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Key Points:
- Across U.S. ecoregions, annual human- and lightning-ignited wildfire burn areas are similarly correlated with environmental conditions
- Climate-driven changes in temperature, precipitation, and humidity will likely impact both human- and lightning-ignited wildfires similarly
- The total mass of particulate matter emissions from human-ignited wildfires is similar in the west and southeastern United States

Supporting Information:
- Supporting Information S1

Correspondence to:
S. J. Brey,
steven.brey@colostate.edu

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Environmental Conditions, Ignition Type, and Air Quality Impacts of Wildfires in the Southeastern and Western United States

Steven J. Brey[1], Elizabeth A. Barnes[1], Jeffrey R. Pierce[1], Christine Wiedinmyer[2], and Emily V. Fischer[1]

[1]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA, [2]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA

Abstract This research contrasts the environmental conditions, meteorological drivers, and air quality impacts of human- and lightning-ignited wildfires in the southeastern and western United States, the two continental U.S. regions with the most wildfire burn area. We use the Fire Program Analysis Wildfire Occurrence Data (FPA FOD) to determine wildfire abundance and ignition sources between 1992 and 2015. We investigate specific ecoregions within these two U.S. regions and find that in the majority of ecoregions, annual lightning- and human-ignited wildfire burn area have similar relationships with key meteorological parameters. We investigate the fuel moisture values where wildfires occur segregated by ignition type and show that within a given ecoregion, the differences in median fuel moisture between ignition types are generally smaller than the differences between ecoregions. Our results suggest that annual wildfire burn area for human- and lightning-ignited wildfires within a given ecoregion are modulated by environmental conditions, and climate change may similarly impact wildfires of both ignition types. Finally, we estimate fine particulate matter emissions for Fire Program Analysis Wildfire Occurrence Data wildfires using the Fire INventory from NCAR model framework. We show that emissions of fine particulate matter from human-ignited wildfires is significant and of a similar total magnitude between the west and southeastern United States. Additionally, the west and southeast have a similar number of wildfires associated with National Weather Service air quality smoke forecasts.

Plain Language Summary This research compares the environmental conditions, meteorological drivers, and air quality impacts of human- and lightning-ignited wildfires in the southeastern and western United States. We use a wildfire occurrence data set that documents wildfire ignition sources. We find that for the majority of land cover types within the west and southeast, annual lightning- and human-ignited wildfire burn area respond similarly to temperature, precipitation, and relative humidity. We investigate the fuel moisture values where wildfires occur segregated by ignition type and show that within a given geographic area, the differences in fuel moisture between ignition types are generally smaller than the differences between geographic areas. Our results suggest that annual wildfire burn area for human- and lightning-ignited wildfires may respond similarly to climate change. Finally, we show that human-ignited wildfires impact air quality in the west and southeast United States.

1. Introduction

Understanding the current and potential future abundance of fire in the United States is important for many reasons, but here we approach this issue from an air quality perspective. Recent work has shown that U.S. wildfires can severely degrade air quality on local to national scales (Baker et al., 2016; Brey et al., 2018; Brey & Fischer, 2016; Ford et al., 2017; Jaffe et al., 2008; Lassman et al., 2017; Saide et al., 2015; Val Martin et al., 2015; Wiedinmyer et al., 2006). For example, on days that exceed $PM_{2.5}$ (mass concentration of particulate matter with diameters smaller than 2.5 μm) regulatory concentrations in the western United States, 71% of the $PM_{2.5}$ can be attributed to wildfires (Liu et al., 2016). Brey and Fischer (2016) show that there are many urban areas that experience increased ozone mixing ratios on days impacted by wildfire smoke. Given these air quality impacts, understanding what drives U.S. wildfire abundance and variability is a priority.

Variations in wildfire activity are due to an assortment of influences including, natural climate variability, human-caused climate change, and the legacy of wildfire suppression (Abatzoglou & Williams, 2016;

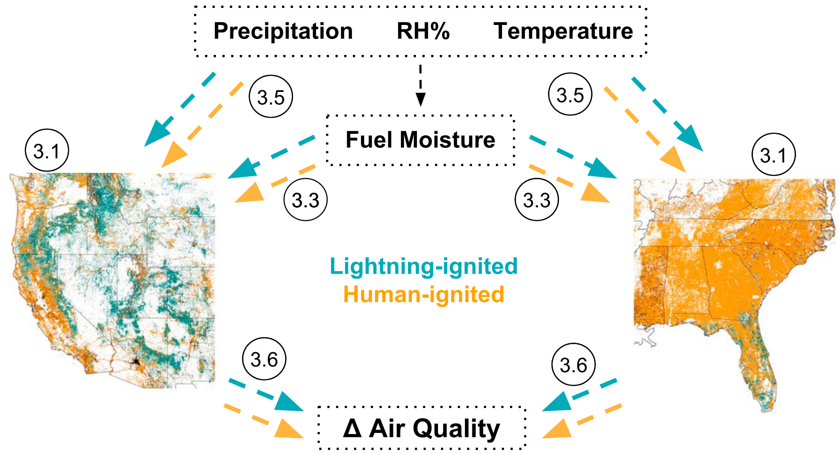

Figure 1. Schematic outlining the components of the U.S. wildfire system explored in this work: wildfire abundance in the west and southeast and how these abundances are influenced by ignition type, precipitation, relative humidity (RH%), temperature, and fuel moisture. Finally, we show the air quality impacts wildfires have in each region and attribute these impacts to different ignition sources. The numbered circles indicate sections of the paper that correspond to different components of the diagram. Not all sections of the paper are shown.

Pechony & Shindell, 2010; Short, 2015; Westerling et al., 2006, 2014). Both long-term and year-to-year climate variability can modulate the availability of fuel in fuel-limited locations (whether or not fuels can survive) and influence fuel flammability in flammability-limited locations (wet fuels do not readily ignite; Littell et al., 2009, 2016). A large body of literature has demonstrated relationships between western U.S. forests wildfire burn area and meteorology (Abatzoglou et al., 2016; Abatzoglou & Kolden, 2013; Barbero et al., 2014; Cansler & McKenzie, 2014; Gannet Hallar et al., 2017; Morton et al., 2013; Park Williams et al., 2015; Riley et al., 2013; Westerling et al., 2014; Yoon et al., 2015). Fewer studies focus on the meteorological drivers of wildfire activity in the southeast United States, possibly because the majority of burn area in the southeast is from prescribed wildfires (Mitchell et al., 2014) and by design, prescribed wildfire burn area extent is not (normally) determined by meteorology. Approximately 70% of all prescribed burn area in the United States occurs in the southeast (Melvin, 2015); however, the use of prescribed fire may be limited in the future, as severe droughts in this region become more likely (Mitchell et al., 2014). Unintentional fires occur in this region as well. In a study that focused on Florida wildfires, Brenner (1991) observed that most wildfires between January and April, months were relative humidity values between 20% and 30% are common, are primarily caused by humans, while lightning activity and lightning-ignited wildfire occurrence peaks in July (Brenner, 1991). Given the large number of wildfires in the southeast, their potential importance for regional air quality, and the susceptibility of the region to climate-driven changes in wildfire occurrence (e.g., Liu et al., 2013), this region needs to be understood in order to prepare for the future impacts of U.S. wildfire.

Recently, Short (2014) compiled the Fire Program Analysis Fire Occurrence Data (FPA FOD), one of the most spatially comprehensive U.S. wildfire-occurrence data sets to date. These data include information on the ignition source of wildfires. As a result, there has been an uptick in the number of studies that consider the regionally varying influence and environmental drivers of human-ignited wildfires (e.g., Abatzoglou et al., 2016; Balch et al., 2017; Fusco et al., 2016; Nagy et al., 2018; Syphard & Keeley, 2015). The goal of our research is to expand on the findings of these studies by showing how the environmental conditions, meteorological drivers, and air quality impacts differ for human- and lightning-ignited wildfires, and to contrast the southeast and western United States (outlined in Figure 1). This is an understudied issue essential to understanding what drives wildfire and wildfire-smoke abundance (i.e., air quality impacts) in the two continental U.S. regions with the most wildfire activity (based on the FPA FOD, the west and southeast account for ~89% of total continental U.S. burn area).

We focus on what drives burn area, rather than number of ignitions, from all wildfires throughout the entire year, including small wildfires. This particular approach is valuable because it reveals several important, but nuanced, new findings. We show that ignoring small wildfires (<1,000 acres), as is often done in similar studies, is not likely appropriate for air-quality-relevant studies. We are able to identify which high-emitting

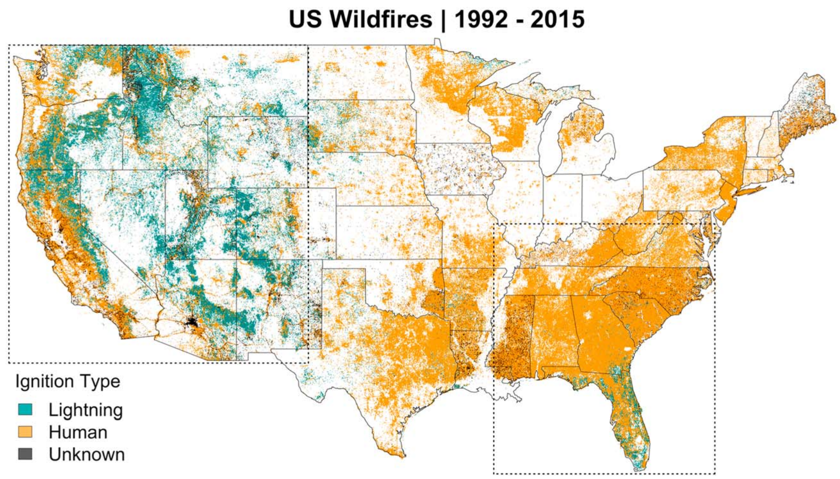

Figure 2. Location and ignition type of all wildfires documented in the Fire Program Analysis Fire Occurrence Data located within the contiguous United States between 1992 and 2015. There are 1,880,465 wildfires in the record, 15% ignited by lightning, 77.7% by humans, and 7.3% fires with an unknown/missing ignition type. The plotted wildfires account for 107,508,006 acres of area burned over the period. The dashed-line box over the western United States shows the geographic extent of the "western United States" (i.e., "west") region. The dashed-line box over the southeast United States shows the region defined as "southeast United States" (i.e., "southeast") in this study.

ecoregions are dominated by human-ignited wildfires. Most importantly, we show that annual wildfire burn area for human- and lightning-ignited wildfires within a given ecoregion are correlated with environmental conditions. This implies that changes in burn area that result from climate change will likely be similar for both ignition types.

This paper describes a wildfire occurrence data set, human- and lightning-ignited wildfire occurrence in the southeast and western United States, how these wildfires correlate to each other and environmental conditions, and an estimate of $PM_{2.5}$ emissions from wildfires of each ignition type in both regions. This work is essential in order for us to understand how the U.S. wildfire system works now and how it might change in the future. This understanding will help us prepare for wildfire air quality impacts in the future.

2. Data and Methods

2.1. Fire Program Analysis Wildfire Occurrence Data

The FPA FOD documents U.S. wildfires that were extinguished or managed by state, federal, or local agencies between 1992 and 2015 (Short, 2014). The database of ~1.88 million wildfires merges records from federal, state, and local fire reporting systems. Each wildfire record includes a discovery date, final fire size, cause, and fire location. The wildfire location data are provided as latitude longitude coordinates. However, these locations do not always represent burn scar centroids, ignition locations, nor are they always as precise as the data imply (Short, 2014). Sometimes wildfire locations are assigned as a public land survey system section centroid (2.6 km^2; Short, 2014). The specific cause of wildfires is stated, although 8.9% (including Hawaii, Alaska, and Puerto Rico) of the wildfires are assigned a cause of "Missing/Undefined". Other fire causes (i.e., ignition sources) in the data include "Lightning," "Children," "Campfire," "Debris Burning," "Arson," "Miscellaneous," "Equipment Use," "Smoking," "Railroad," "Fireworks," "Powerline," and "Structure." For this analysis, wildfires with the cause "Missing/Undefined" are discarded or evaluated separately and causes other than "Lightning" are grouped into a single category of "human-ignition." The FPA FOD purposely exclude prescribed (Rx) fires with the exception of prescribed fires that escaped their planned perimeters and turned into wildfires (Short, 2014). Figure S1 in the supporting information shows the abundance of each ignition type by region and season.

Wildfire characteristics vary significantly between the southeast and western United States. Figure 2 shows the location of continental U.S. (CONUS) FPA FOD wildfires between 1992 and 2015. In the southeast, wildfires are widespread. There are overlapping wildfires (e.g., some lightning-ignited wildfires in the southeast United States are hard to see). Figure S2 shows the location of human- and lightning-ignited wildfires on separate maps.

These data are an incomplete record of total wildfire (or any type of fire) activity on the U.S. landscape (Short, 2014). Many wildfires managed or responded to by local agencies go unreported or do not result in a "viable" report (Thomas & Butry, 2012). The reliability and quality of these data vary across states (e.g., spatial pattern and abundance of ignition type "Unknown/Undefined," gray dots in Figure 2). In some areas it is possible that the ignition type designation "Unknown/Undefined" are wildfires ignited by humans. For example, the Phoenix metropolitan area appears gray in Figure 2. Given the high population density of this urban area it is plausible that these wildfires were started by humans rather than lightning.

Short (2014) estimates how complete the FPA FOD are by state with respect to United States Forest Service and National Interagency Coordination Center wildfire data. These estimates of completeness are provided on a 10-point scale. The scores for states completely within the western region shown in Figure 2 range between 7.4 (Colorado) and 9.9 (Idaho), with a mean score of 9.2. The scores for states in the southeast region range between 6.3 (Tennessee) and 9.9 (Georgia), with a mean score of 8.83 (Short, 2014). In the west and southeast, the FPA FOD is considered complete to the extent that it can be used to characterize patterns of wildfire area burned (Short, 2014).

For this work, the 1992–2015 fire occurrence data were downloaded on 29 January 2018 as a Microsoft Access Database (.accdb) file where the "fires" field was exported. The data are available at the following URL: https://www.fs.usda.gov/rds/archive/Product/RDS-2013-0009.4/.

2.2. North America Level II Ecoregions

We group the fires in the FPA FOD by ecoregion. Ecoregions are geographic areas where the type of ecosystems are broadly similar. Characteristics considered in making ecosystem classifications include, geology, soils, vegetation, climate, land use, and hydrology (Omernik, 1987, 1995). The ecosystems used to separate wildfires in this work were developed by Omernik (1987). These ecosystems serve as a geographic framework for research of areas with similar ecosystem components. Some of the analysis presented in this work is presented on level II ecoregions, a spatial scale useful for subcontinental analysis, and that aggregates wildfires with similar geographic attributes. In this work, FPA FOD wildfires were assigned an ecoregion based on the ecosystem shapefile perimeter in which each fire location fell within, or closest to. The ecoregion shapefile data are available at the following URL: https://www.epa.gov/eco-research/ecoregions-north-america.

2.3. GRIDMet Meteorology and Fuel Moisture Information Data

This work uses the GRIDMet derived variable 1,000-hr dead fuel moisture to assess fuel aridity. The 1,000-hr dead fuel moisture index is determined by ambient environmental conditions and is critical to determining wildfire potential. GRIDMet is a gridded archive of meteorological data over the contiguous United States with 4-km horizontal grid spacing. The data were developed by Abatzoglou (2013) for use in ecological, agriculture, and hydrological models. The data were validated against several weather station networks, including, RAWS, AgriMet, AgWeatherNet, and USHCN-2. These data, as well as documentation, are available at the following URL: http://www.climatologylab.org/gridmet.html

2.4. ECMWF ERA-Interim Reanalysis Meteorology

We use ECMWF ERA-Interim reanalysis fields (Dee et al., 2011) of temperature, precipitation, and relative humidity to determine regional meteorology conditions at annual temporal scales and horizontal grid spacing of 0.75° × 0.75°. We compute annual means by taking the averages of 6-hourly (00z, 06z, 12z, and 18z) analysis fields. Estimating total precipitation requires the use of forecast fields. We combine the 00z and 12z 12-hr total precipitation fields to get total daily accumulated precipitation. The data are available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim

2.5. Global Fire Emissions Data

In this work, we compare Global Fire Emissions Data (GFEDv4s) estimates of burn area to FPA FOD burn area data (Figure S3 shows burn area total estimates for each side by side). FPA FOD are by design an incomplete record of fire activity (no prescribed fire, agricultural burning, fires on private lands, missing reports, etc.). By comparing FPA FOD to the satellite-based GFEDv4s, we can see where FPA FOD wildfires do not capture the majority of satellite detected fire activity. We also use the GFEDv4s estimate of dry fuel consumed to translate regional burn area into total emissions. GFEDv4s better represents the abundance of small fires than previous versions of GFED (e.g., GFEDv4). GFEDv4s burn area is based on remotely sensed observations of burn scars. Emissions are estimated by multiplying fire area by an emission factor (emissions per fuel burned) (Giglio et al., 2013; Randerson et al., 2012). The version of GFEDv4s used for this work is gridded on a 0.25° × 0.25° grid. These data are available at http://www.globalfiredata.org/data.html.

2.6. Fire INventory From NCAR

In this work, $PM_{2.5}$ emissions for different regions and individual FPA FOD wildfires are estimated using the Fire INventory from NCAR (FINN) model framework. FINN produces daily fire emission estimates at roughly 1-km spatial resolution (Wiedinmyer et al., 2006, 2011). FINN emissions are estimated using satellite observations of active fires, the fuel loadings at fire locations, biomass consumed, and emission factors for species burned (Wiedinmyer et al., 2006, 2011). Each of these estimated values have associated uncertainties, when combined this results in a factor of two uncertainty associated with FINN emissions estimates (Wiedinmyer et al., 2011). In this work, FPA FOD wildfire location and year information are used within the FINN model framework instead of MODIS fire detections. Area burned for each fire was assigned based on the FPA FOD data. Updated emission factors and annual-specific MODIS land cover type (2002–2012) and vegetation continuous fields products (2002–2014) were used here to assign land cover and vegetation characteristics. Wildfires where the land cover data indicated the wildfire occurred over water were reassigned as shrubland. Limitations to this method include the assignment to a single land cover and fuel density for each fire based on the latitude and longitude assigned to each fire (not necessarily burn scar centroid). There are uncertainties associated with these emission estimates and it is not clear whether they likely represent overestimates or underestimates of total emissions for wildfires documented in the FPA FOD. For example, if a large wildfire location is classified in shrubs, but most of the large wildfire ended up burning in a forested area, the emissions would be dramatically underestimated. The opposite could also occur. The emission estimates associated with FPA FOD wildfires used in this work are available at the following URL: ftp://ftp.acom.ucar.edu/user/christin/FPAFOD/.

2.7. National Environmental Satellite Data, and Information System Hazard Mapping System (HMS) HYSPLIT Points

To estimate possible air quality impacts of FPA FOD wildfires, we examine how often wildfires documented in the FPA FOD are colocated with satellite detected fires used to initiate the National Weather Service (NWS) smoke forecasts. The HMS is an interactive environmental satellite image display system where trained satellite analysts identify the geographic locations of fire and smoke in the United States (Brey et al., 2018; Ruminski et al., 2006). Relying primarily on visible satellite imagery, analysts identify the location of fires that they confirm to be producing smoke. These detections are called “HYSPLIT points” because they are used to initiate NOAA’s HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model, which is used to estimate the movement of smoke in the NWS smoke forecast (Rolph et al., 2009; Ruminski et al., 2006). The accuracy of the locations assigned to HYSPLIT points is about 2–3 km. The analysis is performed daily. Like many other satellite-based fire-detection methods, smaller wildfires are harder to detect and are more likely to be undercounted than large fires. Analysts make no attempt to distinguish between different types of fires (wildfires, prescribed fires, agriculture fires, etc.). HYSPLIT points with consistent attributes are available from 2007 onward. The data are available at the following URL: ftp://satepsanone.nesdis.noaa.gov/volcano/FIRE/HMS_ARCHIVE/.

3. Results and Discussion

3.1. Human Versus Lightning-Ignited Wildfires in the West and Southeast

Previous work has shown that the number of present-day human ignitions is large, especially in the southeastern United States (Balch et al., 2017; Nagy et al., 2018; Syphard et al., 2017). We focus on the burn area that results from each ignition type rather than the number of wildfires because burn area is more closely related to the societal impacts of wildfires (air quality, visibility, cost of suppression, carbon cycle, ecological, timber resources, etc.). Between 1992 and 2015, the FPA FOD documents ~84 million acres of area burned in the west and ~12 million in the southeast. In the west, ~6% of these acres are from wildfires with a cause of

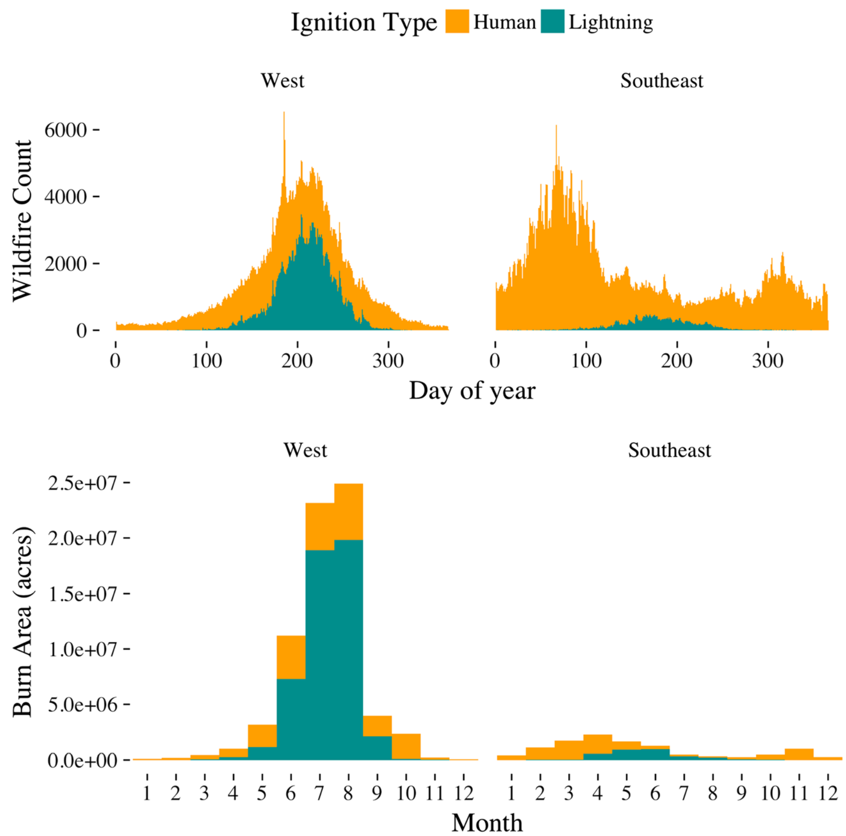

Figure 3. The top row of this figure shows the number of wildfires discovered on a given day of the year in the west (left) and southeast (right) between 1992 and 2015. The bars are color coded by wildfire ignition type. The bottom row shows the monthly burn area that results from the wildfire ignitions shown in the top row. The burn area attributed to a given month is the sum of wildfire burn area for wildfires that started in that month. Wildfires with start causes listed as "Missing/Undefined" have been excluded from this figure. The most common day for ignitions is 4 July, an American holiday where the use of fireworks is a common form of celebration.

"Unknown/Undefined" compared to ~8% in the southeast. Both regions are impacted by many wildfires, but the direct influence humans have on wildfire abundance is very different between the two regions. In the west, 70% of the area burned is from lightning-ignited wildfires (n = 217,187) and 30% is from human-ignited wildfires (n = 350,412). In the southeast, 27% of the area burned results from lightning-ignited wildfires (n = 37,876) and 73% results from human-ignited wildfires (n = 613,013). The large proportion of southeast burn area attributed to human-ignited wildfires suggest that humans are a dominant driver of wildfires activity in this region. Figure S1 shows the regional ignition counts by specific cause and season; differences between the most common types of human ignitions between the southeast and west suggest that there is no single cause that could be jointly eliminated to reduce fires in both regions.

The total number of wildfires during peak wildfire season in the west and southeast are similar (y-axis of top row in Figure 3), but there is an order of magnitude more area burned in the west (y-axis of bottom row in Figure 3). The southeast accumulates less annual burn area compared to the west, but the burned-area accumulation starts earlier in the year. The southeast wildfire season is bimodal. The first and larger peak occurs early in the year (January, February, March, and April), months where parts of the southeast experience low fuel moisture and atmospheric relative humidity (Brenner, 1991). These are the months with the largest number of individual wildfires and burn area. These wildfires are almost exclusively ignited by human activities (primarily debris burning). The months May through July account for the majority of lightning-ignited wildfire ignitions and burn area in the southeast. July can be a wet month in much of the southeast. Chiodi et al. (2018) show that for much of the region the probability of daily precipitation exceeding 0.25 inches ranges between 10% and >35%; this can limit the use of prescribed fire. There is a second but smaller peak in the number of human-ignited wildfires in November.

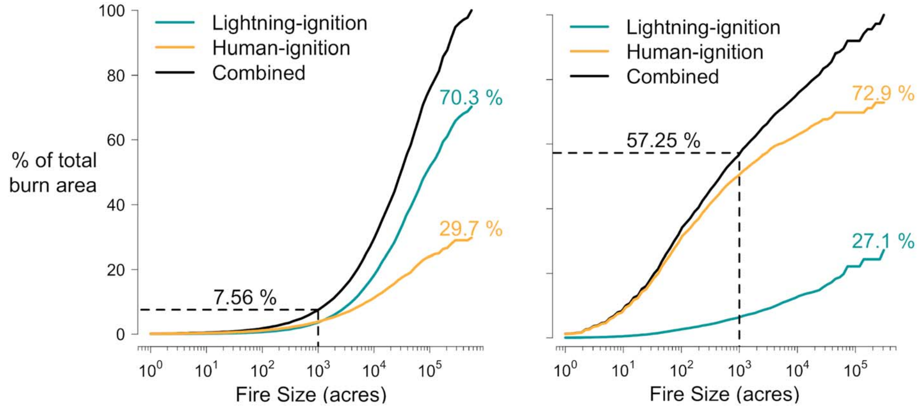

Figure 4. Percent of total wildfire burn area (vertical axis) owed to wildfires less than equal to wildfires of a given size (horizontal axis) in the west (left) and southeast (right). The orange and gray curve represents human- and lightning-ignited wildfires, respectively. The black curve represents the total of the two. The dashed black line shows the percent of wildfire burn area accounted for by wildfires 1,000 acres or smaller (8.54% in the west, 57.25 in the southeast).

In the west, nearly the opposite occurs. There is a single peak for the number of wildfires and accumulation of burn area for human and lightning-ignited wildfires centered around July and August. Similar to the southeast, in the west the lightning ignited wildfire burn area, as defined as the days of the year that bound the 10th and 90th percentile of the accumulated burn area, is shorter than the human-ignited wildfire season, though there is almost twice the burn area attributed to lightning started wildfires as there are human started wildfires.

The opposite wildfire seasons between the southeast and west means that wildfires have the potential to impact air quality year-round in the southeast. In the late winter and early spring, local wildfires degrade air quality (explored in more detail later). In the summer, when local wildfire activity is minimal, the southeast is regularly impacted by smoke plumes originating from western U.S. wildfires (Brey et al., 2018). In the fall, when the smoke plumes that originate in the west go away, local human-ignited wildfire activity picks back up.

3.2. Ignition Type, Wildfire Size, Total Burn Area, and Approximate Emissions

The cumulative burn area as a function of wildfire size is presented in Figure 4. This demonstrates that large wildfires (>1,000 acres) account for the vast majority of wildfire area burned in the west and account for a smaller proportion in the southeast. This illustrates one of the key differences between wildfires in the southeast and west. The west is home to very large wildfires, and the east is home to smaller wildfires. Wildfires 1,000 acres (~405 hectares) or smaller account for ~8% of the burn area in the west and ~57% in the southeast. In the southeast, small human-started wildfires account for half of the wildfire burn area in the region (Figure 4, orange line). While in the west, ignoring small wildfires would not significantly change observed patterns of interannual variability, and many studies do this using a similar cutoff (e.g., Dennison et al., 2014; Westerling et al., 2014). The differences in the size of wildfires that contribute to the total burn area for the west and southeast are due to many factors including fuels, climate, frequency of extreme fire weather, topography, population density, road density, and wildfire management priorities. Level II ecoregions provide a scale where some of these factors are broadly similar; thus, the following sections show differences between the west and southeast at the scale of level II ecoregions.

Figure 5 shows the geographic extent, wildfire burn area, and the dry fuel consumed estimate from GFEDv4s separated by level II ecoregions in the west and southeast. As discussed in the data and methods section, GFEDv4s is a satellite-derived fire emission inventory that includes all satellite detected fires (not just wildfires). This makes comparing GFEDv4s emissions and FPA FOD burn area complicated since there is no assurance that both data sources document the same wildfires. With that said, the GFEDv4s emissions presented in Figure 5 offer context for which ecoregions have the highest fire emissions. The forested mountains, the highest emitting ecoregion, consumes an order of magnitude more dry matter than any other ecoregion in the west or southeast (Figure 5, bottom row, difference in *y*-axis).

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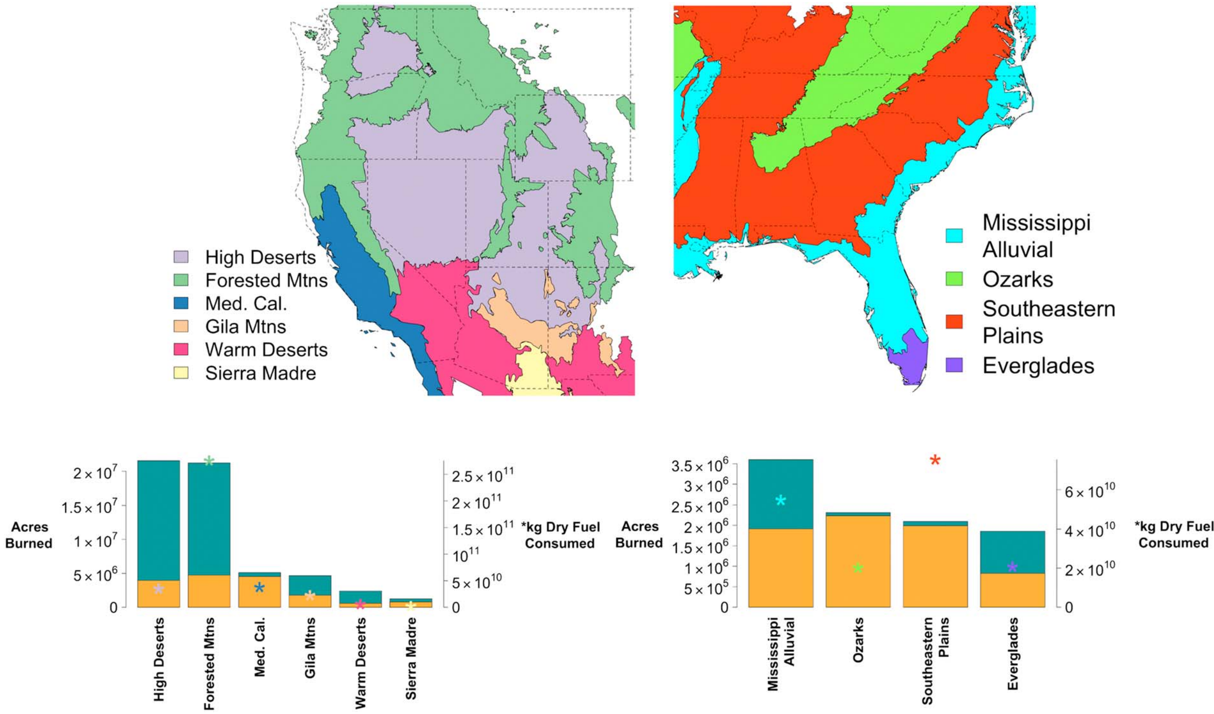

Figure 5. The geographic extent of the ecoregions (top row), total wildfire burn area accounted for by Fire Program Analysis Wildfire Occurrence Data (FPA FOD; bars in bottom row, orange and blue represents human-ignited and lightning-ignited burn area, respectively), and the all-lands dry fuel consumed by fire estimate from GFEDv4s (asterisk symbol "*" in bottom row) are shown in Figure 5. These totals are shown for level II ecoregions within the west (left) and southeast (right). This figure includes wildfire data between 1997 and 2015 because these are the years FPA FOD and GFEDv4s overlap. The patterns in FPA FOD burn area by region, or percent attributed to human ignitions does not significantly change when including fires from 1992 to 1996. This map shows level II ecoregions. The ecoregions are; forested mountains, high deserts, Mediterranean California, Southeastern Plains, Ozarks, Mississippi alluvial, and Everglades. Areas of white in the maps in the top row are level II ecoregions with very small burn area totals. GFEDv4s = Global Fire Emissions Data.

In the west, the high desert and forested mountains account for far more burn area than the other seven ecoregions. The fraction of area burned attributed to human-started wildfires in the Forested Mountains and High Deserts is small (orange portion of bars in bottom left of Figure 5). Mediterranean California is the only ecoregion in the west where the majority of wildfire burn area are due to human-ignited wildfires. When examining emissions, Figure 5 shows that the majority of dry matter consumed in the western United States occurs in the Forested Mountains and that most of these emissions are due to lightning-started wildfires.

In the southeast, the Mississippi Alluvial, the Ozarks, the Southeastern Plains, and Everglades account for the majority of the total burn area. The burn area and total emissions within southeast ecoregions is an order of magnitude less than those in the west, though given the abundance of small wildfires in the southeast (e.g., Figure 4, right panel) and the challenge of detecting small fires with satellites (Randerson et al., 2012), it is possible GFED fire emission estimates in these ecoregions are severely underestimated. Additionally, there is more prescribed fire burn area in the southeast than wildfire burn area (Chiodi et al., 2018; Mitchell et al., 2014), so it is important to keep in mind the large disconnect between total emissions and wildfire burn area presented in the southeast in Figure 5.

3.3. Ecoregion-Specific Relationships Between Ignition and Dead-Fuel Moisture

The dead-fuel moisture index is a measure of the amount of water in dead vegetation and is widely used to estimate wildfire potential ("Did you know?," 2018). It is more difficult to ignite fires when fuel moisture levels are high because energy must be used to evaporate water before combustion can occur (Bradshaw et al., 1984; Fosberg et al., 1971; Rothermel, 1972; Stocks et al., 1989). Dead-fuel moisture content changes in response to environmental conditions ("Did you know?," 2018), that is, dead-fuel moisture is a quantity with memory of meteorological conditions that drive local moisture abundance (e.g., precipitation,

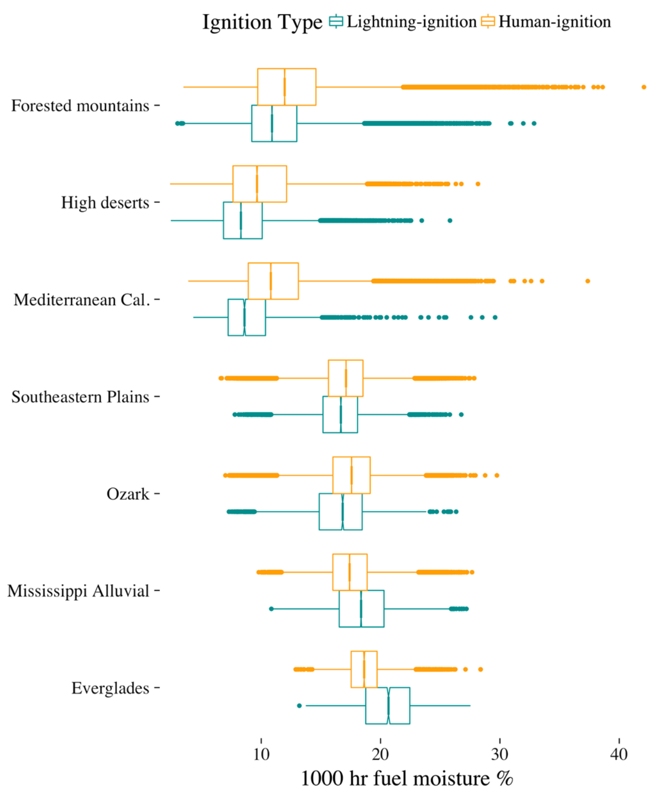

Figure 6. The 1,000-hr fuel moisture percent assigned to wildfires based on the location and discovery date in the Fire Program Analysis Wildfire Occurrence Data. Wildfire 1,000-hr fuel moisture percent values are separated by level II ecoregions (rows) and ignition type (color). All wildfires (size, month, etc.) were retained for this plot. The boxes show the 25th, 50th (notched middle), and 75th percentiles of the data. The upper whiskers show data that are within 1.5 times the length of the interquartile range. Data beyond the whiskers are "outlying" points and are plotted individually. The notches around the median value extend 1.58 times the width of the IQR divided by the square root of the number of samples; this gives an approximate way to compare the median values of distributions with roughly 95% confidence (Mcgill et al., 1978).

temperature, and evaporation). The 1,000-hr dead-fuel moisture is a measure of the amount of water in fuel as a percentage of its mass where it is assumed that there is a 1,000-hr time lag for fuels 3–8 inches in diameter to become two thirds of the way towards equilibrium with the local environment. Fuels with small diameters (e.g., grass, leaves, and twigs) respond to atmospheric moisture levels quickly. FPA FOD wildfires were assigned 1,000-hr dead fuel moisture percentages based on the value of the GRIDMet (Abatzoglou, 2013) grid cell (4 × 4 km) the wildfire location fell within. For the purpose of assigning fuel moisture values to wildfires, the discovery date is treated as the ignition date. In reality these two dates are not always the same and depending on conditions, can be weeks apart.

Figure 6 shows the 1,000-hr fuel moisture percent assigned to wildfires based on the location and the discovery date provided by the FPA FOD. The box and whisker plots show the distribution of fuel moisture values in the level II ecoregions with the most burn area and emissions for both ignition types. The most clear distinction in fuel moisture where wildfires occur is the ecoregion, not the type of ignition (rows rather than colors in Figure 6). On average, wildfires in the southeast (rows 4 through 7) occur at higher fuel moisture percentages than wildfires in the west (rows 1–3). However, due to the abundance of human-ignited wildfires in the southeast and lightning-ignited wildfires in the west, a continental-wide comparison of the fuel moisture percent of wildfires segregated by ignition type would reveal that human-ignited wildfires occur at higher fuel-moisture values than lightning-ignited wildfires. Such a conclusion was made by Balch et al. (2017), who showed that nationally, human-ignited wildfires occur at higher fuel moisture content values than lightning-ignited wildfires. While differences in fuel moisture values between ignition types exist, Figure 6 shows that this difference can be largely explained by contrasting ecoregions in the west and southeast.

In the west, the median fuel moisture for wildfires is always higher than for human-ignited wildfires. This is likely because human-ignited wildfires in the west start earlier, go later in the year (Figure 3), and are on average small (Figure 4). In the southeast ecoregions, the differences between the median fuel-moisture values for each ignition type are generally smaller than the west. In the Everglades and Mississippi Alluvial, the median fuel moisture is higher for lightning-ignited wildfires than human-ignited wildfires. Some of the differences in fuel moisture at wildfire locations in the southeast can be explained by the difference in seasonality for wildfires of each ignition type (bimodal human-started wildfires season, lightning started wildfire season peaks in the summer). On average, small wildfires ($<$1,000 acres) occur at higher fuel-moisture values and on more days of the year than large wildfires ($>$1,000 acres; Figure S4). Within a given ecoregion, most large wildfires occur in similar, temperatures, days of the year, and fuel moisture values regardless of ignition type (Figure S5). There can be large interannual variability in wildfire occurrence and the meteorology that drives 1,000-hr fuel moisture. This will be explored in the next two sections.

3.4. Interannual Variability in Lightning- and Human-Ignited Wildfire Burn Area

Figure 7 shows the Spearman correlation of the interannual variability of lightning and human-ignited burn area for the three ecoregions in the west and four in the southeast that account for the majority of continental U.S. (CONUS) FPA FOD wildfire activity. We used the Spearman correlation coefficient in Figure 7 because we did not want to impose the requirement of a linear relationship between annual human- and lightning-ignited burn area within an ecoregion. For the majority of ecoregions, the interannual variability in burn area between each ignition type are well correlated; however, correlations are generally higher for ecoregions in the west (light blue in Figure 7). The two main exceptions are the Everglades (r = 0.3) and Mediterranean

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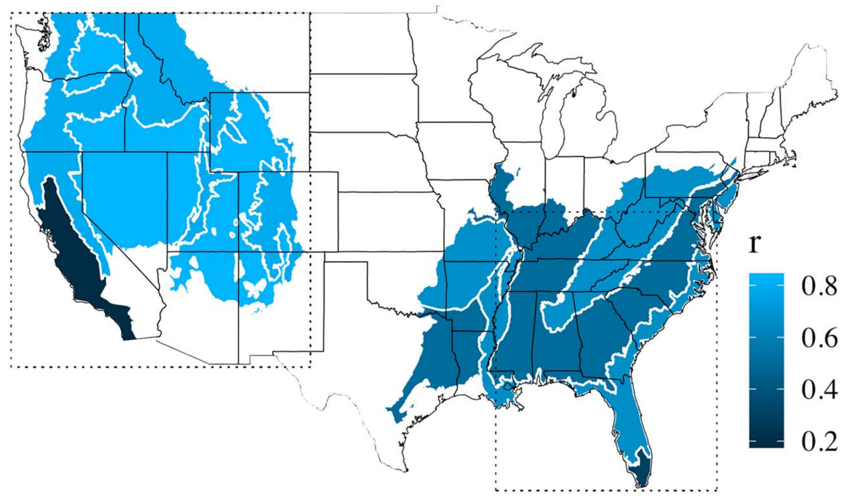

Figure 7. Spearman correlation coefficient (r, mapped as color) for the interannual burn area by ignition type (human and lightning) in each ecoregion between 1992 and 2015. The west and southeast regions are shown with the dashed-line boxes, only wildfires that occurred within the plotted ecoregions and boxes were used for the correlation calculations.

California ($r = 0.19$). The burn area in Mediterranean California is dominated by human-ignited wildfires while the burn area ignition attribution is almost evenly split in the Everglades, so it is not clear that low correlations are associated with a particular dominant ignition type. Wildfire burn area is dominated by human ignitions in the Ozarks and Southeastern Plains and the correlation for burn area between ignition types is high in these ecoregions ($r > 0.5$). The correlation in burn area between ignition types suggests that burn-area totals for both wildfire types are driven by similar factors (e.g., environmental conditions) or that the separate factors driving each ignition type are also well correlated. Figures that show the interannual variability of wildfire burn area by ignition type and ecoregion are available in Figure S6.

3.5. Burn Area and Annual Meteorology Across Human- and Lightning-Ignited Wildfires

An important question is whether the variability in ecoregion area burned for lightning- and human-ignited wildfires can be explained by the annual-mean state of meteorological variables. The goal of this section is to determine if the interannual variability of total burn area for human- and lightning-ignited wildfires (shown in Figure 7) have the same relationship with key meteorology variables that drive aridity and increase wildfire danger rating indices. Under arid conditions, correlated indices such as the Palmer drought severity index, wildfire energy release component, and dead-fuel moisture indices all contribute to heightened fire danger ("Fire Danger Rating," 2018). Each of these indices are at least partially driven by temperature, precipitation, and relative humidity.

Figure 8 shows the Pearson correlation coefficient between total summer wildfire burn area and meteorology variables, segregated by ecoregion (columns) and ignition type (color). Relationships (sign of correlation) between burn area and meteorological variables are consistent across ecoregions and ignition types. The exception is temperature in Mediterranean California and the Everglades. In Mediterranean California, temperature is positively correlated with human-ignited burn area and negatively correlated with lightning-ignited burn area. In the Everglades the opposite is true; however, the values of these correlations are close to zero. Correlations are generally stronger for lightning-ignited wildfires, which could suggest that lightning-ignited wildfire burn area is more strongly influenced by meteorology. There is no obvious difference in the magnitudes of the correlations between ecoregions in the west and southeast. This is surprising given the contrasts in wildfire size, fuels, topography, and dominate ignition types between the two regions.

The expectation that total area burned will increase under climate change can be deduced from first principles of fire behavior. Fires ignite more easily and spread faster in dry wildland environments (Albini & Stocks, 1986; Alexander & Cruz, 2006; Rothermel, 1972; Schaaf et al., 2007; Wagner, 1977, 1998). All of these ecoregions are located where there is a high degree of confidence that mean surface temperatures will increase over the coming century (IPCC AR5, CH. 12). Based on the positive linear correlations between temperature

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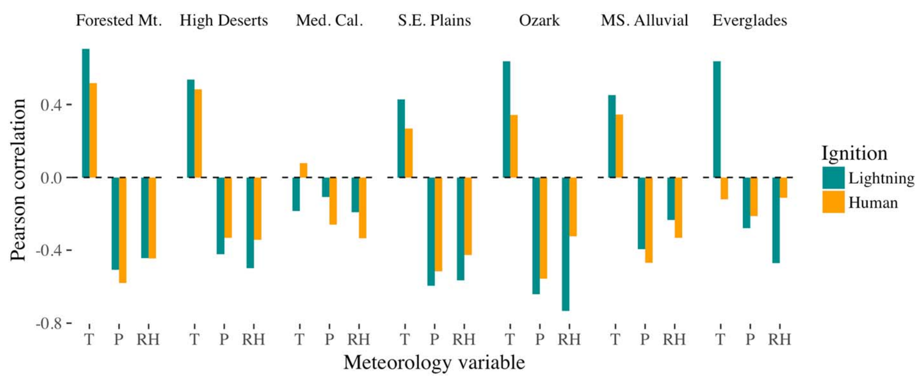

Figure 8. The Pearson (linear) correlation coefficients between total year-long area burned versus mean annual temperature (T), total precipitation (P), and mean relative humidity percent (RH). Correlation values are shown for burn area by ignition type (color). Temperature and relative humidity are calculated using the mean of daily mean 2-m temperature for 0.75 × 0.75° ECMWF reanalysis grid boxes that overlap the specified ecoregions. Total precipitation is the annual sum of precipitation for grid boxes that overlap each ecoregion. Wildfires of all sizes were included in the correlation calculations shown in this plot. Scatterplots of burn area versus meteorology variables are available in Figure S7.

and burn area shown in Figure 8 (warmer years tend to have more burn area), it is possible that the future burn area for both ignition types will increase with increasing temperatures (this is not clear in Mediterranean California or the Everglades). However, this predicted increase assumes that (1) the observed relationships between annual burn area and temperature remain stationary in the future (an assumption Higuera et al. (2015) have shown may not always be true) and (2) these relationships hold when the climate departs from the range of temperatures observed between 1992 and 2015.

Figure 8 shows a negative linear relationship between burn area and total annual precipitation in every region for each ignition type. What this anticorrelation implies for changes to wildfire abundance under climate change is limited by the same challenges outlined in discussing temperature, with the added complication that the changes in the quantity and variability of precipitation is not as certain as temperature (Collins et al., 2013; Pendergrass et al., 2017).

This section does not intend to make predictions of future wildfire abundance based on these correlations, but rather to show that whatever climate-driven changes occur in temperature, total precipitation, and relative humidity, Figure 8 suggest that the impact on human- and lightning-ignited wildfire burn area may be similar. Syphard et al. (2017) and Parisien et al. (2016) argue that climate may be less important for driving wildfire activity in areas where human activities and ignitions are pervasive. While humans are responsible for igniting the majority of wildfires in the southeast, our analysis implies that the annual burn area that results from these wildfires is modulated by environmental conditions and therefore future burn-area totals are unlikely to be independent of climate change. Thus, a singular focus on human ignitions as the driver of southeast wildfire occurrence (expanding season, number of wildfires, fuel moisture where wildfires occur, etc.) and ignoring climate change is not be the most productive way to prepare for the future.

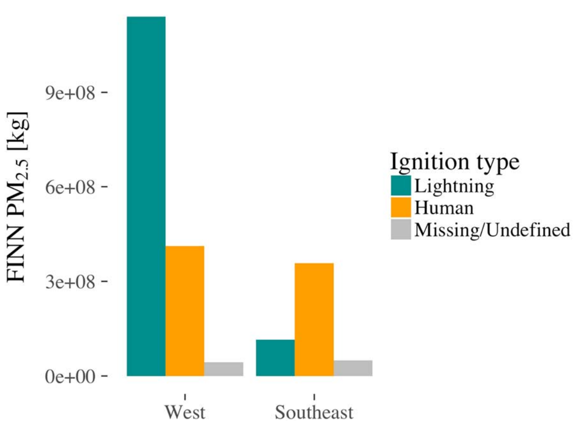

Figure 9. The total $PM_{2.5}$ emissions from Fire Program Analysis Wildfire Occurrence Data (FPA FOD) wildfires between 2002 and 2015 in the west and southeast color coded by ignition type. $PM_{2.5}$ emissions were made using the FINN model framework. FPA FOD wildfires between 2002 and 2015 and all months were used (*n* = 1,086,712), these are the years the two data sources overlap. Only FINN emissions derived from FPA FOD wildfires are shown. FINN = Fire INventory from NCAR.

3.6. $PM_{2.5}$ Emission Estimates by Region and Ignition Type

Wildfires emit particulate matter pollution, which can degrade local and regional air quality (Baker et al., 2016; Brey et al., 2018; Brey & Fischer, 2016; Ford et al., 2017; Jaffe et al., 2008; Lassman et al., 2017; Saide et al., 2015; Val Martin et al., 2015; Wiedinmyer et al., 2006). In the present study, the potential air quality impacts of human- and lightning-ignited wildfires are estimated based on the $PM_{2.5}$ emitted by these wildfires. The $PM_{2.5}$ emissions presented here were estimated for each FPA FOD wildfire

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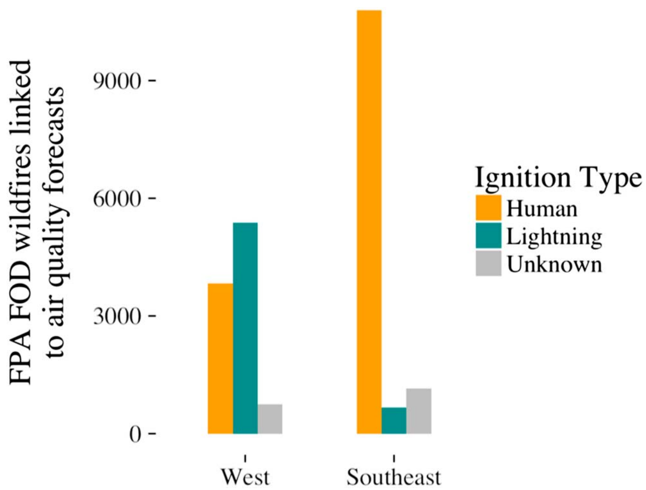

Figure 10. Count of Fire Program Analysis Wildfire Occurrence Data (FPA FOD) wildfires associated with NESDIS HMS analyzed Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) points used to initiate the NWS smoke forecast, occurring in the west and southeast regions between 2007 and 2015 (the years these data overlap). The colors indicate the cause of the FPA FOD wildfire. FPA FOD wildfires that were not colocated with HYSPLIT points have been excluded from this plot. There are 9,938 wildfires in the west and 12,588 in the southeast associated with HYSPLIT points. A similar figure that shows the proportion total number of HYSPLIT points in the west and southeast, as well as the proportion colocated with FPA FOD wildfires, is available in Figure S8.

between 2002 and 2015 using the FINN model framework, described in detail in section 2.6.

The bars in Figure 9 show the total estimated $PM_{2.5}$ emissions of FPA FOD wildfires within the west and southeast regions between 2002 and 2015. The blue and orange bars in Figure 9 show the cumulative $PM_{2.5}$ emissions that result from lightning- and human-ignited wildfires, respectively. The ignition type that accounts for the most $PM_{2.5}$ is the same as the ignition type responsible for the majority of burn area within a given region (Figure 4). There is more wildfire $PM_{2.5}$ emitted in the west than the southeast between 2002 and 2015. However, there are similar amounts of $PM_{2.5}$ that are a result of human-ignited wildfires in both regions. Although southeast emissions are lower than the west, it is clear that southeast wildfires, although on average smaller, in aggregate emit substantial amounts of $PM_{2.5}$, which have the potential to significantly impact air quality. The $PM_{2.5}$ emissions presented in this section are an incomplete account of $PM_{2.5}$ in both regions since prescribed fire, agricultural burning, and fires on private land are omitted from the FPA FOD.

3.7. Ignition Types for Wildfires Leading to U.S. Smoke Air Quality Forecasts

This section examines the air quality impacts of FPA FOD wildfires through a different lens, by investigating how often FPA FOD wildfires can be linked to NWS smoke forecasts. This provides a second perspective on the possible air quality impacts of wildfires of different ignition types. We identified the wildfires that were colocated in space and time with HYSPLIT points (human analyzed wildfires used to initiate NWS smoke forecast described in section 2.7). We consider HYSPLIT points and FPA FOD wildfires to be colocated, or paired, when two conditions are met: (1) The HYSPLIT point must have been analyzed on the day before or up to 7 days after the wildfire discovery date documented in the FPA FOD. (2) The distance between the HYSPLIT point and the FPA FOD wildfire location must be no greater than 10 km. These combined criteria are very strict and most likely underestimate the number of HYSPLIT point detections paired to large FPA FOD wildfires and overestimate the number of HYSPLIT point detections paired to small FPA FOD wildfires. FPA FOD data between 2007 and 2015 was used for pairing, as these are the years FPA FOD and HYSPLIT point data overlap. When we adjust our pairing criteria by changing the distance and time requirements for FPA FOD wildfires and HYSPLIT points to be considered colocated, the total number of wildfires paired changes, but the patterns shown in Figure 10 and presented in the following paragraphs do not change significantly.

The majority of FPA FOD wildfires are not paired with HYSPLIT points. Between 2007 and 2015, only 5.5% of FPA FOD wildfires (5.2% in the west, 5.8% in the southeast) are colocated with HYSPLIT points. The low number of FPA FOD wildfires paired to HYSPLIT points is not surprising given the abundance of very small (<10 acres) wildfires documented in the FPA FOD and the challenge of detecting small wildfires via satellite. The similar percent of wildfires paired in the southeast and west is surprising, given that wildfires in the west are on average larger than wildfires in the southeast. It is likely that our methods underestimate the number of colocated HYSPLIT points for very large FPA FOD wildfires since large wildfires can last longer than the allowable time period for pairing (1 day before and 7 days after the wildfire discovery date). Additionally, the wildfire locations provided in the FPA FOD data are not necessary burn scar centroids, and wildfire burn scars are not always circular, which compromises our method's ability to pair all appropriate HYSPLIT points to large wildfires.

4. Conclusion

We use the FPA FOD to contrast the environmental conditions, meteorological drivers and air quality impacts of human- versus lightning-ignited wildfires in the southeast and western United States. We find that the proportion of wildfires that are started by humans is higher in the southeast United States than in the west, though the seasonality of when these wildfires occur is also different (i.e., the wildfires in the southeast are bimodal with more occurrences in the spring and fall months, whereas the majority of wildfires in the west occur during July/August). We show that there are larger contrasts in 1,000-hr fuel-moisture between ecoregions than between ignition types, which implies that both ignition types are similarly constrained by fuel-moisture within a given ecoregion. Presently, both human- and lightning-ignited wildfire burn area are anticorrelated with total annual precipitation and will likely react similarly to future changes in precipitation (assuming a stationary relationship between precipitation and burn area). Between 1992 and 2015 humans were the dominant source of wildfire ignitions in the southeast United States. However, the annual burn area of these wildfires is still linked to environmental conditions that allow fuels to ignite and wildfires to spread. Thus, climate change, not just human-ignited wildfires, will be an important driver of future wildfire activity and the resulting air quality impacts in the southeast United States. The same is true for the west, where summertime burn area for both ignition types is greater in warmer, drier years. On average, wildfires in the southeast are smaller than in the west. However, these small wildfires significantly impact southeast air quality because (1) there is a large number of southeast wildfires associated with NWS air quality smoke forecasts and (2) total $PM_{2.5}$ emissions from human-ignited wildfires in the southeast are similar to the total $PM_{2.5}$ emissions from human-ignited wildfires in the west.

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References

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology*, *33*(1), 121–131.

Abatzoglou, J. T., & Kolden, C. A. (2013). Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire*, *22*(7), 1003–1020.

Abatzoglou, J. T., Kolden, C. A., Balch, J. K., & Bradley, B. A. (2016). Controls on interannual variability in lightning-caused fire activity in the western US. *Environmental Research Letters: ERL [Web Site]*, *11*(4), 045005.

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(42), 11,770–11,775.

Albini, F. A., & Stocks, B. J. (1986). Predicted and observed rates of spread of crown fires in immature jack pine. Retrieved from http://cfs.nrcan.gc.ca/publications?id=21390

Alexander, M. E., & Cruz, M. G. (2006). Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Canadian Journal of Forest Research*. *Journal Canadien de La Recherche Forestiere*, *36*(11), 3015–3028.

Baker, K. R., Woody, M. C., Tonnesen, G. S., Hutzell, W., Pye, H. O. T., Beaver, M. R., et al. (2016). Contribution of regional-scale fire events to ozone and PM2.5 air quality estimated by photochemical modeling approaches. *Atmospheric Environment*, *140*, 539–554.

Balch, J. K., Bradley, B. A., Abatzoglou, J. T., Nagy, R. C., Fusco, E. J., & Mahood, A. L. (2017). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(11), 2946–2951.

Barbero, R., Abatzoglou, J. T., Steel, E. A., & Larkin, N. K. (2014). Modeling very large-fire occurrences over the continental United States from weather and climate forcing. *Environmental Research Letters: ERL [Web Site]*, *9*(12), 124009.

Bradshaw, L. S., Deeming, J. E., Burgan, R. E., & Cohen, J. D. (1984). The 1978 National Fire-Danger Rating System: Technical documentation. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. https://doi.org/10.2737/INT-GTR-169

Brenner, J. (1991). Southern oscillation anomalies and their relationship to wildfire activity in Florida. *International Journal of Wildland Fire*, *1*(1), 73–78.

Brey, S. J., & Fischer, E. V. (2016). Smoke in the city: How often and where does smoke impact summertime ozone in the United States? *Environmental Science & Technology*, *50*(3), 1288–1294.

Brey, S. J., Ruminski, M., Atwood, S. A., & Fischer, E. V. (2018). Connecting smoke plumes to sources using Hazard Mapping System (HMS) smoke and fire location data over North America. *Atmospheric Chemistry and Physics*, *18*(3), 1745–1761.

Cansler, C. A., & McKenzie, D. (2014). Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecological Applications: A Publication of the Ecological Society of America*, *24*(5), 1037–1056.

Chiodi, A. M., Larkin, N. S., & Morgan Varner, J. (2018). An analysis of Southeastern US prescribed burn weather windows: Seasonal variability and El Niño associations. *International Journal of Wildland Fire*, *27*(3), 176–189.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J., Fichefet, T., Friedlingstein, R., et al. (2013). Long-term climate change: Projections, commitments and irreversibility. In: Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597.

Dennison, P. E., Brewer, S. C., Arnold, J. D., & Moritz, M. A. (2014). Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, *41*, 2928–2933. https://doi.org/10.1002/2014GL059576

Did you know? (2018). Retrieved 2018, from https://www.ncdc.noaa.gov/monitoring-references/dyk/deadfuelmoisture

Fire Danger Rating (2018). Retrieved 2018, from https://www.wfas.net/index.php/fire-danger-rating- fire-potential--danger-32

Ford, B., Burke, M., Lassman, W., Pfister, G., & Pierce, J. R. (2017). Status update: is smoke on your mind? Using social media to assess smoke exposure. *Atmospheric Chemistry and Physics*, *17*(12), 7541–7554.

Fosberg, M. A., Deeming, J. E., & Rocky Mountain Forest and Range Experiment Station (Fort Collins, Colo.) (1971). Derivation of the one- and ten-hour timelag fuel moisture calculations for fire-danger rating. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture.

Fusco, E. J., Abatzoglou, J. T., Balch, J. K., Finn, J. T., & Bradley, B. A. (2016). Quantifying the human influence on fire ignition across the western USA. *Ecological Applications: A Publication of the Ecological Society of America*, *26*(8), 2388–2399.

Gannet Hallar, A., Molotch, N. P., Hand, J. L., Livneh, B., McCubbin, I. B., Petersen, R., et al. (2017). Impacts of increasing aridity and wildfires on aerosol loading in the intermountain Western US. *Environmental Research Letters: ERL [Web Site]*, *12*(1), 014006.

Giglio, L., Randerson, J. T., & van der Werf, G. R. (2013). Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences*, *118*, 317–328. https://doi.org/10.1002/jgrg.20042

Higuera, P. E., Abatzoglou, J. T., Littell, J. S., & Morgan, P. (2015). The Changing Strength and Nature of Fire-Climate Relationships in the Northern Rocky Mountains, U.S.A., 1902–2008. *PLoS One*, *10*(6), e0127563.

Jaffe, D., Hafner, W., Chand, D., Westerling, A. L., & Spracklen, D. (2008). Interannual Variations in PM2.5 due to Wildfires in the Western United States. *Environmental Science & Technology*, *42*(8), 2812–2818.

Lassman, W., Ford, B., Gan, R. W., Pfister, G., Magzamen, S., Fischer, E. V., et al. (2017). Spatial and temporal estimates of population exposure to wildfire smoke during the Washington state 2012 wildfire season using blended model, satellite, and in situ data. *GeoHealth*, *1*, 106–121. https://doi.org/10.1002/2017GH000049

Littell, J. S., McKenzie, D., Peterson, D. L., & Westerling, A. L. (2009). Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications: A Publication of the Ecological Society of America*, *19*(4), 1003–1021.

Littell, J. S., Peterson, D. L., Riley, K. L., Liu, Y., & Luce, C. H. (2016). A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, *22*(7), 2353–2369.

Liu, J. C., Mickley, L. J., Sulprizio, M. P., Dominici, F., Yue, X., Ebisu, K., et al. (2016). Particulate air pollution from wildfires in the Western US under climate change. *Climatic Change*, 1–12. https://doi.org/10.1007/s10584-016-1762-6

Liu, Y., Goodrick, S. L., & Stanturf, J. A. (2013). Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management*, *294*, 120–135.

Mcgill, R., Tukey, J. W., & Larsen, W. A. (1978). Variations of box plots. *The American Statistician*, *32*(1), 12–16.

Melvin, M. (2015). National Prescribed Fire Use Survey Report. Coalition of Prescribed Fire Councils.

Mitchell, R. J., Liu, Y., O'Brien, J. J., Elliott, K. J., Starr, G., Miniat, C. F., et al. (2014). Future climate and fire interactions in the southeastern region of the United States. *Forest Ecology and Management*, *327*, 316–326.

Morton, D. C., Collatz, G. J., Wang, D., Randerson, J. T., Giglio, L., & Chen, Y. (2013). Satellite-based assessment of climate controls on US burned area. *Biogeosciences*, *10*(1), 247–260.

Nagy, R. C., Fusco, E., Bradley, B., Abatzoglou, J. T., & Balch, J. (2018). Human-related ignitions increase the number of large wildfires across U.S. ecoregions. *Fire*, *1*(1), 4.

Omernik, J. M. (1987). Ecoregions of the conterminous United States. *Annals of the Association of American Geographers. Association of American Geographers*, *77*(1), 118–125.

Omernik, J. M. (1995). Ecoregions: A spatial framework for environmental management. In W. S. Davis & T. Simon (Eds.), *Biological assessment and criteria: Tools for water resource planning and decision making* (pp. 49–62). Boca Raton, Florida: Lewis Publishers.

Parisien, M.-A., Miller, C., Parks, S. A., DeLancey, E. R., Robinne, F.-N., & Flannigan, M. D. (2016). The spatially varying influence of humans on fire probability in North America. *Environmental Research Letters: ERL [Web Site]*, *11*(7), 075005.

Park Williams, A., Seager, R., Macalady, A. K., Berkelhammer, M., Crimmins, M. A., Swetnam, T. W., et al. (2015). Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. *International Journal of Wildland Fire*, *24*(1), 14–26.

Pechony, O., & Shindell, D. T. (2010). Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(45), 19,167–19,170.

Pendergrass, A. G., Knutti, R., Lehner, F., Deser, C., & Sanderson, B. M. (2017). Precipitation variability increases in a warmer climate. *Scientific Reports*, *7*(1), 17966.

Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M., & Morton, D. C. (2012). Global burned area and biomass burning emissions from small fires. *Journal of Geophysical Research*, *117*, G04012. https://doi.org/10.1029/2012JG002128

Riley, K. L., Abatzoglou, J. T., Grenfell, I. C., Klene, A. E., & Heinsch, F. A. (2013). The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: The role of temporal scale. *International Journal of Wildland Fire*, *22*(7), 894–909.

Rolph, G. D., Draxler, R. R., Stein, A. F., Taylor, A., Ruminski, M. G., Kondragunta, S., et al. (2009). Description and Verification of the NOAA Smoke Forecasting System: The 2007 Fire Season. *Weather and Forecasting*, *24*(2), 361–378.

Rothermel, R. C. (1972). A mathematical model for predicting fire spread in wildland fuels. *Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 40 P., 115*. Retrieved from https://www.fs.usda.gov/treesearch/pubs/32533

Ruminski, M., Kondragunta, S., Draxler, R., & Zeng, J. (2006). Recent changes to the Hazard Mapping System. *15th International Emission Inventory Conf*, (Reinventing Inventories). Retrieved from https://www.researchgate.net/publication/228625934_Recent_changes_to_the_Hazard_Mapping_System

Saide, P. E., Peterson, D. A., da Silva, A., Anderson, B., Ziemba, L. D., Diskin, G., et al. (2015). Revealing important nocturnal and day-to-day variations in fire smoke emissions through a multiplatform inversion. *Geophysical Research Letters*, *42*, 3609–3618. https://doi.org/10.1002/2015GL063737

Schaaf, M. D., Sandberg, D. V., Schreuder, M. D., & Riccardi, C. L. (2007). A conceptual framework for ranking crown fire potential in wildland fuelbeds. *Canadian Journal of Forest Research. Journal Canadien de La Recherche Forestiere*, *37*, 2464–2478.

Short, K. C. (2014). A spatial database of wildfires in the United States, 1992–2011. *Earth System Science Data*, *6*(1), 1–27.

Short, K. C. (2015). Spatial wildfire occurrence data for the United States 1992–2013. *Forest Service Research Data Archive, 3rd Edition*.

Stocks, B. J., Lynham, T. J., Lawson, B. D., Alexander, M. E., Wagner, C. E. V., McAlpine, R. S., et al. (1989). Canadian forest fire danger rating system: An overview. *Forestry Chronicle*, *65*(4), 258–265.

Syphard, A. D., & Keeley, J. E. (2015). Location, timing and extent of wildfire vary by cause of ignition. *International Journal of Wildland Fire*, *24*(1), 37–47.

Syphard, A. D., Keeley, J. E., Pfaff, A. H., & Ferschweiler, K. (2017). Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(52), 13,750–13,755.

Thomas, D. S., & Butry, D. T. (2012). Wildland fires within municipal jurisdictions. *Journal of Forestry*, *110,* 34–41. Retrieved from https://www.nist.gov/publications/wildland-fires-within-municipal-jurisdictions

Val Martin, M., Heald, C. L., Lamarque, J.-F., Tilmes, S., Emmons, L. K., & Schichtel, B. A. (2015). How emissions, climate, and land use change will impact mid-century air quality over the United States: a focus on effects at national parks. *Atmospheric Chemistry and Physics*, *15*(5), 2805–2823.

Wagner, C. E. V. (1977). Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research. Journal Canadien de La Recherche Forestiere*, *7*(1), 23–34.

Wagner, C. E. V. (1998). Modelling logic and the Canadian Forest Fire Behavior Prediction System. *Forestry Chronicle*, *74*(1), 50–52.

10.1029/2018EF000972

Westerling, A. L., Brown, T., Schoennagel, T., Swetnam, T., Turner, M., & Veblen, T. (2014). Briefing: Climate and wildfire in western U.S. forests (pp. 81–102).
Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, *313*(5789), 940–943.
Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., et al. (2011). The Fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning. *Geoscientific Model Development*, *4*(3), 625–641.
Wiedinmyer, C., Quayle, B., Geron, C., Belote, A., McKenzie, D., Zhang, X., et al. (2006). Estimating emissions from fires in North America for air quality modeling. *Atmospheric Environment*, *40*(19), 3419–3432.
Yoon, J.-H., Kravitz, B., Rasch, P. J., Simon Wang, S.-Y., Gillies, R. R., & Hipps, L. (2015). Extreme fire season in California: A glimpse into the future? *Bulletin of the American Meteorological Society*, *96*(12), S5–S9.