .01$) followed by pairwise Wilcoxon rank sum tests (alpha $< .01$) when there are three data sources. Because ignition type is extracted from the FPA-FOD data, all analyses referring to ignition source (human or lightning) refer to the FPA-FOD derived ignition type in that pixel. We report on the FPA-FOD-derived characteristics in the Results section for consistency when possible, but we do not include patterns of fire characteristics by ecoregion using the FPA-FOD data in the Results section due to known inconsistencies in the reporting by state and over time (Short, 2014). Results using all variables are included in the Supporting Information. Ignition type and thus the relative influence of human versus lightning ignitions would not be subject to the aforementioned reporting bias.

Table 1. Fire characteristics derived for the contiguous U.S.A. at a 50-km spatial resolution and an annual temporal resolution (values are per pixel per year) from satellite data and government records to evaluate the effect of anthropogenic ignitions on physical characteristics of modern fires. All data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) MCD14ML for 2001–2015, from Monitoring Trends in Burn Severity (MTBS) for 1984–2015, and from Fire Program Analysis fire-occurrence database (FPA-FOD) for 1992–2015.

Characteristic	Data Source(s)	Units
Fire frequency	MODIS, MTBS, FPA-FOD	Total number of fires or fire detections
Fire intensity	MODIS	
Average		Mean Fire Radiative Power (FRP) (megawatts)
Extreme		Maximum FRP (megawatts)
Fire event size	MTBS, FPA-FOD	
Average		Mean area (hectares)
Extreme		Maximum area (hectares)
Burned area	MTBS, FPA-FOD	Sum area (hectares)
Fire season length	MODIS, MTBS, FPA-FOD	Standard deviation Julian Day * 2
Ignition type	FPA-FOD	Proportion of fires ignited by humans or lightning

2.2 Analysis

All analyses were conducted in the R programming environment (R Core Team. 2018). To determine how fire physical characteristics and the proportion of anthropogenic ignitions are changing over time at a national scale, the rate of change over the timespan of the relevant dataset for each fire characteristic was estimated as the slope of linear models of each characteristic at an annual timestep using the R package 'nlme' (Pinheiro, Bates, DebRoy, & Sarkar, 2018; Supporting Information Figure S2 and Table S1). We included pixels absent of fire when deriving the fire frequency variables and omitted them for all other variables. We use the term fire frequency to refer to the number of fires for a

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given pixel over an annual period and do not consider the time between fire occurrences in a given pixel (i.e., fire return interval) or the time required to burn an area equivalent to one pixel (i.e., fire rotation interval). The percent changes were estimated from the predicted values based on the linear model objects.

To determine if lightning- and human-started fires have fundamentally different characteristics, we retained just the pixels that are dominated by either human or lightning ignitions (i.e., 75% or more of the fires in a given pixel are human or lightning started according to the FPA-FOD database; human-dominated: n = 2,161, lightning-dominated: n = 347; distribution o f percent anthropogenic ignitions in Supporting Information Figure S3). We employed Wilcoxon rank sum tests to determine if each of the fire physical characteristics listed in Table 1 (the mean value over the timespan of the relevant dataset) varies as a function of the FPA-FOD derived dominant ignition type (Supporting Information Figure S4 and Table S2). We analysed if human ignition-dominated areas experience smaller and less intense fires because fire is more frequent and occurs over a longer season length in these areas by modelling both mean fire size and mean FRP as a function of fire frequency, fire season length, fire ignition type using linear models (all variables were scaled), and we analysed the relative importance of these predictive variables using the averaging over orderings proposed by Lindeman, Merenda and Gold (lmg) metrics, which provides a decomposition of the model explained variance into non-negative contributions using the R package 'relaimpo' (Groemping, 2006).

To determine how fire characteristics are changing over time for each ignition type, the rate of change over the timespan of the relevant dataset for each fire characteristic was estimated as the slope of linear models of each fire physical characteristic fitted for each ignition type at an annual timestep using the R package 'nlme' (Supporting Information Figure S5 and Table S3). One of the ignition type groups was determined to have a higher rate of change only if confidence intervals were non-overlapping. The percent changes were estimated from the predicted values based on the linear model objects. To determine how the difference between the fire physical characteristics for each of the characteristics listed in Table 1 for each ignition type varies among ecoregions, and how the difference between rate of change varies among ecoregions, we repeated the Wilcoxon rank sum test and linear model analyses for each United States Environmental Protection Agency (EPA) Level 1 Ecoregion (Omernik, 1987, 1995, 2004; Supporting Information Figures S6, S7 and Tables S5, S6).

To determine the effect of anthropogenic ignitions on fire characteristics, we fit regression models on each fire characteristics as a function of proportion anthropogenic ignitions using all pixels in the study area (Supporting Information Table S4). We identified if threshold behaviours in fire physical characteristics exist as anthropogenic ignitions increase – or if distinct points exist at which the response of a given fire characteristic to anthropogenic ignitions changes slope – by computing Davies' significance tests on the regression model outputs at the .05 significance level using the R package 'segmented' (Muggeo, 2003, 2008). If the test was significant, a segmented regression specifying one breakpoint was computed on the data and breakpoint locations were estimated within the model.

3. Results

3.1 Human Ignitions Are Increasing, and Fire Physical Characteristics Are Becoming More Extreme Over Time

In answer to our first question regarding how anthropogenic ignitions and fire physical characteristics are changing over time, at a national scale, the proportion of fires that are started by people is increasing over time, with a 9% proportional increase from 1992–2015 ($p < .01$; Figure 1). Moreover, fires are becoming larger ($p < .01$) and more frequent ($p < .01$) over a longer fire season but are not necessarily becoming more intense (all variables in Supporting Information Table S1; Figure S2). According to FPA-FOD, mean fire size has increased 78%, fire frequency has increased 12% and season length has increased 17% from 1992–2015. Fire event size for the largest fires is increasing even more rapidly at 87%. The rate of change is significantly increasing for every fire characteristic derived from MTBS and FPA-FOD, but for none of the characteristics derived from MODIS.

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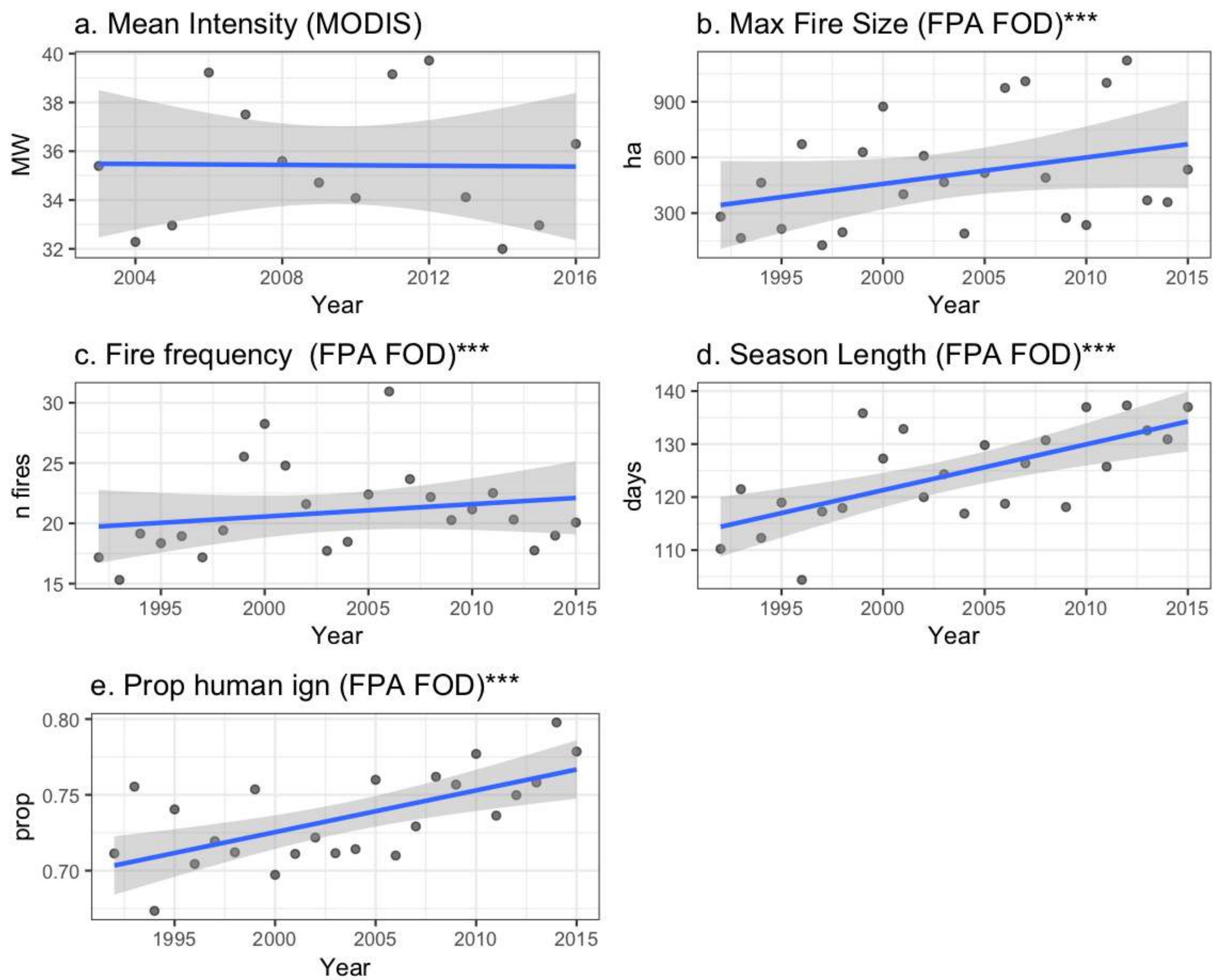

Figure 1. At a national scale, fires are becoming larger and more frequent over time, and are occurring over a longer season length, but not necessarily more intense. Further, the proportion of fires that are human-started fires is increasing over time. (a) Mean fire radiative power (FRP) in megawatts (MW) (Moderate Resolution Imaging Spectroradiometer, MODIS), (b) mean fire event size (Fire Program Analysis fire-occurrence database, FPA-FOD), (c) number of fires (FPA-FOD), (d) 2*Standard deviation Julian day (FPA-FOD), and (e) the proportion of fires that are human-started (FPA-FOD). All values are annual pixel means. Grey areas represent the 95% confidence level interval for linear model predictions. Code for significance of the slopes: ***$p \leq .01$.

3.2 Fire Ignition Type Influences Fire Physical Characteristics

In answer to our second question, we find that areas under heavy human ignition pressure experience fires with fundamentally different physical characteristics than areas dominated by lightning ignitions, and these characteristics are changing through time at different rates for each ignition type. Areas dominated by human- and lightning-started fires are significantly different from one another for every fire characteristic evaluated (Supporting Information Figure S4 and Table S2) and have different rates of change over time (i.e., non-overlapping confidence intervals) for every fire characteristic except two (MODIS-derived fire frequency and mean FRP) (Supporting Information Figure S5 and Table S3). Areas dominated by lightning ignitions experience average fires that are 2.4 times more intense and 9.2 times larger than areas dominated by anthropogenic ignitions (mean FRP and mean FPA-FOD fire event size) and extreme fires that are 2.9 times more intense and 6 times larger (maximum FRP and maximum fire event size) (Figure 2 and Supporting Information Table S2). Further, areas dominated by lightning ignitions experience average fires that are increasing 23 times faster in size over time than areas dominated by anthropogenic ignitions, and extreme fires that are increasing 12.2 times faster in size; areas dominated by human ignitions experience fires that are 2 times more frequent and that occur over fire season lengths that are 2.4 times longer (FPA-FOD; Figure 2 and Supporting Information Table S3). Trends in fire frequency and season length over time are not all significant; however, every fire variable with a significant slope for change over time indicates that human-started fires are increasing in frequency and season length over time more rapidly than lightning-started fires.

We explore if areas dominated by human ignitions are smaller or less intense because they are more frequent over a longer season length. When mean FRP is modelled as a function of fire frequency, fire season length and fire ignition type (adjusted R-squared: .273, $p < .01$), only the proportion anthropogenic ignitions contributes significantly to the model ($p < .01$), a t 8 1.2% relative importance. Mean fire size modelled as a function of fire frequency, fire season length and fire ignition type accounts for a relatively low amount of the variation (adjusted R-squared: .085, $p < .01$), and proportion anthropogenic ignitions and fire frequency both contribute significantly to the model (both $p < .01$) at 66.8 and 10.4% relative importance, respectively, but season length does not.

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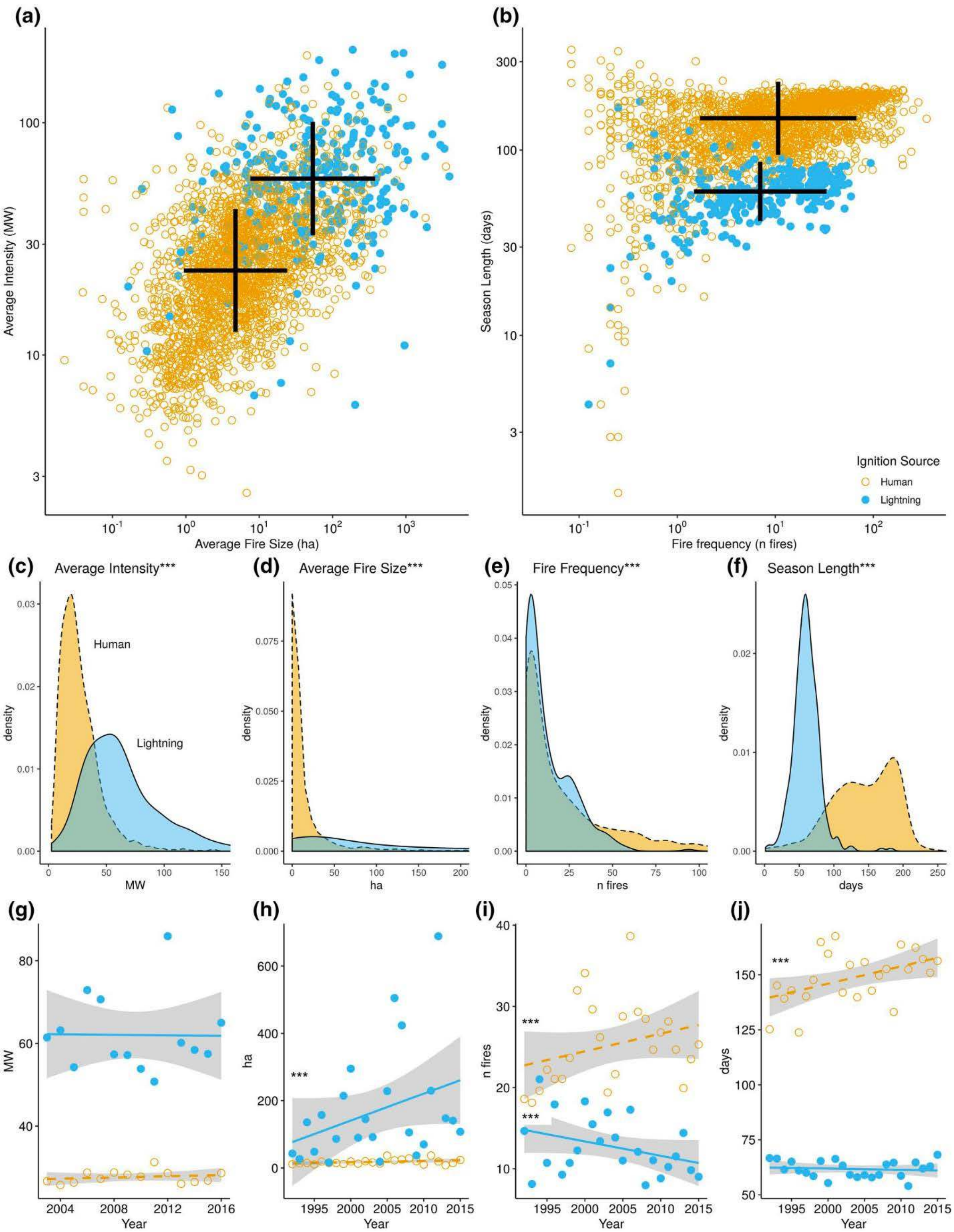

Figure 2. Lightning-started fires are more intense and larger relative to human-started fires, and lightning-started fires also have a faster rate of increase over time for fire size. Human-started fires have a longer season length and are more frequent, with faster rates of change for those variables. (a) Mean fire radiative power (FRP) in megawatts (MW)

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(Moderate Resolution Imaging Spectroradiometer, MODIS) by mean fire event size (Fire Program Analysis fire-occurrence database, FPA-FOD) with mean and SD for each ignition type, (b) number of fires (FPA-FOD) by 2*Standard deviation Julian day (FPA FOD), with mean and SD for each ignition type, (c) kernel density of mean FRP (MODIS), (d) kernel density of mean fire event size (FPA-FOD), (e) kernel density of number of fires (FPA-FOD), (f) kernel density of 2*Standard deviation Julian day (FPA-FOD), and (g–j) rates of change for those variables. All values are annual pixel means. Grey areas represent the 95% confidence level interval for linear model predictions. Code for significance of differences and of the slopes: ***$p \leq .01$.

3.3 Increasing Human Ignitions Results in Threshold Behavior

In answer to our third question, we find, at a national scale, increasing human ignitions have a negative relationship with FRP and fire event size for both average and extreme fires and for burned area and, conversely, a positive relationship with fire frequency and season length (Figure 3, all variables in Supporting Information Table S4). Furthermore, we identify threshold behavior in some fire physical characteristics as anthropogenic ignitions increase. FRP decreases with increasing anthropogenic ignitions, and decreases even more so after a breakpoint at 81% anthropogenic ignitions (slopes: −35 and −103, respectively; $p < .01$; Figure 3a), and mean event size decreases with increasing anthropogenic ignitions and, again, and decreases even more so after a breakpoint at 55% anthropogenic ignitions (slopes: −127 and +344, respectively; $p < .01$; Figure 3b). The FPA-FOD data indicate that fire frequency increases with increasing anthropogenic ignitions after a breakpoint at 71% anthropogenic ignitions (slope: 45; $p < .01$; Figure 3c), and fire season length increases with increasing anthropogenic ignitions (slope: 108; $p < .01$; Figure 3d).

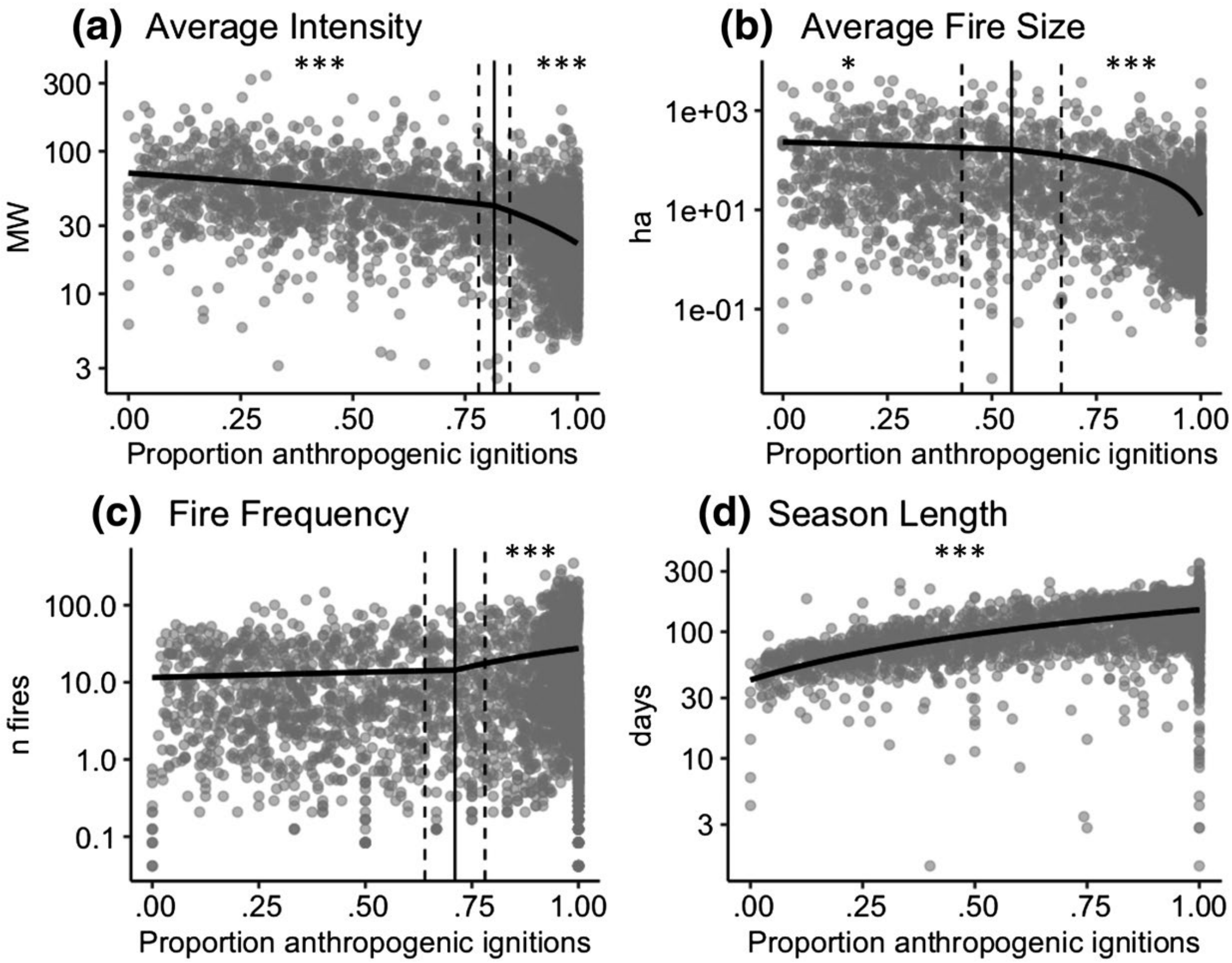

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Figure 3. Relationship between proportion anthropogenic ignitions and fire characteristics as determined by linear regression and segmented linear regression. Increasing human ignitions have a negative relationship with fire radiative power (FRP) and fire event size and a positive relationship with fire frequency and season length: (a) mean FRP in megawatts (MW) (Moderate Resolution Imaging Spectroradiometer, MODIS), (b) mean fire event size (Fire Program Analysis fire-occurrence database, FPA-FOD), (c) number of fires (FPAFOD), and (d) 2*Standard deviation Julian day (FPA-FOD). A breakpoint is determined by Davies' tests at or above the .05 significance level. All values are annual pixel means. Codes for significance of slopes for each segment: ***$p \leq .01$; *$p \leq .1$. Breakpoints at 95% confidence are shown as vertical lines.

3.4 The Influence of Ignition Type on Fire Physical Characteristics Varies Spatially

We found that the relationships between ignition source (i.e., lightning- versus human-started fires) and both fire physical characteristics (Figure 4 and Supporting Information Figure S6 and Table S5) and the rate of change over time of fire physical characteristics (Supporting Information Figure S7 and Table S6) varies geographically by EPA Level 1 Ecoregions. The Eastern Temperate Forests, Marine West Coast Forest, Mediterranean California, Northern Forests, Southern Semiarid Highlands and Tropical Wet Forests ecoregions have pixels that are dominated by human ignitions (> 75% ignitions), but none of these ecoregions has lightning ignition-dominated pixels. For those ecoregions, we are unable to compare fire physical characteristics of lightning- versus human-started fires.

For the remaining ecoregions (Great Plains, North American Deserts, Northwestern Forested Mountains and the Temperate Sierras), a general pattern exists that areas dominated by lightning- ignited fires within a given ecoregion have higher values of FRP and size, including for average and extreme fires, than areas dominated by human-ignited fires (with some exceptions; Figure 4 and Supporting Information Figure S6 and Table S5). Across all ecoregions, areas dominated by human-ignited fires have longer season lengths. Patterns in fire frequency are less spatially uniform.

Patterns in the rates of change over time of fire physical characteristics are geographically mixed (Supporting Information Figure S7 and Table S6). Generally, when the difference in rates of change is significant between ignition types, areas dominated by lightning ignited fires within a given ecoregion are becoming more intense and larger at faster rates than areas dominated by human-ignited fires, both for average and extreme fires (but human-ignited fires are more rapidly increasing in some cases). According to FPA-FOD, areas dominated by human-ignited fires have more rapidly increasing fire season lengths than lightning-dominated areas across all ecoregions, but the pattern is less clear according to the other datasets. Additionally, most datasets indicate the areas dominated by human-ignited fires have more rapidly increasing fire frequency in the Great Plains than lightning-dominated area, but patterns are less consistent elsewhere.

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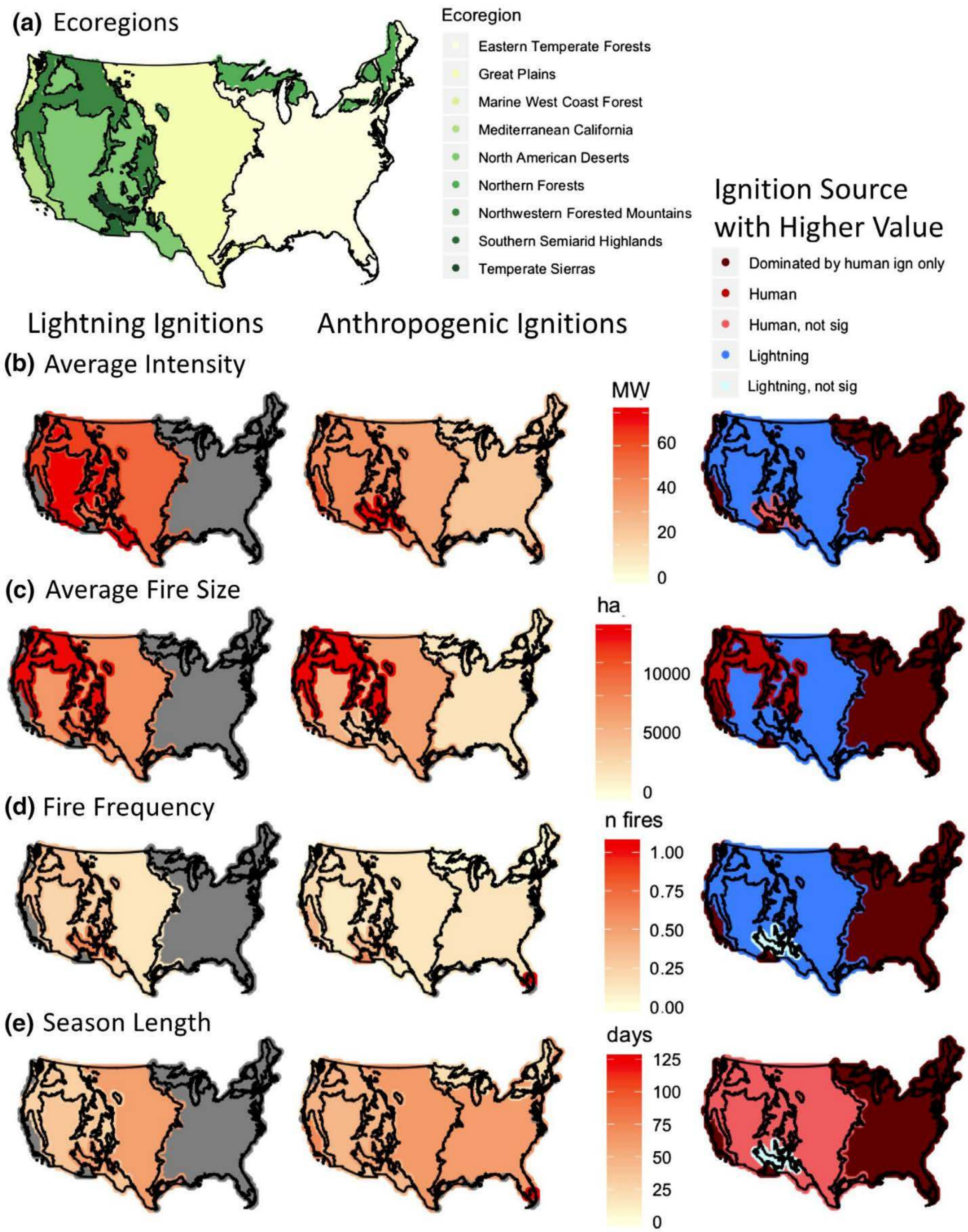

Figure 4. Fire characteristics for each EPA Level 1 Ecoregion divided by dominant ignition type (anthropogenic- or lightning-started), and the ignition source with higher values of fire characteristics. Several ecoregions do not have lightning-dominated areas. For the other ecoregions, generally, areas dominated by lightning ignitions have more

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intense and larger fires than areas dominated by human ignitions. Generally, areas dominated by human-started fires have longer season lengths and, less consistently, higher fire frequencies across the United States: (a) United States Environmental Protection Agency (EPA) Level 1 Ecoregions, (b) mean fire radiative power (FRP) in megawatts (MW) (Moderate Resolution Imaging Spectroradiometer, MODIS), (c) mean fire event size (Monitoring Trends in Burn Severity, MTBS), (d) number of fires (MTBS), and (e) 2*Standard deviation Julian day (MTBS). All values are annual pixel means for each ecoregion.

4. Discussion

At a national scale, we find that fires are becoming larger and more frequent over longer fire seasons, but not necessarily more intense, and that the proportion of ignitions that are human-caused is increasing over time. These trends are consistent with findings from other studies examining contemporary patterns of fire activity in the western U.S.A. that demonstrate increases in fire frequency, burned area, high-severity burned area, duration and/ or fire season length (Balch et al., 2018; Dennison et al., 2014; Dillon et al., 2011; Westerling, 2016; Westerling et al., 2006). We expand on this work by (a) scaling up evaluations of trends in fire event size, burned area and fire frequency to the national scale, (b) including all detectable fires rather than focusing exclusively on large fires in order to capture the aggregate area and impact of small fires, and (c) evaluating these trends over time in the context of ignition type. Further, to our knowledge, this study is the first to track national trends over time of anthropogenic ignitions and of FRP-based fire intensity.

Anthropogenic ignitions are shaping modern fires across the contiguous U.S.A. Areas dominated by lightning-started fires experience more intense and larger fires and have a faster rate of increase in size than areas dominated by human-started fires – both for average and extreme fires. Areas dominated by human-started fires, on the contrary, experience higher fire frequency over a longer fire season and have a faster rate of increase for frequency and season length. Consistent with this, we find a negative relationship between anthropogenic ignitions and both fire size and FRP and a positive relationship between anthropogenic ignitions and both fire frequency and fire season length. Our findings support previous studies demonstrating that modern anthropogenic ignitions are extending the fire season (i.e., expanding into the shoulder seasons; Balch et al., 2017; Bartlein et al., 2008) and that human ignitions may affect spatial patterns of large fire occurrence (Balch et al., 2017; Malamud et al., 2005; Nagy et al., 2018).

Further, we identify threshold behavior in some fire characteristics whereby they change more rapidly beyond a certain level of anthropogenic ignitions. For example, a positive relationship between anthropogenic ignitions and fire frequency exists only beyond c. 70% anthropogenic ignitions. There is evidence for the presence of fire regime thresholds in the context of shifts in fire size distributions (e.g., Zinck, Pascual, Grimm, 2011), and there has been much discussion surrounding the appropriate distribution to describe fire size/burned area and thus to capture deviations from that distribution (e.g., Reed & McKelvey, 2002). Much focus has been directed toward shifts toward more 'extreme' fires (e.g., larger or more severe) and the associated ecological and societal costs. However, increasing anthropogenic ignitions and the subsequent shifts toward smaller, less intense, and more frequent fires may also have species- to ecosystem-level implications in some systems. For example, large, severe infrequent fires have been part of natural fire regimes historically in montane forests in the western U.S.A., and these regimes increase resilience to subsequent disturbances (Baker, 2018), which could be compromised given changes in fire size, severity and frequency. A shift in fire regime characteristics in any direction away from its historical state impacts the survival probability of plants that have co-evolved with that historical regime, as well as the persistence of ecological processes and wildlife species that depend on that vegetation. It is important to note that these fire characteristics, any given one or several in combination, are not directly equivalent to ecological or human impact. For example, FRP does not directly correspond to fire severity or impacts on soil or vegetation, although some evidence exists that they are linked (Heward et al., 2013). Furthermore, as discussed in the Materials and Methods, we use the term 'dominated' here to refer to the dominant ignition source (i.e., > 75% human or lightning) in a given 50-km resolution pixel according to the FPA-FOD database. We do not, however, evaluate the impacts of individual fires in a given pixel; thus, for example, the < 25% of fires in a pixel started by the non-dominant ignition type could have a larger 'impact' than the > 75% started by the dominant ignition type. Additional research is warranted concerning how nonlinear responses of the fire system to human ignitions may influence the inherent resilience of these systems, including if they result in regime shifts, and how these thresholds might vary as a function of historical fire regimes and ecosystem adaptations, as well as underlying vegetation or climatological conditions that affect fuel extent and connectivity. Furthermore, we see increasing human ignitions across the country, and thus there may exist interactions and threshold behaviors for which we have no historical precedent given concurrent changes in climate and land cover.

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Anthropogenic fires are lower intensity and smaller in size relative to lightning fires, and our analysis indicates that this pattern cannot be explained by increased fire frequency or increased season length alone. The explanations that increased fire frequency or season length would reduce FRP and size are as follows: (a) human fires, which are more frequent, preclude large, intense fires that require time for sufficient fuel accumulation; and/or (b) human fires, which occur over a longer season length, are more likely to burn in times that are not amenable to large, intense fires (e.g., wetter conditions Balch et al., 2017). Although these explanations may be true in part, much previous work modelling wildfire occurrence has found that human-started fires often occur close to infrastructure (Grala & Cooke, 2010; Grala, Grala, Hussain, Cooke, & Varner, 2017), indicating that these fires may be easier to detect, more likely to be suppressed due to earlier detection and threatened human structures, and easier to access for suppression efforts – which would contribute to anthropogenic fires being less intense and smaller.

The MTBS dataset includes prescribed and wildfires over a size threshold that are detectible by Landsat satellite imagery, the MODIS dataset includes all fires detectible from their thermal signal (not grouped into fire events) and the FPA-FOD dataset includes wildfires only (including prescribed fires only if they escaped and required a suppression response). Some prescribed fires and thus fire trends would be captured by the MODIS and MTBS datasets, but not the FPA-FOD dataset, which provides the best available national-scale information regarding fire ignition source. Comparisons of different satellite-based fire products indicate little agreement among products (Fusco et al., 2019) and some satellite sensors capture radically different fire signals (Hawbaker et al., 2017; Vanderhoof, Fairaux, Beal, & Hawbaker, 2017). We find all variables capturing the same characteristic (e.g., fire frequency) but derived from different data sources have significantly different values, indicating that complementary information is embedded in each data source. For example, MODIS' sub-daily return interval and rapid data availability after overpass allows for the detection of fires in near real-time with the MODIS Active Fire Product. However, these data are relatively spatially coarse at 1-km resolution and the fire detections are not grouped into unique fires [i.e., a single event with common ignition source(s)]. The burn severity indices derived from Landsat data that are used to develop the MTBS burned area data can be computed at 30-m resolution and are delivered as fire events; however, with a satellite return interval of 16 days, Landsat may miss short-lived fires in areas with rapid post-fire vegetative regrowth (i.e., grass, herbaceous and some shrubland, e.g., Li & Xulin, 2018). Further, fire databases/government records and remotely sensed data contain different and complementary information. For example, satellite products can detect fires that do not merit a suppression response and thus are not reported, and therefore do not contain the human detection biases embedded in government records. Satellite products also do not contain the same spatio-temporal inconsistencies as government records, which suffer from differences in reporting among states and over time. On the contrary, government records indicate the source of ignition, vital to understanding the anthropogenic contribution to contemporary fires.

The trends derived from different data sources agree in many cases. Differences among trends for the same fire characteristics derived from different data sources may be a result of the unique data characteristics that create different representations of fire. For example, for trends in fire characteristics over time at a national scale, the rate of change for every fire characteristic derived from MTBS and FPA-FOD is significantly increasing; however, none of the characteristics derived from MODIS shows significant rates of change, which could perhaps be attributed to the shorter timeframe covered by the MODIS dataset. For this reason, national trends in fire characteristics, including fire FRP-based intensity may also not be detectible until the dataset is extended. For fire characteristics by ignition type, all data types indicate lightning-dominated areas exhibit higher values in FRP, fire event size and burned area, and that human-dominated areas do for season length and frequency (but not MTBS for frequency). This particular discrepancy can likely be attributed to the fact that, if human-started fires are smaller, the size threshold of MTBS would preclude many human-started fires from being included in the database. Segmentation analyses show negative relationships between human ignitions and FRP, event size and burned area and positive relationships between human ignitions and both season length and frequency (except season length beyond 95% human ignitions for MTBS, likely an artifact of urbanization). Similarly, for all significant trends in fire characteristics over time by ignition type, all data types indicate that lightning-dominated areas exhibit higher rates of increase in FRP-based intensity, event size, and burned area, and that human-dominated areas do for season length and frequency. The only significant negative trend is the number of fires in lightning-dominated areas according to FPA-FOD. This trend is not apparent in the MODIS or MTBS datasets and, given potential reporting issues with this dataset, should be considered critically. Because of these reporting issues among states, we do not consider differences among ecoregions according to the FPA-FOD data. Any differences between the MTBS and MODIS datasets can likely be attributed to the small wildfires that MODIS captures that are excluded from MTBS and/or that the MTBS fires are represented as fire events whereas the MODIS data are not. There is a clear need for a fire product that aggregates the various fire products available and represents

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the differences among them so that the error associated with the different products can be quantified and included in subsequent analyses. Further, an exploration of how prescribed fires are altering fire characteristics nationally was outside the scope of this study. We do see national trends in fire characteristics here that are consistent between datasets that include prescribed fire and those that do not. A spatio-temporally explicit, national-scale, and easily accessible database on prescribed fire would be valuable for exploring the effects of prescribed fire, as changes in policy and public opinion concerning prescribed fires over time have certainly played a large part in the history of fire across the U.S.A. (Ryan, Knapp, & Varner, 2013).

The influence of ignition type on fire physical characteristics varies spatially. Many ecoregions – including the entire eastern United States and much of the western coast do not have any areas (i.e., 50-km pixels) that are dominated by lightning ignitions. As there is little dry lightning in tropical southern Florida and few lightning strikes at all west of the Sierras, the Tropical Wet Forests, Marine West Coast Forest and Mediterranean California ecoregions would likely have been historically ignition-limited in the absence of human ignitions (e.g., Keeley, 2002). In the Eastern Temperate Forests, Northern Forests and Southern Semiarid Highlands ecoregions, on the contrary, lightning ignitions were likely historically present, but humans have completely superseded lightning as the dominant ignition source. The extent to which ignitions have limited fire across the country has varied over time and space. The prevalence of human-started fire has fluctuated over time, from widespread use for land management activities by Native people, to declines in ignitions during industrialization, and further declines during the era of fire suppression in the 20th century, affecting fire characteristics through changes in fire frequency and fire return intervals (Van Lear & Harlow, 2002; Stambaugh et al., 2018; Taylor, Trouet, Skinner, & Stephens, 2016). Evidence for this so-called 'wave of fire' exists in several places in North America, but it is still unknown to what extent it is geographically prevalent, which would influence our current interpretations of the influence of anthropogenic ignitions on contemporary fire regimes within the historical context of human fire-use across broad landscapes. We emphasize that we evaluate here trends in fire behavior over modern rather than historical times. We do find that longer season lengths are associated with areas dominated by human-started fires rather than lightning-started across all ecoregions, demonstrating that, in recent times, human ignitions have expanded fire into the shoulder seasons across the country. Although ignitions may have been prevalent historically (Van Lear & Harlow, 2002), these intentional fires set for indigenous land management may have a markedly different temporal and spatial signal than contemporary, accidental fires explored here. The scales of indigenous management activities are thought to be more consistent with the broader landscape, allowing for the co-evolution of indigenous land management practices with endemic flora and fauna (Codding & Bird, 2013), and future fire management could be immensely benefited by indigenous knowledge concerning fire use and management.

The areas in which more intense and larger fire can be attributed to lightning-started fires, both for average and extreme fires, are restricted to the western U.S.A., where the phenomenon of increasingly extreme fires and a strong climate signal have been demonstrated (Balch et al., 2018; Dennison et al., 2014; Dillon et al., 2011; Westerling, 2016; Westerling et al., 2006), as well as the Great Plains. The human influence on fire in the western U.S.A. is more strongly defined by how people alter the factors that predispose the landscape to burning rather than by increasing ignitions directly. For example, some areas in the U.S.A. have seen increases in the amount of area burned by lightning without significant increases in lightning ignitions (Stephens, 2005), indicating that fire in those areas was likely not controlled by ignitions but rather by the factors affecting landscape flammability. It is of key interest to determine the mechanisms of human influence on these fire characteristics across the U.S.A.; for example, the extent to which altered fuel availability through climate and land cover change alters fire behavior. It has been demonstrated that fire activity in the U.S.A. will likely be affected by changing climate, although not uniformly (Morton et al., 2013). On the contrary, more direct human influence may also play a significant role in altering future fire characteristics, as the extent to which climate can explain variance in fire activity in both contemporary (Syphard, Keeley, Pfaff, & Ferschweiler, 2017) and historical (Taylor et al., 2016) fire regimes is reduced in areas where humans are more prevalent. Further, changes in fire suppression tactics, which vary regionally and over time, could have an impact on trends in fire characteristics.

Trends in fire characteristics over time vary spatially. Previous national assessments demonstrate that burned area and severity have increased over time in only roughly 26–30% of the vegetation groups evaluated (Picotte, Peterson, Meier, & Howard, 2016). Although we find that trends over time are significantly positive at a national scale for many of the fire characteristics evaluated, they are not significantly positive in all 10 ecoregions for any fire characteristic. Further, although areas dominated by lightning-ignited fires within a given ecoregion are generally becoming more intense and larger at faster rates than areas dominated by human-ignited fires, the rates of change over time are not always positive, and patterns in the rates of change over time are geographically mixed. Variability in fire characteristics may be explained by the unique interplay between climate, anthropogenic ignitions, and vegetation type/fuel conditions in each ecoregion, and spatial correlation between human and environmental factors plays a strong role in shaping fire regimes nationally (see extensive literature on modelling wildfire occurrence as a function of biophysical, societal and management variables, e.g., Prestemon et al., 2013). Additionally, the areas with the more rapidly increasing fire season lengths are dominated by human-ignited fires in some ecoregions and lightning-ignited fires in others, indicating that perhaps the fire season length of lightning-started fire is expanding as well in tandem with climate and land use changes. Stratifying by vegetation type and climatological zone would allow for the consideration of interactions and feedbacks between those characteristics and increasing ignitions. The national trend that lightning-started fires are larger and more intense and are becoming larger over time at faster rates than human-started fires appears to be driven by fire behavior in the western U.S.A. However, it is important to note the importance of proportionally intense and large fires in less fire-prone regions in the eastern U.S.A. (e.g., Nagy et al., 2018) and the large effect that anthropogenic ignitions are having in those areas.

5. Conclusions

In summary, the analysis of fire disturbance presented here uses the wealth of data available on fire occurrence to demonstrate how the physical characteristics of modern fires are changing across the contiguous U.S.A. and to elucidate how those characteristics are changing given increasing anthropogenic ignitions. Anthropogenic ignitions are fundamentally changing the characteristics of our modern fire regimes. Lightning ignitions are associated with more intense and larger fires – with faster rates of increase in size at a national scale, but anthropogenic ignitions contribute more frequent small fires over a longer fire season that impact fire landscapes. The effect of anthropogenic ignitions on fire physical characteristics generally follows an east–west dichotomy, with areas in the eastern U.S.A. dominated by human ignitions, and with hotter and larger fires being started primarily by lightning in ecoregions in the western U.S.A. Longer season lengths are associated with human-started fires across the United States, and human ignitions are introducing ignitions in some areas where they have not been prevalent in recent times. Increasing anthropogenic ignitions – in tandem with climate and land cover change– are contributing to a ‘new normal’ of fire activity occurring across continental scales. As both human- and lightning-started fires are becoming larger and more frequent over a longer fire season, it is a pivotal moment to consider together all of the controls on fire – ignitions, climate and fuel – as well as the interactions between them.

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Data Accessibility

All data that support the findings of this study are available for direct download in public repositories. The code to access these data and generate the analyses is publicly available on GitHub: https://github.com/mcattau/anthro_ign_code.

Biosketch

Megan Cattau uses big data approaches to address theory and management-relevant questions across scales. Her research is centred around the general issues: how do anthropogenic factors interact with biophysical factors to alter ecological disturbance regimes and subsequent recovery, and how effective are the intervention options in increasing social-ecological resilience? She is an advocate for making environmental science more accessible through inclusive pedagogical approaches, stakeholder involvement in research, and collaborations with artists that bring science to the public.

Supporting Information

Additional supporting information may be found online in the Supporting Information section.

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List of Figures and Tables in Supporting Information