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Fires of Unusual Size: Future of Extreme and Emerging Wildfire in a Warming United States (2020–2060)

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Abstract

Observed increases in wildfire activity across the contiguous United States (U.S.), together with continued warming and expanding development in fire-prone landscapes, highlight the need to anticipate near-term changes in fire regimes. We apply a Bayesian statistical model that integrates projected population density (SSP2) and downscaled climate simulations under a moderate emissions scenario (RCP 4.5) to estimate future wildfire occurrence, maximum fire size (using the 90th percentile of fire size distribution), and total area burned for large fires (>1000 acres) across all EPA Level III ecoregions for 2020–2060. Relative to 1984–2019, we project nationwide increases of 56% in fire occurrence and 59% in area burned, with larger increases in maximum fire size (63%) in 2020–2060. Spatial patterns vary substantially: fire occurrence increases most strongly in the eastern U.S., including regions where large fires have historically been rare, while western ecoregions experience the largest absolute increases in burned area and extreme fire size. The disproportionate growth in maximum fire size suggests that changes in fire weather will amplify extreme events beyond increases in ignition frequency alone. These projections indicate expanding wildfire risk across diverse U.S. landscapes and underscore the need for regionally tailored fire management and preparedness strategies.

Keywords: future wildfire; maximum fires; climate change; extreme wildfires

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1. Introduction

Over the past forty years, burned area in the United States (U.S.) has increased fourfold—at a rate of approximately 173,000 acres per year [1]. Numerous studies have focused on the western U.S. fire-climate relationships [2–4], projecting future burned area [5–8], and large/extreme fires [9], but few studies have examined these trends at a national-scale [10–14] or focused on areas with lower fire activity in the latter half of the

20th century like the Great Plains [15] and eastern U.S. [16,17], where there is also evidence of fire being responsive to warming and drying [18–20].

While climate variability and change explain a majority of area burned in many regions [18], human activity influences area burned through ignitions, suppression efforts, and land use/land cover change [21–23]. These impacts become even more complex through non-linear interactions with environmental drivers [24–27]. Moreover, due to the ever-expanding wildland urban interface (WUI) [21], more homes and people are now located in fire-prone areas [28] than ever before. Humans are responsible for igniting four times as many large wildfires as lightning across the U.S. and are today the primary source of large wildfires in both the eastern and the West Coast regions of the U.S., despite human-ignited fires being smaller in size relative to lightning fires [22,29]. It is important to account for these direct anthropogenic effects—especially the spatial distribution of people across the landscape—when considering future fire patterns.

Although large fires account for only a small percentage of the total number of fires, they comprise the majority of total burned area across the U.S. [9,10], and their capacity to exceed or escape suppression often makes them the most dangerous and costly wildfires to manage [30]. Since large fires pose a significant threat to ecosystems, fire and ecosystem managers need to be better informed about where fires are expected to become more frequent, and how large the largest fires will become. To date, most future fire research that predicts annual burned area or probability of fire has excluded large regions of the U.S. defined as non-burnable by the presence of agriculture and barren land cover types, e.g., the Great Plains [9,10]. These studies also lack explicit consideration of anthropogenic forces that lead to increased ignitions, peaking around a population density of approximately 10 people/km^2 [31], and changes in fuel.

In this study, we predict future fire events and sizes from 2020 to 2060 in the contiguous U.S. using Bayesian statistical models trained on historical fire, climate, and population data [32]. Historical fire events were obtained from the Monitoring Trends and Burn Severity (MTBS) program and were filtered to include only wildfire events that were greater than 1000 acres (~405 ha) and occurred in 1984–2019 across the contiguous U.S., excluding prescribed and agricultural fires, with no land types being excluded (e.g., agricultural land) [33]. We then use our models to estimate spatiotemporal trends in fires driven by projected future climate from eight global climate models (GCMs) under the RCP 4.5 scenario, an intermediate emission scenario, along with projected population data under a population growth scenario where social, economic and technological trends do not shift significantly from historical patterns (SSP2: Shared Socioeconomic Pathway 2). Predicting the largest fire to ever occur in every ecoregion is extremely difficult, so it is common to use a fire size (ha, acres) threshold to capture a range of the largest fires [9,10], but this method often leads to the elimination of many ecoregions that only experience smaller fire sizes, which are significant for a given ecoregion. Thus, we utilize a percentile threshold as done in Nagy et al. (2019) [22], which identifies large fires proportionally as the largest 10% or 90th percentile of fires occurring within each EPA Level III U.S. ecoregion.

Our modeling approach in this study represents a substantial advance in three distinct ways. First, while most existing models are regional in scope and rely on simple linear regression models of climate and fire [7,8], our model incorporates spatially varying non-linear effects of climate and population at a national scale. Second, our Bayesian approach explicitly propagates uncertainty for derived parameters, and when we integrate over the uncertainty in the predicted number of fires and the burned area, we obtain the predicted maximum fire size per ecoregion [32]. Third, our use of the EPA hierarchical nesting of ecoregions across Level I, II, and III allows for the sharing of information among climatologically similar ecoregions (since level III ecoregions in a level II ecoregion are often adjacent). This nested approach, therefore, allows for the consideration of non-stationarity in relationships between climate and fire behavior for ecoregions that may shift in a warming climate.

Our key research questions are: (1) How much are large fires expected to increase over the next 40 years; (2) Where will the most extreme fires occur in the future; and (3) Where will we see emerging fire regimes (i.e., in areas where fires have not been recently prominent)? The results presented are the ensemble average of the eight GCMs' results, with individual model results presented in the Supplementary Information.

2. Materials and Methods

2.1. New Bayesian Statistical Models to Predict Fire Regimes

We used the models developed by Joseph et al. (2019) to predict wildfire extremes across the contiguous United States [32]. Joseph et al. (2019) [32] combined a 30-yr wildfire record with meteorological and housing data in spatiotemporal Bayesian statistical models, with spatially varying non-linear effects to predict wildfires. Joseph et al. (2019) [32] built one model to describe the total number of fires occurring and another to describe the size of each wildfire. They constructed four models to model fire occurrence and compared the various models' predictive performance based on test-set log likelihood and posterior predictive checks for the proportion of zeros, maximum count, and total count. The models differed in the distributions used in the likelihood, with the zero-inflated negative binomial model having the best performance based on posterior predictive checks. They developed five models for fire size, each with a different distribution of fire size or burned area for a given fire event, and evaluated each model in terms of test-set log likelihood and posterior predictive checks for fire size extremes. The lognormal model for the burned area provided the best performance based on posterior predictive checks. The model was trained on data from 1984 to 2009, withholding the period from 2010 to 2016 to evaluate predictive performance. By allowing the non-linear effects of weather and housing density to vary across space, this model achieved good predictive accuracy for fire extremes at a regional scale over the six-year prediction window. Further model details are located in the Supplementary Information.

2.2. Model Implementation

Further model details can be found in the Supplementary Information as well as published in Joseph et al. (2019) [32]. We used the best performing models from Joseph et al. (2019) [32] to accurately capture the proportion of zeros, maximum count, and total count of fire occurrence extreme tail-behavior for wildfire size for this analysis. Predictors in each type of model included air temperature, housing density, precipitation in the preceding 12 months, precipitation in the same month, relative humidity, and wind speed averaged at monthly timesteps for each Level III ecoregion. The model includes spatiotemporal random effects to capture residual variation in fire activity across ecoregions and time not explained by the predictor variables. An area offset term is also included to account for differences in ecoregion size, ensuring that fire occurrence is modeled relative to area rather than total spatial extent. A Hamiltonian Monte Carlo method was used to sample from the posterior distributions of count and burned area models. The models were fitted using the No-U-Turn Sampler [34]. Models were fitted in the Stan probabilistic programming language using the rstan package [35,36]. Four chains of 1000 iterations each were run, with the first 500 iterations discarded as warmup. After obtaining the output for each GCM, the results were averaged to produce the ensemble mean, which is presented in the main text, and individual model results are provided in the Supplementary Information.

2.3. Model Training Data

Wildfire event data for the contiguous United States was obtained from the Monitoring Trends and Burn Severity (MTBS) program for the years 1984–2019 [33]. MTBS data contains spatiotemporal information on the extent of large wildfire events from 1984 to 2024. Each event has a unique ID, start date, location information, and final fire size. They define large fires as a fire 1000 acres (~405 ha) or greater in the western United States and a fire 500 acres (~202 ha) or greater in the eastern United States. To maintain a consistent analysis across the U.S., we analyzed only fires greater than 1000 acres, leaving 12,219 fire events. Applying the uniform threshold of 1000 acres enabled cross-regional comparison of large fires, but it did eliminate 7.72% of observed fires from the record, with most of those fires occurring in the eastern U.S. Implications of this include a smaller sample size, particularly in certain ecoregions, which creates higher posterior uncertainty in the Bayesian estimates, increased sensitivity to individual fire events with a single anomalous fire season that disproportionately influences trend estimates, and a lack of learning by the model from fires that almost crossed the threshold.

The models were driven by meteorological variables from the Gridded Surface Meteorological Dataset (gridMET) [37], a gridded product that blends monthly high-spatial resolution (~4 km) climate data from the Parameter-elevation Relationships on Independent Slopes Model [38] with temporal attributes from the National Land Data Assimilation System (NLDAS2) regional reanalysis using climatologically aided interpolation to produce daily surface meteorological variables. Daily total precipitation, minimum relative humidity, mean wind speed, and maximum air temperature were averaged monthly from 1984 to 2019 at the 84 EPA Level III ecoregion across the contiguous United States [39]. We calculated the cumulative monthly precipitation over the previous 12 months for each ecoregion-month combination.

Population density was used as a proxy for the spread in ignitions caused by humans [21]. Population density estimates were obtained from the Integrated Climate and Land Use Scenarios (ICLUS, https://www.epa.gov/gcx/iclus-fourth-national-climate-assessment accessed on 1 November 2021) Version 2.1 Fourth National Climate Assessment, which reports population data for the contiguous U.S. based on 2010 U.S. decennial census data.

We estimated the number of fires and the maximum fire size using posterior predictive simulation to generate distributions of the number of fires and fire sizes for each ecoregion and time period. Specifically, we first drew the number of fires from the fitted occurrence model and then drew individual fire sizes from the fitted burned area model. For each simulated realization, we calculated the maximum fire size and repeated this process across posterior samples to obtain a distribution of maximum fire sizes. We summarized this distribution using the 90th percentile, represented by the size exceeded by the largest 10% of fires within each ecoregion. This approach accounted for uncertainty in both the number and size of fires when estimating extreme fire behavior.

2.4. Future Model Input Data

We utilized the Multivariate Adaptive Constructed Analogs (MACA) dataset consisting of 20 Coupled Model Intercomparison Project (CMIP5) GCMs that provided daily output of the requisite variables for future experiments under the RCP 4.5 scenario [40]. We used the MACA product where the GCM model output is statistically downscaled by bias correcting the GCM outputs with training data from gridMET for 1979–2019 (MACAv2-METDATA). This allowed for the continuity of analysis between Joseph et al. (2019) [32] and this project. From the MACA dataset, we obtained monthly values of precipitation, minimum relative humidity, maximum air temperature, and mean wind speed. We then calculated the average of each climate variable at the LIII ecoregion scale for each month in 2020–2060. From the monthly ecoregion precipitation, we calculated the previous 12-month precipitation total for each ecoregion.

Of the 20 models available in the MACA dataset, we chose eight models based on the reported selection process for the United States Department of Agriculture (USDA) Forest Service to identify the best scenarios, climate models, and climate projections that could be applied at the scale of the contiguous United States [41]. They ranked the models by the historical model performance, which was based on 18 variable metrics [42,43]. We used eight out of the top 10 models ranked by both metrics, as the other two models were missing the minimum relative humidity needed to run the model. The eight models were CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-MR, MIROC5, and MRI-CGCM3. While this analysis focuses on RCP 4.5 to characterize mid-century fire dynamics, higher-emissions scenarios (e.g., RCP 8.5) would likely result in larger absolute increases in fire activity. However, prior work suggests that differences among emissions scenarios are relatively modest at mid-century compared to later in the century. Thus, the spatial patterns and relative changes identified here are expected to be robust across scenarios. We decided to only use the RCP 4.5 emission scenario because the choice of scenario has a very limited impact on climate projections by the mid-century, our cutoff period [44], and RCP 4.5 is considered a more likely scenario when compared to RCP 8.5, given our current commitments and observed trajectory [45–47].

Decadal projections of population up to 2100 were obtained from the ICLUS dataset based on 2010 Census population data, along with fertility, mortality, and immigration rates from the Wittgenstein Center (http://www.wittgensteincentre.org/en/index.htm accessed on 1 November 2021). These projections are consistent with the demographic assumptions of the Shared Socioeconomic Pathways (SSPs). We used the population projections from SSP2, known as the "middle-of-the-road" projection, where social, economic and technological trends do not differ greatly from the historical patterns. ICLUS v2 population is reported at geographical units, resulting in 2256 units comprising Metropolitan and Micropolitan Statistical Areas and stand-alone rural counties. We used linear interpolation to estimate population density at the monthly time step per geographical unit and then aggregated across the geographical units to obtain an ecoregion-scale mean monthly population density estimate for 2020–2060.

2.5. Model Caveats

Our model does not include explicit vegetation information; rather, it uses ecoregions as a proxy for expected variability in vegetation, fuels, and topography. Without explicit vegetation information, there is no vegetation feedback (i.e., recently burned areas limit the potential for reburn within a certain timeframe) [48] or climate or land-use-driven changes in vegetation distribution and subsequent climate-fire relationships. We limited the scope of our study, like others who realize that future changes in fire will require simulation of vegetation response to both climate and disturbance, including fire [7]. Some research found that when vegetation change is included in future fire modeling, the total burned area increases dramatically compared to if it is excluded [6], while others found that when future projections accounted for interactions among prior fires on surface and canopy fuel availability, area burned reduced by 14.3% in the Sierra Nevada compared to projections where only climate drivers were considered [49]. This limitation may be particularly important in regions where vegetation dynamics and management strongly influence fire regimes. For example, in parts of the southeastern U.S., widespread use of prescribed fire reduces fuel accumulation and can limit the size and spread of wildfires. Because our model does not explicitly account for these fuel treatments or vegetation feedbacks, projections of "emerging" fire activity in historically low-fire regions should be interpreted with caution, as management practices may mitigate some of the increases in fire occurrence or size. More broadly, vegetation-fire feedbacks can either amplify or dampen future fire activity depending on how fuels respond to climate and disturbance. For instance, incorporating vegetation change and fuel feedbacks has been shown to substantially alter projections of burned area, in some cases reducing fire extent when prior disturbance limits fuel availability (e.g., [49]). As such, our projections represent climate- and population-driven potential fire activity rather than a fully coupled vegetation–fire system. The GCMs that provided the climate data for this study can represent fire occurrence but poorly, and there is no agreement between models on past fire occurrence and how it might change in the future [50]. Future fire predictions are present in some GCMs in CMIP6, but none are able to capture the extent of current extreme fire events [51].

While the underlying population density data contains population density for metropolitan and rural geographical units, and we use linear interpolation to estimate population density at monthly time steps per geographical unit, we aggregate across geographical units per ecoregion to calculate a mean monthly population density estimate used for modeling. In ecoregions that have very large cities, the average population density may be skewed, leading to an overestimation of the amount of interaction that people who reside in those ecoregions have with the WUI and other forested areas. This overestimation in mean population density means that sources of ignition are possibly also overestimated.

Another caveat to our analysis comes from the calibration/validation based on the MTBS dataset. The MTBS burned area data derived from the Landsat satellite has a return interval of 16 days, so it may miss short fires in areas with rapid post-fire regeneration, like in grasslands [52]. MTBS has a threshold of over 405 ha in the west, and when researchers included smaller fires, the total burned area increased by 116% in the United States [22]. The short time period of analysis also contributes to this caveat; some ecoregions are sufficiently data sparse (possibly due to low fire activity or frequency, small ecoregion area, or other factors) that they complicate future predictions.

3. Results

3.1. Large Fire Occurrence Is Likely to Increase 56% over the Next Four Decades

We predict that new patterns of projected fire events across the contiguous U.S. will emerge through 2020–2060. Broadly, the largest increases in fire activity and maximum fire size are concentrated in the western United States, particularly across the Western Cordillera and arid interior regions, while the largest relative increases in fire occurrence occur in historically low-fire regions of the eastern United States. In contrast, a small number of ecoregions, including parts of the Coast Range and Central Appalachians, show modest declines in projected fire activity. The model predicts an increasing number of fires in nearly all ecoregions, with some ecoregions projected to increase significantly more than others (Figure 1A–C), which is consistent with previous research [13,14,53]. From the MTBS dataset from 1984 to 2019, there were 12,219 large fires (>1000 acres or 405 ha) or an average of 339 fires per year. In contrast, we predict a total of 21,132 (CI:16,701; 25,536) large fires or 528 fires per year (CI:441; 673) for 2020–2060 (Figure 2A), for an average increase in fires per year of 56%. From 1984 to 2019, eight ecoregions had zero fire events, while not a single model predicted an ecoregion experiencing less than one fire event in the next 40 years (mean = 1.5 fires for those ecoregions). Across the U.S., the median number of fires predicted per ecoregion was 125, and the mean was 251 fires. Places that had the largest number of fires in the recent past are projected to have the largest number of fires in the future. These ecoregions include the cold deserts of Utah, Nevada and the southern regions of Idaho and Oregon; the Northwestern Great Plains centered on the border of Wyoming, Montana and the Dakotas; California Coastal Mountains and foothills; Arizona/New Mexico Mountains (Figure 3A) and much of the Western Cordillera, which encompasses the Sierra Nevadas as well as the Rockies. For much of the intermountain west, including the cold deserts of the Great Basin, fire activity has increased due to the presence of invasive annual grasses, including *Bromus tectorum* L. [54,55]. There is evidence of invasive grasses altering fire regimes in ecoregions across the U.S., including the desert southwest, eastern temperate deciduous forests and southern pine savannah [56]. For much of the Southwest and the Great Basin, fuel availability is the factor limiting fires in these arid environments, with the abundance of precipitation in the previous year determining the current-year fire season [3,57].

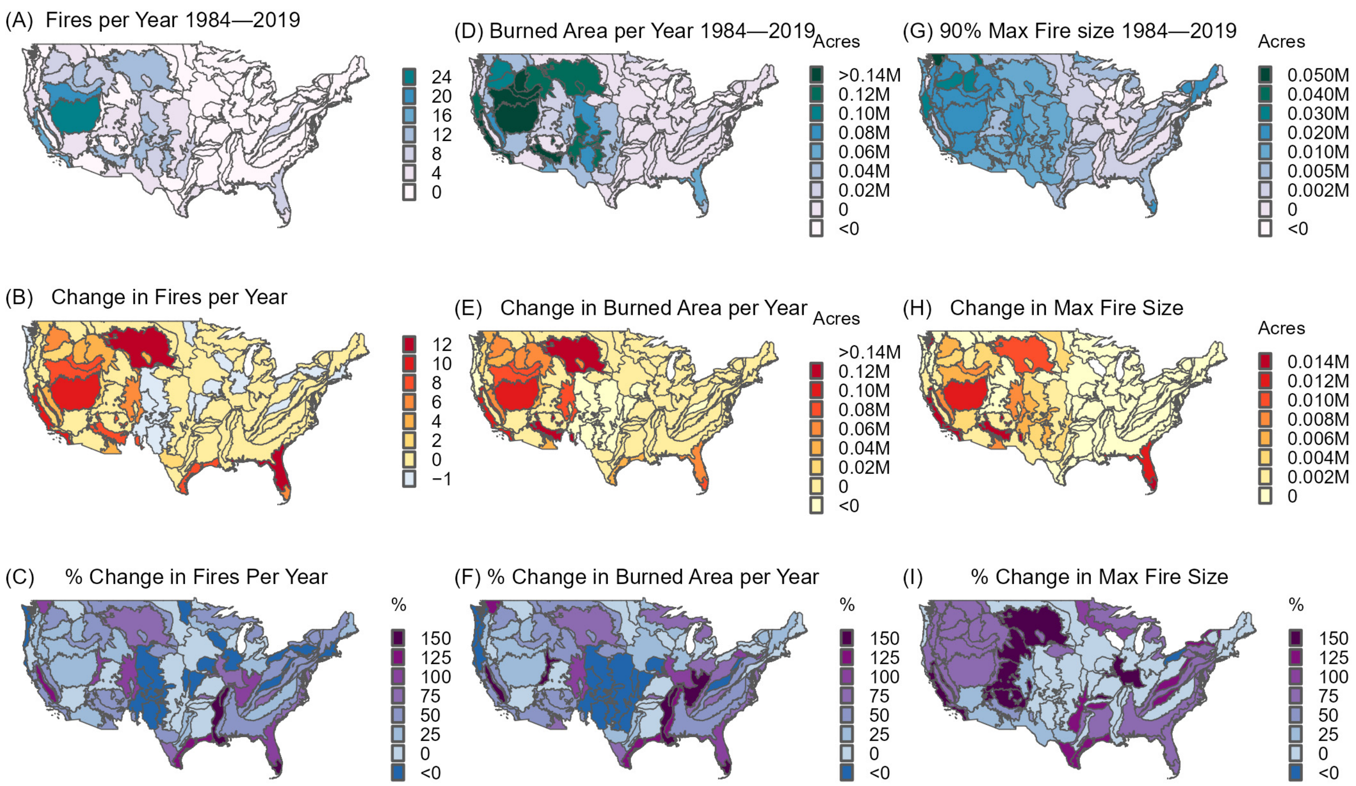

Figure 1. Baseline and change in wildfires, 1984–2019 vs. 2020–2060. (**A**) Number of large fires per year per ecoregion from the 1984–2019 Monitoring Trends in Burn Severity (MTBS), (**B**) Change in the number of fires per year per ecoregion comparing predicted 2020–2060 values to modeled 1990–2019 values, (**C**) Percent change in the number of fires per year per ecoregion predicted 2020–2060 vs. modeled 1990–2019, (**D**) Burned area per year (acres) per ecoregion from 1984 to 2019 (MTBS), (**E**) Change in the burned area per year per ecoregion, predicted 2020–2060 vs. modeled 1990–2019, (**F**) Percent change in the burned area per year per ecoregion, predicted 2020–2060 vs. modeled 1990–2019, (**G**) 90% maximum fire size (acres) per ecoregion from 1984 to 2019 (MTBS), (**H**) Change (acres) in the 90% maximum fire size, predicted 2020–2060 vs. modeled 1990–2019, (**I**) Percent change in the 90% maximum fire size (acres) per ecoregion, predicted 2020–2060 vs. modeled 1990–2019.

Our model predicts that the ecoregion with the largest increase in the number of fire events was the Northwestern Great Plains, with a mean increase of 14.5 fires per year. The ecoregions that ranked 2nd to 5th by average annual increase per year were: Southern Coastal Plain (13.7) (Figure 3C); California Coastal Sage (11); Central Basin and Range (10.8) (Figure 3B); Arizona/New Mexico Mountains (10) (Figure 3A); Snake River Plain (9.2). There were 26 regions that had no change or a slightly negative change in fires per year (Figure 1B). Our model predicts that recent trends in large fire occurrences in a warming climate will greatly increase. The Arizona/New Mexico Mountains and Sierra/Klamath/Cascade Mountains ecoregions experienced increases of 0.6 fires per year from 1984 to 2011 [4], and here, we predict that this will increase to 12.5 fires per year from 2020 to 2060. No significant trends were observed for the Basin and Range ecoregions in the recent past [4], but we project them to increase to 35.8 fires per year from 2020 to 2060. The Great Plains have seen an increase from only 33 fires per year from 1985 to 1995 up to 117 fires per year from 2005 to 2014 [15], and have doubled to quadrupled from 2014 to 2018 [20]. Similarly, our model predicts the largest increase in the number of fires at 30.9 fires per year to occur in the Northwestern Great Plains. In the future, even under lower emission scenarios, like the RCP 4.5, the fire frequency and size are still projected to increase dramatically in regions like the Northern Great Plains, as well as the central and southeastern United States [14].

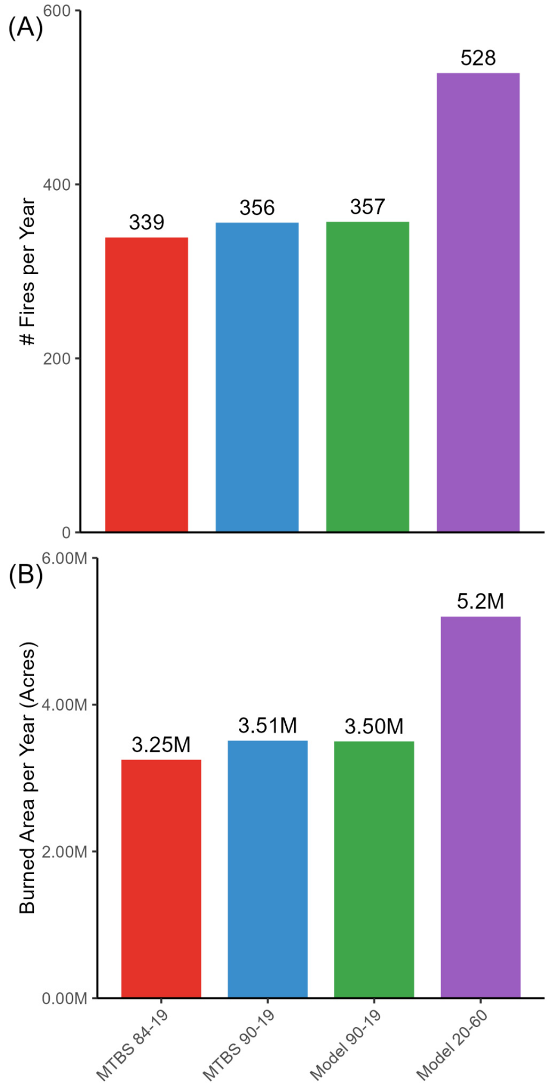

Figure 2. Observed and modeled average number of fires and burned area per year for the contiguous United States. (**A**) Average number of fires per year across the contiguous U.S. from 1984 to 2019. Monitoring Trends in Burn Severity (MTBS) in red, 1990–2019 MTBS in blue, modeled past 1990–2019 in green, and modeled future 2020–2060 in purple. (**B**) Average burned area per year across the contiguous U.S. from 1984 to 2019, Monitoring Trends in Burn Severity (MTBS) in red, 1990–2019 MTBS in blue, modeled past 1990–2019 in green, and modeled future 2020–2060 in purple.

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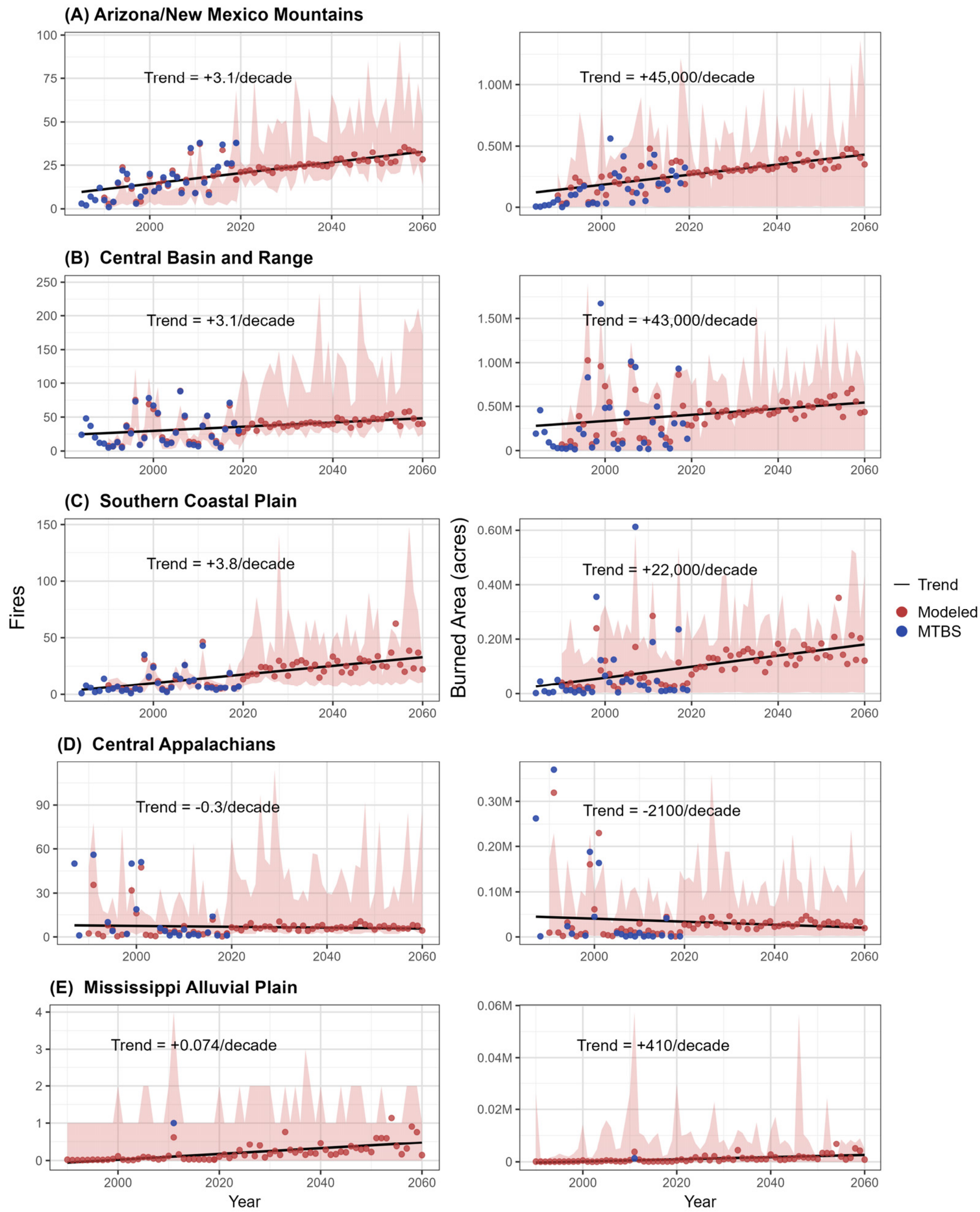

Figure 3. Trends in the number of fires and area burned for selected ecoregions. Number of fires (**left column**) and burned area (acres) (**right column**) per year from the Monitoring Trends in Burn Severity (MTBS) (blue dots: 1984–2019) and median Modeled (ensemble red dots, shading is the range in median estimates from eight GCMs: 1990–2060) along with decadal trends for the (**A**) Arizona/New Mexico Mountains, (**B**) Central Basin and Range, (**C**) Southern Coastal Plain, (**D**) Central Appalachians, (**E**) Mississippi Alluvial Plain ecoregions. All trends, except the Central Appalachians, are statistically significant, $p < 0.05$.

Many ecoregions had little to no fire activity per year from 1984 to 2019 (Figure 1A). In these regions, even a modest positive increase in fires per year (Figure 1B) resulted in substantial relative increases in fire occurrence from 2020 to 2060 (Figure 1C). The ecoregion with the largest relative change in the number of fires per year is predicted to be the Mississippi Alluvial Plain (233%), the area surrounding the Mississippi River (Figures 1C and 3E), as well as the Southeast Coastal Plains, and Southeastern Plains in parts of western Kentucky and Tennessee. While we found the largest relative increase in fire events to occur in the Mississippi Alluvial Plain, others projected the highest relative increase in fire probabilities across the U.S. to occur in the Upper Great Lakes (Minnesota, Wisconsin, Michigan) [13], which are among the ecoregions where we find an emergence of fire in the future. Eleven ecoregions are predicted to have fewer fires per year in the future. These regions are predicted to have a decrease in fires per year and therefore a negative percent change in the future: Coast Range (−25%) encompassing the coasts of California, Oregon and Washington; Central Appalachians (−10%) (Figure 3D); and the Southwestern Tablelands (−1.5%) in northeastern New Mexico. Projected declines in some ecoregions (e.g., Coast Range, Central Appalachians) may reflect different underlying mechanisms. In the Coast Range, relatively high and persistent moisture availability and limited fire weather windows may constrain future fire activity despite warming. In the Central Appalachians, declines may reflect a combination of generally humid conditions, fragmented landscapes, and effective suppression and management in more densely populated regions. However, these patterns should be interpreted cautiously, as they may also reflect model uncertainty, particularly in regions with lower historical fire activity or greater interannual variability. Some of the regions that are predicted to have the largest number of fires in the future, but also have historically experienced many fires, will still see moderate relative increases, with a 44.8% increase in Cold Deserts and a 65.6% increase in the Central Semi-Arid Prairies (Figure 1C).

3.2. Annual Burned Area Is Likely to Increase 59% over the Next Four Decades

For 1984–2019, the MTBS dataset reported a total burned area of 117M acres and an ecoregion average of 3.25M burned acres per year from large fires. The predicted total burned area for 2020–2060 is 207M acres (CI:157M, 257M) with an average of 5.2M burned acres per year (CI: 4.28M, 6.90M) across all ecoregions (Figure 2B), an increase of 59% over the observed past burned area per year. Similar to the observed burned area per year (Figure 1D), the Cold Deserts were predicted to be the ecoregion with the largest burned area per year, with the Central Basin and Range (0.46 M acres/yr) (Figure 3B), followed by the Northern Basin and Range (0.34 M acres/yr). Fourteen ecoregions had a predicted total burned area of less than 10,000 acres. These 14 ecoregions were the same regions that had zero to one events during the 36-year MTBS record.

The model predicts the ecoregion with the largest increase in burned area per year over 2020–2060 was the Arizona/New Mexico Mountains with an increase of 0.13 M acres per year (Figure 3A). The top five regions with the largest increasing change in burned area per year are all located in the western United States (Figure 1E). Eleven ecoregions, mostly clustered in the South Central Semi-Arid Prairies located from Nebraska to Texas, along with the Central Appalachians, were predicted to have a decrease in burned area per year. Outside of the western U.S., the only regions predicted to have large increases in burned area per year are in the Southern Coastal Plains and Western Gulf Coastal Plains of Texas, predicted to have an average annual burned area of 0.12 M acres. Other research predicts a small increase in annual area burned for the entire Southeast, but for an ecoregion that includes the Southern Coastal Plain of Florida and the Middle Atlantic Coastal Plain (coastline of Georgia and Carolinas), the median annual area burned is projected to rise by 21.6% [17]. Our model predicts the largest increases per year in burned area for much of the western U.S., but research comparing annual area burned from 1972 to 2015 with projections for 2010–2030, saw significantly larger change, with a greater than five times increase in annual area burned over the northwestern Intermountain U.S. (including northern Idaho, western Montana and western Wyoming), Central Rockies (central Utah and northern Colorado), Southern Rockies (Colorado and northern New Mexico), and Southwest (New Mexico and northern Arizona) [7].

Similar to the percent change in total number of fires, the model predicts larger increases in burned area per year along the Mississippi River down to the Gulf Coast, with large percent changes also occurring in the Southeastern Plains of Alabama, Georgia, and the Carolinas (Figure 1F). The model predicted ecoregion with the biggest percent change in burned area per year is the Mississippi Alluvial Plain (372%), followed by the Southern Florida Coastal Plain (172%). In the West, the Central California Valley (171%) is predicted to see the largest percent increase in burned area per year. The model predicted that the coast from Washington to Northern California would see the greatest negative percent change (−29%) in burned area per year. The ecoregion with the second largest predicted negative percent change is the Central Appalachians (−23%). The Southern Rockies in Colorado are among the regions projected to see an over 100% increase in burned area per year. Research found even greater percent changes in annual area burned with an increase of 175% for the Rocky Mountain Forest by 2046–2055 compared to 1996–2005 [5]. They found little change in area burned by 2050 for the Eastern Rocky Mountains/Great Plains ecoregions, but our model predicts the Northern Great Plains will see an average increase of 74% in burned area per year, while the South-Central Prairies of the Great Plains will have an average increase of 5%, with many of the ecoregions seeing slight decreases in burned area per year.

3.3. Widespread Increases in the Sizes of the Largest Fires

The places that recently had the largest burned area per year were also among the regions that had larger maximum fire sizes. The among-ecoregion median of the 90th percentile fire size from the MTBS dataset for 1984–2019 was 8558 acres, while the largest 90th percentile fire size was 53,377 acres in the North Cascades in central Washington. These ecoregions include much of the mountains in the western U.S. that make up the Western Cordillera (Figure 1G). The 90th percentile maximum fire sizes are an order of magnitude smaller than the largest events observed in an ecoregion because the largest fires are extreme tail events, where the 90th percentile value indicates that 10% of all the events in that ecoregion are larger. The ecoregions with the largest change in maximum fire size were similar to the ecoregions that had the largest change in number of fires and burned area per year. The California Coastal Mountains and Foothills are predicted to have the largest change in maximum fire size with an increase of 28,192 acres (Figure 1H) and an increasing trend of 2000 acres per decade (Figure 4B). The Arizona/New Mexico Mountains is the ecoregion with the second largest projected increase in maximum fire size of 27,869 acres or a trend of 2400 acres per decade (Figure 4A), which is a 51% decrease from the observed trend in maximum fire sizes from 1984 to 2011 for the Arizona/New Mexico Mountains [4]. For the same time period, the Sierra/Klamath/Cascade Mountains ecoregion had a negative trend of over 500 acres per year [4] for the maximum fire size, which our model predicts to reverse and increase to a trend of 158 acres per year. The Rocky Mountains and Cold Deserts are also expected to have large increases in the maximum fire size by 2060 (Figure 1H). This is consistent with the projected increases in the probability of very large fires across the contiguous U.S., with the largest increases occurring in regions that had observed many very large fires in recent decades, including the Intermountain West covering the Great Basin and Western Cordillera [16].

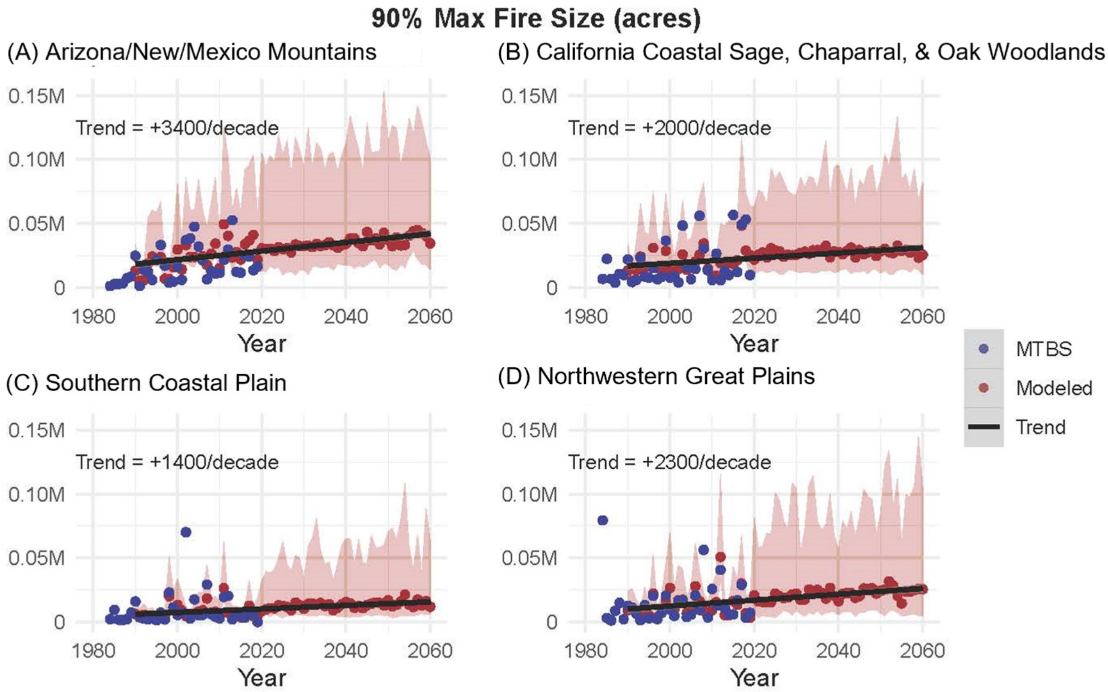

Figure 4. Trends in maximum fire size for selected ecoregions. 90% maximum fire size per year from the Monitoring Trends in Burn Severity (MTBS) (blue dots: 1984–2019) and median Modeled (ensemble red dots, shading is the range in median values from eight GCMs: 2020–2060) along with decadal trends for the (**A**) Arizona/New Mexico Mountains, (**B**) California Coastal Sage, Chaparral, and Oak Woodlands, (**C**) Southern Coastal Plain, (**D**) Northwestern Great Plains ecoregions. All trends are statistically significant, $p < 0.005$.

Across the U.S., our model predicts that maximum fire sizes will increase by an average of 63%. The regions to see the largest relative increase in the maximum fire size occur mostly in the western U.S. (including the Rockies, Sierra-Nevadas and the Great Basin regions) (Figure 1I), similar to previous research on very large fire probability [11]. The southern two-thirds of the western U.S. had a 132% linear increase in the probabilities of very large fires from 1984 to 2010, as well as a significant increase in probabilities across the southeastern U.S., especially in Florida [10]. For the southwestern U.S., our model predicts a similar average increase of 128% in the maximum fire size and for the Southeastern Coastal Plains, an average increase of 92% for 2020–2060 compared to the modeled 1990–2019 values, or a trend of 1400 acres per decade (Figure 4C). In the future, the mean probability of a very large fire across the western U.S. increased 30% for 2031–2060 compared to 1950–2005 observations, with Eastern Great Basin (Idaho), Pacific Northwest, Rocky Mountains, and Southwest (Arizona and New Mexico), showing at least a 200% increase in probability of a very large fire [9]. The model predicted ecoregion with the biggest percent change in the maximum fire size is the Snake River Plain (207%).

3.4. Emerging Fire Regimes Expected in the Eastern U.S. Over the Next Four Decades

In the recent past, much of the eastern U.S. has observed minimal fire events, burned area, and maximum fire sizes (Figure 1A,D,G), but our models predict small absolute increases in the number and sizes of future events over the next four decades (Figure 1B,E,H), which lead to large increases in the percent change in the number of fires, burned area, and maximum fire sizes in the future (Figure 1C,F,I). Among the eastern regions, the Mississippi Alluvial Plain, the area surrounding most of the Mississippi River, is the ecoregion predicted to have the largest relative change in both the number of fires per year (233%) and burned area per year (372%). The Southeastern Plains in parts of western Kentucky

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and Tennessee are predicted to have large relative increases in the number of fires per year in the future, while the Southeastern Plains of Alabama, Georgia and the Carolinas are predicted to have large relative increases in burned area per year. These regions, along with the rest of the U.S., see increases in the percent change in maximum fire size. It is important to reiterate here that climate forcing suggests the potential for emerging fire regimes in these eastern ecoregions that have traditionally been proactively managed with extensive prescribed burning, reinforcing the value of proactive fuels management to offset the potential for climate-driven increases to fire size and frequency.

4. Discussion

Our results suggest that the observed increasing trends in the number of fires and fire size across the contiguous U.S. will continue over the next several decades, even on a moderate warming trajectory (RCP 4.5) and moderate population growth scenario (SSP2). In the present study, we seek for the first time to incorporate all of the key elements: number of fires and maximum fire size, in addition to area burned for the entire contiguous United States, while accounting for human ignitions, in a single comprehensive study across all EPA ecoregions. To date, most future fire research has focused on projections of fire probability or burned areas, and the relative change in these quantities, rather than the actual number of fire events, and most such studies have omitted direct anthropogenic influences on ignition likelihood [9,10]. In addition, prior research on U.S. wildfires has mainly focused on the drier western third of the country while ignoring the Great Plains and lower fire frequency zones in the southern and eastern United States.

We find that climate change will likely cause wildfires to spread into regions where such events were rare in the recent past (e.g., around the Great Lakes, along the Mississippi River down to the Gulf of Mexico), and lead to much larger wildfires that reach historically unprecedented sizes in regions where fires were historically common (e.g., the Cold Deserts and Western Cordillera). Ecoregions that are predicted to have the largest total number of fire events are not the same ecoregions that are predicted to have the largest total burned area under the same moderate (RCP 4.5) climate model forcing. On a contiguous U.S.-wide basis, we find that the number of large fires is expected to increase over 2020–2060. Regions that had the most fires in the past will generally remain the most frequent burning regions in the future. The Southern Florida Coastal Plain provides an interesting test for model assumptions, where climate forcing suggests it has the potential to emerge as a new frequent wildfire region, though historically large wildfires have been curtailed through intensive prescribed burning programs that may or may not enable fuels management to offset climate forcing [58]. Further, we find that the changes in percent area burned in the future (+59%) are slightly larger than the percent increase in the number of fire events (+56%), and that maximum fire size increases more (+63%) than either of the other two metrics. Though our modeling predicts larger relative increases in burned area in the eastern U.S., where large fires were rare in the observed record, the largest absolute increases in area burned occur in the West (specifically, the Western Mountains and Cold Desert ecoregions).

Historically, many eastern U.S. ecoregions have experienced relatively low wildfire activity due to a combination of climatic and anthropogenic factors, including higher fuel moisture associated with humid conditions, limited fire weather windows, and effective suppression within more fragmented and densely populated landscapes. These conditions have constrained the occurrence and spread of large fires despite the presence of substantial biomass. However, projected climate change is expected to weaken these limiting factors through increased temperatures, atmospheric drying, and greater variability in precipitation, potentially creating more frequent windows of flammable conditions. In addition, continued human presence may increase ignition pressure. Together, these changes point to an emergence of fire activity in historically low-fire regions. While some eastern ecoregions exhibit large relative increases in fire occurrence, these changes often arise from low historical baselines, and absolute fire activity remains lower than in western regions.

The fact that overall burned area as well as maximum fire size increases by a larger increment than the number of fires suggests a possible non-linear relationship between climate change and the most extreme wildfires, as has been hinted at in recent research based on observed trends in the U.S. West [59]. This may relate to the relatively stronger climate signal, compared to the anthropogenic ignition signal—though we note that both forcings could potentially be underestimated if either climate change or population growth occurs faster than the intermediate scenarios used in this study. Although we did not formally partition the variance among predictors, the magnitude and spatial coherence of projected increases, particularly in maximum fire size and burned area, closely track projected changes in climate variables rather than shifts in population density alone. Population growth primarily modulates ignition likelihood, especially near expanding WUIs, whereas the capacity for fires to grow large is more directly constrained by fuel aridity and fire weather conditions. The larger proportional increases in burned area and maximum fire size relative to fire counts, therefore, suggest that climate-driven changes in fire weather exert a dominant influence on long-term trends, with demographic changes acting as an important but secondary modifier.

Additionally, historically, it is the largest wildfires that are most likely to exceed active firefighting efforts (for a variety of reasons, including rapidly expanding perimeters, the increased likelihood of expanding amid complex topography, and/or firefighting resource exhaustion). Although active fire suppression is not explicitly included in our modeling, it is plausible that any underlying non-linear empirical relationships in the real-world fire training dataset—on which active suppression occurred in many cases—are nonetheless indirectly represented in the predictive model. Either way, one key implication of our predictions is that much larger future fires will increasingly challenge suppression efforts in a warming climate—perhaps acting as positive feedback to maximum fire size. The disproportionate increase in maximum fire size relative to fire frequency and total burned area has important implications for wildfire management and risk mitigation. Larger fires are more likely to exceed suppression capacity, particularly during periods of extreme fire weather, leading to longer-duration incidents and increased demand on firefighting resources. This may necessitate changes in resource allocation strategies, including pre-positioning of personnel and equipment and increased interagency coordination to manage simultaneous large fire events. In addition, larger fires can reduce evacuation lead times and increase the spatial extent of risk to communities, particularly in the wildland–urban interface. As a result, emergency planning may need to adapt to account for faster-growing and more expansive fire events, including improved early warning systems and evacuation protocols designed for large, rapidly evolving fires.

One key conclusion from our study is the high likelihood of more frequent and larger extreme fire events in most parts of the U.S. Regions currently experiencing few fires will see the smallest relative increases in maximum fire size, while the places that burn regularly will see the largest relative increases as well as the largest maximum fire sizes. Most of the southeastern ecoregions are among those expected to see the largest relative increases in the number of fires and acres burned per year, while the western ecoregions see the largest relative increases in 90th percentile maximum fire sizes. Previous work demonstrated that total annual area burned in a given region is strongly influenced by the largest wildfires [9], but as our results show, there can be significant increases in maximum fire sizes despite minimal increases in annual burned area in the same ecoregion. It has already been recognized that human ignitions affect the spatial patterns of large fires [22,29], and the very largest fires are driven by different climatic conditions compared to other large fires in the western and eastern United States [9,10]. However, our own previous work developing the predictive model used in the present study suggests that ordinary events provide information on extremes, which would not be the case if extreme events were driven by completely unique climatic conditions from the ordinary events [32]. Previous studies have also excluded agricultural areas (deeming them "non-burnable") and regions that experienced fewer than five very large fires in their training data—but in the present study, these are some of the regions we project to have the largest relative increase in maximum fire size (including the Central Valley of California and parts of the Great Plains). In the only other study (to the authors' knowledge) that uses Bayesian statistics and climate from multiple GCMs to predict very large fire occurrence across the contiguous U.S., the authors only considered 16 ecoregions [12] (rather than the 84 ecoregions in the present work).

By including regions often excluded or overlooked, along with the human impact on ignitions, our study provides a more complete prediction for the future of fire across all regions in the U.S. The projected increase in fire has substantial yet notably different ecological, societal, disaster response, and public policy implications for the western and eastern U.S., respectively. In the West, which has a recent history of frequent and large fires, the future fire regime will only become more extreme, with ever greater influences on the forests and other ecosystems, populated areas via direct fire threats as well as indirect air pollution hazards related to smoke, and raising the prospect of even greater need for resource allocation to fire management and response. In the western U.S., increasing fire size and severity are expected to drive shifts in forest composition and structure, with implications for carbon storage and ecosystem resilience [14]. In addition, larger and more frequent fires are likely to exacerbate smoke exposure, with documented impacts on air quality and public health across broad regions [60]. Fire-driven changes to vegetation and soil structure can also affect hydrological processes, including water quality and runoff in fire-affected watersheds [61]. At the same time, expanding fire activity, particularly in the wildland–urban interface, poses increasing risks to communities through direct exposure to fire, evacuation challenges, and infrastructure vulnerability [21]. The findings of this study assume that large wildfires will not significantly alter fuel continuity at the ecoregion scale over the next four decades. This assumption seems probable in the western U.S., where the accumulation of forest fuels over more than a century of fire exclusion has created a significant fire deficit [62] (though see Yocom et al. 2019 [63]). Conversely, in the southeastern U.S., where intensive prescribed burning programs influence fuel loads over large areas, wildfire size and frequency are diminished by the density of burn footprints and extensive road networks. In these regions, future fire outcomes will depend not only on climate and ignition pressure but also on management decisions that influence fuel accumulation. Incorporating these dynamics remains an important direction for future work.

Currently, the USDA Forest Service Wildfire Crisis Implementation Plan only covers eight western states with no mention of the eastern United States [64]. For these reasons, it will be increasingly important to develop cohesive national wildfire policies [65] that account for future fire predictions across the wide range of background ecologies, climates, and human geographies that will be interacting in a warming climate. Our results suggest that national wildfire policy may need to expand beyond its current western focus to better account for emerging fire risk in the eastern U.S. In these regions, where fire has historically been less frequent, existing management systems, infrastructure, and public

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awareness may be less prepared for increases in wildfire occurrence and size. Policy adjustments could include expanding fuel management and prescribed fire programs, increasing monitoring and early detection capacity, and investing in fire preparedness and response infrastructure in historically low-fire regions. Additionally, integrating fire risk into land-use planning and development decisions in eastern landscapes may be critical as human populations continue to expand into flammable environments. Together, these findings highlight the importance of a more geographically inclusive, forward-looking national wildfire strategy that anticipates both intensifying fire regimes in the West and emerging fire regimes in the East.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire9050208/s1. Further model details can be found in the Supplementary Information [66–73].

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Data Availability Statement: The following publicly available datasets, which were inputs to the fire models, can be found: (1) Monitoring Trends in Burn Severity (https://mtbs.gov/direct-download) accessed on 1 November 2021; (2) GridMET (https://www.climatologylab.org/gridmet.html) accessed on 1 November 2021; (3) Integrated Climate and Land Use Scenarios (https://www.epa.gov/gcx/iclus-fourth-national-climate-assessment) accessed on 1 November 2021; (4) Multivariate Adaptive Constructed Analogs (https://climate.northwestknowledge.net/MACA/index.php) accessed on 1 November 2021. The new data generated for this analysis is available on Zenodo at: https://doi.org/10.5281/zenodo.18613396. R code for this analysis is available on Zenodo at: https://doi.org/10.5281/zenodo.18625661.

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Abbreviations

The following abbreviations are used in the manuscript:

CMIP5	Coupled Model Intercomparison Project
EPA	Environmental Protection Agency
GCMs	Global Climate Models
gridMET	Gridded Surface Meteorological Dataset
ICLUS	Integrated Climate and Land Use Scenarios
MACA	Multivariate Adaptive Constructed Analogs
MTBS	Monitoring Trends and Burn Severity

NLDAS2	National Land Data Assimilation System
RCP 4.5	Representative Concentration Pathway 4.5
RCP 8.5	Representative Concentration Pathway 8.5
SSPs	Shared Socioeconomic Pathways
SSP2	Shared Socioeconomic Pathway 2
WUI	Wiland Urban Interface
U.S.	United States
USDA	United States Department of Agriculture

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