Human-caused fires release more carbon than lightning-caused fires in the conterminous United States

Meng Liu and Linqing Yang
Department of Ecosystem Science and Management, Texas A&M University, 534 John Kimbrough Blvd, College Station, TX 77843, United States of America
E-mail: meng.liu@tamu.edu

Keywords: fire, carbon emissions, biomass burning, human-caused fires, burned area, drought, prescribed fires

Abstract
Anthropogenic carbon emissions from fires impact the global carbon budget and contribute to global warming. However, due to the lack of inventory data, little was known about how carbon emissions differed between human-caused and lightning-caused fires previously. In this study, the Fire Program Analysis fire-occurrence database (FPA FOD) and the Global Fire Emissions Database (GFED) were combined to analyze the influences of human-caused fires on carbon emissions. We found that the GFED burned area was larger than that of the FPA FOD since the FPA FOD did not cover human-caused fire usages like prescribed fires. Carbon emissions over the conterminous United States were increasing significantly from 1997 to 2015. Human-caused fires released 9.99 Tg C yr\(^{-1}\) over the conterminous United States, which were approximately twice those of carbon emissions from lightning-caused fires, 5.44 Tg C yr\(^{-1}\). Carbon emissions of lightning-caused fires were increasing while those of human-caused fires were decreasing significantly with rising temperatures. Emissions in ecoregions such as the Eastern Temperate Forests, the Great Plains, the Marine West Coast Forests, and the Northern Forests were dominated by human-caused fire emissions, whose proportions were over 86%. These results highlight the importance of human activities on carbon emissions, offering new insights into the role of humans in climate change mitigation.

1. Introduction
Global warming has become a worldwide concern in the past several decades, with higher temperatures, more extreme weather events and more wildfires (Jolly \textit{et al} 2015, Bowman \textit{et al} 2020). Carbon emissions released by fire-caused biomass burning contribute to the warming climate (Schoennagel \textit{et al} 2017) and impact biological and geophysical processes (Archibald \textit{et al} 2018). Biomass burning emission is a major source of uncertainty in terrestrial biogeochemical cycles and global climate models (van der Werf \textit{et al} 2017, Shi \textit{et al} 2020), especially in tropical and boreal regions. There is also a lack of a thorough understanding of the human-fire relationship in global scale modeling (Lasslof \textit{et al} 2019, Rogers \textit{et al} 2020). Improved representations of human-caused fire processes in earth system models are necessary to constrain carbon cycles for more accurate climate projection (Tharammal \textit{et al} 2019). Given the impacts of fires on carbon dynamics and climate change, evaluation and analysis of human effects on carbon emissions from biomass burning are crucial to terrestrial ecosystem sustainability and climate change mitigation.

There are two major types of fire events: wildfires and prescribed fires (Nowell \textit{et al} 2018), where prescribed fires are fires employed by humans for land and ecosystem management, and wildfires are unplanned, uncontrolled and require suppression if they threaten urban areas. Based on ignition types, wildfires are further divided into lightning-caused and human-caused wildfires (Balch \textit{et al} 2017, Cattau \textit{et al} 2020). Lightning-caused wildfires often happen in sparsely populated regions (Balch \textit{et al} 2017). However, human-caused wildfires tend to break in densely populated areas with various ignition reasons such as camp fires, malfunction of power lines, debris burning, and arson. When estimating biomass burning emissions at the regional or global scale, few studies...
divided human-caused and lightning-caused fires as there was little ignition information available previously. For example, the satellite-based Global Fire Emissions Database (GFED) (van der Werf et al 2017) provides monthly carbon emissions of global fires but no information on causes. Little is known about how carbon emissions differed between human-caused and lightning-caused fires.

As wildfire inventory data became available over the conterminous United States, e.g. the Fire Program Analysis fire-occurrence database (FPA FOD) (Short 2017), scientists investigated the differences between human-caused and lightning-caused wildfires. Balch et al. (2017) compared lightning-caused and human-caused wildfires from 1992 to 2012 in the conterminous United States, showing that human-caused wildfires account for 84% of the number of wildfires and 44% of total burned area. They concluded that human-caused wildfires expand geographic and seasonal niche of wildfires. Abatzoglou et al. (2018) illustrated that high wind speed before fire events contributed to large human-caused wildfires in the conterminous United States. Cattau et al. (2020) found that human-caused wildfires were more frequent with longer fire seasons than lightning-caused wildfires while lightning-caused wildfires had higher intensity in the conterminous United States. These researchers demonstrate that human-caused wildfires are important to the sustainability of terrestrial ecosystems and require further research. Yet, these results and conclusions were derived from wildfire inventory data only without information of prescribed fires. As a complement, Nowell et al. (2018) employed prescribed fire inventory data in Florida and demonstrated that prescribed fires burned more area than wildfires, which illustrates the significance of prescribed fires. However, few studies have analyzed the differences of carbon emissions between human-caused and lightning-caused fires and their responses to climate change.

In this study, we investigated the influences of human-caused fire activities on carbon emissions and evaluated the differences of carbon emissions between human-caused and lightning-caused fires over the conterminous United States. Prescribed fires and non-prescribed anthropogenic burning (human-caused wildfires) were combined and herein referred to as human-caused fires, whose carbon emissions were the sum of prescribed fire emissions and human-caused wildfire emissions. Similarly, lightning-caused wildfires were referred to as lightning-caused fires. The FPA FOD and the GFED data were adopted to match fires and carbon emissions as well as separating human-caused and lightning-caused fires. Our specific goals include: (a) compare burned area in the FPA FOD and the GFED data; (b) analyze the relationships of carbon emissions and climate variables; and (c) compare the differences of carbon emissions between human-caused and lightning-caused fires.

## 2. Materials and methods

The latest FPA FOD (Short 2017), offered by the United States Department of Agriculture, contains 1.88 million data records of all wildfires from 1992 to 2015 in the United States, including elements such as discovery date, cause, fire size, and point location. The data records come from reporting systems of federal, state, and local fire organizations. Fires of all sizes were included, and error-checking was performed by the publication team to ensure reliability. The FPA FOD is regarded as the truth of wildfire data. Those wildfires which happened within the conterminous United States were employed in this study. As for carbon emission data, the GFED was adopted, which offers monthly burned area and biomass burning emissions (which are the product of the burned area, fuel loads, and combustion completeness) from all fires globally at the spatial resolution of 0.25° from 1997 to 2016. Monthly net primary productivity (NPP) data were also provided by the GFED database. The GFED is a standard fire database which provides long term global fire and emission data for the science communities (Giglio et al. 2013, van der Werf et al. 2017). The latest version of the GFED, the GFED 4.1 s, contains burned area from small fires (fires below detection limits, i.e. smaller than footprint), which can help to improve biomass emissions monitoring.

Climate variables such as monthly maximum temperature in °C (Max T) and monthly precipitation in mm (P) were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate group (Daly et al 2002), which provides long term climate data at the spatial resolution of 4 km over the United States. The 4 km monthly Palmer Drought Severity Index (PDSI) (Palmer 1965, Xiao and Zhuang 2007), where negative values indicate drought and positive values mean wet, was derived based on the PRISM climate data and provided by the West Wide Drought Tracker (Abatzoglou et al. 2017). In this study, only the data from 1997 to 2015, which were the intersection of timelines between the FPA FOD and the GFED, were employed in the analysis. All data were aggregated to the spatial resolution of 0.5° (approximately 50 km) (Balch et al. 2017, Cattau et al. 2020), which corresponds to the size of an average Unites States county.

Annual burned area from the FPA FOD and the GFED 4.1 s was compared and the proportion of burned area in the FPA FOD to that of the GFED 4.1 s was derived, to get the differences between inventory data and satellite-based fire products. Correlations between climate variables (averaged max T, P, and PDSI) in different seasons (Dennison et al. 2014, Balch et al. 2017), winter (December, January, and February), spring (March, April, and May), summer (June, July, and August) and autumn (September,
October, and November), and fire-caused carbon emissions were analyzed. Annual biomass emissions were divided by the corresponding NPP to derive the ratio of emissions to NPP. In this study, both carbon emissions and NPP were expressed by the amount of carbon (Tg C). The United States ecoregions level 1 (US EPA 2015) were leveraged to analyze the differences in carbon emissions of various ecosystems and vegetation types. A 0.5° grid was assigned to an ecoregion if its center point was within the ecoregion.

To match the FPA FOD records with the GFED 4.1s data, we calculated the proportion of burned area of lightning-caused fires within each 0.5° grid. To be specific, the proportion of lightning-caused fires is the ratio of burned area of lightning-caused fires to the GFED 4.1s burned area (containing all fires) within the grid. The grid was defined as lightning-caused fires dominated if the proportion was greater than 75% (Cattau et al 2020). In contrast, if the proportion of lightning-caused fires was less than 25%, the grid was defined as human-caused fires dominated. If the proportion of lightning-caused fires is between 25% and 75%, this grid is regarded as a mixed one. We separated mixed grids and calculated their emissions in table 1. The differences of carbon emissions between human-caused and lightning-caused fires were compared based on the corresponding grids. Seasonal max T, P, and PDSI were employed to derive the responses of carbon emissions from human-caused and lightning-caused fires to global warming.

3. Results

3.1. Comparisons of burned area

3.1.1. Regional comparisons

Annual burned area of the GFED 4.1s (figures 1(b) and S1(b) available online at https://stacks.iop.org/ERL/16/014013/mmedia) is larger than that of the FPA FOD (figures 1(a) and S1(a)), and the differences mainly come from the southeast part of the USA. The GFED 4.1s burned area is 2.78 million ha yr⁻¹ over the conterminous United States (table 1), which is larger than that of the FPA FOD (1.81 million ha yr⁻¹) as the FPA FOD data only cover wildfires while the GFED 4.1s contains all fires. Theoretically, the differences between the GFED 4.1s burned area and that of the FPA FOD are attributed to prescribed fires if both the GFED 4.1s and the FPA FOD are accurate. In different ecoregions, burned area varies greatly. For the GFED 4.1s data, the Eastern Temperate Forests and the Great Plains have the most burned area which is over 0.7 million ha yr⁻¹ (table 1). As for the FPA FOD data, the North American Deserts have the most burned area, 0.56 million ha yr⁻¹. The proportion of annual burned area to the total area of an ecoregion is the highest in the Tropical Wet Forest no matter in the GFED 4.1s or the FPA FOD. When comparing burned area between the GFED 4.1s and the FPA FOD, the Northwestern Forested Mountains, the North American Deserts, the Temperate Sierras, and the Northern Forests have lower burned area in the GFED 4.1s, which indicates there are omissions of fires and burned area in the GFED 4.1s relative to the FPA FOD. In contrast, burned area in the Eastern Temperate Forests and the Great Plains is high (>0.7 million ha yr⁻¹) in the GFED 4.1s and much larger than that of the FPA FOD, which is due to common prescribed fire activities over these regions.

3.1.2. National level comparisons

There were no significant increases detected in burned area at a national scale between 1997 and 2015 using both the FPA FOD and GFED 4.1s data. The proportion of burned area in the FPA FOD to that of the GFED 4.1s was also not changing significantly from 1997 to 2015 (figure 2(c)). However, annual burned area in the FPA FOD, which increases significantly in hot and dry conditions, is sensitive to climate change (figure 3(a)). Using seasonal max T, P, and PDSI over the conterminous United States, the FPA FOD burned area is rising significantly with higher spring and summer temperatures and decreasing significantly with more summer and autumn precipitation. As for drought (negative PDSI), more drought in summer, autumn, and winter is significantly correlated with more burned area in the FPA FOD. In the GFED 4.1s, burned area significantly increases with higher spring and summer temperatures but not for less precipitation and more drought (figure 3(b)). The proportion of burned area in the FPA FOD to that of the GFED 4.1s is increasing significantly with rising temperatures (summer and winter max T), decreasing precipitation (summer, autumn, and winter P), and increasing drought (drought in all seasons) (figure 3(c)). In hot and dry (drought) conditions, the proportion of burned area in the FPA FOD to that of the GFED 4.1s is high (figures 4(a)–(c)), which means burned area is close (or even equal) in the two databases and most fires are wildfires. However, the proportion decreases in wet and cold years, indicating burned area in the FPA FOD is much lower and there are more prescribed fire usages. These results confirm that prescribed fires decrease in drought conditions, which is consistent with the results in Nowell et al (2018). When there is a drought, fires are more likely to be severe as fuels are more available for burning and can cause safety related issues, which constrains human dominated fire activities. During wet conditions fire managers are able to allow more prescribed fires for multiple purposes such as reducing fuel, controlling invasive species, and managing land. As the FPA FOD does not contain prescribed fires, some burned area in wet conditions is not recorded.

In 2002, the proportion of burned area in the FPA FOD to that of the GFED 4.1s (104.58%) was more than 100% (figure 2(c)), which means the GFED...
Table 1. Annual burned area (ha) and carbon emissions (Tg C) within different ecoregions in the conterminous United States from 1997 to 2015. Permillage in parentheses is the proportion of annual burned area to the total area of the corresponding ecoregion.

| Ecoregion | Burned area (ha) | Carbon (Tg) | Emissions (Tg) | Ratio (%) | Lightning-caused | Human-caused | Mixed region | Human-caused (%) |
|-----------|------------------|-------------|----------------|-----------|------------------|--------------|--------------|------------------|
|           | GFED 4.1s | FPA FOD Fire-caused | NPP |  | Lightning-caused | Human-caused | Mixed region | Human-caused (%) |
| NFM       | 401,087  | 427,896  7.131 | 438,428 | 1.627 | 4.222 | 1.271 | 1.638 | 17.826 |
| ETF       | 788,352  | 222,696  6.000 | 204,465 | 0.293 | 0.290 | 5.548 | 0.162 | 92.481 |
| GP        | 759,281  | 337,258  1.414 | 1,024,181 | 0.138 | 0.113 | 1.218 | 0.084 | 86.111 |
| MC        | 154,044  | 119,554  1.070 | 121,001 | 0.884 | 0.174 | 0.801 | 0.095 | 74.839 |
| NAD       | 483,458  | 557,823  0.937 | 316,506 | 0.296 | 0.380 | 0.301 | 0.256 | 32.128 |
| TS        | 74,122   | 86,024   0.617 | 45,796  | 1.348 | 0.203 | 0.279 | 0.135 | 45.148 |
| TWF       | 85,998   | 34,691   0.476 | 16,318  | 2.919 | 0.014 | 0.347 | 0.116 | 72.779 |
| MWCF      | 6497     | 1365     0.129 | 63,622  | 0.202 | 0.018 | 0.111 | 0.000 | 86.221 |
| NF        | 8597     | 9626     0.110 | 229,456 | 0.048 | 0.010 | 0.097 | 0.003 | 87.710 |
| SSH       | 17,112   | 16,109   0.037 | 9,696   | 0.379 | 0.016 | 0.021 | 0.000 | 57.491 |
| CONUS     | 2,778,547 | 1,813,542 | 17.922 | 4309,655 | 0.416 | 5,440 | 9,994 | 2,488 | 55,762 |

Note: NFM, Northwestern Forested Mountains; ETF, Eastern Temperate Forests; GP, Great Plains; MC, Mediterranean California; NAD, North American Desert; TS, Temperate Sierras; TWF, Tropical Wet Forests; MWCF, Marine West Coast Forests; NF, Northern Forests; SSH, Southern Semi-arid Highlands; CONUS, the conterminous United States. Ratio (%) = fire-caused carbon emissions/NPP × 100%. Human-caused (%) = human-caused carbon emissions/fire-caused carbon emissions × 100%.
Figure 1. Annual burned area (ha), carbon emissions (Tg C), and NPP (Tg C) over the conterminous United States from 1997 to 2015 with 0.5° resolution: (a) annual burned area of the FPA FOD, (b) annual burned area of the GFED 4.1s, (c) annual carbon emissions from biomass burning, (d) annual NPP, (e) proportions of lightning-caused fires, and (f) ecoregions level 1.

Figure 2. Trends of annual burned area and carbon emissions from 1997 to 2015: (a) the FPA FOD burned area; (b) the GFED 4.1s burned area; (c) proportion of burned area in the FPA FOD to that of the GFED 4.1s; (d) fire-caused carbon emissions from biomass burning; (e) NPP (Pg); (f) ratio of emissions to NPP (=fire-caused carbon emissions/NPP × 100%); (g) carbon emissions of lightning-caused fires; and (h) carbon emissions of human-caused fires. Red lines are the regression lines which are significant.
4.1s missed some burned area relative to the FPA FOD. This result is consistent with the smaller burned area of the GFED 4.1s in the Northwestern Forested Mountains and the North American Deserts (table 1).

3.2. Correlations of carbon emissions to climate variables

3.2.1. National trends and regional comparisons

Fire-caused carbon emissions were rising significantly with a rate of 0.47 Tg C yr\(^{-1}\) (figure 2(d)) from 1997 to 2015 while NPP was stable. The ratio of emissions to NPP was also increasing significantly (figure 2(f)). Carbon emissions are dominated in the west and southeast of the conterminous United States (figure 1(c)). When divided into different ecoregions, the Northwestern Forested Mountains release most carbon from fire-caused biomass burning, 7.13 Tg C yr\(^{-1}\), and have high ratio of emissions to NPP, 1.63% (table 1). The carbon emissions from the Eastern Temperate Forests are also high, 6.0 Tg C yr\(^{-1}\), but the ratio of emissions to NPP is small, 0.29%, which is due to great forest storage (high NPP) in this region (figure 1(d)). Interestingly, burned area of the Northwestern Forested Mountains is only 50.88% of that in the Eastern Temperate Forests based on the GFED 4.1s but the Northwestern Forested Mountains release more carbon, which indicates the Northwestern Forested Mountains have higher bulk density and burning efficiency. Similarly, burned area in the Eastern Temperate Forests is close to that of the Great Plains (0.79 vs 0.76 million ha yr\(^{-1}\)) while carbon emissions in the Eastern Temperate Forests are more than four times of those in the Great Plains, which is due to greater fuel density in forests than in grasslands.

3.2.2. Responses to climate variables

Through using seasonal max T, P, and PDSI over the conterminous United States, it could be seen that annual carbon emissions from biomass burning are rising significantly along with increasing spring and summer temperatures (figure 3(d)). More drought in autumn is also correlated with more carbon emissions. The average ratio of emissions to NPP over the conterminous United States is 0.42% (table 1) which is small, but the trends are increasing significantly with elevating spring and summer
temperature and more autumn drought (figure 3(e)). These results illustrate that more NPP is burned by fires in the warming world and there will be less NPP remaining for the sustainability of earth ecosystems. Based on the level 1 ecoregion data, climate variables were calculated in each ecoregion and the responses of fire-caused carbon emissions to climate variations were compared separately. In the Northwestern Forested Mountains (figure 3(f)), the Mediterranean California (figure 3(i)) and the Temperate Sierra (figure 3(k)), high temperature, low precipitation, and more drought (negative PDSI) contribute to more fire-caused carbon emissions though seasons are not always the same. However, in the Eastern Temperate Forests (figure 3(g)), the Great Plains (figure 3(h)), the Northern American Deserts (figure 3(j)), and the Marine West Coast Forests (figure 3(m)), only temperature is significantly correlated with carbon emissions. Higher temperature contributes to more carbon emissions except in the Eastern Temperate Forests where carbon emissions are negatively impacted by winter temperature and positively influenced by autumn temperature.

Interestingly, carbon emissions are only influenced by precipitation in the Northern Forests (figure 3(n)) where more spring precipitation relates to more carbon emissions. The relations between climate variables and fire-caused carbon emissions are not significant in both the Tropical Wet Forests (figure 3(l)) and the Southern Semi-arid Highlands (figure 3(o)). These results reveal that the relationships between climate variables and carbon emissions vary regionally though high temperatures and drought contribute to fire-caused carbon emissions over the whole conterminous United States.

3.3 Differences of human-caused and lightning-caused fire (carbon) emissions

3.3.1 Regional comparisons

Using 75% (Cattau et al 2020) as a threshold to define lightning-caused fires dominated grids and human-caused fires dominated grids, 18.31% and 68.25% of the conterminous United States are dominated by lightning-caused and human-caused fires, respectively. The mixed regions count 11.0%, and the rest 2.44% are free of fires. Lightning-caused
fires dominated in the west of the conterminous United States (figure 1(e)). Annual lightning-caused fire emissions were not significantly increasing (figure 2(g)) while human-caused fire emissions were rising significantly from 1997 to 2015 by 0.27 Tg C yr\(^{-1}\) (figure 2(h)). Carbon emissions from human-caused fires are 9.99 Tg C yr\(^{-1}\) (table 1), which are approximately twice of emissions from lightning-caused fires, 5.44 Tg C yr\(^{-1}\). The mixed regions release 2.49 Tg C yr\(^{-1}\) which is 13.88% of annual carbon emissions (17.92 Tg C yr\(^{-1}\)) over the conterminous United States. Among different ecoregions, the Northwestern Forested Mountains have the most carbon emissions from lightning-caused fires, 4.22 Tg C yr\(^{-1}\) (table 1), which is 59.21% of annual emissions in this ecoregion and 77.61% of lightning-caused annual carbon emissions over the conterminous United States. Carbon emission in this ecoregion is controlled by lightning-caused fires. For human-caused fires, the Eastern Temperate Forests have the highest carbon emissions, 5.55 Tg C yr\(^{-1}\) (92.48% of carbon emissions in this region). The Eastern Temperate Forests, the Great Plains, the Marine West Coast Forests, and the Northern Forests are all controlled by human-caused fires since the proportions of human-caused emissions are greater than 86% (table 1). The Mediterranean California and the Tropical Wet Forests also have high proportions of human-caused fire emissions, 74.84% and 72.78%, respectively.

### 3.3.2. Responses to climate variables

Seasonal max T, P, and PDSI over the lightning-caused fire dominated grids were calculated for analysis of lightning-caused fire emissions. Carbon emissions of lightning dominated areas are increasing significantly with higher temperatures (summer and winter temperatures) and more drought (summer and autumn drought) (figures 3(p), 4(e) and (f)). Less summer precipitation also promotes more lightning-caused fire emissions. High temperatures and low precipitation in summer and more drought in autumn are the most favorable to lightning-caused fire emissions, which partly explains the frequent lightning-caused fires in summer and autumn. Using seasonal climate variables within human-caused fire dominated regions, carbon emissions are significantly decreasing with higher winter temperature and more summer and winter drought (figures 3(q), 4(h), and (i)). Besides, more spring precipitation is related to more human-caused fire emissions, which might be due to the promotion of vegetation growth with more spring precipitation after a dry winter, producing more fuels. The decrease of human-caused fire emissions in high temperature and drought shows the negotiation of human dominated fire activities to climate change. For the safety and the sustainability of ecosystems, humans will cancel fire usages such as prescribed fires, camp fires, and debris burning, or reschedule them if it is hot and dry, leading to fewer human-caused fires in hot days.

### 4. Discussion

Fire-caused carbon emissions produce great uncertainties in earth system modeling and climate mitigation. It is crucial to monitor and analyze the dynamics of fire-caused carbon emissions and their responses to climate change. Over the conterminous United States, fire-caused carbon emissions and the ratio of emissions to NPP were rising significantly from 1997 to 2015. High spring or summer temperature and autumn drought contribute to more fire-caused carbon emissions and higher ratios of emissions to NPP. Human-caused fires, which are the major source of fire emissions over the conterminous United States, release approximately twice as much carbon as lightning-caused fires. Over 68% of area in the conterminous United States is dominated by human-caused fires and only 18% is dominated by lightning-caused fires. The Eastern Temperate Forests, the Great Plains, the Marine West Coast Forests, and the Northern Forests are all dominated by human-caused fire emissions. These findings highlight the importance of human effects on fire-caused carbon emissions.

Human-caused fire emissions, which are the combination of carbon emissions from prescribed fires and non-prescribed anthropogenic burning in this study, are negatively correlated with winter temperature and drought (also negatively related to summer drought) while more spring precipitation contributes to more human-caused fire emissions (figure 3(q)). These results are related to fewer human-caused fire activities in severe climate conditions (hot and dry). For example, humans will reduce outdoor activities if it is hot and dry, thus limiting human-caused ignitions such as camp fires or debris burning. Prescribed fires are also not recommended if the temperature is high for safety purposes. Actually, most prescribed fires are conducted in winter or early spring so as to avoid hot and dry seasons. Relatively low temperature and humid atmosphere are preferred for prescribed fires, which is consistent with the comparison results of burned area in the FPA FOD and the GFED 4.1s. The proportion of burned area in the FPA FOD to that of the GFED 4.1s decreases in low temperature and wet conditions (figures 4(b) and (c)), which is due to the increase of prescribed fire usages (Nowell et al 2018). Moreover, prescribed fires in wet years help to reduce fuels and decrease fuel continuities, which can restrict the risk of large wildfires. There are also a few prescribed fires in hot and dry days. For specific purposes such as species removal and parasite control, it is better to use prescribed fires in severe weather since high temperatures and heat help to kill unwanted trees or shrubs (Twidell et al 2016) and remove diseases. Prescribed fires are the balance of land management purposes, climate conditions, and policies.
The impacts of humans have become more and more important in fire management (Andela et al 2017) and climate change. More attention should be paid to the monitoring and regulation of human-caused fire activities.

To mitigate climate change, humans can try to diminish non-prescribed anthropogenic burning. For example, check power lines frequently to avoid fires. Use strict laws and more education to stop arson. Camp on open ground and stop all sparks. As for prescribed fires, they are helpful and necessary for land management. Prescribed burners should use more well-organized and safer plans to burn effectively and avoid the escape of fires. Moreover, humans can employ prescribed fires to thin forests and build fire breaks to constraint lightning-caused fires. Following these manners, both the emissions of human-caused fires and lightning-caused fires will decrease in the future. As for importance, human-caused fire emissions might still be more important than those of lightning-caused fire since some lightning-caused fire emissions are converted to prescribed fire emissions. However, this conversion is safe and environment-friendly.

This study analyzed the differences of carbon emissions between human-caused fires and lightning-caused fires based on the FPA FOD and the GFED 4.1s data. However, the timeline is not long enough since we only have data from 1997 to 2015. Detailed long-term fire records over the conterminous United States to accurately measure human-caused fire activities are still absent. To get effective carbon monitoring, more detailed and widespread fire inventory records are indispensable. We expect more well defined and accurate fire records will be available in the future to support fire and carbon related researches.

5. Conclusions
Carbon emissions from biomass burning impact carbon budget and climate change, especially in the current warming world. This study focuses on the comparisons of carbon emissions from human-caused and lightning-caused fires. The FPA FOD and the GFED were combined to analyze the influences of human effects on fire-caused carbon emissions. We found that carbon emissions over the conterminous United States were rising significantly in response to increasing temperature and drought. Human-caused fires released approximately twice as much carbon as lightning-caused fires and were negatively correlated with winter temperature and drought. In contrast, carbon emissions of lightning-caused fires increased significantly with rising summer temperatures and drought. Carbon emissions of human-caused fires were dominant in the Eastern Temperate Forests, the Great Plains, the Marine West Coast Forests, and the Northern Forests. The contributions of human-caused fires are more important than those of lightning-caused fires in carbon emissions. More detailed and widespread fire inventory data considering human activities are necessary for carbon monitoring, earth system modeling, and climate mitigation.

Data availability statement
The data that support the findings of this study are openly available at the following URL/DOI: https://www.geo.vu.nl/~gwerf/GFED/GFED4/.

Acknowledgments
The authors declare no conflict of interests. The open access publishing fees for this article have been partially covered by the Texas A&M University Open Access to Knowledge Fund (OAK Fund), supported by the University Libraries. The FPA FOD is available from the USDA: https://www.fs.usda.gov/rds/archive/Catalog/RDS-2013-0009-4/. https://www.geo.vu.nl/~gwerf/GFED/GFED4/ Climate data is published on PRISM: https://prism.oregonstate.edu/. We appreciate the individuals and organizations that make these data publicly available. We also thank the anonymous reviewers for their constructive advice.

ORCID iDs
Meng Liu @ https://orcid.org/0000-0002-1962-9154 Linqing Yang @ https://orcid.org/0000-0002-6646-0718

References
Abatzoglou J T, Balch J K, Bradley B A and Kolden C A 2018 Human-related ignitions concurrent with high winds promote large wildfires across the USA Int. J. Wildland Fire 27 377–86
Abatzoglou J T, Mcevoy D J and Redmond K T 2017 the west wide drought tracker: drought monitoring at fine spatial scales Bull. Amer. Meteor. Soc. 98 1813–20
Andela N et al 2017 A human-driven decline in global burned area Science 356 1356–62
Archibald S et al 2018 Biological and geophysical feedbacks with fire in the Earth system Environ. Res. Lett. 13 033003
Balch J K, Bradley B A, Abatzoglou J T, Nagy R C, Fusco E J and Mahood A L 2017 Human-started wildfires expand the fire niche across the United States Proc. Natl Acad. Sci. 114 2946–51
Bowman D M J S, Kolden C A, Abatzoglou J T, Johnston F H, van der Werf G R and Flannigan M 2020 Vegetation fires in the Anthropocene Nat. Rev. Earth Environ. 1 500–515
Cattau M E, Wessman C, Mahood A and Balch J K 2020 Anthropogenic and lightning-started fires are becoming larger and more frequent over a longer season length in the U.S.A Global Ecol. Biogeogr. 29 668–81
Daly C, Gibson W P, Taylor G H, Johnson G L and Pasteris P 2002 A knowledge-based approach to the statistical mapping of climate Climate Research 22 99–113
Dennison P E, Brewer S C, Arnold J D and Moritz M A 2014 Large wildfire trends in the western United States, 1984–2011 Geophys. Res. Lett. 41 2928–33
Giglio L, Randerson J T and van der Werf G R 2013 Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4) J. Geophys. Res. 118 317–28
Jolly W M, Cochrane M A, Freeborn P H, Holden Z A, Brown T J, Williamson G J and Bowman D M J S 2015 Climate-induced variations in global wildfire danger from 1979 to 2013 Nat. Commun. 6 7537
Lasslop G, Coppola A I, Voulgarakis A, Yue C and Veraverbeke S 2019 Influence of fire on the carbon cycle and climate Curr. Clim. Change Rep. 5 112–23
Nowell H K, Holmes C D, Robertson K, Teske C and Hiers J K 2018 A new picture of fire extent, variability, and drought interaction in prescribed fire landscapes: insights from Florida government records Geophys. Res. Lett. 45 7874–84
Palmer W C 1965 Meteorological Drought U.S. Weather Bureau (available at: https://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf)
Rogers B M, Balch J K, Goetz S J, Lehmann C E R and Turetsky M 2020 Focus on changing fire regimes: interactions with climate, ecosystems, and society Environ. Res. Lett. 15 030201
Schoennagel T et al 2017 Adapt to more wildfire in western North American forests as climate changes Proc. Natl Acad. Sci. USA 114 4582–90
Shi Y, Zang S, Matsunaga T and Yamaguchi Y 2020 A multi-year and high-resolution inventory of biomass burning emissions in tropical continents from 2001–2017 based on satellite observations J. Clean. Prod. 270 122511
Short K C 2017 Spatial wildfire occurrence data for the United States, 1992–2015 [EPA_FOD_20170508] (4th Edition) (available at: https://www.fsis.usda.gov/rdc/archive/Catalog/RDS-2013-0009-4/)
Tharammal T, Bala G, Devaraju N and Nemani R 2019 A review of the major drivers of the terrestrial carbon uptake: model-based assessments, consensus, and uncertainties Environ. Res. Lett. 14 093005
Twidwell D, Rogers W E, Wonka C L, Taylor C A and Kreuter U P 2016 Extreme prescribed fire during drought reduces survival and density of woody resprouters J. Appl. Ecol. 53 1585–96
US EPA O 2015 Ecoregions of North America US EPA (available at: https://www.epa.gov/eco-research/ecoregions-north-america)
vander Werf G R et al 2017 Global fire emissions estimates during 1997–2016 Earth Syst. Sci. Data 9 697–720
Xiao J and Zhuang Q 2007 Drought effects on large fire activity in Canadian and Alaskan forests Environ. Res. Lett. 2 044003