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Effects of Climate Change on Natural-Caused Fire Activity in Western U.S. National Forests

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Abstract: Climate change, with warming temperatures and shifting precipitation patterns, may increase natural-caused forest fire activity. Increasing natural-caused fires throughout western United States national forests could place people, property, and infrastructure at risk in the future. We used the fine K nearest neighbor (KNN) method coupled with the downscaled Multivariate Adaptive Constructed Analogs (MACA) climate dataset to estimate changes in the rate of natural-caused fires in western United States national forests. We projected changes in the rate of minor and major forest fires from historical (1986–2015) to future (2070–2099) conditions to characterize fire-prone national forests under a range of climate change scenarios. The results indicate that climate change can add to the occurrence of forest fires in western United States national forests, particularly in Rocky Mountain, Pacific Southwest, and Southwestern United States Forest Service regions. Although summer months are projected to have the highest rate of natural-caused forest fire activity in the future, the rate of natural-caused forest fires is likely to increase from August to December in the future compared to the historical conditions. Improved understanding of altered forest fire regimes can help forest managers to better understand the potential effects of climate change on future fire activity and implement actions to attenuate possible negative consequences.

Keywords: national forests; climate change; wildfire; warming temperature

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1. Introduction

Wildfires have increased in size and frequency throughout western United States national forests between 1980–2015 [1–6]. Increased wildfire activity already posed severe economic, social, ecological, and environmental damage such as the destruction of homes, adverse air and water quality, extra costs, and loss of life that are likely to accelerate with climate change [4,7,8]. Changes in high-severity fire activity may lead to the loss of forest ecosystem resilience and the conversion of the forest structure, dominant species, life forms, or functions [9–11]. In addition, increasing forest fire activity can have several adverse consequences on carbon emission, water supply, and the wildland–urban interface (WUI), etc. [10]. Current fire management problems (e.g., logging operations, fire suppression, water quality) in national forests may get worse due to the increase in severity and length of forest fires as a consequence of climate change [10].

In western national forests, the buildup of forest fuels due to decades of fire exclusion combined with a warming climate may lead to the spread of fires to urban areas [12]. A USD 3.13 billion, annually, was invested in wildfire protection by federal agencies from 2002 to 2012 and approximately 4500 km^2 are annually affected in the United States [13]. This number is on the rise as fire events become more frequent and their damage becomes more catastrophic [13]. Wildfire losses in developed areas could substantially increase in the western United States due to the expanding wildland–urban interface [12] in which the buildup of forest fuels coupled with increasing aridification, drought, and urbanization [8,14,15] are likely to catalyze plume-driven fires spreading to developed areas. As wildfire losses continue to grow and the WUI problems gain more attention, the enhanced understanding of changes in future forest fires is vital and further study is needed to develop community mitigation and planning strategies to adapt to the increasing incidence of natural-caused forest fires [12].

Adapting to the impacts of climate change on forest fire activity will involve adjusting future behaviors that account for possible changes in the frequency of future natural-caused wildfires [16]. Wildfire prediction under future climate change is complicated by complex integrated drivers [16,17]. In general, the occurrence and number of wildfires and area burned are functions of fuel quantity, fuel type, moisture content, aridity, ignitions (e.g., lightning strikes), weather (e.g., temperature, precipitation, wind), and anthropogenic factors (e.g., fire suppression efforts) [16]. It is difficult to estimate the future occurrences of human-caused forest fires based on societal behavior [18]. Thus, we focused only on shifts in future natural-caused wildfire regimes and excluded all forest fires with other ignition sources that are not tightly related to climate conditions [18]. Natural-caused wildfires currently contribute to approximately 20% of total wildfires in the United States [19].

Climate plays a key role in increasing forest vulnerability to natural-caused fires [20]. Interactions between climate and natural wildfires are known as the most important drivers of national forest ecosystem responses to future climate change. The increase in forest fires is associated with warmer temperatures and decreasing summer precipitation [1,3,7,21–24], both of which are projected to continue under plausible future climate scenarios throughout the 21st century [8,25–28]. An improved understanding of linkages between climate variables and natural wildfires is required to forecast future fire activity [10].

Previous studies assessed changes in wildfire events in the western United States with warming climate [1,9,29] at various regional and spatial scales [1,21,22,30–34]. Most studies used regression methods [35,36] or process-based fire models [37–39] to estimate future fire activities at the state or larger regional scales [30]. They reported a significant linkage between fire frequency, historical climate variability, and future climate change [10,21,40]. Gao et al., (2021) used the combination of the Global Climate Models (GCMs) and Physical Chemistry Fire Frequency Model (PC2fM) to project changes in annual fire occurrence probabilities across the contiguous United States (CONUS) [6]. They reported that the potential fire probability is likely to increase across the CONUS, particularly in high-risk areas such as the Coastal California Mountains [6]. Littell et al., (2018) developed an ecologically-based climate-fire projection to investigate how future areas burned might be affected by climate change for 70 different ecosystems across the western United States [41]. Gergel et al., (2017) assessed the effects of future climate change scenarios for snow, soil moisture, and fuel moisture across the western United States and concluded that the mountain regions are likely to have higher fire potential. Furthermore, lowland regions have higher uncertainties and less agreement between GCMs projections [42]. McKenzie and Littell (2017) evaluated the drought–fire relationship across the western United States and recommended that future wildfire prediction should consider both vegetation changes and potential changes in the drought–fire dynamic [42].

Although extensive efforts and progress have been made in understanding the effects of climate change on the western United States, most knowledge about the effects of climate change on United States national forest fire regimes is too broad to fully inform the decisionmakers of specific ecosystems [18,43]. Five important considerations must be addressed to improve the characterization of future natural-caused fire activities in response to climate change:

First, United States national forests are currently known as one of the most vulnerable regions to wildfire. Fire management and adaptation strategies should be implemented and prioritized at the national forest scale to characterize high-value and high-risk fire-prone national forests in response to climate change [1]. Second, further information is needed on the seasonal aspect of changes in future natural-caused forest fires by modeling each month separately. The characterization of future changes in forest fire activity at the monthly scale can inform forest managers to improve the implementation of mitigation strategies over the fire season. Third, the implementation of various GCMs that cover different climate scenarios for western United States national forests can inform decisionmakers to improve adaptation strategies for different climate conditions in the future. Fourth, using a simplistic machine learning model to focus only on changes in natural-caused fires on western United States national forests leads to reducing uncertainties in data. Fifth, climate change can affect the minor and major forest fires differently in western United States national forests. Natural-caused wildfire in the western contiguous United States can be divided into two categories including major fires (>400 ha) and minor fires (<400 ha) [44,45].

Thus, in this study, we considered the larger picture of changes in forest fire activity for the 52 western United States national forests. We estimated changes in natural-caused minor and major wildfire activity in response to climate change from historical (1986–2015) to future conditions (2070–2099). While the unit of analysis is individual national forests, we also aggregated the results to the level of United States Forest Service regions. We first assessed the historically observed natural-caused fire data from Welty and Jeffries (2020) [19] and described relationships between the climate variability and forest fire activities using the fine K nearest neighbor (KNN) machine learning method. An immediate benefit from this simplistic model is the ability to assess changes in the fire seasons.

The fire prediction model was used to predict future natural-caused fire activity in western United States national forests based on results from WARM (lowest increase in temperature), WET (highest increase in precipitation), DRY (highest decrease in precipitation), HOT (highest increase in temperature), and MID GCMs. These scenarios have been selected according to average changes in precipitation and temperature for the United States [46]. The use of these five climate change scenarios allows us to project a range of future fire activity for each Forest Service region [8].

Thus, the objective of this study is to (1) characterize changes in natural-caused minor and major fire rates in response to climate change; (2) assess shifts in the forest fire season; and finally, (3) determine fire-prone national forests that are likely to be highly affected by climate change. By drawing on this knowledge, the findings can help mitigate or adapt to climate change impacts on United States national forests to protect human society, ecosystem, environment, and infrastructures [18].

2. Materials and Methods

We selected western United States national forests for analysis that are located in different physiographic and climatic regions. Historical fire data time series were compiled from Welty and Jeffries (2020) [19] covering 1986–2015 for individual national forests. Although the current database provided by Welty and Jeffries (2020) [19] includes historical information on both human-caused and natural-caused fires; we only focused on natural-caused fires and excluded all forest fires with other ignition sources due to the complicated prediction of future human-caused fires and lower associations with climate change.

We used the combination of Daymet [47] and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) [48] datasets at the grid size of ~4 km [28]. First, historic daily CONUS precipitation and temperature from 1986–2015 were organized by Naz et al., (2016) [49], which were based on the Daymet dataset and rescaled by the PRISM dataset at the monthly scale [28]. The wind speed was summarized from the North American Regional Reanalysis (NARR) dataset [50] for the 1986–2015 period.

The 2070–2099 future climate was obtained from the downscaled Multivariate Adaptive Constructed Analogs (MACA) [51] datasets at the grid size of ~4 km (1/24 degree). The projected changes in climate may widely differ across projected models [27]. Among the available MACA models, we selected five climate models ranging from wettest to driest and warmest to hottest climate scenarios to capture the possible range of future climate changes [8,28,46].

The WARM (MRI-CGCM3), WET (CNRM-CM5), MID (NorESM1-M), DRY (IPSL-CM5A-MR), and HOT (HadGEM2-ES365) models under representative concentration pathways (RCP) 8.5 were selected based on a range of changes in precipitation and temperature from historical to future conditions [46]. While these five selected GCMs only represent a small subset of a much larger number of models and emission scenarios, the use of these models allows us to characterize the estimated range in projected annual precipitation change across all projections for the entire CONUS. Readers are referred to Heidari et al., (2020) [27] and Joyce et al., (2020) [46] for further details on model selection and climate projections.

We used the two-sample Kolmogorov–Smirnov test at the 5% significance level to assess the null hypothesis that the distributions of precipitation, temperature, and wind speed for months with fire and without fire are from the same distribution. Note that the test decision (h) = 1 means that the null hypothesis is rejected and the distribution of precipitation, temperature, and wind speed for months with fire and without fire is significantly different.

We analyzed relationships between national forest fire activity and climate variabilities using the fine k-nearest neighbor algorithm (KNN) machine learning method. We used the Classification Learner Application in MATLAB to evaluate the accuracy of different classifiers and found that the KNN method leads to the highest accuracy. The KNN method is a simple but effective classification method that classifies examples based on the intuitive premise and similar data points in close proximity in the feature space. The KNN calculates the similarity of data points using the Euclidean distance between the k nearest data points [52].

We developed natural fire prediction models by associating climate variables from the historical conditions with historically observed natural-caused fire data. We estimated forest fires as a function of monthly precipitation, temperature, and wind speed [10].

$$\mathrm{F(P,\ T,\ W,\ Lat,\ Lon)} = \begin{cases} 0\ (\text{No Fire}) \\ 1\ (\text{Minor Fire}) \\ 2\ (\text{Major Fire}) \end{cases} \tag{1}$$

where P is the monthly total precipitation, T is the monthly average temperature, and W is the monthly average wind speed. Additionally, we added latitude (Lat) and longitude (Lon) of each national forest as predictors of forest fires to improve and regionalize our predictions [7]. Adding latitude and longitude helps the model to capture other regional characterizations of national forests. The responses of our fire prediction function include three classes; 0 indicates the months with no fire events, and 1 and 2, respectively, indicate months with minor and major fires (Equation (1)).

We evaluated the performance of the presented model using the cross-validation method in the Classification Learner Application in MATLAB. The cross-validation method partitions the data into disjoint folds and for each fold trains the model using in-fold data and calculates the average test error over all of the defined folds. The cross-validation method protects against overfitting by partitioning the data set into folds and estimating accuracy on each fold. Figure 1 provides the accuracy of each class based on the 5-fold cross-validation using the confusion matrix. Additionally, we presented the confusion matrix of 10-fold and 15-fold in Figures S1 and S2, Supplementary Materials. We also calculated the accuracy of the model based on the holdout validation and selected 25% of the data to use as a test set. The results from the holdout validation are also provided in Figure S3.

The validation accuracy based on the 5-fold cross-validation is 97.9%, 71.7%, and 64.0%, respectively, for class 0, 1, and 2. The True Positive Rates (TPR) and the False Negative Rates (FNR) are characterized in the figures. The accuracy assessment indicates that the model may underestimate the rate of major and minor fires, respectively, however, the accuracy of the model is acceptable. The approach applied here estimates the occurrence of natural-caused forest fires in each national forest for each month.

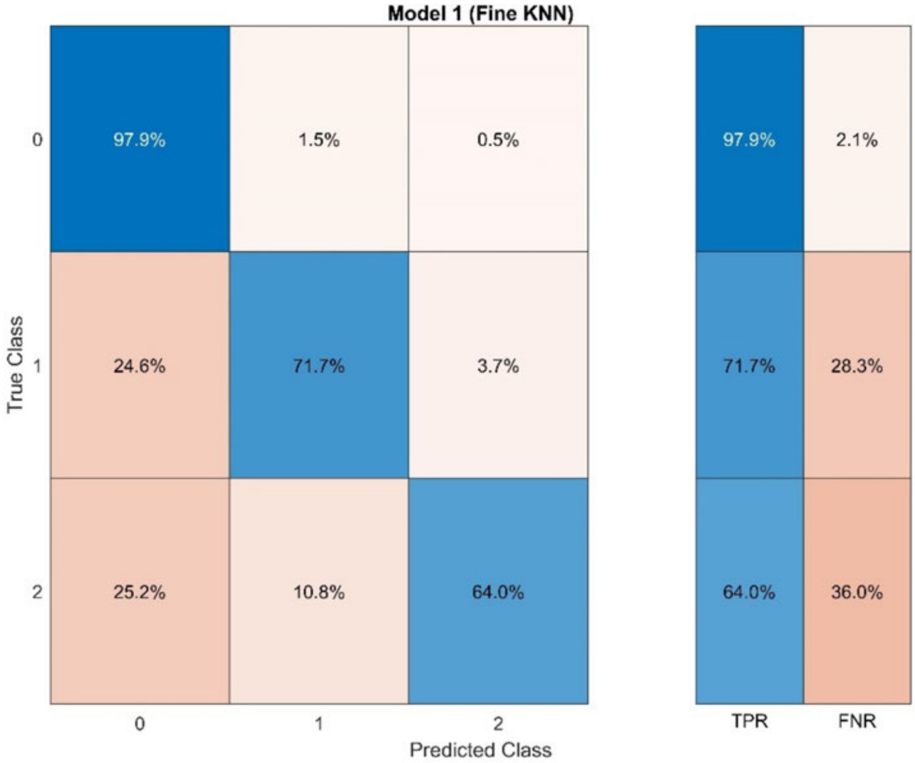

Figure 1. The confusion matrix of the Fine KNN model with 5-fold cross-validation.

The MACA climate dataset was then applied in Equation (1) to project future fires in the western United States at the national forest scale. We quantified the robustness of our forest fire projections by applying the climate variables from five MACA climate models to our fire prediction functions. Additionally, we aggregated the results of this study from the United States Forest Service regions including Pacific Northwest, Northern, Pacific Southwest, Intermountain, Rocky Mountain, and Southwestern (see Figure S4).

3. Results and Discussion

3.1. Trends in Historical Forest Fires

Figure 2 shows the total rate of minor and major forest fires from 1986 to 2015 for western United States national forests. The fire rate is defined as the number of months with fires per national forest over the 30-year period (1986–2015). Southwestern, Pacific Southwest, and Intermountain regions have the highest occurrence of minor forest fires. However, the Southwestern region currently has the highest occurrence of major forest fires. In total, Gila (NM), Apache-Sitgreaves (AZ), Custer (MT), Santa (NM), Modoc (CA), Coconino (AZ), and Cibola (NM) national forests have currently the highest occurrence of natural-caused fires (Figure S4).

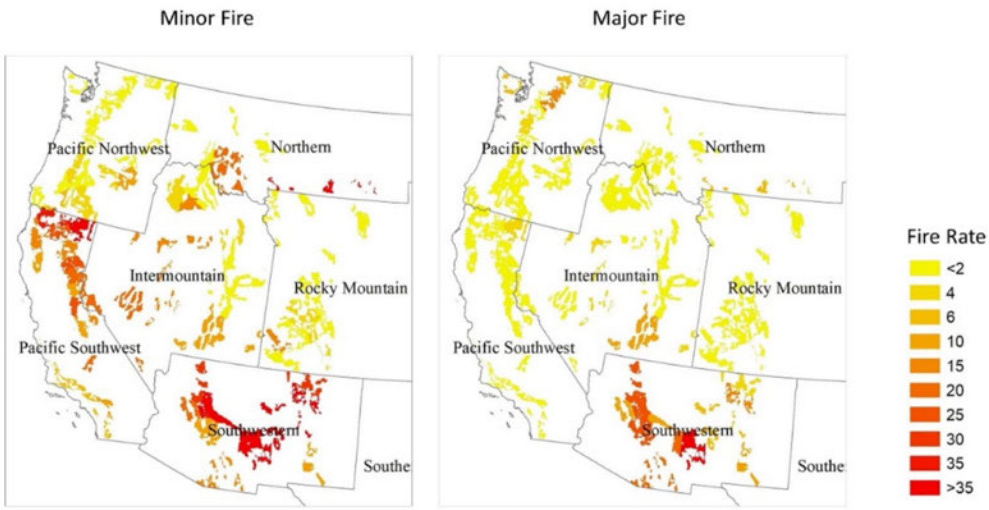

Figure 2. Total rate of minor and major forest fires in western U.S. forests over the historical period (1986–2015).

Figure 3 describes changes in the occurrence of natural-caused forest fires over the historical period. There is a rapidly emerging consensus that natural-caused forest fires have substantially increased in western United States national forests. The occurrence of minor fires has increased at a rate of 40 fires per year, while total fires have increased at a rate of 150 per year, nearly tripling the total forest fires from 1980 to 2015.

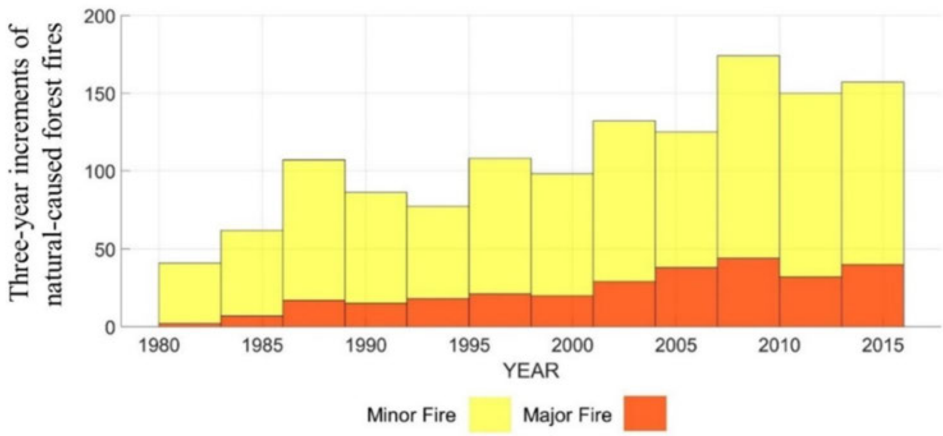

Figure 3. Three-year increments of natural-caused forest fires over the historical period (1980–2015) in western U.S. forests.

3.2. Forest Fires and Climate Variability Relationship

Figure 4 presents differences in climatic conditions (precipitation, temperature, and wind speed) of historical months with and without fires. The relative frequency of months with precipitation less than 50 mm has increased for months with fire events. There is no month with a major fire and monthly precipitation greater than 100 mm. Furthermore, the distribution of temperature and wind speed for months with no fire is significantly different from the months with fire. The results of the two-sample Kolmogorov–Smirnov test at the 5% significance level are provided in Table 1.

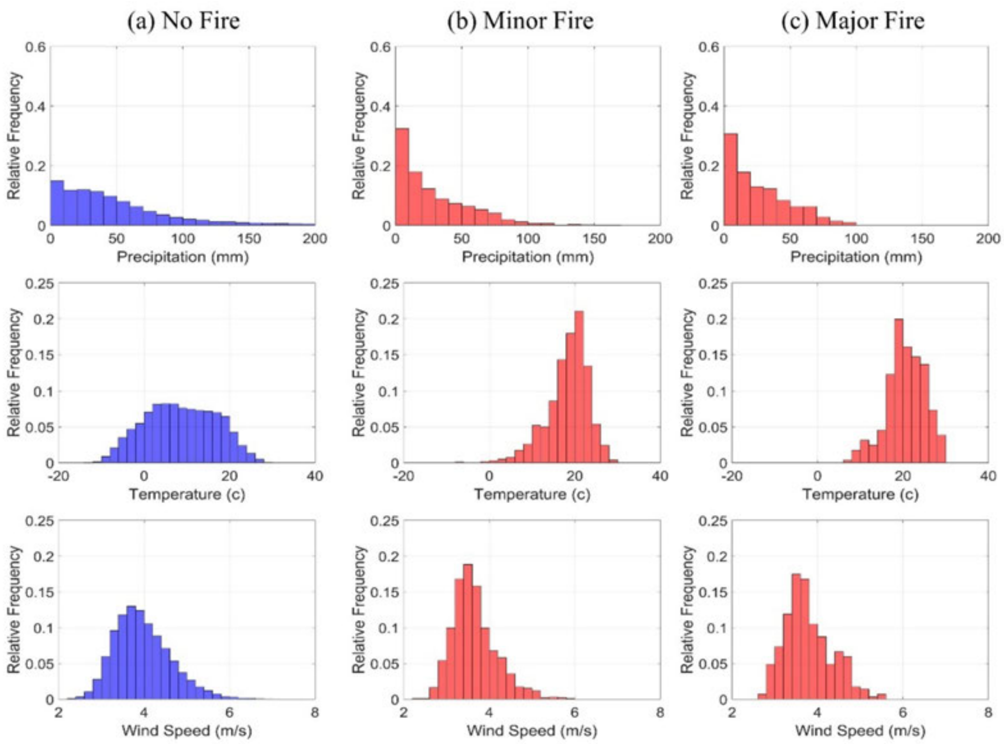

Figure 4. Relative frequency of monthly precipitation, temperature, and wind speed for months (**a**) without fire, (**b**) minor fire, and (**c**) major fire over the historical period (1986–2015).

Table 1. The results of Kolmogorov–Smirnov test.

	Kolmogorov–Smirnov Test		
	Test Decision (h)	***p*-Value**	**Test Statistic (k)**
Precipitation	1	2.27×10^{-67}	0.2457
Temperature	1	0	0.5668
Wind Speed	1	1.13×10^{-55}	0.2234

For months with fire, the distribution is skewed to the left, and in many months, the temperature is greater than 20 centigrade, while for months with no fire, there are a few months with a temperature greater than 20 centigrade. The results regarding the wind speed indicated that the average monthly wind speed is concentrated on 3.6 m/s meaning that most months with fire have an average wind speed of 3.6 m/s. The results highlight that forest fire activities highly depend on past climate variability. Forest fires have significant relationships with temperature, precipitation, and wind speed over the historical period. The forest fires are associated with warm and dry months and increasing warm and dry months may lead to growing fire activity. There is a higher risk of natural-caused fire ignition during the dry, hot periods when forests are most vulnerable.

3.3. Forest Fires and Climate Change

The average annual temperature is projected to consistently increase across the western United States under all five selected climate scenarios (Figure S5). However, the average annual precipitation is projected to vary from one scenario to another one. It has been projected to increase under WET, WARM, and MID climate scenarios, remain almost the same under the HOT scenario and decrease under the DRY scenario (Figure S5).

Figure 5 shows changes in the 30-year average of annual minor and major fires in western U.S. national forests under historical and five climate scenarios. All five climate scenarios projected an increase in the annual number of forest fires by the end of the century, with the lowest increase under the WARM scenario, and the highest increase under the HOT scenario for minor fires and under the DRY scenario for major fires.

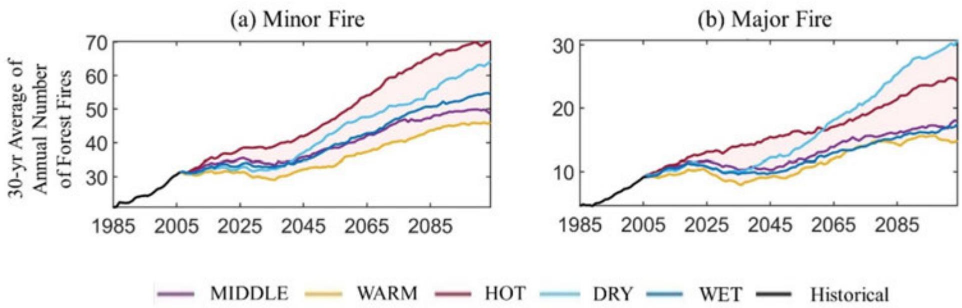

Figure 5. Changes in the rate of (**a**) minor fire, and (**b**) major fire from 1985 to 2099 under the historical and five climate scenarios.

Figures 6 and 7 display results from the fine KNN method predicting changes in the spatial distribution of minor and major wildfire rates from historical (1986–2015) to future conditions (2070–2099). Note that fire rate is defined as the number of months with fires per national forest over the 30-year period.

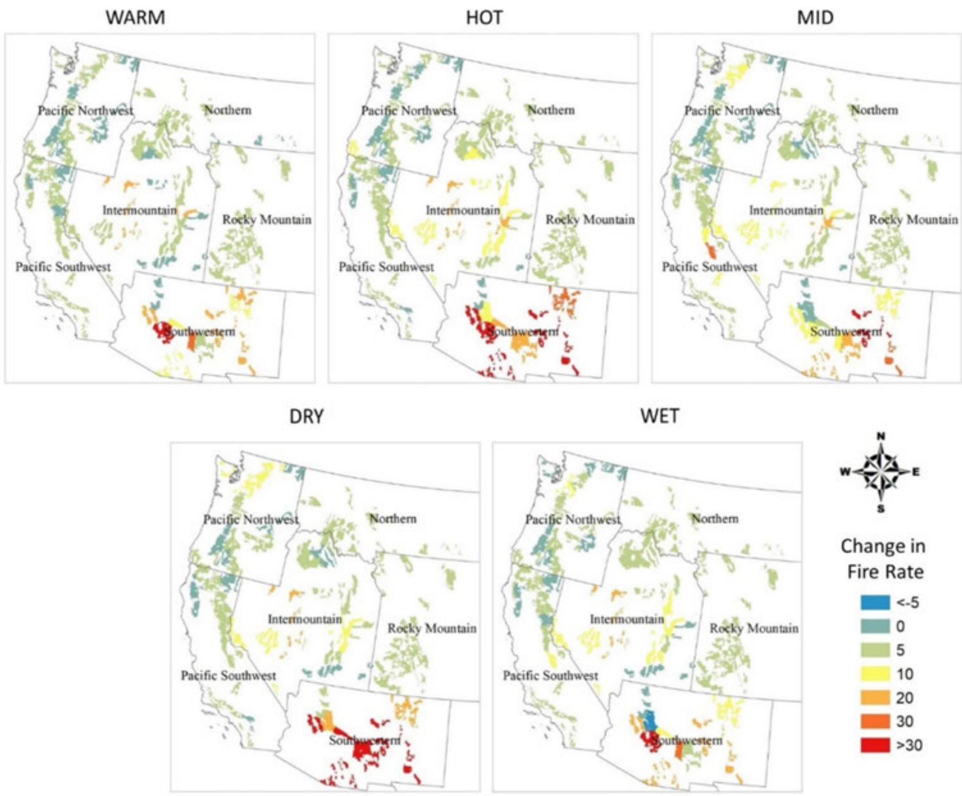

Figure 6. Changes in rate of minor forest fires from historical (1986–2015) to future conditions (2070–2099) in western U.S. forests.

The results indicate that the rate of natural forest fires shows various sensitivity to climate change from one national forest to another. However, on an average basis, the rate of natural wildfires in western national forests is likely to increase at a greater magnitude as experienced during recent decades. Future forest fires are likely to become more frequent in most western national forests. Regardless of the magnitude of change, increasing trends in the frequency of forest fires were found in all United States Forest Service regions. Our findings were supported by previous studies that have simulated changes in wildfire frequency under altered climatic conditions [10,21,40]. On average, Cibola (NM), Shasta (CA), Tonto (AZ), Lincoln (NM), Lassen (CA), Coronado (AZ), Conecuh (AZ), Prescott (AZ), Carson (NM), Custer (MT), Gila (NM), and Santa Fe (NM) national forests are likely to experience the highest increases in total fire rate (Figure S4).

Climate change is likely to initially result in larger forest fires in the Southwestern, Pacific Southwest, and Intermountain United States Forest Service regions in the future (Figure 7). The results indicate that some national forests in the Southwestern region are likely to experience an increase of more than 30 major fires in the future period (2070–2099) compared to the major fire rate over the historical period (1986–2015). Note that the lack of major fires over the past period may increase uncertainty in future projections [1].

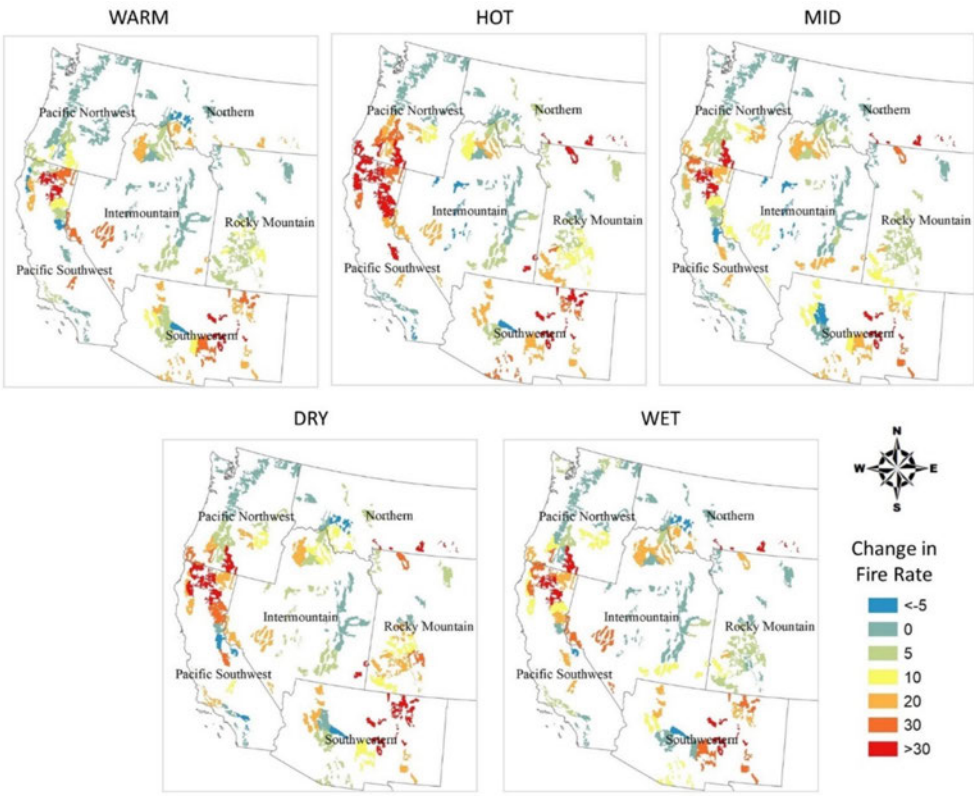

Figure 7. Changes in rate of major forest fires from historical (1986–2015) to future conditions (2070–2099) in western U.S. forests.

Figure 8 illustrates aggregated changes in the total fire rate of six western United States Forest Service regions from historical (1986–2015) to future conditions (2070–2099) under the five climate models. Although the Southwestern and Pacific Southwest regions have the highest increase in the occurrence of forest fires, the Rocky Mountain region is likely to experience a higher percentage increase in forest fires. Forest fires are likely to occur five times more often (400% increase) under the DRY climate model in the future compared to the historical forest fires. On average, however, the results highlight that climate change would likely result in a substantial increase in wildfire activity in western United States national forests.

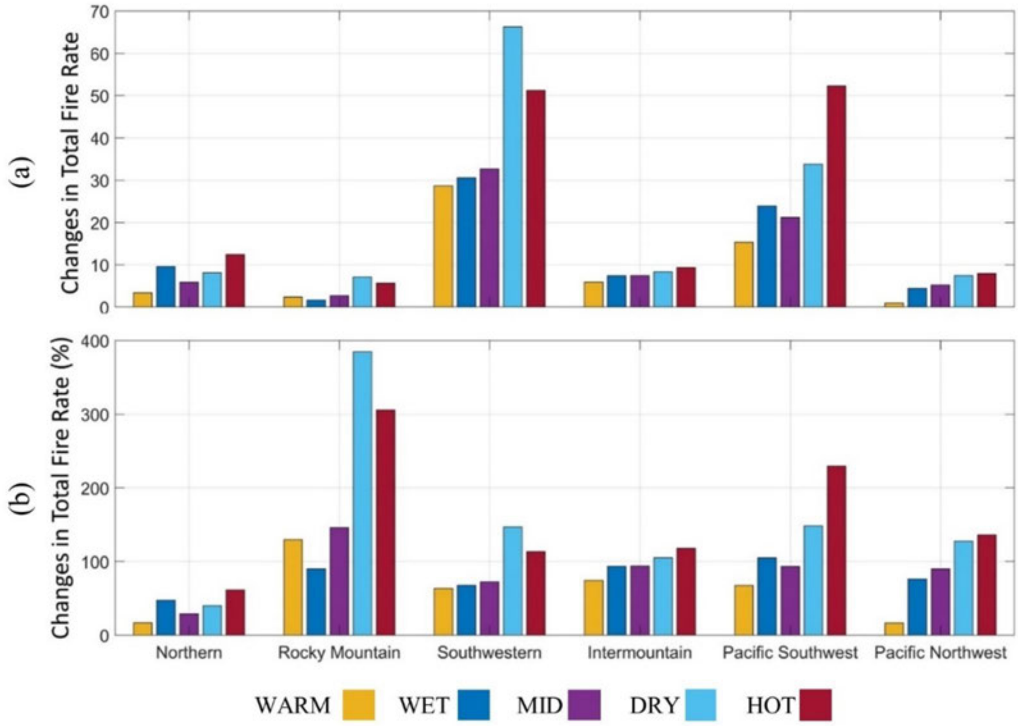

Figure 8. (**a**) Absolute changes in total fire rate and (**b**) percentage changes on total fire rate of United States Forest Service regions from historical (1986–2015) to future conditions (2070–2099).

3.4. Changes in Forest Fire Season

Natural wildfires in western national forests are highly seasonal, with most fires occurring between May and October over the historical period (1986–2015) (Figure 9). However, an increase in temperature combined with shifts in the monthly distribution of precipitation can alter forest fire seasons. Figure 9 compares the monthly rate of minor and major forest fires under historical and future climate conditions by assuming that the monthly distribution of fire events follows a normal distribution. The results indicate that historical natural-caused forest fires highly occurred over summer months with the highest rate in July. However, the distributions of future natural-caused forest fires under all five climate scenarios shift to the right and have ticker tails compared to the distribution of historical forest fires indicating that, although the natural-caused forest fires still have the highest rate of occurrence over the summer months in the future (2070–2099), they will also be likely to occur over fall and even winter months in the future with a higher rate compared to the historical conditions.

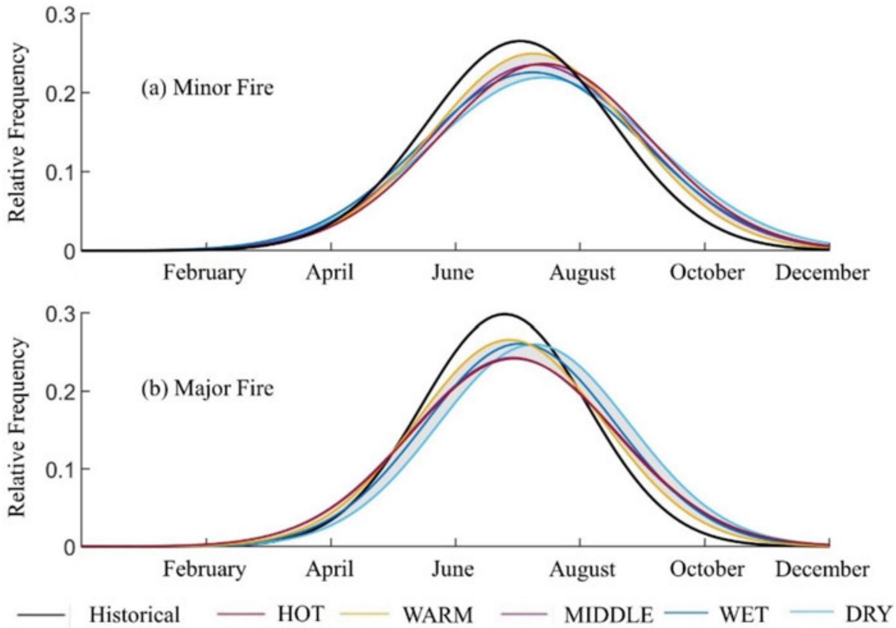

Figure 9. Monthly distribution of (**a**) minor and (**b**) major forest fires under historical (1986–2015) and future (2070–2099) climate conditions.

4. Uncertainties and Limitations

The main finding of our study is consistent with the results of previous studies, such as Gergel et al., (2017) [53], that predicted fire potential in flammability-limited forested systems is likely to increase because of a decrease in the spring mountain snowpack, summer soil moisture, and fuel moisture across the western mountain ranges in the United States [53]. Additionally, Gao et al., (2021) projected that potential annual fire occurrence probabilities will increase across the CONUS [6]. However, there are some differences between results, particularly for spatial changes in future fire rates. This inconsistency in results can stem from differences in temporal and spatial scales of analysis, considering only natural-caused forest fires, applied GCMs, and uncertainties that are explained in this section.

There are a number of uncertainties in our analysis from input data, projecting precipitation, temperature, and wind speed to linking climate variables with natural-caused fire activity using the fine KNN method and predicting future fire rates in response to climate change.

Historical major fire data obtained from Welty and Jeffries (2020) [19] are mapped by the Monitoring Trends in Burn Severity program and, therefore, they should be highly accurate. However, information on minor fires has been compiled based on state and federal archives from different agencies, and the accuracy of this component of the dataset should vary both spatially and temporally following the accuracy and completeness of agency records.

Furthermore, our findings are sensitive to the scenario as well as to the fire prediction function. The results presented in this study under WARM, WET, MID, DRY, and HOT climate models are indicative of the effect the uncertainty associated with future climate change impacts on forest fires regimes. Note that machine learning may lack adequate initial information to produce valid estimates in regions with few historical natural-caused fires. Additionally, the area burned can have strong relationships with integrated variables that relate to fuel aridity and fuel productivity, such as water deficit, actual evapotranspiration, vapor pressure deficit, or the energy release component which are not considered in this study due to the limitation on the availability of projected climate data and avoiding adding further uncertainties to our estimations by adding input data.

In addition, there are other important drivers that influence fire activity such as synoptic-scale sequences of weather [10]. Climate change may change species composition and structure of forests at multiple spatial scales [1,54,55]. Additionally, warmer temperatures, and increased precipitation during the growing season may increase forest productivity that can lead to increased fuel loading and increased fire frequency in the future. With an increase in heavy precipitation, fire risk may subsequently increase as more moisture can lead to further vegetation growth and provide additional fuel [30]. Projections of forest fire frequency without considering vegetation productivity may overestimate the frequency of national forest fires in the future [1].

Note that this study does not consider interactions between past forest fires and the occurrence of subsequent fires. The relationship between past fires and the probability of future fires may decrease the spread of forest fires through fine fuels [56]. Past fires can be effective in preventing the spread of subsequent fires in their perimeters [57,58]. Tree mortality may affect the spread of wildland fires and micrometeorological conditions that can influence fire regimes [59]. It should be noted that climate change is expected to alter vegetation covers [42]. Our machine learning function does not account for such potential changes in national forests. Wildfires can cause changes to vegetation and fuels that can both limit and promote fire occurrence. For instance, Serra-Diaz et al., (2018) [60] reported that approximately one-third of the Klamath forest landscape (500,000 ha) is likely to shift from conifer-dominated forest to shrub/hardwood chaparral due to the increasing fire activity coupled with lower post-fire conifer establishment [60].

Other research shows that stand density management, surface fuel reduction, and the control of invasive species can increase resilience to climate change [61], and fuel treatments and fuel breaks can help to decrease fire activity [1]. Fuel treatments may decrease fire frequency at regional scales [62] and increase ecological and economic benefits. Fuels can be removed using prescribed controlled fires such as burning hazardous woodpiles to safely reduce fuel while mimicking natural forest fire processes. Forest density reduction can also increase forest resistance and resilience to fire hazards in the future [63].

5. Summary and Conclusions

Climate change can alter wildfire activity at various spatial and temporal scales. This study investigates the potential impacts of climate change on changes in natural-caused wildfire events in western United States national forests from historical (1986–2015) to future (2070–2099) conditions. Fire activity on national forests is projected to increase over the 21st century in response to future increases in temperature and decreases in precipitation, indicating that western United States national forests are likely to face an increased wildfire risk under climate change.

Although the rate of natural forest fires shows various sensitivity to climate change and varies from one national forest to another due to the regional characteristics of national forests (accounted by Lat and Long), the total rate of natural-caused forest fires is projected to increase in the western United States by the end of the century in response to future increases in temperature and decreases in precipitation, indicating that western United States national forests are likely to face an increased wildfire risk under climate change.

Furthermore, variability in the projection of future fire events is dominated by variability in climate change scenarios. The rate of change in forest fire activity is relatively different among the five climate scenarios and among the 52 national forests analyzed, suggesting a need for flexible and regionalized fire management strategies under these scenario-sensitive, spatially heterogeneous projections of future natural wildfires. However, projected changes in future wildfire hazards showed some consistency across climate change scenarios in terms of the direction and magnitude of changes. Overall, six important outcomes of this study are:

1. Over the historical period, the natural-caused forest fires have been increasing across the western United States. The Southwestern region has the highest rate of forest fire activity under the historical conditions;

2. Historical natural-caused forest fires have a significant relationship with monthly temperature, precipitation, and wind speed, with a higher chance of wildfires in the hot and dry months;
3. On an average basis, natural-caused forest fires are likely to increase in most western United States national forests;
4. The Southwestern and Pacific Southwest regions are more likely to experience a higher increase in the number of future forest fires from historical to future conditions;
5. The Rocky Mountain region is likely to experience a higher percentage increase in forest fires from historical to future conditions;
6. The rate of natural-caused forest fires is likely to increase from August to December in the future compared to the historical conditions. However, the summer months have the highest rate of forest fire activity under the future conditions.

Fire management of forest ecosystems prone to large and frequent wildfires such as Rocky Mountain is likely to differ from the current conditions leading to rising challenges related to the development and the wildland–urban interface. Decisionmakers in the projected fire-prone regions are required to improve mitigation and adaptation strategies to reduce fire risks and the consequences on the environment, ecology, economy, and water resources and increase ecosystem resilience in the face of climate and fire regimes.

This study improves our ability to characterize future wildfire activity and implement appropriate adaptation and mitigation strategies. The findings of this study can enhance the ability to cope with future natural-caused forest fires coupled with climate change. Adapting forest management to future climate change and fire regimes can help resource managers of public lands to preserve forest ecosystems while continuing to provide timber, water, recreation, and habitat. However, uncertainties remain many related to future climate projections, human activities, and carbon dioxide fertilization. While this study focused on western United States national forests, the methodologies described here can be applied to model wildfire hazards under climate change scenarios in other regions.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos12080981/s1, Figure S1: The confusion matrix of the fine KNN model for the 10-fold cross-validation, Figure S2: The confusion matrix of the fine KNN model for the 15-fold cross validation, Figure S3: The confusion matrix of the fine KNN model for the 25% holdout validation, Figure S4: Annual occurrence of natural-caused forest fires over the historical period (1986–2015), Figure S5: Changes in (a) annual precipitation, and (b) annual temperature from 1980 to 2099 under the historical and five climate scenarios.

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