We thank the reviewers for their insightful comments. Below we provide detailed responses in black, with quotation marks showing the changes made in the manuscript. The line numbers in black refer to the revised (un-tracked) manuscript. The reviewers' comments are in blue.

Author Response to Reviewer #1

This paper presents future projections of burned area and smoke concentrations from lightning fires on national forest and national park lands in the western US. The paper is generally well written and presents some interesting results. However, I think it could use some clarification before publishing.

Major Suggestions:

- I'd really like a figure that shows specifically the domain that they are looking at with all the national forest and national park lands outlined. This might be the green line on Figure 3, but it is not labeled as such in the caption. Additionally, I think any parks/forests that are mentioned by name in the text (example line 282-283) should have their state location listed and be labeled on a map (it should not be assumed that all readers know these locations by name).

We added the map of national forest and park fraction in the Supplement (Fig. S3), which specified our domain with all the national forests and parks. We also revised Fig. 3, Fig. S4, Figs. S7-8 to show results in the national forests and parks only.
We added the state locations of the parks and forests as "the Flathead (Montana), Nez Perce-Clearwater (Idaho), and Arapaho and Roosevelt (Colorado) National Forests." Fig. 4 is now updated to denote the locations of these parks and forests.

-I know this will make it wordy and redundant sounding, but I think the authors need to be explicit throughout the paper, every time they mention results, that all their results are only from fires on national park and national forest land in the western US. I think this is especially important in their discussion on smoke concentrations and their comparisons with other studies. It should also be specific in the title.

The title has been changed to "Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the national forests and parks of the western United States."
We also now clarify in the discussion that our study focused on fires in the national forests and parks.

Line 55- 58 states that one of their aims is to provide results at a higher resolution. I think with this being one of their stated goals, there needs to be more discussion of resolution. They did model simulations at two resolutions, so how do these two resolutions compare? What value does the finer resolution add? How might this finer resolution impact comparisons with other studies?

We have removed the mention of finer spatial resolution as an aim of the study, and now clarify that the manuscript focuses on the drivers of lightning fires. In Fig. S5 in the Supplement, we provide a comparison of simulated fire-season smoke PM at the resolutions of 0.5° × 0.625° and 4° x 5°. In the supplement we also added:

Supplement, Lines 42-43. "The finer-resolution simulation provides more detailed distributions of fire activity in the WUS, which are of greater utility to environmental managers."

Minor suggestions:

- It should be "western United States" not "Western United States" throughout the paper. It is incorrect in the title and abstract and switches back and forth throughout the text. I also think national parks and national forests shouldn't be capitalized unless the authors are referring to specific national parks or forests.

Done.

- About half-way through the paper, the authors stop using "National Forests and National Parks" and just use "National Forests". I think they should stick with parks as well.

Done.

- A flowchart of the modeling set up in the supplement would be beneficial. I found it difficult to follow the input/output of each step in the modeling process. They also need to be clear throughout the text about what each model is actually simulating. For example, they say that LPJ-LMFire simulates meteorology (line 339), but I think they mean that it simulates the effects of meteorology and the meteorology is input. Likewise they say that LPJ-LMFire simulates emissions (line 88), but I think it simulates area burned, and then they apply the Akagi emission factors to create an emission inventory for GEOS-Chem. (Example: line 39, lightning-caused fire emissions aren't simulated with GEOS-Chem, they are put into GEOS-Chem)

We have added a flowchart of modeling setup (Fig. S1) in the Supplement.
We have also made the following changes to the main text.
Line 367. We now say, "…fire behavior and therefore burned area simulated by LPJ-LMfire are primarily governed by meteorology and fuel structure."
Line 88. we revised the wording as "Combined with emission factors from Akagi et al., 2011, dry matter burned calculated by LPJ-LMfire can be used to estimate natural wildfire emissions of black carbon (BC) and organic carbon (OC) particles, which are then passed to GEOS-Chem, a 3-D chemical transport model, to simulate the transport and distribution of wildfire smoke across the WUS." We also moved this sentence to the method section.
Line 38. "In this study, we project lightning-caused fire emissions and wildfire-specific PM concentrations over the national forests and parks of the WUS in the mid- and late- 21st century, using a dynamic global vegetation model combined with a chemical transport model."

- Table 1 should also have the total BC+OC emissions. I don't think the Dm for the Sierra Nevada needs to be included here. I'd suggest instead adding a supplemental table with several of the large national forests and their results.

We have added BC+OC emissions to the table, following the reviewer's suggestion. We also removed DM for the Sierra Nevada from Table 1. Large national forests and parks are typically geographically connected, which indicates fire can easily spread from one forest to the nearby forest lands. Therefore, it might make more sense to discuss the changes in fire activity in these forests together.

- I don’t think Table 2 needs to be in the main text.

We moved Table 2 to the Supplement as Table S1.

- I think Table S1 needs to be in the main text since 2 whole paragraphs discuss it.

Done.

-Figure S3 is mentioned in the text as an evaluation with GFED4s, nothing about IMPROVE. I was really confused when I read the acknowledgement section that a large section devoted to IMPROVE when there was no mention of it in the text. This evaluation should be mentioned in the main text, likely under section 2.3.

We now mention our use of IMPROVE data in the main text.
Lines 196-198. “Implementing the combined emissions allow us to validate the simulated results in this study using observations from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network (Figs. S5-S6).”

Line by Line Comments:

Line 19-20: restate that this is for national park and forest lands in the western US.

Done.

Line 21-22: This is confusing. Isn’t the dry matter burned by lightning-caused fires? A shift in fuel loading could lead to more fires, but if it is already burned, should it not lead to fewer fires?

Lines 21-22. “RCP8.5 also shows enhanced lightning-caused fire activity, especially over forests in the northern states.”

Line 29-32: Brey et al. (2018) suggests that it is about 30% caused by human ignition in the west. They also note that there are similar drivers for lightning and human caused fires, thus climate changes would likely have a similar impact on both.

Brey et al. (2018) suggested that lightning wildfires cause the majority of burned area in the western U.S., especially during the fire season. Over national forests and parks, Brey et al. (2018) also showed lightning was the dominant driver of fire ignition. We have added this citation into our manuscript.
Lines 30-31. “Over the forests of the western United States (WUS), lightning-caused wildfires account for the majority of burned area (Abatzoglou et al., 2016; Brey et al., 2018).”

Line 35: Studies of what? Be specific.

Lines 36-37. “Not all these studies that attempt to predict future fire activity have accounted for changing land cover or have distinguished the effects of lightning fire ignitions from human-started fires.”

Line 81: Is a second source missing here (there is a comma and the sentence says “Several studies”)? If not, the sentence should read “One study predicted”. Also, is there not any more recent papers on lightning and climate change?

Fixed.

Line 83-85: It might be worth noting that this lightning parameterization does not include any potential impacts of aerosols since this work is suggesting an increase in aerosol concentrations.

Lines 115-122. "Several studies have predicted future increases in lightning due to climate change (e.g., Price and Rind, 1994a, Romps et al., 2014). However, the relationship between lightning flash rate and meteorology is poorly constrained in models and depends largely on physical parameters such as cold cloud thickness, cloud top height, or convective available potential energy. In our study, lightning strike density for application in LPJ-LMfire is calculated using the GISS convective mass flux following the empirical parameterization of Magi, 2015. Although observations suggest a link between aerosol load and lightning frequency (e.g., Altaratz et al., 2017), we do not consider that relationship here."

Line 86-87: I think it would be beneficial to restate this at the end, that lightning isn't increasing, but the area burned from lightning fires is.

Done.
Line 314. In the discussion, we added "The GISS model predicts a warmer and drier climate but nearly constant lightning frequency in both scenarios."

Line 91: Is a couple years a long enough spin-up for a vegetation model?

We now clarify our method of spin-up.
Lines 140-142: "For each RCP, LPJ-LMfire simulates vegetation dynamics and fire continuously for the period 1701-2100, with monthly resolution. Continuous 400-year simulations allow for sufficient spin-up."

Line 88-94: seems like this should just be in the methods section.

We have moved all the sentences in this paragraph to the method section on line 88 and line 112.

Line 94: Is a five-year time slice long enough to represent the range of interannual variability?

The reviewer raises an important issue.
Lines 177-184. "Simulations with the fine-scale GEOS-Chem are computationally expensive, and we first test whether performing five-year simulations will adequately capture the interannual variability in fire activity generated by the LPJ-LMfire model. We take the average of fire-season total dry matter burned over five-year time slices in different periods across the 21st century, and find that these averages differ from the same quantity averaged over ten-year time slices by less than 20%, which is much less than the discrepancies caused by using different climate models in future predictions (Sheffield et al., 2013). This relatively small difference gives us confidence that five-year simulations in GEOS-Chem will suffice for this study."

Line 108: What does the "coalescence of fires" mean?

By "coalescence," we refer to the merging of fires.
We now more clearly explain how the LPJ-LMfire model simulates fires.

Lines 99-104. “LPJ-LMfire calculates fire starts as a function of lightning ground strikes and ignition efficiency. Not every lightning strike causes fire. The model accounts for the flammability of different plant types, fuel moisture, the spatial autocorrelation of lightning strikes, and previously burned area. As fires grow in size, the likelihood of fire coalescence or merging increases. Fires are extinguished by consuming the available fuel or by experiencing sustained precipitation (Pfeiffer et al., 2013).”

Line115-117: How does the model go from lightning density to fire? Does every lightning strike initiate a fire if there is fuel there?

Lines 99-100. “LPJ-LMfire calculates fire starts as a function of lightning ground strikes and ignition efficiency. Not every lightning strike causes fire.”

Line 139: can you use “grid” instead of “raster”? Also, this needs clarification. Is this grid used to create the emissions or just for choosing the analysis area? I’m assuming this is for creating the emissions and the authors use the fraction of the grid box multiplied by the dry area burned and then that gets multiplied by the emission factor to create the emissions to be put into GEOS-Chem? And then for the analysis, do they use any grid box that has any fraction of national park or forest land?

Here we used “raster” to distinguish from “grid cell.” The rasters provide information on the fraction in each grid cell that is used to filter and scale the original data.
We now clarify:
Lines 155-156. “To calculate fire emissions, we multiply the simulated dry matter burned by the fraction of national forest or park within each grid cell.”
Also, we added the map of national forest and park fraction in the Supplement (Fig. S3).

Line 161-162: is this lack of difference for the CTM or LPJ-LMFire and for what variable (20% for emissions seems significant?)?

Lines 179-184. We clarified “We take the average of fire-season total dry matter burned over five-year time slices in different periods across the 21st century, and find that these averages differ from the same quantity averaged over ten-year time slices by less than 20%, which is much less than the discrepancies caused by using different climate models in future predictions (Sheffield et al., 2013). This relatively small difference gives us confidence that five-year simulations in GEOS-Chem will suffice for this study.”

Line 164-167 should be moved to line 158.

Done.

Line 176: why do the GFED4s emissions need to be included at all? If you are just looking at the difference and those are being held the same, it doesn’t seem necessary to include them in the simulation at all. Line 178-179 says that they can be compared to observations, but this isn’t actually done in the text at all.

We included a comparison with the IMPROVE dataset in the Supplement:

- Lines 38-50. “We compare the GEOS-Chem results against ground-based measurements from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network in the western U.S.…”
- Figs. S5-S6.

The reviewer is correct that we do not need GFED4s if we focused on the differences only. But with GFED4s emissions outside national forests and parks, we were able to provide a complete map which could be potentially useful for health studies.

Line 196-213: What is causing these increases? Just the warmer climate or is it the shift in biomass type? Does the decrease in precipitation not have a large impact?

Lines 264-268. "In our study, we show that total living biomass mostly decreases at latitudes ~45° N by ~2100 under RCP8.5, but the peak enhancements in dry matter burned also occur at these latitudes. This finding indicates that the modeled changes in fire activity are driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas."
Lines 322-324. In the discussion section, we also added "Increased fire activity is driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas."
Our study did not distinguish the impacts of precipitation only. The changes in fire activity are driven by the combined effects of changes in temperature and precipitation.

Line 213: will not "limit fuel load" for what or with respect to what?

We now address this question.
Lines 229-231. "Despite this decrease, living biomass in this scenario is still abundant in the West in 2100, especially over the northern forests (not shown), suggesting that future climate change will not limit fuel load for fire ignition or spread."

Line 236: changes in what?

We clarified as
Line 256. "The changes in area burned we calculate at 2050 are also within the range of previous studies using statistical methods for this region."

Line 243-247: This is a long, confusing sentence.

Fixed.
Lines 264-268. "In our study, we show that total living biomass mostly decreases at latitudes ~45° N by ~2100 under RCP8.5, but the peak enhancements in dry matter burned also occur at these latitudes. This finding indicates that the modeled changes in fire activity are driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas."

Line 263: what region? The SN or WUS?

Line 282. "We find significant increases in dry matter burned of 81% by 2100 under RCP8.5 in the SN region."

Line 267-268: and the model doesn't simulate this right? Otherwise, you'd need to also include gas-phase precursor emissions calculated for your fire emissions.

The reviewer is correct.

Line 273-274: Figure 3 does not show lightning fire activity. It shows changes in dry matter burned and total living biomass.

Fixed.

Line 303-304: be specific that this is for the western US. Also, can you show a map of this, maybe in the supplement? Is this because your area includes any grid box that has any fraction with national park or national forest land? Less than 1% seems really low (protected lands make up <20% of the US)?

Lines 328-329. “However, we find that in the GFED4s inventory, present-day fire emissions outside these federally managed areas contribute less than 1% of total DM in the WUS.”

We understand the concern brought up by the reviewer.
Lines 329-332. “For area burned, the fraction outside national forests and parks could be higher than 1%. In contrast, national forests and parks have abundant fuel supplies, making their fractional contribution to total DM much higher than would be implied by their fractional contribution to area burned.”

Line 312-316: It seems strange to put in the same sentence that there are low smoke emissions compared to some studies, but similar area burned to another study. Do the two studies for the smoke emissions also provide area burned estimates? Otherwise, these should be discussed separately.

We removed the comparison with area burned here.

Line 308-333: The domain difference and difference in years should be noted along with the difference in resolution.

Lines 338-339. “These discrepancies arise from differences in the methodologies, fire assumptions, future scenarios applied, domain and time period considered, and model resolution.”

Line 334-345: Also, there is no feedback of smoke/aerosols on climate included. Also, transport pathways may not vary much, but there are likely some mismatches in the CTM simulation in that the meteorology that is conducive to fires may be more conducive to smoke transport, and the CTM is not using the same input meteorology that was used with LPJ-LMFire.

We have revised the sentence.
Lines 371-372. “Our study also does not consider the effects of future climate change on the transport or lifetime of smoke PM, nor the feedback of smoke aerosols on regional climate.”

Lines 363-366. “Also, the GEOS-Chem simulations are driven with present-day MERRA-2 meteorology. Besides changes in fire emissions, future work could examine how changing meteorology may further influence smoke lifetime and transport processes, and investigate the feedback of fire on meteorology by developing an online coupled modeling approach.”

Author Response to Reviewer #2 - Dr. Alan Wei Lun Lim

This paper talks about the impacts of future lightning induced wildfires in western United States as projected by a series of computational models. The main model is a fire model that uses future meteorological and land properties as inputs and predicts the occurrences of fires and how much smoke particulate emissions (black carbon and organic carbon) are generated as a result of the fires. Emissions are then used as inputs for a chemistry transport model to predict future impacts on air quality. The paper presents some very interesting results. Parts of the paper lacks specificity, hence some clarifications are necessary.

Major Suggestions

The authors may want to consider to implement land use changes according to the RCP scenarios in the LPJ-LMfire dynamic vegetation model instead of just assuming 30% increase in cropland and pastures. I understand that anthropogenic effects may be hard to ascertain as per discussed in the paper, but it may be worthwhile to at least look at changes in croplands versus forest cover. For example in RCP4.5: more forests, less crops; RCP8.5: less forests, more crops. Having more cropland in RCP8.5 scenario may lead to more agricultural fires whereas having larger forest cover without human intervention in RCP4.5 scenario may lead to more lightning fires.

We did indeed implement scenarios of land use change from different RCPs, and we now clarify our methods.
Lines 143-146: “We apply future land use scenarios following the two RCPs in CMIP5, in which the extent of crop and pasture cover in the WUS increases by 30% in future climates, with most of these changes occurring outside the national forest and park lands in the region (Brovkin et al., 2013; Kumar et al., 2013).”
Line 104. “Our study does not consider changes in human-caused fires, including agricultural fires.”

I would like to clarify if the model account for agricultural fires? In Table 2, the column for LPJ-LMfire seem to suggest that this fire model does not model agricultural fires although the GEOS-Chem model has a PFT for crops. I guess if the focus of the paper is not about anthropogenic influences on land use changes, and thus lightning fires, then not having this is fine.

The reviewer is referred to the previous response.

It may make the paper more interesting if the authors also list and discuss in greater detail about the possible reasons for the increase in fires, for example, despite having similar lightning activity, stable air and decreased wind led to higher temperatures and hence increasing the occurrences of lightning fires. It may be scientifically interesting to also discuss the most important factor in determining lightning induced fires.

The reviewer suggested very interesting and important topics to look into. Although these topics were beyond the scope of this study, the suggestions provided good guidance for future work.
Lines 322-324. In the discussion section, we added “Increased fire activity is driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas.”

The paper could not discuss any feedback effects of fire on meteorology because the methodology employed simply did not allow such an investigation. Feedback effects of fire on meteorology can be very scientifically interesting, but complicated to investigate. Perhaps this could be future work.

We now mention this direction for future research.
Lines 364-366. “Besides changes in fire emissions, future work could examine how changing meteorology may further influence smoke lifetime and transport processes, and investigate the feedback of fire on meteorology by developing an online coupled modeling approach.”

Minor Suggestions

Line 26: I suggest looking at Val Martin, et.al., 2015. Atmos. Chem. Phys., 15, 2805–2823, 2015. It may be a better cite since it also looks at air pollution and national parks, and is a later research paper.

Done.

Line 47: Also check out Li, et. al., 2019. Atmos. Chem. Phys., 19, 12545–12567, 2019 for many different fire models.

Done.
Lines 55-58. “Dynamic vegetation models with interactive fire modeling provide important estimates for long-term and large-scale changes in fire emissions, with most of these models simulating present-day fire emissions within the range of satellite products but failing to reproduce the interannual variability (Li et al., 2019; Hamilton et al., 2018).”

Line 81 seems to have a missing citation.

Done.

Line 84: A clarification on how the GISS model predicts lightning flashes would be beneficial. Also, only cloud to ground lightning would affect your study. A further clarification on whether cloud to ground lightning remains unchanged throughout the century would be good.

The GISS model results archived for CMIP5 does not provide lightning density.
Line 119. “In our study, lightning strike density for application in LPJ-LMfire is calculated using the GISS convective mass flux following the empirical parameterization of Magi, 2015.”

It is true that cloud-to-ground lightning is the direct cause of natural wildfires. We now clarify.
Line 124. “LPJ-LMfire scales lightning flashes to cloud-to-ground lightning strikes, which are the portion of total flashes in clouds that directly causes natural wildfires (Pfeiffer et al., 2013). Therefore, cloud-to-ground lightning frequencies are also considered constant during the 21st century.”

Line 106: It may be necessary to describe in greater detail how each factor in the LPJLM fire model affect the predicted fires (incidences of fires, intensity, area burned, etc.) because this is what the whole paper is about.

Lines 99-104. “LPJ-LMfire calculates fire starts as a function of lightning ground strikes and ignition efficiency. Not every lightning strike causes fire. The model accounts for the flammability of different plant types, fuel moisture, the spatial autocorrelation of lightning strikes, and previously burned area. As fires grow in size, the likelihood of fire coalescence or merging increases. Fires are extinguished by consuming the available fuel or by experiencing sustained precipitation (Pfeiffer et al., 2013).”

Line 174: Smoke PM definition should be moved to line 42 to define smoke PM earlier.

Fixed.

Line 291: I would like to suggest a clarification: You are using an offline coupling technique. The present way of phrasing may confuse readers into thinking the fire and atmosphere model are fully coupled.

Lines 312. “We apply an offline, coupled modeling approach.”

Supplement Line 24: spelling of lightning

Fixed.

Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the national forests and parks of the western United States

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Abstract. Almost US$ 3bn per year is appropriated for wildfire management on public land in the United States. Recent studies have suggested that ongoing climate change will lead to warmer and drier conditions in the western United States with a consequent increase in the number and size of wildfires, yet large uncertainty exists in these projections. To assess the influence of future changes in climate and land cover on lightning-caused wildfires in the national forests and parks of the western United States and the consequences of these fires on air quality, we link a dynamic vegetation model that includes a process-based representation of fire (LPJ-LMfire) to a global chemical transport model (GEOS-Chem). Under a scenario of moderate future climate change (RCP4.5), increasing lightning-caused wildfire enhances the burden of smoke fine particulate matter (PM), with mass concentration increases of ~53% by the late-21st century during the fire season in the national forests and parks of the western United States. In a high-emissions scenario (RCP8.5), smoke PM concentrations double by 2100. RCP8.5 also shows enhanced lightning-caused fire activity, especially over forests in the northern states.

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1 Introduction

Both the incidence and duration of large wildfires in the forests of the western United States have increased since the mid-1980s (Westerling et al., 2006; Abatzoglou and Williams, 2016), affecting surface levels of particulate matter (Val Martin et al., 2006; Val Martin et al., 2015), with consequences for human health (Liu et al., 2017) and visibility (Spracklen et al., 2009; Ford et al., 2018). Wildfire activity is influenced by a combination of different factors, including fuel load, fire suppression practices, land use, land cover change, and meteorology (Pechony and Shindell, 2010). Over the forests of the western United States (WUS), lightning-caused wildfires account for the majority of burned area (Abatzoglou et al., 2016; Brey et al., 2018) and have driven most of the recent increase in large wildfires, with human ignition contributing less than 12% to this trend (Westerling, 2016). Studies suggest that a warming climate could enhance wildfires in the WUS (Yue et al., 2013; Abatzoglou and Williams, 2016), but quantifying future wildfire activity is challenging, given uncertainties in land cover trends and in the relationships between fire and weather. Not all these studies that attempt to predict future fire activity have accounted for changing land cover or have distinguished the effects of lightning fire ignitions from human-started fires. In this study, we project lightning-caused fire emissions and wildfire-specific PM concentrations over the national forests and parks of the WUS in the mid- and late- 21st century, using a dynamic global vegetation model combined with a chemical transport model. Our goal is to understand how trends in both land cover and meteorology may affect natural fire activity and smoke air quality over the 21st century.

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Consistent with projections of increasing wildfire in the WUS, recent studies have also predicted enhancement of fire-generated PM (smoke PM; BC+OC) under a warmer and drier climate in this region (Yue et al., 2013; Yue et al., 2014; Spracklen et al., 2009; Ford et al., 2018;

Westerling et al., 2006). Some of these studies relied on statistical models that relate meteorological variables to fire metrics such as area burned; these models can then be applied to projections from climate models (Yue et al., 2013; Yue et al., 2014; Spracklen et al., 2009; Archibald et al., 2009; Wotton et al., 2003; Westerling and Bryant, 2008). However, these statistical methods do not account for changes in vegetation due to climate, increasing atmospheric CO_2 concentrations, or land use. A further weakness of these studies is that they do not consider whether enhanced fire activity in the future atmosphere may ultimately deplete the supply of woody fuels (Yue et al., 2013; Yue et al., 2014). Other studies have coupled global vegetation models to climate models to better represent such fire-vegetation-climate interactions (Chaste et al., 2018; Ford et al., 2018). Dynamic vegetation models with interactive fire modeling provide important estimates for long-term and large-scale changes in fire emissions, with most of these models simulating present-day fire emissions within the range of satellite products but failing to reproduce the interannual variability (Li et al., 2019; Hamilton et al., 2018). The coupled modeling approaches integrate vegetation dynamics, land-atmosphere exchanges, and other key physical processes, allowing consideration of many factors driving fire activity and smoke pollution on regional scales. Building on this research, we use an integrated vegetation-climate model system with the aim of clarifying how changing meteorology and vegetation together drive future lightning-caused wildfire activity. We also provide predictions of smoke pollution at finer spatial resolution than previously. Our approach accounts for the impact of future climate and lightning fires on fuel structure, and these fine-scale predictions are of greater utility to environmental managers and especially the health impacts community.

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Lightning is the predominant cause of wildfire ignition in most mountainous and forest regions of the WUS during months that have high fire frequency (Abatzoglou et al., 2016; Balch et al., 2017). In remote and mountainous terrain, anthropogenic ignitions are infrequent and >90% of total area burned is caused by lightning-started fires (Abatzoglou et al., 2016). Here we study lightning-caused fires over the national forests and parks of the WUS in the mid- and late- 21st century under two future climate change scenarios defined by Representative Concentration Pathways (RCPs). RCP4.5 represents a moderate pathway with gradual reduction in greenhouse gas (GHG) emissions after 2050, while RCP8.5 assumes continued increases in GHGs throughout the 21st century. We use the Lund-Potsdam-Jena-Lausanne-Mainz (LPJ-LMfire) Dynamic Global Vegetation Model (Pfeiffer et al., 2013) to simulate dynamic fire-vegetation interactions under future climate. LPJ-LMfire, which has been used previously to investigate historical fire activity (e.g., Chaste et al., 2018), is applied here to estimate natural fire emissions under future climate simulated by the Goddard Institute for Space Studies (GISS) Model E climate model. July, August, and September (JAS) are the months of greatest fire activity in WUS forests (Park et al., 2003) and the focus of our study. We limit the spatial extent of our analyses to the national forests and parks of the WUS, here defined as 31°N – 49°N, 100°W – 125°W.

2 Methods

We quantify the effects of changing climate on area burned and fire emissions caused by lightning over the national forests and parks in the WUS using the LPJ-LMfire model (Pfeiffer et al., 2013), driven by meteorological fields from the GISS-E2-R climate model (Nazarenko et al., 2015). Combined with emission factors from Akagi et al., 2011, dry matter burned calculated by LPJ-LMfire can be used to estimate natural wildfire emissions of black carbon (BC) and organic carbon (OC) particles, which are then passed to GEOS-Chem, a 3-D chemical transport model, to simulate the transport and distribution of wildfire smoke across the WUS. A flowchart of modeling

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Moved down [1]: For RCP4.5, the GISS model predicts a statistically significant increase in surface temperature of 1.4 K averaged over the entire region by 2050 during JAS; for RCP8.5, the mean JAS temperature increase is 3.7 K by 2100. In both future climate scenarios, significant precipitation decreases of ~20% by 2100 are simulated.

Deleted: Several studies have predicted future increases in lightning due to climate change (e.g., Price and Rind, 1994b, Romps et al., 2014). However, the relationship between lightning flash rate and meteorology is poorly constrained in models and depends largely on physical parameters such as cold cloud thickness, cloud top height, or convective available potential energy. In our study, we use the convective mass flux from the GISS model to calculate lightning density in terms of flashes km^{-2} day^{-1}. Unlike surface temperature and precipitation, we find that average lightning density over the West does not change significantly during the 21st century, as described in Fig. S1. (Pfeiffer et al., 2013)¶
LPJ-LMfire simulates wildfire emissions of black carbon (BC) and organic carbon (OC) particles, which are then passed to the global atmospheric chemistry-transport model GEOS-Chem, to simulate the transport and distribution of wildfire smoke across the West. For each RCP, LPJ-LMfire simulates vegetation dynamics and fire continuously for the period 2006-2100, with monthly resolution. For reasons of computational demand, we were limited to conducting two time-slice simulations with GEOS-Chem focused around 2010 and 2100, with each time slice covering 5 continuous years. For further details, see Methods section below.¶

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2.1 LPJ-LMfire

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The LPJ-LMfire dynamic vegetation model is driven by gridded climate, soil, land use fields, and atmospheric CO_2 concentrations, and simulates vegetation structure, biogeochemical cycling, and wildfire (Pfeiffer et al., 2013; Sitch et al., 2003). Wildfires are simulated based on processes including explicit calculation of lightning ignitions, the representation of multi-day burning and coalescence of fires, and the calculation of rates of spread in different vegetation types (Pfeiffer et al., 2013). LPJ-LMfire calculates fire starts as a function of lightning ground strikes and ignition efficiency. Not every lightning strike causes fire. The model accounts for the flammability of different plant types, fuel moisture, the spatial autocorrelation of lightning strikes, and previously burned area. As fires grow in size, the likelihood of fire coalescence or merging increases. Fires are extinguished by consuming the available fuel or by experiencing sustained precipitation (Pfeiffer et al., 2013). Our study does not consider changes in human-caused fires, including agricultural fires.

The climate anomaly fields from the GISS-E2-R climate model used to prepare a future scenario for LPJ-LMfire are monthly mean surface temperature, diurnal temperature range (i.e., the difference between monthly mean daily maximum and daily minimum temperatures), total monthly precipitation, number of days in the month with precipitation greater than 0.1 mm, monthly mean total cloud cover fraction, and monthly mean surface wind speed. This version of the GISS model was configured for Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Nazarenko et al., 2015). For RCP4.5, the GISS model predicts a statistically significant increase in surface temperature of 1.4 K averaged over the entire region by 2050 during JAS; for RCP8.5, the mean JAS temperature increase is 3.7 K by 2100. In both future climate scenarios,

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significant precipitation decreases of ~20% by 2100 are simulated. Several studies have predicted future increases in lightning due to climate change (e.g., Price and Rind, 1994a, Romps et al., 2014). However, the relationship between lightning flash rate and meteorology is poorly constrained in models and depends largely on physical parameters such as cold cloud thickness, cloud top height, or convective available potential energy. In our study, lightning strike density for application in LPJ-LMfire is calculated using the GISS convective mass flux following the empirical parameterization of Magi, 2015. Although observations suggest a link between aerosol load and lightning frequency (e.g., Altaratz et al., 2017), we do not consider that relationship here. Unlike surface temperature and precipitation, we find that average lightning density over the West does not change significantly during the 21st century, as described in Fig. S2. LPJ-LMfire scales lightning flashes to cloud-to-ground lightning strikes, which are the portion of total flashes in clouds that directly causes natural wildfires (Pfeiffer et al., 2013). Therefore, cloud-to-ground lightning frequencies are also considered constant during the 21st century. We run LPJ-LMfire on a 0.5°×0.5° global grid, though for this study only results over the national forests and parks of the WUS are analyzed.

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The GISS-E2-R meteorology used here covers the period 1701-2100 at a resolution of 2° latitude x 2.5° longitude. The start year of the two climate scenarios, RCP4.5 and RCP8.5, is 2006. The two RCPs capture a range of possible climate trajectories over the 21st century, with radiative forcings at 2100 relative to pre-industrial values of +4.5 W m^{-2} for RCP4.5 and +8.5 W m^{-2} for RCP8.5. From 2011 to 2015, the greenhouse gas concentrations of the two scenarios are nearly identical. To downscale the GISS meteorological fields to finer resolution for LPJ-LMfire, we first calculate the 2010-2100 monthly anomalies relative to the average over the 1961-1990 period, and then add the resulting timeseries to a high-resolution observationally based climatology at 0.5°

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latitude × 0.5° longitude spatial resolution. The climatology was prepared using the datasets including WorldClim 2.1, Climate WNA, CRU CL 2.0, Wisconsin HIRS Cloud Climatology, and LIS/OTD, as described in Pfeiffer et al., 2013. For each RCP, LPJ-LMfire simulates vegetation dynamics and fire continuously for the period 1701-2100, with monthly resolution. Continuous 400-year simulations allow for sufficient spin-up. The LPJ-LMfire simulations used here cover the period 2006-2100. We apply future land use scenarios following the two RCPs in CMIP5, in which the extent of crop and pasture cover in the WUS increases by 30% in future climates, with most of these changes occurring outside the national forest and park lands in the region (Brovkin et al., 2013; Kumar et al., 2013).

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Passive fire suppression results from landscape fragmentation caused by land use (e.g., for crop and grazing land, roads, and urban areas), and this influence on fire activity is included in the LPJ-LMfire simulations (Pfeiffer et al., 2013). The model does not, however, consider the active fire suppression practiced throughout much of the WUS. We therefore limit our study to wildfire activity on the national forest and park lands of the WUS that are dominated by lightning fires and where land use for agriculture and urban areas is minimal. To focus only on national forest and park lands, we apply a 0.5° × 0.5° raster across the WUS that identifies the fraction of each grid cell that belongs to a national forest or national park (Fig. S3), and we consider only these areas in our analysis. To calculate fire emissions, we multiply the simulated dry matter burned by the fraction of national forest or park within each grid cell.

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2.2 Fire emissions

Fuel biomass in LPJ-LMfire is discretized by plant functional type (PFT) into specific live biomass and litter categories, and across four size classes for dead fuels. The model simulates monthly values of total dry matter burned for nine PFTs as in Pfeiffer et al., 2013. To pass LPJ-

LMfire biomass burning emissions to GEOS-Chem, we first reclassify these nine PFTs into the six land cover types considered by GEOS-Chem. See Table S1 for a summary of the reclassification scheme. Tropical broadleaf evergreen, tropical broadleaf raingreen, and C_4 grasses are not simulated by LPJ-LMfire in the national forests and parks of the WUS. Emission factors based on the six land cover types in GEOS-Chem are then applied to dry matter burned from LPJ-LMfire, resulting in monthly BC and OC emissions over national forests and parks. These factors are from Akagi et al., 2011. As lightning-started wildfires are dominant over the WUS forests, an evaluation of fire emissions over national forest and park lands from the LPJ-LMfire model against the Global Fire Emissions Database (GFED4s) inventory (Giglio et al., 2013) is included in the Supplement (Fig. S4).

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2.3 GEOS-Chem

We use the GEOS-Chem chemical transport model (version 12.0.1; http://acmg.seas.harvard.edu/geos/). We first carry out a global simulation at 4° latitude x 5° longitude spatial resolution, and then downscale to 0.5° × 0.625° over the WUS via grid nesting over the North America domain. For computational efficiency, we use the aerosol-only version of GEOS-Chem, with monthly mean oxidants archived from a full-chemistry simulation, as described in Park et al., 2004. Simulations with the fine-scale GEOS-Chem are computationally expensive, and we first test whether performing five-year simulations will adequately capture the interannual variability in fire activity generated by the LPJ-LMfire model. We take the average of fire-season total dry matter burned over five-year time slices in different periods across the 21st century, and find that these averages differ from the same quantity averaged over ten-year time slices by less than 20%, which is much less than the discrepancies caused by using different climate models in future predictions (Sheffield et al., 2013). This relatively small difference gives us confidence that

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five-year simulations in GEOS-Chem will suffice for this study. We therefore perform two five-year time slice simulations for each RCP, covering the present day (2011-2015) and the late-21st century (2096-2100). The GEOS-Chem simulations are driven with present-day MERRA-2 reanalysis meteorology from NASA/GMAO (Gelaro et al., 2017) to isolate the effect of changing wildfires on U.S. air quality. The simulations include emissions of all primary PM and the gas-phase precursors to secondary particles, with non-fire particle sources comprising fossil fuel combustion from transportation, industry, and power plants from the 2011 EPA NEI inventory. In the future time slices, non-fire emissions remain fixed at present-day levels.

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Our study focuses on carbonaceous PM (smoke PM; BC+OC), which are the main components in wildfire smoke (Chow et al., 2011). For the present day, we apply 5-year (2011-2015) averaged GFED4s emissions to those regions that fall outside national forests and parks and temporally changing LPJ-LMfire emissions from the two RCPs within the Forests. Implementing the combined emissions allow us to further validate the simulated results in this study using observations from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network (Figs. S5-S6). For the future time slices, we assume that fires outside national forests and parks remain at present-day levels, and we again combine the 2011-2015 GFED4s fire emissions with the temporally changing, future LPJ-LMfire emissions over the national forests and parks.

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3 Results

3.1 Spatial shifts in fire activity

Under both RCPs, 21st century climate change and increasing atmospheric CO_2 concentrations lead to shifts in the distribution of total living biomass and dry matter burned. Fig. 1 shows the changes in monthly mean temperature and precipitation averaged zonally over grid cells at each 1° latitude of the West, relative to the present day, defined as ~2010. Peak temperature enhancements in JAS occur between 36°-42° N for ~2050 and ~2100 in both RCPs, with a maximum enhancement of 4 °C for RCP4.5 and 6 °C for RCP8.5 in 2100. Significant decreases in JAS precipitation occur between 33°-45° N under RCP4.5 and at latitudes north of 39° N under RCP8.5 for ~2100. The maximum decrease in monthly precipitation over the West is ~40 kg m^{-2} (~60%) in JAS under both RCPs. These warmer and drier conditions favor fire activity under future climate.

Fires and smoke production are dependent on fuel load, and throughout the 21st century, total living biomass in the WUS is primarily concentrated in northern forests (Fig. 2). For RCP4.5, living biomass exhibits significant enhancements in U.S. national forests and parks at latitudes north of 43° N in the 2050 time slice and north of 45° N in the 2100 time slice. North of 46° N, the change in living biomass at 2100 (~0.4 kg C m^{-2}) is double that at 2050 (~0.2 kg C m^{-2}). At latitudes south of 40°N, living biomass in RCP4.5 is generally invariant over the 21st century. In RCP8.5, living biomass also increases significantly near the Canadian border – e.g., as much as ~0.2 kg C m^{-2} for the 2050 time slice and ~0.4 kg C m^{-2} for the 2100 time slice, relative to the present day. In contrast, at latitudes between 42°-47° N in RCP8.5, total living biomass decreases by as much as -0.6 kg C m^{-2} for ~2100. For both RCPs, these mid-century and late-century changes in total living biomass are significant ($p < 0.05$) across nearly all latitudes. In RCP4.5, the spatial shifts of total living biomass are relatively weak from 2050 to 2100, consistent with the moderate climate scenario with gradual reduction in greenhouse gas emissions after 2050. However, under the continued-emissions climate scenario RCP8.5, total living biomass in these forests first increases by 2050 and then decreases by ~10% by 2100, indicating a strongly disturbed vegetation system due to climate change. Despite this decrease, living biomass in this scenario is still

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abundant in the West in 2100, especially over the northern forests (not shown), suggesting that future climate change will not limit fuel load for fire ignition or spread. Table 1 summarizes these results.

LPJ-LMfire simulates boreal needleleaf evergreen and boreal and temperate summergreen (broadleaf) trees as the dominant plant functional types (PFTs) in the national forests and parks of the WUS; these PFTs together account for ~90% of the total biomass in our study domain. Changes over the 21st century (Fig. 2) reflect the changes in the growth and distribution of these PFTs, with increases in living biomass in the north and decreases in the south in both RCP scenarios (Fig. S7). In the 2100 time slice, vegetation shifts further north than in the 2050 time slice. The reasons for this shift can be traced to the climate regimes favored by different vegetation types, with temperate and boreal trees showing moderate to strong inclination in their growth along the north-south temperature gradient (Aitken et al., 2008). For example, the temperate broadleaf summergreen PFT favors regions with moderate mean annual temperatures and distinct warm and cool seasons (Jarvis and Leverenz, 1983), while boreal needleleaf evergreen generally occurs in colder climate regimes (Aerts, 1995). With rising temperatures, the living biomass of temperate summergreen trees increases in most states in the WUS, with maximum enhancement of +1.0 kg C m^{-2} in western Washington, northern Montana, and Idaho by 2100 in RCP8.5 relative to 2010. Decreases in this vegetation type for this scenario occur in the south, as much as -0.5 kg C m^{-2} in New Mexico. In contrast, boreal trees increase in only a few regions in the far north, with a substantial contraction in their abundance over much of the West, as much as -4.0 kg C m^{-2} for boreal needleleaf evergreen by 2100 in RCP8.5 over the northern forests.

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Simulated area burned from lightning-ignited fires in the national forests and parks of the WUS increases by ~30% by ~2050, and by ~50% by ~2100 for both RCPs (not shown),

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comparable to the predicted 78% increase in lightning-caused area burned in the U.S. under a doubled CO_2 climate by Price and Rind, 1994b, which did not account for vegetation changes due to climate change or changing CO_2. That study, however, projected an increase in lightning flashes and did not consider changing land cover. The changes in area burned we calculate at 2050 are also within the range of previous studies using statistical methods for this region (e.g., 54% in Spracklen et al., 2009 and 10-50% in Yue et al., 2013). Fig. 2 further shows that dry matter burned, a function of both area burned and fuel load, increases relative to the present at most latitudes at both 2050 and 2100 and in both RCPs. Year-to-year variations in dry matter burned are greater than those in living biomass due to variations in the meteorological conditions driving fire occurrence. Previous studies have found that interannual variability in wildfire activity is strongly associated with regional surface temperature (Westerling et al., 2006; Yue et al., 2013). In our study, we show that total living biomass mostly decreases at latitudes ~45° N by ~2100 under RCP8.5, but the peak enhancements in dry matter burned also occur at these latitudes. This finding indicates that the modeled changes in fire activity are driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas. As with biomass, lighting-caused fires also shift northward over the 21st century, especially in RCP8.5. In this scenario, dry matter burned increases by as much as 35 g m^{-2} mon^{-1} across 40°-48°N at ~2100 compared to the present day. By 2100, the fire-season total dry matter burned over the forests in the West increases by 24.58 Tg/JAS (111%) under RCP4.5 and by 50.00 Tg/JAS (161%) in RCP8.5 (Table 1).

The spatial distributions of changes in total living biomass and dry matter burned are shown in Fig. 3. Under RCP4.5, moderate decreases in total living biomass (by as much as -2.5 kg C m^{-2}) and increases in dry matter burned by 2100 (up to ~70 g m^{-2} mon^{-1}) are concentrated in central

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Idaho, Wyoming, and Colorado. Large declines in total living biomass and enhancements in dry matter burned occur in the forests of Idaho and Montana by 2100 under RCP8.5, with a hotspot of -5.0 kg C m^{-2} in biomass and +100 g m^{-2} mon^{-1} in dry matter burned in Yellowstone National Park. Similar trends in total living biomass and dry matter burned are also predicted for the Sierra Nevada (SN) region in California (Fig. S8), with the region defined as in Yue et al., 2014. Predicted changes in dry matter burned over the SN forests by 2050 are 17-44%, comparable to the calculated future increases of 30-50% by Yue et al., 2014. We find significant increases in dry matter burned of 81% by 2100 under RCP8.5 in the SN region. Our results suggest that even as future climate change diminishes vegetation biomass in some regions of the WUS, sufficient fuel still exists to allow increases in fire activity and dry matter burned.

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3.2 Smoke PM

Given the large uncertainty in secondary aerosol formation within smoke plumes (Ortega et al., 2013), we assume that smoke PM mainly consists of primary BC and OC. We calculate emissions of fire-specific BC and OC by combining the estimates of the dry matter burned with emission factors from Akagi et al., 2011, which are dependent on land cover type. Application of these emissions to GEOS-Chem allows us to simulate the transport and distribution of smoke PM across the WUS.

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With increasing lightning fire activity in most of the national forest and park areas of the WUS over the 21st century, smoke PM shows modest enhancement for RCP4.5, but more substantial increases for RCP8.5 (Fig. 4). Smoke PM enhancements in RCP4.5 occur primarily over the forests along the state boundaries of Idaho, Montana, and Wyoming, with large increases by as much as ~10 µg m^{-3} in Yellowstone National Park. Scattered increases in smoke PM in RCP4.5 are also predicted over the forests in northern Colorado, northern California, western

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Oregon, and central Arizona. In RCP8.5, smoke PM enhancements are widespread over the northern states of the WUS by 2100, with significant increases in regions east of the Rocky Mountains. Increased fire activity and large smoke PM enhancements are seen by 2100 in RCP8.5, including large areas of the Flathead (Montana), Nez Perce-Clearwater (Idaho), and Arapaho and Roosevelt (Colorado) National Forests. Particularly large increases – as much as ~40 $\mu g\ m^{-3}$ – occur in Yellowstone National Park (Wyoming). The increases in fire in these forests significantly influences air quality over the entire area of Idaho, Montana, Wyoming, and Colorado, with effects extending eastward to Nebraska and the Dakotas. Increased smoke PM is also predicted over the Sierra Nevada in both RCPs. In RCP4.5, average smoke PM over the entire WUS increases by 53% compared to present (Table 1). For RCP8.5, smoke PM more than doubles (109% increase) at ~2100.

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4 Discussion

We apply an offline, coupled modeling approach to investigate the impact of changes in climate and vegetation on future lightning-caused wildfires and smoke pollution across the national forests and parks of the WUS in the 21st century. The GISS model predicts a warmer and drier climate but nearly constant lightning frequency in both scenarios. For RCP4.5, the late-21st century lightning-caused wildfire-specific smoke PM in the national forests and parks of the West increases ~53% relative to present. Comparable fire activity between 2050 and 2100 reflect the effectiveness of the emission reduction strategies after 2050 under RCP4.5, as temperature changes across the West are relatively flat from 2050 to 2100, with a nearly constant area-averaged mean annual temperature of ~19.2°C. In RCP8.5, mean annual temperatures continue increasing over the second half of the 21st century across the West, nearly 2.1°C from 2050, and wildfire-specific

PM concentrations double by 2100. Increased fire activity is driven by changes in meteorological conditions that favor fire, as well as by shifts towards more pyrophilic landscapes such as open woodlands and savannas.

In Table 2, we compare predictions in this study with previous fire estimates under future climate. A difference between these studies and ours is that we consider only changes in fire activity over the national forests and parks while others examine changes over the whole WUS. However, we find that in the GFED4s inventory, present-day fire emissions outside these federally managed areas contribute less than 1% of total DM in the WUS. For area burned, the fraction outside national forests and parks could be higher than 1%. In contrast, national forests and parks have abundant fuel supplies, making their fractional contribution to total DM much higher than would be implied by their fractional contribution to area burned. Also, the fact that lightning is the dominant driver of wildfire activity over the WUS forests (Balch et al., 2017) allows a reasonable comparison of the estimates in this study with those in previous studies that include both lightning and human-started fires over the West.

Table 2 shows that fire activity in the U.S. is predicted to increase in all studies cited. However, the projected changes in fire metrics such as area burned or in emissions or concentrations of smoke vary greatly across studies, from ~10-300% relative to present-day values. These discrepancies arise from differences in the methodologies, fire assumptions, future scenarios applied, domain and time period considered, and model resolution. The ~80% increases in smoke emissions that we project by 2050 is generally lower than estimates in previous statistical studies (e.g., 150-170% in Yue et al., 2013 or 100% in Spracklen et al., 2009). In contrast, the ~80% increase in smoke emissions in this study at ~2050 are substantially higher than the ~40% increases predicted by Ford et al., 2018 over the West, though the magnitudes of emission changes in the

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two studies are similar. As in our study, Ford et al., 2018 relied on a land cover model, but they also attempted to account for the influence of future changes in meteorology and population on the suppression and ignition of fires. Ford et al., 2018 predicted scattered emission increases of 40-45% over the West and a large increase of 85-220% over the Southeast due to increasing population and the role of human ignition. However, human activities have diverse impacts on wildfires, and those impacts are a function of land management policy, economics, and other social trends, making it challenging to predict how trends in human ignitions, fuel treatment, and fire suppression will evolve in the future (Fusco et al., 2016). In our study, we confine our focus to fires in national forests and parks in the West, where human activities such as landscape fragmentation through land use are less important. We further find that the patterns of increasing fire emissions by 2100 in our study – i.e., over the forests in northern Idaho, western Montana, and over the U.S. Pacific Northwest – are similar to those predicted by other studies, including Rogers et al., 2011 and Ford et al., 2018. Our study also predicts significantly elevated smoke PM in Utah, Wyoming, and Colorado in the late-21st century under RCP8.5 and in regions east of the Rocky Mountains because of the prevailing westerly winds.

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The following limitations apply to our study. The vegetation model simulations of biomass and fire are driven by meteorology from just one climate model, GISS-E2-R. Over the WUS, this model simulates future temperature changes at the low end of projections by the CMIP5 ensemble, making our predictions of future fire conservative (Sheffield et al., 2013; Ahlström et al., 2012; Rupp et al., 2013). Also, the GEOS-Chem simulations are driven with present-day MERRA-2 meteorology. Besides changes in fire emissions, future work could examine how changing meteorology may further influence smoke lifetime and transport processes, and investigate the feedback of fire on meteorology by developing an online coupled modeling approach.

Anthropogenic ignitions are not considered in this study, but fire behavior and therefore burned area simulated by LPJ-LMfire are primarily governed by meteorology and fuel structure. The fire simulations are performed on a 0.5°×0.5° grid, which cannot capture some the fine-grain structure of the complex topography and sharp ecotones present in our study area (e.g., Shafer et al., 2015). Our study also does not consider the effects of future climate change on the transport or lifetime of smoke PM, nor the feedback of smoke aerosols on regional climate. Previous work, however, has shown that climate effects on smoke PM are likely to be small relative to the effect of changing wildfire activity (Spracklen et al., 2009).

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Within these limitations, our results highlight the vulnerability of the WUS to lightning-caused wildfire in a changing climate. Even though a changing climate decreases the living biomass in some regions, we find that ample vegetation exists to fuel increases in fire activity and smoke. Especially strong enhancements in smoke PM occur in the Northern Rockies in the late-21st century under both the moderate and strong future emissions scenarios, suggesting that climate change will have a large, detrimental impact on air quality, visibility, and human health in a region valued for its national forests and parks. Our study thus provides a resource for environmental managers to better prepare for air quality challenges under a future climate change regime.

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Data availability

Data related to this paper may be requested from the authors.

Author contributions

Y.L. conceived and designed the study, performed the GEOS-Chem simulations, analyzed the data, and wrote the manuscript, with contributions from all coauthors. J.O.K. performed the LPJ-LMfire simulations.

Competing interests

The authors declare that they have no competing interest.

Acknowledgments

This research was developed under Assistance Agreements 83587501 and 83587201 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by the EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the EPA. We thank all of the data providers of the datasets used in this study. PM data was provided by the Interagency Monitoring of Protected Visual Environments (IMPROVE; available online at http://vista.cira.colostate.edu/improve). IMPROVE is a collaborative association of state, tribal, and federal agencies, and international partners. U.S. Environmental Protection Agency is the primary funding source, with contracting and research support from the National Park Service. JOK is grateful for access to computing resources provided by the School of Geography and the Environment, University of Oxford. The Air Quality Group at the University of California, Davis is the central analytical laboratory, with ion analysis provided by the Research Triangle Institute, and carbon analysis provided by the Desert Research Institute. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the group of NASA Goddard Institute for Space Studies for producing and making available their GISS-E2-R climate model output. For CMIP the U.S.

Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The GISS-E2-R dataset were downloaded from https://cmip.llnl.gov/cmip5/. We thank the Land-use Harmonization team for producing the harmonized set of land-use scenarios and making available the dataset online at http://tntcat.iiasa.ac.at/RcpDb/. We also thank X. Yue for providing the raster of southern California.

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Figures and tables

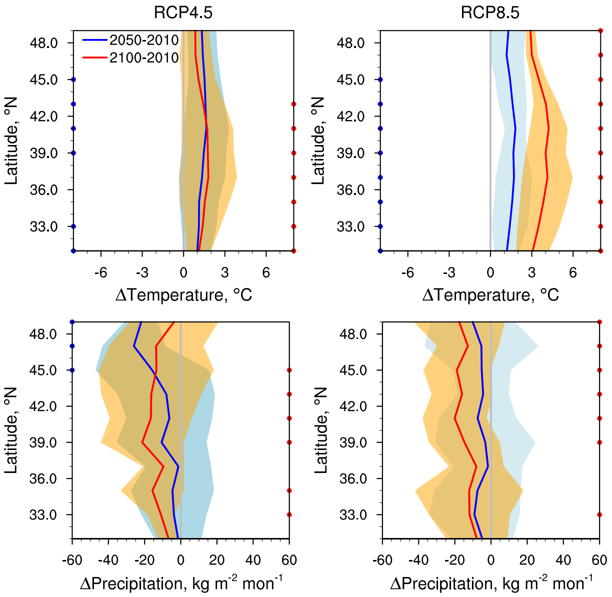


Figure 1. Modeled changes in temperature (top) and precipitation (bottom) in July-August-September (JAS) at ~2050 and ~2100 as a function of latitude over the WUS for RCP4.5 (left) and RCP8.5 (Nadelhoffer et al.). Changes are zonally averaged and relative to the present day (~2010), with 5-year averages in each time slice. The bold blue lines show the changes between 2010 and 2050, averaged over all longitudes in the WUS (31°N – 49°N, 100°W – 125°W); bold red lines show the mean changes between 2010 and 2100. Light blue and orange shadings represent the temporal standard deviation across the 15 months (5 years x 3 months) of each time slice. Blue dots along the axes mark those latitudes showing statistically significant differences between the JAS 2010 and 2050 time slices ($p < 0.05$); red dots mark those latitudes with statistically significant differences at 2100. Temperatures and precipitations are from the GISS-E2-R climate model.

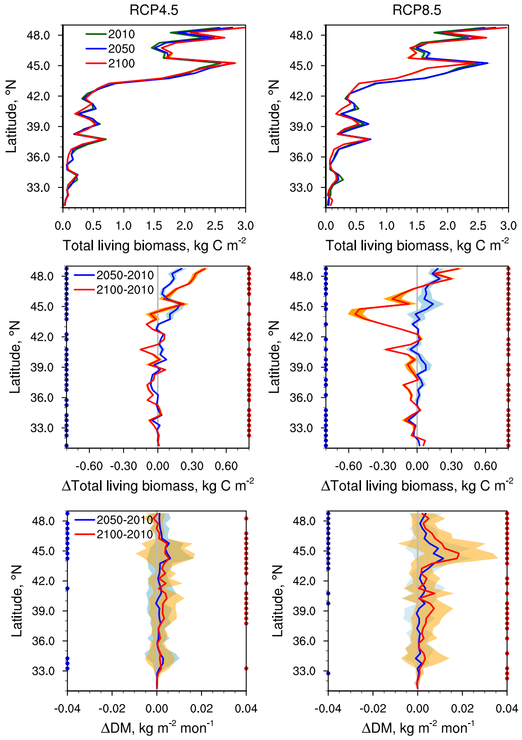


Figure 2. The top panel shows total living biomass at ~2010, ~2050 and ~2100 as a function of latitude over the WUS for RCP4.5 (left) and RCP8.5 (Nadelhoffer et al.), with 5-year averages in each time slice. The lower four panels are as in Figure 1, but for changes in total living biomass (middle) and lightning-caused dry matter burned (DM; bottom) as a function of latitude over the WUS. Results of living biomass and DM are from LPJ-LMfire. As in Figure 1, dots along the axes mark those latitudes showing statistically significant differences.

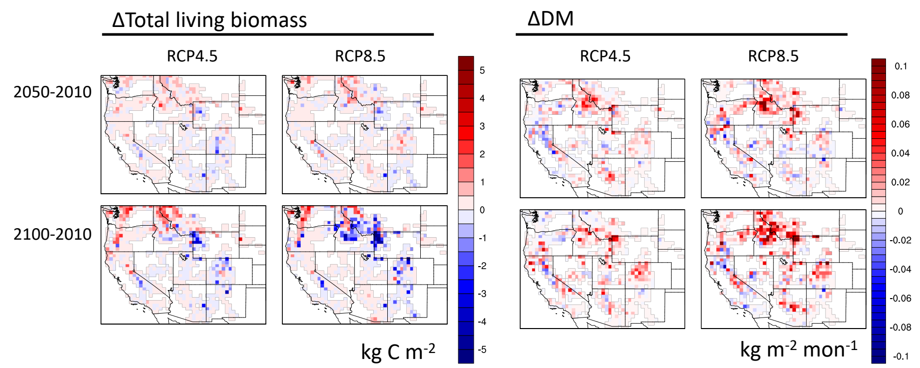
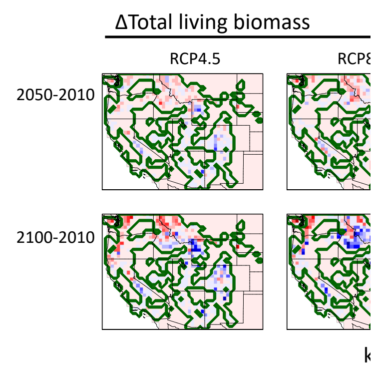


Figure 3. Simulated changes in yearly mean total living biomass and monthly mean DM averaged over the fire season in the national forests and parks across the WUS for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire, with five years representing each time period. The fire season is July, August, and September. White spaces indicate areas outside the national forests and parks.



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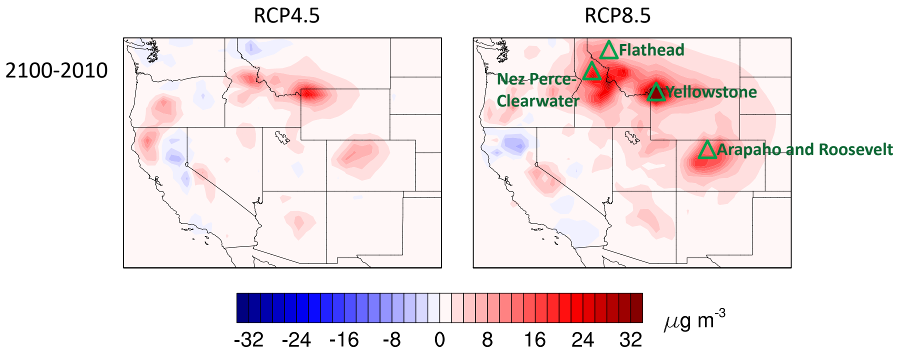

Figure 4. Simulated changes in fire-season smoke PM (BC+OC) at ~2100 relative to the present day for RCP4.5 and RCP8.5. Results are from GEOS-Chem at a spatial resolution 0.5° x 0.625°, averaged over July, August, and September. Each time period is represented by a 5-year time slice. National parks and forests that experience large smoke PM enhancements are labeled by green triangles.

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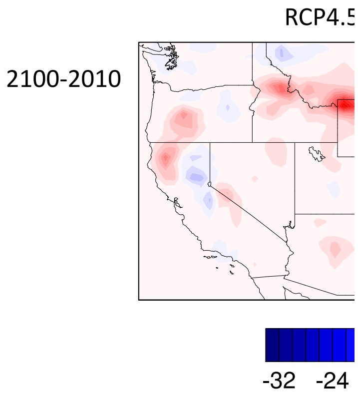

Table 1. Total living biomass, dry matter burned (DM), and smoke PM (BC+OC) emissions over national forests and parks in the WUS and smoke PM concentrations averaged across the entire West. Values for the present day (~2010) are shown in the top row; changes in ~2050 and ~2100 relative to the present day are shown in bottom two rows. Statistically significant changes are in boldface.

Time slices	**Living biomass[b], Tg/yr**		**DM[b], Tg/JAS**		**BC+OC emission[b], Tg/JAS**		**BC+OC[c], $\mu g\ m^{-3}$**	
	RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
2010[a]	3074.8±33.7	3036.9±55.5	22.16±4.16	30.96±7.15	0.15±0.04	0.21±0.06	2.11±0.48	2.55±0.81
2050-2010[a]	138.2±46.0	126.2±80.2	**18.0±16.1**	**26.7±14.8**	**0.15±0.13**	**0.23±0.15**	--	--
2100-2010[a]	119.6±34.4	-270.7±76.1	**24.6±13.2**	**50.0±18.0**	**0.18±0.14**	**0.39±0.17**	**1.11±1.02**	**2.78±1.73**

[a] Each time slice represents 5 years; [b] Values are fire-season summations over national forests and parks;
[c] BC+OC concentrations are fire-season averages over the West;
Statistical significance is not calculated for living biomass.

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Table 2. Reclassification of LPJ-LMfire PFTs.
LPJ-LMfire (9 pfts) ... [1]

Table 2. Comparison of fire predictions in the U.S. under future climate.

Methods	**Region, scenarios, and future time slice**	**Fire metric and percent increase relative to present day**	**Smoke PM and percent increase relative to present day**	**Reference**
Statistical models for lightning fires	Entire U.S. Doubled CO_2 climate	Number of fires: 44% Area burned: 78%		Price and Rind, 1994b
Two climate models	Entire U.S. Doubled CO_2 climate ~2060	Seasonal fire severity rating: 10-50%		Flannigan et al., 2000
Statistical model	California, U.S. A2 ~2100	Large fire risk: 12-53%		Westerling and Bryant, 2008
Statistical models and GEOS-Chem	Western U.S. A1B ~2050	Area burned: 54% Smoke emission: 100%	Smoke PM concentrations BC: 20% OC: 40%	Spracklen et al., 2009
Climate model with global-scale fire parameterization	Global B1, A1B, A2 ~2100	Fire occurrence in the western U.S. B1: 120% A1B: 233% A2: 242%		Pechony and Shindell, 2010
MAPSS-CENTURY 1 dynamic general vegetation model	U.S. Pacific Northwest A2 ~2100	Area burned: 76-310% Burn severity: 29-41%		Rogers et al., 2011
Statistical models + GEOS-Chem	Western U.S. A1B ~2050	Area burned: 63-169% Smoke PM emissions: 150-170%	Smoke PM concentrations: 43-55%	Yue et al., 2013
Statistical models	California, U.S. A1B ~2050	Area burned: 10-100%		Yue et al., 2014
Coupled Community Land Model (CLMv4) and Community Earth System Model (CESM)[2]	Western U.S. RCP4.5 and RCP8.5 ~2050	Smoke PM emissions: • RCP4.5: 100% • RCP8.5: 50%	Total $PM_{2.5}$ concentrations[1] • RCP4.5: 22% • RCP8.5: 63%	Val Martin et al., 2015

CLMv4.5-BGC with fire parameterization coupled with CESM[3]	Contiguous U.S. RCP4.5 and RCP8.5 ~2050 and ~2100 Relative to the present day (1995-2005)	Area burned by 2050: • RCP4.5: 67% • RCP8.5: 50% by 2100: • RCP4.5: 58% • RCP8.5: 108%	Total $PM_{2.5}$ concentrations[1] by 2050: • RCP4.5: 146% • RCP8.5: 85% by 2100: • RCP4.5: 108% • RCP8.5: 246%	Pierce et al., 2017
CLMv4.5 with fire parameterization coupled with CESM[3]	Contiguous U.S. RCP4.5 & RCP8.5 ~2050 and ~2100 Relative to the present day (2000-2010)	Smoke PM emissions by 2050: • RCP4.5: 126% • RCP8.5: 54% by 2100: • RCP4.5: 125% • RCP8.5: 149% by 2050 over the West: • RCP4.5: 45% • RCP8.5: 40%	Total $PM_{2.5}$ concentrations[1] by 2050: • RCP4.5: 113% • RCP8.5: 27% by 2100: • RCP4.5: 93% • RCP8.5: 127%	Ford et al., 2018
LPJ-LMfire coupled with GEOS-Chem	Western U.S. RCP4.5 and RCP8.5 ~2050 and ~2100 Relative to the present day (2011-2015)	Smoke PM emissions by 2050: • RCP4.5: 81% • RCP8.5: 86% by 2100: • RCP4.5: 111% • RCP8.5: 161%	Smoke PM concentrations by 2100: • RCP4.5: 53% • RCP8.5: 109%	This study

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[1] Total $PM_{2.5}$ is the combination of sulfate, ammonium nitrate, secondary organic aerosols, fine dust, fine sea salt, BC and OC.

[2] This model considers changes in climate, anthropogenic emissions, land cover, and land use.

[3] This model considers changes in climate, anthropogenic emissions, land cover, land use, and population.

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Supplementary material

Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the forests of the Western United States

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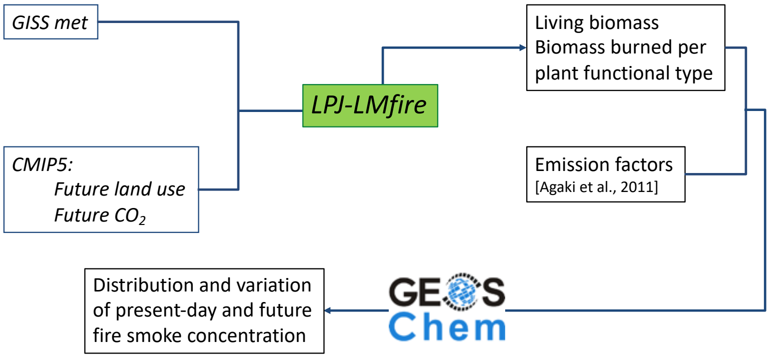

Fig. S1. Flowchart of modeling setup.

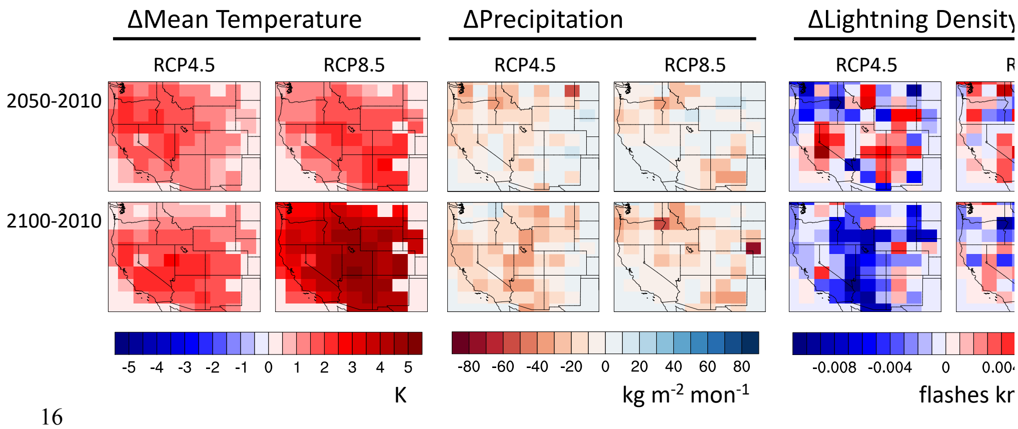

Fig. S2. Changes in monthly mean temperature, precipitation and lightning density averaged over the fire season in the western U.S. for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Temperature and precipitation are from GISS-E2-R for the RCP4.5 and RCP8.5 scenarios, with five years representing each time period. Lightning density is calculated using the GISS convective mass flux following the empirical parameterization of *Magi* [2015]. The fire season is July, August, and September.

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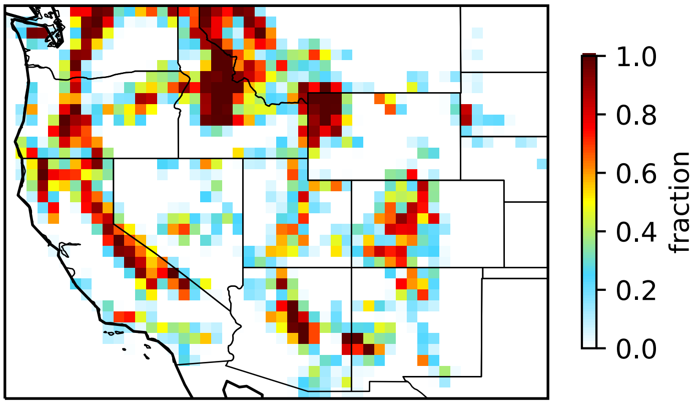

Fig. S3. Map of the National Forest and Park fraction.

Evaluation of LPJ-LMfire fire emissions

We first evaluate the lightning-caused wildfire emissions from LPJ-LMfire over the National Forests in the western U.S. by comparing with the Global Fire Emissions Database (GFED4s) emissions over the same regions (Fig. S4). Lightning is the dominant fire source over the western U.S. forests, allowing a reasonable comparison between the two emission inventories over the forest areas in the West. The total fire-season dry matter burned (DM) over National Forests and Parks from LPJ-LMfire is 22.11 Tg for July-August-September (JAS), comparable to that from GFED4s (19.89 Tg), providing confidence in the LPJ-LMfire representation of fires without active suppression. GFED4s shows greater DM over northern Washington, Idaho, and northern California than LPJ-LMfire but overall the spatial mismatches are not large.

We then validate the carbonaceous fine particulate matter ($PM_{2.5}$; BC+OC) generated by GEOS-Chem in a simulation with the combined emissions (LPJ-LMfire over the National Forests and Parks and GFED4s elsewhere) during JAS. Simulated BC and OC also include contributions from non-fire sources, such as fossil fuel combustion from transportation, industry, and power plants. We compare the GEOS-Chem results against ground-based measurements from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network in the western U.S. We find that GEOS-Chem generally reproduces the IMPROVE observations, with elevated concentrations (~3.0-5.0 µg m^{-3}) over the northern states and in California (Fig. S5). The finer-resolution simulation provides more detailed distributions of fire activity in the western U.S., which are of greater utility to environmental managers. In JAS, large amounts of smoke PM are transported from Canada, as implied by some IMPROVE observations in Idaho and Montana. GFED4s includes the smoke from these Canadian fires, as reflected by elevated smoke PM in the northeast corner of the domain in the GEOS-Chem results. Results in RCP8.5 for the present-day

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are similar to those under RCP4.5 (not shown). We also compare 5-year fire-season averages of smoke PM in each grid cell in the western U.S. from GEOS-Chem against those from IMPROVE observations (Fig. S6). The GEOS-Chem simulation with combined emissions generally reproduces smoke PM within an uncertainty of 50%.

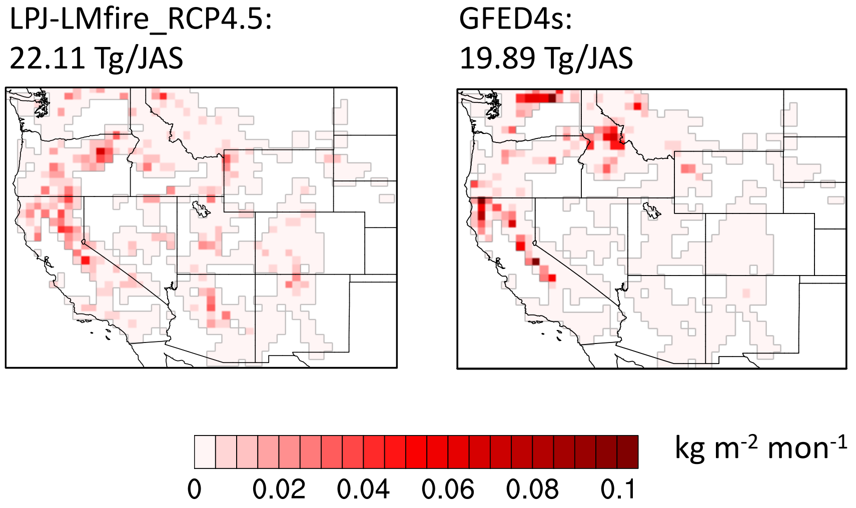

Fig. S4. Present-day (2011-2015) fire-season averaged lightning-caused dry matter burned (DM) over the national forests and parks in the western U.S. for LPJ RCP4.5 and GFED4s. Value are the total fire-season DM over the national forests and parks in the two inventories. The fire season is July, August, and September. White spaces indicate areas outside the national forests and parks.

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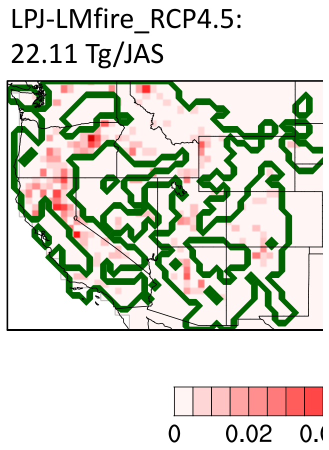

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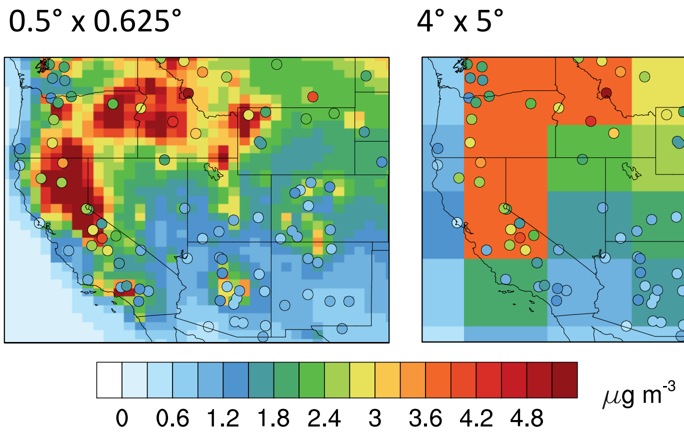

Fig. S5. Fire-season averaged smoke PM. Circles represent ground-based observations from the IMPROVE network. The colored background is from GEOS-Chem simulations at 0.5° x 0.625° and 4° x 5° spatial resolutions for the present-day (2011-2015) using the combined fire emissions from LPJ-LMfire over the national forests and parks and GFED4s over other regions. The fire season is July, August, and September.

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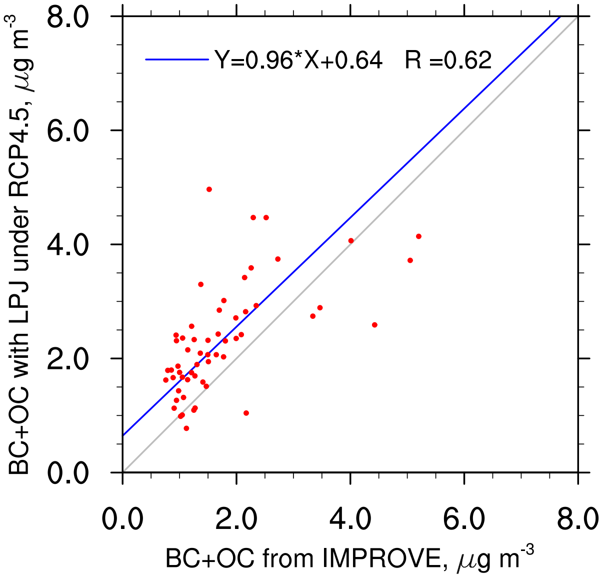

Fig. S6. BC+OC concentrations simulated with the present-day combined fire emissions from LPJ RCP4.5 (over National Forests) and GFED4s (over other regions) compared to those from IMPROVE observations. Each dot represents the 5-year fire-season average of concentrations in each grid square (with the resolution of 4° x 5°) across the western U.S. The blue line is the fitted line using reduced major axis (RMA) regression between the GEOS-Chem simulations and those from IMPROVE. The grey line denotes the 1:1 line.

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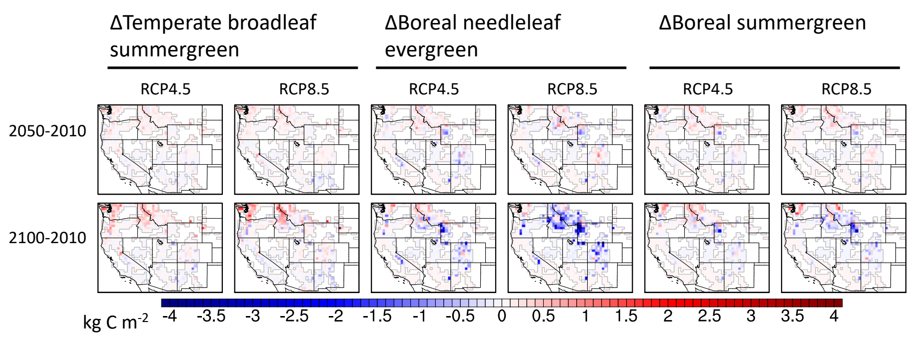
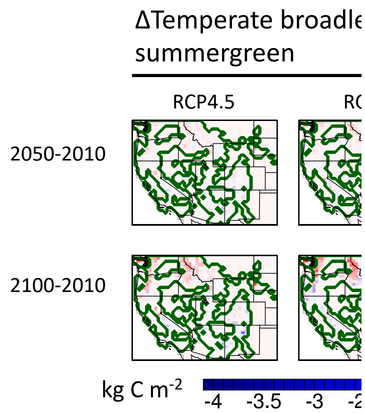


Fig. S7. Simulated changes in living biomass for the three most dominant plant functional types over the national forests and parks in the western U.S. for the RCP4.5 and RCP8.5 scenarios. The top row shows changes between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire, with five years representing each time period. The fire season is July, August, and September. White spaces indicate areas outside the national forests and parks.



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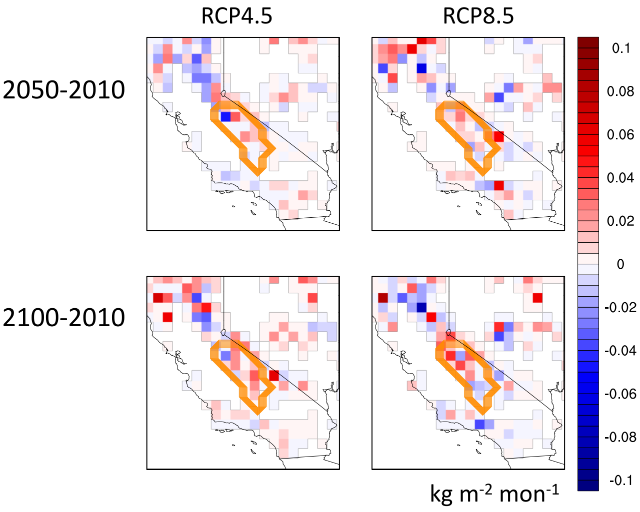
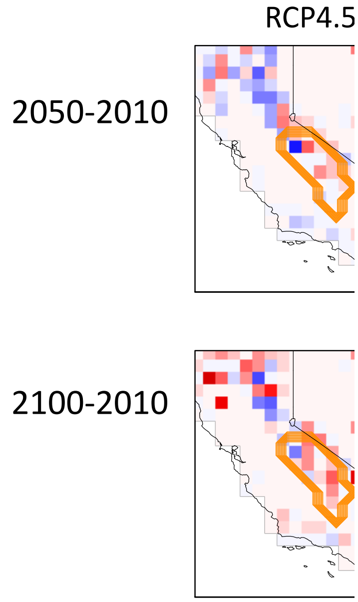


Fig. S8. Simulated changes in monthly mean lightning-caused DM averaged over the fire season over the national forests and parks in California for the RCP4.5 and RCP8.5 scenarios. The top row shows changes in DM between the present day and 2050, and the bottom row shows changes between the present day and 2100. Results are from LPJ-LMfire for the RCP4.5 and RCP8.5 scenarios, with five years representing each time period. The fire season is July, August, and September. Bold orange lines mark the boundaries of the Sierra Nevada (SN). White spaces indicate areas outside the national forests and parks.



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Methods ... [1]

Table S1. Reclassification of LPJ-LMfire PFTs.

LPJ-LMfire (9 pfts)	**GEOS-Chem (6 pfts)**
Tropical broadleaf evergreen	Tropical forest
Tropical broadleaf raingreen	Tropical forest
Temperate needleleaf evergreen	Temperate forest
Temperate broadleaf evergreen	Temperate forest
Temperate broadleaf summergreen	Temperate forest
Boreal needleleaf evergreen	Boreal forest
Boreal summergreen	Boreal forest
C_3 grass	Crop, pasture
C_4 grass	*50%* -> savanna, grassland, shrubland; 50% -> crop, pasture

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