Response to reviewers

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 reviewers' comments are in blue, and line numbers in blue refer to the original submission. The line numbers in black refer to the revised manuscript.

Summary of revisions. The manuscript now goes into more detail about the processes simulated by LPJ-LMfire, and we more clearly acknowledge the shortcomings in our dust simulation. We have attempted to show how our modeled trends in vegetation across the southwestern United States are consistent with present-day changes. We also now emphasize that the meteorological conditions projected for 2100 in our model are consistent with the increased drought predicted by other studies. We clarify that the trends in vegetation and hence dust are caused by three factors – changes in climate (temperature and precipitation), enhanced CO_2 fertilization, and land use change.

Finally, we have reorganized parts of the Introduction and Methods sections. We now use the term "scenario" to refer to the IPCC scenarios RCP4.5 and RCP8.5, and we use the term "case" to refer to the three conditions applied (all-factor, fixed CO_2 fertilization, and fixed land use.).

Author Response to Reviewer #1

This manuscript describes a coupled modeling study to investigate the role of climate change on dust emissions in southwestern North America (SW). The role of dust emissions and transport in the SW is important for air quality impacts in the region and has been suggested by other research that dust concentrations and associated impacts will likely worsen. The authors incorporate a dynamic vegetation model and a chemical transport model with two different future emission scenarios to examine the effects of land use change and CO_2 fertilization on dust emissions in the SW. They found that under the most extreme future warming scenario used (RCP8.5), the absence of CO_2 fertilization provides an upper bound on increased dust emissions across the SW, but especially in SE New Mexico (NM) and the border between NM and Mexico. It is important to consider various causal impacts in order to design appropriate mitigation strategies, so the types of analyses described in this paper are important and worthwhile.

However, a significant weakness of the paper is the discussion and accounting for the role of drought impacts on dust emissions. The authors don't reference this very important impact to the region and how it might impact CO_2 fertilization and the competing impacts on plant growth through water stress. The paper would also benefit from additional organization and clarification. I recommend a major revision to deal with some of these issues- see detailed in the comments below.

The reviewer raises an important issue. It is true that our study does not consider the direct effects of changes in meteorology – e.g., changes in wind speeds -- on dust emissions. However, we do take into account the effects of soil moisture and drought on plant growth, and such effects do, in turn, influence dust mobilization. Put another way, our study considers the impact of future drought on vegetation, and from there on dust mobilization. We now clarify this point in several places of our manuscript.

Lines 13-29: “Here we drive a dynamic vegetation model (LPJ-LMfire) with future scenarios of climate and land use, and link the results to a chemical transport model (GEOS-Chem) to assess the impacts of land cover on dust mobilization and fine dust concentrations (defined as dust particles less than 2.5 microns in diameter) on surface air quality. In the most extreme warming scenario (RCP8.5), we find that surface temperatures in southwestern North America during the season of greatest dust emissions (March, April, and May) warm by 3.3 K and precipitation decreases by nearly 40% by 2100. These conditions lead to vegetation dieback and an increase in dust-producing bare ground. Enhanced CO_2 fertilization, however, offsets the modeled effects of warming temperatures and rainfall deficit on vegetation in some areas of the southwestern United States. Considering all three factors in RCP8.5 scenario, dust concentrations decrease over Arizona and New Mexico in spring by the late 21st century due to greater CO_2 fertilization and a more densely vegetated environment, which inhibits dust mobilization. Along *Mexico's northern* border, dust concentrations increase as a result of land use intensification. In contrast, when CO_2 fertilization is not considered in the RCP8.5 scenario, vegetation cover declines significantly across most of the domain by 2100, leading to widespread increases in fine dust concentrations, especially in southeastern New Mexico (up to ~2.0 μg m^{-3} relative to the present day) and along the border between New Mexico and Mexico (up to ~2.5 μg m^{-3}).”

Lines 43-48. “Wind speed and vegetation cover are two key factors that determine soil erodibility and dust emissions. Wind gusts mobilize dust particles from the earth’s surface, while vegetation constrains dust emissions by reducing bare land extent and preserving soil moisture (Zender et al., 2003). The high temperatures and reduced soil moisture characteristic of drought play an important role in dust mobilization, since the resulting loss of vegetative cover increases soil erosion (Archer and Predick, 2008; Bestelmeyer et al., 2018).

Lines 56-60: “Climate models predict a warmer and drier environment in southwestern North America through the 21st century, with more frequent and severe drought (Seager and Vecchi, 2010; MacDonald, 2010; Stahle, 2020; Prein et al., 2016; Williams et al., 2020). Such conditions would decrease vegetative cover and allow for greater dust mobilization.”

Lines 152-157: “In our study, we do not specifically track drought frequency under future climate, as the definition of drought is elusive (Andreadis et al., 2005; van Loon et al., 2016). Nonetheless, the meteorological conditions predicted in the RCP8.5 scenario for 2100 align with previous studies projecting increased risk of drought in this region (e.g., Williams et al., 2020), and as we shall see, such conditions, in the absence of CO_2 fertilization, result in decreased vegetation and greater dust mobilization.”

In the Discussion section, we clarify a limitation of our study.

Lines 445-447: “Finally, our study focuses only on the effect of changing vegetation on dust mobilization and does not take into account how changing windspeeds or drier soils in the future atmosphere may more directly influence dust.”

Finally, LPJ-LMfire takes into account the interactions of water stress and CO_2 fertilization.

Lines 59-62: "On the other hand, elevated CO_2 concentrations could increase photosynthesis and decrease transpiration of some vegetation species, allowing for more efficient water use and enhancing growth (Poorter and Perez-Soba, 2002; Polley et al., 2013)."

Lines 167-170: "The model considers the coupling of different ecosystem processes, such as the interactions between CO_2 fertilization, evapotranspiration, and temperature, as well as the competition among different PFTs for water resources (e.g., precipitation, surface runoff, and drainage)."

Line 14: How is surface air quality defined here? Do the authors mean only particulate matter?

Yes. We have restated as follows.

Lines 14-16: "…, and link the results to a chemical transport model (GEOS-Chem) to assess the impacts of land cover on dust mobilization and fine dust concentrations (defined as dust particles less than 2.5 microns in diameter) on surface air quality."

Line 16: Perhaps refer to the "spring time" earlier, it's not clear whether decreasing trends were observed year round and then increasing trends were only in spring? (how is spring defined?)

Done.

Lines 17-19: "In the most extreme warming scenario (RCP8.5), we find that surface temperatures in southwestern North America during the season of greatest dust emissions (March, April, and May) warm by 3.3 K and precipitation decreases by nearly 40% by 2100."

Line 20: Perhaps refer to the fact that only these two drivers were investigated- the role of drought is very important in this region and does not seem to be addressed in this work. (e.g., see Archer and Predick, 2008; MacDonald, 2010; Prein et al., 2016; Stahle, 2020; William et al., 2020)

In this paper, we consider three drivers of dust: climate (including drought), CO_2 fertilization of vegetation, and land use. We have clarified this issue in the Abstract, as described above, and elsewhere.

Lines 39-42: "In this study, we use a suite of models to predict the future influence of three factors – climate change, increasing atmospheric CO_2 concentrations, and land use change – on land cover in this region, and assess the consequences for dust mobilization and dust concentrations."

Lines 375-382: "We apply a coupled modeling approach to investigate the impact of future changes in climate, CO_2 fertilization, and land use on dust mobilization and fine dust concentration in southwestern North America by the end of the 21^{st} century. Table 1 summarizes our findings for the two RCP scenarios and three conditions – all-factor, fixed CO_2, and fixed land use – in spring, when dust concentrations are greatest. We find that in the RCP8.5 fixed-CO_2 scenario, in which the effects of CO_2 fertilization are neglected, VAI decreases by 26% across the region due mainly to warmer temperatures and drier conditions, yielding an increase of 58% in fine dust emission averaged over the southwestern North America."

We have also added the citations suggested by the reviewer.

Line 22: Instead of RCP8.5, just use "most extreme future warming scenario" like was used in line 15. Or define RCP8.5.

Fixed.

Line 17-19: "In the most extreme warming scenario (RCP8.5), we find that surface temperatures in southwestern North America during the season of greatest dust emissions (March, April, and May) warm by 3.3 K and precipitation decreases by nearly 40% by 2100."

Line 24: Above some reference value?

We have clarified as follows.

Lines 25-29: "In contrast, when CO_2 fertilization is not considered in the RCP8.5 scenario, vegetation cover declines significantly across most of the domain by 2100, leading to widespread increases in fine dust concentrations, especially in southeastern New Mexico (up to ~2.0 μg m^{-3} relative to the present day) and along the border between New Mexico and Mexico (up to ~2.5 μg m^{-3})."

Line 25: It would be helpful to the reader if the authors leave them with a motivation for this study. Why should the reader care? Future mitigation strategies? Also, some reference to the fact that drought was not studied because many readers will be familiar with the role of drought in this area and wonder if/how/why it was accounted for in this study.

We have made the following changes.

Lines 11-13: "The consequences of climate change for dust mobilization and concentrations are unknown, but could have large implications for human health, given connections between dust inhalation and disease."

Lines 29-31: "Our results have implications for human health, especially for the health of the indigenous people who make up a large percentage of the population in this region."

Lines 103-105: "Given the deleterious impacts of airborne dust on human health, our dust projections under different climate scenarios have value for understanding the full array of potential consequences of anthropogenic climate change."

We now tie our results to the predicted trends in drought, as described in pages 1-2 of this document.

Line 32: And soil moisture? Drought? (for example, see references listed above)

Yes. We now clarify.

Lines 46-48: “The high temperatures and reduced soil moisture characteristic of drought play an important role in dust mobilization, since loss of vegetative cover during drought increases soil erosion (Archer and Predick, 2008; Bestelmeyer et al., 2018).”

Line 39: Here and throughout the paper it is unclear what the authors define as “climate change” and it is important to define it here. Do they just mean increased emissions? Or increased temperatures? Increased drought?

We have clarified our approach.

Lines 93-98: “In this study, we investigate the effects of climate change, increasing CO_2 fertilization, and future land use practices on vegetation in southwestern North America, and we examine the response of dust mobilization due to these changes in vegetation. With regard to climate, we examine whether a shift to warmer, drier conditions by 2100 enhances dust mobilization in this region by reducing vegetation cover and exposing bare land.”

Line 39-42: These sentences read like they should come towards the end of the Introduction.

Done.

Line 44-49: Where did these studies occur? It also seems that the estimates would depend largely on the particular region of study, since different regions may have different controlling factors.

These are all global studies.

Lines 70-72: “For example, Woodward et al., 2005 predicted a tripling of the global dust burden by 2100 relative to the present day, while other studies suggested a decrease in the global dust burden (e.g., Harrison et al., 2001, Mahowald and Luo, 2003 and Mahowald et al., 2006).”

Line 60: This study indicates the importance of drought, but again, it is not clear whether the impacts of increased drought is included in this study?

See response to next comment.

Line 69: If “climate-induced changes” includes the role of drought, it should be described here because it is unclear. If it is not, the authors need to address why this very important role was not considered.

As clarified on pages 1-2 of this document, our study takes into account the effect of changing temperatures and precipitation on vegetation, which in turn influences dust mobilization. Here is another place in the revised manuscript where we emphasize the role of drought.

Lines 153-157: “Nonetheless, the meteorological conditions predicted in the RCP8.5 scenario for 2100 align with previous studies projecting increased risk of drought in this region (e.g., Williams et al., 2020), and as we shall see, such conditions, in the absence of CO_2 fertilization, result in decreased vegetation and greater dust mobilization.

Line 75: Like the abstract, the end of the Introduction would benefit from an implications statement, or some description of what these results could inform in terms of public policy or future studies.

We now add a description.

Lines 103-105: “Given the deleterious effects of airborne dust on human health, our dust projections under different climate scenarios have value for understanding the full array of potential consequences of anthropogenic climate change.”

Line 77: An overall statement about the Methods section. It is difficult to follow, descriptions of some of the models and methods are scattered throughout the sections. The entire section would benefit from a streamlining and overall organization. It seems like the authors are giving a brief overview of the method at the beginning, which is fine, but in its present form it includes some details that leave the reader looking around for descriptions that aren’t included until later. Perhaps leave the overview very general and then describe each step in more detail.

We have restructured the overview of the Methods section and now include a new subsection describing the GISS Model E (Section 2.1).

Line 85:86- Time periods aren’t given, GISS is discussed here but then again in line 133 (maybe a separate “GISS” section, like the other models have?).

We now include information about the time period simulated by the GISS model.

Lines 132-133: “The simulations cover the years 1801 to 2100 at a spatial resolution of 2° latitude x 2.5° longitude.”

Line 88: Again, what does “changes in climate” mean in this context?

We now clarify.

Lines 180-186. “For this study we follow Li et al., 2020, in linking meteorology from GISS-E2-R to LPJ-LMfire in order to capture the effects of climate change on vegetation. Meteorological fields from the GISS model include monthly mean surface temperature, diurnal temperature range, 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. Monthly mean lightning strike density, calculated using the GISS convective mass flux and the empirical parameterization of Magi, 2015, is also applied to LPJ-LMfire.”

Lines 189-190. “LPJ-LMfire then simulates the response of natural vegetation to the 21st century trends in these meteorological fields and to increasing CO_2.”

Line 93: How is "fine dust" defined (again, this comes later).

As described above, we define fine dust in the Abstract and also now in the Introduction.
Lines 35-37: "By causing respiratory and cardiovascular diseases, fine dust particles – i.e., those particles with diameter less than 2.5 microns – can have negative effects on human health..."

Line 100: We are in the Methods section?

Fixed.

Line 102-107: This seems misplaced, perhaps it should go in a separate "GISS" section?

We have a new section on the GISS model, with more detail on the simulation. For example, we now say the following.

Lines 133-135: "Changes in climate in the GISS model are driven by increasing greenhouse gases. In RCP4.5, CO_2 concentrations increase to 550 ppm by 2100; in RCP8.5 the CO_2 increases to 1960 ppm (Meinshausen et al., 2011)."

Line 109: What land use fields are included in the model and where do they come from? Some reference to this is included in line 237 but would be useful to know sooner. Where does the vegetation information come from? Is it representative of desert vegetation? Where does wildfire information come from and does it change over time? Do the meteorological anomalies characterize future drought?

We have revamped part of Section 2.2 on LPJ-LMfire.

Lines 180-191: "For this study we follow Li et al., 2020, in linking meteorology from GISS-E2-R to LPJ-LMfire in order to capture the effects of climate change on vegetation. Meteorological fields from the GISS model include monthly mean surface temperature, diurnal temperature range, 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. Monthly mean lightning strike density, calculated using the GISS convective mass flux and the empirical parameterization of Magi, 2015, is also applied to LPJ-LMfire. To downscale the 2° x 2.5° GISS meteorology to finer resolution for LPJ-LMfire, we calculate the 2010-2100 monthly anomalies relative to the average over the 1961-1990 period, and then add these anomalies to an observationally based climatology (Pfeiffer et al., 2013). Natural vegetation in LPJ-LMfire then simulates the response to the 21st century trends in these meteorological fields and to increasing CO_2. We apply the same changes in CO_2 concentrations as those applied to the GISS model."

Lines 192-196: "We overlay the changes in natural land cover with future land use scenarios from CMIP5 (LUH; Hurtt et al., 2011; http://tntcat.iiasa.ac.at/RcpDb/, last accessed on 17 July 2020). These scenarios include land used for crops, ranching (rangeland), and urban areas, all of which result in reduction in aboveground biomass, an increase in herbaceous relative to woody plants, and an increase in the extent of bare ground."

Lines 205-210: "The LPJ-LMfire simulations yield monthly timeseries of the leaf area indices (LAI) and fractional vegetation cover (σ_v) for nine plant functional types (PFTs): tropical broadleaf evergreen, tropical broadleaf raingreen, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, boreal needleleaf evergreen, and boreal summergreen trees, as well as C_3 and C_4 grasses."

We convert the LAI from LPJ-LMfire to vegetation area index (VAI), and the result is generally comparable with satellite derived VAI for this region as well as observed land cover over the principle dust-producing regions.

Lines 30-37 (Supplement): "Figure S4 compares the differences in springtime VAI generated by LPJ-LMfire for the present day and that derived from 1-km reflectance data from the Advanced Very High Resolution Radiometer (AVHRR, Bonan et al., 2002). This satellite-based VAI is the default dataset in the DEAD module (Zender et al., 2003). The differences between these two VAI datasets are mostly small, within ± 1 m^2 m^{-2}, across southwestern North America, giving us confidence in the performance of LPJ-LMfire. In addition, we categorize the LPJ-LMfire simulated land cover types as trees and shrubs, grasses, and barren land (Figure S5). The high-dust emission region shown in Figure S3 is dominated by grass ecosystems and barren land, roughly consistent with observed land cover shown in the photos of four locations (southwest New Mexico, southeast New Mexico, west Texas, and northern Chihuahua state, Mexico) selected from the principle dust-producing regions in our study (Figure S5)."

Lines 42-45 (Supplement). "The dominant plant functional types in LPJ-LMfire in the southwestern North America include temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 perennial grass, consistent with observed, present-day vegetation types (McClaran and van Devender, 1997)."

The LPJ-LMfire model simulates wildfire and its changes under future climate.

We now add more explanations.

Lines 172-179: "Wildfire in LPJ-LMfire depends on lightning ignition, and the simulation considers multiday burning, coalescence of fires, and the spread rates of different vegetation types. The effects of changing fire activity on vegetation cover are then taken into account (Pfeiffer et al., 2013; Sitch et al., 2003; Chaste et al., 2019). Li et al., 2020 predicted a ~50% increase in fire-season area burned by 2100 under scenarios of both moderate and intense future climate change over the western United States. However, the effects of changing fire on vegetation cover are insignificant in the grass and bare ground-dominated ecosystems of the desert Southwest, where the low biomass fuels cannot support extensive spread of fires."

As emphasized in pages 1-2 of this response document, the GISS meteorology in RCP8.5 by 2100 is indeed consistent with drought.

Lines 153-157: "Nonetheless, the meteorological conditions predicted in the RCP8.5 scenario for 2100 align with previous studies projecting increased risk of drought in this region (e.g., Williams et al., 2020), and as we shall see, such conditions, in the absence of CO_2 fertilization, result in decreased vegetation and greater dust mobilization."

Line 118: "Future land use scenarios applied follow CMIP5". Can the authors expand and define CMIP5? What all types of land use scenarios are included?

We now define CMIP5 and clarify what is meant by land use.

Lines 130-132: "…, configured for Phase 5 of the Coupled Model Intercomparison Project (CMIP5; https://esgf-node.llnl.gov/search/cmip5/, last accessed on 17 July 2020)."

Lines 192-196: "We overlay the changes in natural land cover with future land use scenarios from CMIP5 (LUH; Hurtt et al., 2011; http://tntcat.iiasa.ac.at/RcpDb/, last accessed on 17 July 2020). These scenarios include land used for crops, ranching (rangeland), and urban areas, all of which result in reduction in aboveground biomass, an increase in herbaceous relative to woody plants, and an increase in the extent of bare ground."

Line 121-122: Some discussion here regarding how the model accounts for hydrologic feedbacks, such as whether plants react to water limitation?

We have added more details about hydrologic feedbacks in the LPJ-LMfire model.

Lines 165-170: "More specifically, LPJ-LMfire simulates the impacts of photosynthesis, evapotranspiration, and soil water dynamics on vegetation structure and the population densities of different plants functional types (PFTs). The model considers the coupling of different ecosystem processes, such as the interactions between CO_2 fertilization, evapotranspiration, and temperature, as well as the competition among different PFTs for water resources (e.g., precipitation, surface runoff, and drainage)."

Line 122: "…and analyze results over…" This sentence is redundant and unnecessary.

Deleted.

Line 125-128: Discussion of RCP4.5 and RCP4.8 seems out of order here.

We have moved the discussion of the RCPs to the beginning of Section 2.

Line 129-133: Redundant, see lines 85-87. Again, move the GISS information into a GISS section.

Done. We now have a new section on the GISS model, Section 2.1.

Line 161: How representative are these of desert plants in the Southwest?

Although cactuses are missing from LPJ-LMfire, overall, the simulated vegetation distribution and composition is consistent with observations. We now add more explanations.

Lines 241-244: "Of the nine PFTs, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C3 grasses dominate the region, with temperate needleleaf evergreen having the highest LAI in spring. This mix of vegetation type is consistent with observations (e.g., McClaran and van Devender, 1997)."

Lines 42-45 (Supplement): "The dominant plant functional types in LPJ-LMfire in the southwestern North America include temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 perennial grass, consistent with observed, present-day vegetation types (McClaran and van Devender, 1997)."

Line 165: I assume (based on equation 3) that 7 different PFTs are included to represent stem area index? What are they?

We consider the stem area index from just 7 PFTs.

Lines 235-237. "We also assume that C_3 and C_4 grasses have zero stem area to avoid overestimating VAI during the winter and early spring when such grasses are dead."

The term σ_v refers to fractional vegetation cover.
Lines 240-241: "…LAI is for the nine PFTs from LPJ-LMfire, but σ_v is for just seven PFTs, with σ_v for C_3 and C_4 grasses not considered."

Line 170: Are all plants represented here responsive to CO_2 fertilization? How do the effects of drought, heat, and evapotranspiration offset gains in CO_2 fertilization and can this be captured by the model? If not, it should be stated.

Yes, all PFTs in LPJ-LMfire respond to changing CO_2. We show this through the series of sensitivity tests we performed (e.g., Figure S10).

Lines 170-172: "The different PFTs in LPJ-LMfire respond differently to changing CO_2, with CO_2 enrichment preferentially stimulating photosynthesis in woody vegetation and C_3 grasses compared to C_4 grasses (Polley et al., 2013)."

We also have clarified the interactions considered by the model.

Lines 167-170: "The model considers the coupling of different ecosystem processes, such as the interactions between CO_2 fertilization, evapotranspiration, and temperature, as well as the competition among PFTs for water resources (e.g., precipitation, surface runoff, and drainage)."

We have also made more clear in the Results section how CO_2 fertilization may offset the impact of climate change.

Lines 291-293: "For the fixed-CO_2 case, western New Mexico and northern Mexico show greater decreases in VAI, indicating how CO_2 fertilization in the other two cases offsets the effects of the warmer and drier climate on vegetation in this region."

Line 177: MERRA is mentioned here for the first time?

We now clarify.

Lines 247-250: "We feed into the DEAD module both the VAI generated by LPJ-LMfire and meteorological fields from Modern-Era Retrospective analysis for Research and Applications (MERRA-2) at a spatial resolution of 0.5° latitude x 0.625° longitude (Gelaro et al., 2017)."

Line 202: Define "springtime"

Done in the Abstract and at the end of the Introduction.

Line 205: These boundaries are not shown on the figures and probably aren't important to mention here.

We have removed "National Forests and Parks."

Lines 283-285: "Strong enhancements (up to ~2.5 m^2 m^{-2}) extend across much of Arizona, especially in the northwestern corner."

Line 237: This description of land use change would be helpful earlier.

Done.

Lines 62-67: "Land use practices, e.g., farming and ranching, industrial activities including mining, and urban sprawl, have changed dramatically over the southwestern North America in recent decades, with Arizona and New Mexico showing decreasing cropland area and northern Mexico experiencing increasing pasture area (Figure S1). Future land use practices could also influence the propensity for dust mobilization by disturbing crustal biomass (e.g., Belnap and Gillette, 1998)."

Lines 192-196: "We overlay the changes in natural land cover with future land use scenarios from CMIP5 (LUH; Hurtt et al., 2011; http://tntcat.iiasa.ac.at/RcpDb/, last accessed on 17 July 2020). These scenarios include land used for crops, ranching (rangeland), and urban areas, all of which result in reduction in aboveground biomass, an increase in herbaceous relative to woody plants, and an increase in the extent of bare ground."

Also, we now provide a figure showing changes in land use in the Supplement, and describe this in the text.

Lines 325-328: "Combined changes in land use are greater under RCP8.5 than RCP4.5, with large increases in RCP8.5 across Mexico but only modest changes in Arizona, New Mexico, and Texas (Figure S9). The increases in Mexico result in the fragmentation of forested landscapes and decrease VAI, especially in coastal forest regions and along the border with the United States."

Line 246: How is "desertification" defined? Does this imply anything about drought?

We have removed the reference to “desertification.”

Line 257: How are “climate stresses” defined and quantified in the model? This implies impacts from drought and water stress on plants, but as mentioned before, this doesn’t seem to be captured by the model? Should “temperature” be “temperate”?

Yes, climate stresses here do imply impacts from drought and water stress. We have fixed the typo. Lines 343-345: “These trends occur due to the climate stresses, e.g., warmer temperatures and decreased precipitation, that impair the growth of temperature broadleaf trees and C_3 grasses. In this case, such stresses are not offset by CO_2 fertilization (Figure S10).”

Line 264: What is the land use type shifting towards in these regions?

We have revised the sentence.

Lines 348-353: “Figure 3 also reveals that land use trends are a major driver of increased dust emissions along the ANM border and western Texas in RCP8.5, as crop- and rangelands expand in this region and temperature broadleaf trees decline (Hurtt et al., 2011). Similarly, the expansion of rangelands in northern Mexico in RCP8.5 reduces natural vegetation cover there (Hurtt et al., 2011), contributing to the increase of fine dust emissions by up to ~0.7 kg m^{-2} mon^{-1}.”

Line 277-278. I am not sure I understand this sentence. Land use is the driver, but climate change makes up the bulk of the increases?

We now clarify with several sentences.

Lines 361-363: “Results from GEOS-Chem in the fixed-CO_2 case for RCP8.5 show that the concentrations of spring fine dust are significantly enhanced in the southeastern half of New Mexico and along the ANM border, with increases up to ~2.5 µg m^{-3} (Figure 4).”

Lines 364-369: “As Figure 3 implies, land use along the ANM border contributes to the increased dust emissions in that area, by up to ~0.7 kg m^{-2} mon^{-1}. Climate change impacts on natural vegetation, however, account for the bulk of the modeled increases in dust emissions in this scenario, by as much as ~1.2 kg m^{-2} mon^{-1} (Figure 2). The modeled wind fields, which are the same in all scenarios, transport the dust from source regions, leading to the enhanced concentrations across much of the domain, as seen in Figure 4.”

Line 279: The authors seem to be implying that winds are also involved in these differences?

Yes, climate change leads to increased dust mobilization in the fixed CO_2 RCP8.5 scenario, and the winds carry the dust across the region, as described in the response above.

Line 292: This wasn’t specifically shown in the results (shifts in land surface type).

We have clarified this issue in the Results section. See Lines 346-353 quoted above.

Line 298-299: And this study doesn't include changes in wind speed, so it's hard to say that the differences between the Pu and Ginoux study are primarily due to the changes in vegetation.

We have clarified the comparison to Pu and Ginoux.

Lines 394-402: "In contrast, the statistical model of Pu and Ginoux, 2017 estimated a 2% decrease in the springtime frequency of extreme dust events in the Southwest U.S., driven mainly by reductions in bare ground fraction and wind speed. Like Pu and Ginoux, 2017, we also find that dust emissions decrease across a broad region of the Southwest when CO_2 fertilization is taken into account, as shown in Figure 2. Pu and Ginoux, 2017 relied on limited data for capturing the sensitivity of dust event frequency to land cover in this region, and neither that study nor Achakulwisut et al., 2018 considered changes in land use, as we do here. The role of changing wind speed, however, is not included in our study, but could be tested in future work."

Line 308: So that I am understanding what is presented in the Table, CO_2 fertilization would correspond to "fixed land use" but I don't see 30% or 64% in the table?

We now clarify this statement.

Lines 407-410: "Correspondingly, in the RCP4.5 scenario for 2100, CO_2 fertilization enhances VAI by 30% in the all-factor case compared to the fixed-CO_2 case (1.07 m^2m^{-2} vs. 0.79 m^2m^{-2}); in RCP 8.5, the 2100 enhancement is 64% (1.11 m^2m^{-2} vs. 0.55 m^2m^{-2}), as shown in Table 1."

Line 312-213: But, as stated previously, it is unclear whether future drought is accounted for, or whether the role of increased temperature and water stress on whether plants are responsive to CO_2 fertilization is addressed. This seems like an important question the authors need to address, as it could change the directions of trends in dust emission. The authors need to discuss how or whether this was accounted for.

We have clarified the role of meteorological variables, including drought, as described on pages 1-2 of this document. We also now make clear that the coupling between CO_2, water stress, and temperature is considered. New text is shown on Lines 160-170 (described above).

Line 367: References: There appears to be formatting inconsistencies with several of the references. I encourage the authors to check their reference manager settings (e.g., line 396, 399, 417, 433, 435, etc.). In addition, "doi's" were not included for any of the references.

We have updated the references and added DOIs for some of the references. Final corrections will be competed in the proofreading phase.

Line 486: Figure 1: This is the first time land use is referred to as "anthropogenic" and would benefit from a description of what this means (in text).

Land use is by definition anthropogenic. We acknowledge that the term "anthropogenic land use" is redundant and have fixed it in multiple places in the manuscript. We now describe land use in more detail (Lines 62-65), as mentioned above in this document.

Line 517: In the "a" description, include whether "2010" is the first year in the 5 year slice.

We now clarify this detail.

Lines 725-726: "Each time slice represents 5 years (i.e., 2011-2015 represents the 2010 time slice and 2095-2099 represents the 2100 time slice)."

Archer and Predick, 2008, "Climate change and ecosystems of the Southwestern United States", Rangelands, 30(3):23-28

Cited.

MacDonald, G.M., 2010 "Water, climate change, and sustainability in the Southwest", PNAS, 107(50).

Cited.

Prein et al., 2016, "Running dry: The U.S. Southwest's drift into a drier climate state", GRL, 43, doi:10.1002/2015GL066727.

Cited.

Stahle, D.W. 2020, "Anthropogenic megadrought", Science, 368 (6488).

Cited.

Williams, A. P., et al., 2020, "Large contribution from anthropogenic warming to an emerging North American megadrought", Science, 368 (314-318).

Cited.

Author Response to Reviewer #2

The authors present a study of how dust emissions across southwestern US states could respond to projected climate changes, elevated atmospheric CO_2 and land use change. Projected climate changes are assessed for two Representative Concentration Pathways (RCP 4.5 and 8.5) representing moderate and continued increases in greenhouse gas concentrations through the 21st century. The effects of the climate projections on surface erodibility are represented through a dynamic vegetation model that is linked to a dust emission scheme and the GEOS-Chem chemical transport model. The general subject matter of the manuscript and approach taken is consistent with regional dust modelling approaches today. Linking a dynamic vegetation model to a dust model to investigate projected climate changes is novel, not straightforward, and has potential to provide new insights into the effects (and interactions) of dust emission under changing land uses and climate.

Overall, my assessment is that, while the subject matter is timely, the manuscript has a number of shortcomings that reduce the relevance of the work and confidence that the conclusions are adequately supported by the approach. These include:

1) While the first paragraph of the Introduction seeks to establish the relevance of the study, this is done only at a very high level and specific research and management impetus are not provided. This high-level treatment of the rationale for the work is carried throughout the manuscript, with the text rarely going deeper than general drivers and responses to justify why the work is important, how it can have impact, who it may have impact for, or how any of the processes and interactions between vegetation, land use and climate actually work and may influence future dust emissions. The superficial treatment of these important elements reduces the impact of the work. Adding detail to these elements would give the work more weight and enable the authors to show exactly what the new insights are that they provide, how they are relevant, and where key uncertainties are.

We thank the reviewer for these thoughtful comments, which we break down into the components below.

1a. Why is the work important, and how can it have impact?

Lines 10-13: "Climate models predict a shift toward warmer and drier environments in southwestern North America over the 21st century. The consequences of climate change for dust mobilization and concentrations are unknown, but could have large implications for human health, given connections between dust inhalation and disease."

Lines 96-98: "With regard to climate, we examine whether a shift to warmer, drier conditions by 2100 enhances dust mobilization in this region by reducing vegetation cover and exposing bare land."

Lines 103-105: "Given the deleterious impacts of airborne dust on human health, our dust projections under different climate scenarios have value in understanding the full array of potential consequences of anthropogenic climate change."

1b. Whom does the work has impact on?

Lines 29-31: "Our results have implications for human health, especially for the health of the indigenous people who make up a large percentage of the population in this region."

Lines 457-462: "In the absence of increased CO_2 fertilization, our work suggests that vegetated cover will contract in response to the warmer, drier climate, exposing bared ground and significantly increasing dust concentrations by 2100. In this way, dust enhancement could impose a potentially large climate penalty on $PM_{2.5}$ air quality, with consequences for human health across much of southwestern North America."

Lines 463-468: "Our finding of the potential for an increased dust burden in the future atmosphere has special relevance for environmental justice in this region, where much of the current population is of Native American and/ or Latino descent. For example, in New Mexico, 10% of the population is Native American and 50% identifies as either Hispanic or Latino. By some measures, New Mexico has also one of highest poverty rates of the United States (https://www.census.gov /quickfacts/NM, last accessed on August 20, 2020)."

1c. How do the processes and interactions between vegetation, land use, and climate actually work and how do they influence dust mobilization?

Lines 96-98: "With regard to climate, we examine whether a shift to warmer, drier conditions by 2100 enhances dust mobilization in this region by reducing vegetation cover and exposing bare land."

Lines 165-179: "More specifically, LPJ-LMfire simulates the impacts of photosynthesis, evapotranspiration, and soil water dynamics on vegetation structure and the population densities of different plants functional types (PFTs). The model considers the coupling of different ecosystem processes, such as the interactions between CO_2 fertilization, evapotranspiration, and temperature as well as the competition among different PFTs for water resources (e.g., precipitation, surface runoff, and drainage). The different PFTs in LPJ-LMfire respond differently to changing CO_2, with CO_2 enrichment preferentially stimulating photosynthesis in woody vegetation and C_3 grass compared to C_4, (Polley et al., 2013). Wildfire in LPJ-LMfire depends on lightning ignition, and the simulation considers multiday burning, coalescence of fires, and the spread rates of different vegetation types. The effects of changing fire activity on vegetation cover are then taken into account (Pfeiffer et al., 2013; Sitch et al., 2003; Chaste et al., 2019). Li et al., 2020 predicted a ~50% increase in fire-season area burned by 2100 under scenarios of both moderate and intense future climate change over the western United States. However, the effects of changing fire on vegetation cover are insignificant in the grass and bare ground-dominated ecosystems of the desert Southwest, where the low biomass fuels cannot support extensive spread of fires."

Lines 414-423: "In summary, we find that as atmospheric CO_2 levels rise vegetation growth is enhanced and dust mobilization decreases, offsetting the impacts of warmer temperatures and reduced rainfall, at least in some areas. These results are consistent with evidence that CO_2 fertilization is already occurring in arid or semiarid environments like southwestern North America (Donohue et al., 2013; Haverd et al., 2020). In such environments, water availability is the dominant constraint on vegetation growth, and the recent increases in atmospheric CO_2 may have reduced stomatal conductance and limited evaporative water loss. The effects of CO_2 fertilization on vegetation growth are uncertain, however, and may be attenuated by the limited supply of nitrogen and phosphorus in soil (Wieder et al., 2015). These nutritional constraints vary greatly among different PFTs (Shaw et al., 2002; Nadelhoffer et al., 1999)."

Lines 457-460: "In the absence of increased CO_2 fertilization, our work suggests that vegetated cover will contract in response to the warmer, drier climate, exposing bared ground and significantly increasing dust concentrations by 2100."

2) A focus of the manuscript is establishing how future vegetation and land use changes may influence dust emissions. However, the authors have not grounded the manuscript in the present situation – What types of vegetation communities are there across the study area? What types of land use changes are occurring today? How important is land use versus land management? How do these present changes relate to the modeled vegetation and land use change scenarios? How are the vegetation communities changing today? What are the implications of vegetation change trajectories today for future responses to elevated CO_2, climate change, and land use? How are these changes related to and influence aeolian processes? By not addressing these questions, the work presents as a typical dust modelling study and/but detached from reality. Expanding the Introduction and Discussion sections is needed to ground the work 'in the real world' and could help the authors demonstrate the relevance and contribution of the study (point #1 above).

Again, we break down the reviewer's questions into components.

2a. What types of vegetation communities are there across the study area?

Lines 49-50: "Southwestern North America is covered by desert grassland, perennial grassland, savanna, desert scrub, and grassy shrublands or woodlands (McClaran and Van Devender, 1997)."

Lines 241-244: "Of the nine PFTs, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 grasses dominate the region, with temperate needleleaf evergreen having the highest LAI in spring. This mix of vegetation type is consistent with observations (e.g., McClaran and van Devender, 1997)."

Figure S4 compares the differences between springtime VAI simulated by LPJ-LMfire and that derived from 1-km satellite data in southwestern North America. Figure S5 further compares LPJ simulated vegetation types with observed land cover for four selected locations across the principle dust-producing regions.

Lines 30-41 (Supplement): "Figure S4 compares the differences in springtime VAI generated by LPJ-LMfire for the present day and that derived from 1-km reflectance data from the Advanced Very High Resolution Radiometer (AVHRR, Bonan et al., 2002). This satellite-based VAI is the default dataset in the DEAD module (Zender et al., 2003). The differences between these two VAI datasets are mostly small, within ± 1 m^2 m^{-2}, across southwestern North America, giving us confidence in the performance of LPJ-LMfire. In addition, we categorize the LPJ-LMfire simulated land cover types as trees and shrubs, grasses, and barren land (Figure S5). The high-dust emission region shown in Figure S3 is dominated by grass ecosystems and barren land, roughly consistent with observed land cover shown in the photos of four locations (southwest New Mexico, southeast New Mexico, west Texas, and northern Chihuahua state, Mexico) selected from the principle dust-producing regions in our study (Figure S5)."

Lines 42-45 (Supplement): "The dominant plant functional types in LPJ-LMfire in the southwestern North America include temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 perennial grass, roughly consistent with observed, present-day vegetation types (McClaran and van Devender, 1997)."

2b. What types of land use changes are occurring today?

Lines 62-65: "Land use practices, e.g., farming and ranching, industrial activities including mining, and urban sprawl, have changed dramatically over the southwestern North America in recent decades, with Arizona and New Mexico showing decreasing cropland area and northern Mexico experiencing increasing pasture area (Figure S1)."

2c. How important is land use versus land management?

In our study, land use refers to the human use of land – e.g., establishing and maintaining croplands or settlements. Land management typically refers to how humans manage the land once natural vegetation has been altered – e.g., through fertilizer use, crop rotation, agricultural fires, or fire suppression. In our simulations, fire is not allowed to occur on cropland and rangeland, so we do have some land management. On the other hand, we do not account for stocking densities on rangeland, which when mismanaged, can lead to reduction of vegetation cover and enhanced dust emissions.

Lines 192-201. "We overlay the changes in natural land cover with future land use scenarios from CMIP5 (LUH; Hurtt et al., 2011; http://tntcat.iiasa.ac.at/RcpDb/, last accessed on 17 July 2020). These scenarios include land used for crops, ranching (rangeland), and urban areas, all of which result in reduction in aboveground biomass, an increase in herbaceous relative to woody plants, and an increase in the extent of bare ground. The present-day land use in the LUH dataset is taken from the HYDE database v3.1 (Goldewijk, 2001; Goldewijk et al., 2010), which in turn is based on array of sources, including satellite observations and government statistics. In RCP8.5, the extent of crop- and rangeland cover increases by ~30% in Mexico but decreases by 10-20% over areas along Mexico's northern border in the U.S. (Hurtt et al., 2011). Only minor changes in land use practices by 2100 are predicted under RCP4.5 (Hurtt et al., 2011)."

2d. How do present changes in land use relate to the modeled vegetation and land use change scenarios?

We validate the present-day land cover in LPJ-LMfire, as described in #2a above, and we discuss the extent of present-day land use and recent changes in #2b above. The source of present-day land use is the HYDE database v3.1.

Lines 196-198: "The present-day land use in the LUH dataset is taken from the HYDE database v3.1 (Goldewijk, 2001; Goldewijk et al., 2010), which in turn is based on array of sources, including satellite observations and government statistics."

2e. How are the vegetation communities changing today? What are the implications of vegetation change trajectories today for future responses to elevated CO2, climate change, and land use?

We now comment on recently observed changes in land cover in response to drought.

Lines 384-390: "Our findings of decreasing VAI with future climate change are consistent with observed trends in vegetation during recent droughts in this region. For example, Breshears et al., 2005 documented large-scale die-off of overstory trees across southwestern North America in 2002-2003 in response to short-term drought accompanied by bark beetle infestations. Similarly, during a multi-year (2004-2014) drought in southern Arizona, Bodner and Robles, 2017 found that the spatial extent of both C_4 grass cover and shrub cover decreased in the southeastern part of that state."

3) The modeled vegetation changes appear unconnected to vegetation changes occurring across southwestern US landscapes today and are not adequately represented in the dust model. As described in Sections 2.2 and 2.3, the DEAD model is used to estimate dust emissions, with vegetation effects represented through a linear adjustment term Av that is calculated from VAI that is the sum of leaf and stem area indices. This approach makes two assumptions that are inconsistent with the physics of aeolian transport and drag partition theory: 1) fractional vegetation cover adequately represents lateral surface aerodynamic sheltering – ergo structural changes in surface roughness due to changing vegetation were not represented while they are likely to have a greater influence on dust emissions than fractional ground cover (Av), and 2) adjustments to the fractional vegetation cover can be made through a dynamic vegetation model (to represent vegetation change) that are separate to the dust model drag partition scheme and its use of aerodynamic roughness lengths (z0) – creating a functional disparity in how vegetation is represented in different parts of the model. I identify these issues in full recognition of the difficulty of accurately representing future vegetation change in a dust model. However, these two assumptions also potentially undermine the validity of the model experiments and so need to be addressed transparently. Further, what are the implications of the model parameterization for the rigor of the results? How much confidence can we have in the outcomes of the study? Where are the gaps that need to be addressed? Turning this challenge into a positive – what insights does this work provide for how future research can address interactions among climate change, vegetation change, land use and dust emissions?

Again, we address the comments by component.

3a. The reviewer states that the modeled vegetation changes appear "unconnected" to observed vegetation changes occurring across southwestern US landscapes today.

We validate the present-day land cover, as described in #2a above. Present-day land-use is from the HYDE database, which in turn depends on satellite observations and government statistics, as described in #2d above.

3b. The reviewer points out that fractional vegetation cover may not adequately represent lateral surface aerodynamic sheltering. This is a common weakness among dust models, and we now acknowledge this shortcoming in the Discussion.

Lines 430-440. "Other uncertainties in our study can be traced to the dust simulation. The different vegetation types in our model are quantified as fractions of gridcells, which have relatively large spatial dimensions of ~50 km × 60 km. This means the model cannot capture the spatial heterogeneity of land cover, and the aerodynamic sheltering effects of vegetation on wind erosion are neglected, as they are in most 3-D global model studies. Such sheltering could play a large role in dust mobilization (e.g., Liu, 1990). New methods involving satellite observations of surface albedo promise to improve understanding of the effects of aerodynamic sheltering on dust mobilization, at least for the present-day (Chappell and Webb, 2016; Webb and Pierre, 2018). Implementation of aerodynamic sheltering in simulations of future climate regimes would need to account for fine-scale spatial distributions of vegetation."

3c. Finally, the reviewer points out a "functional disparity" in our approach, with vegetation changes applied to the calculation of VAI but not to that of aerodynamic roughness length. We now acknowledge this disconnect.

Lines 253-256: "The scheme assumes that the vertical flux of dust is proportional to the horizontal saltation flux, which in turn depends on surface friction velocity and the aerodynamic roughness length Z_0. As recommended by Zender et al., 2003, and consistent with Fairlie et al. (2007) and Ridley et al. (2013), we uniformly set Z_0 to 100 μm across all dust candidate grid cells."

Lines 440-443: "In addition, as recommended by Zender et al. (2003), we apply a globally uniform surface roughness Z_0 in the model, which means that the impact of changing vegetation conditions on friction velocity is not taken into account. Future work could address this weakness by varying friction velocity according to vegetation type."

While we have not explored the entire range of parameter uncertainty in the model, we do tackle the principle drivers of vegetation/dust change by running sensitivity tests with fixed climate and CO_2 and land use. These scenarios allow us to show the range of potential possible outcomes.

4) Literature cited is constrained to dust modelling studies and a few supporting studies related to the vegetation and climate modelling. In addressing my concerns above, the authors could draw on the rich and diverse literature addressing vegetation and land use changes, and their interactions with aeolian processes, across the southwestern US.

We have added a lot of citations that address vegetation and land use change. Here are some examples:

Andreadis, K. M., E. A. Clark, A. W. Wood, A. F. Hamlet, and D. P. Lettenmaier (2005), Twentieth-century drought in the conterminous United States, *J. Hydrometeorology*, *6*(6), 985–1001.

Belnap, J., and D. A. Gillette (1998), Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance, *Journal of Arid Environments*, *39*, 133–142.

Bodner, G. S., and M. D. Robles (2017), Enduring a decade of drought: Patterns and drivers of vegetation change in a semi-arid grassland, *Journal of Arid Environments*, *136*(C), 1–14, doi:10.1016/j.jaridenv.2016.09.002.

Breshears, D. D. et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci.*, *102*(42), 15144–15148, doi:10.1073/pnas.0505734102.

Chappell, A., and N.P. Webb (2016), Using albedo to reform wind erosion modelling, mapping and monitoring, Aeolian Research, 23, 63-78, doi:10.1016/j.aeolia.2016.09.006

Chaste, E., M. P. Girardin, J. O. Kaplan, Y. Bergeron, and C. Hély (2019), Increases in heat-induced tree mortality could drive reductions of biomass resources in Canada's managed boreal forest, *Landscape Ecology*, *34*(2), 403–426, doi:10.1007/s10980-019-00780-4.

Donohue, R. J., M. L. Roderick, T. R. McVicar, and G. D. Farquhar (2013), Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments, *Geophysical Research letters.*, *40*(12), 3031–3035, doi:10.1002/grl.50563.

Edwards, B. L., N. P. Webb, D. P. Brown, E. Elias, D. E. Peck, F. B. Pierson, C. J. Williams, and J. E. Herrick (2019), Climate change impacts on wind and water erosion on US rangelands, *Journal of Soil and Water Conservation*, *74*(4), 405–418, doi:10.2489/jswc.74.4.405.

Fairlie, T. D., D. J. Jacob, and R. J. Park (2007), The impact of transpacific transport of mineral dust in the United States, *Atmos. Env.*, *41*(6), 1251–1266, doi:10.1016/j.atmosenv.2006.09.048.

Haverd, V., B. Smith, J. G. Canadell, M. Cuntz, S. Mikaloff Fletcher, G. Farquhar, W. Woodgate, P. R. Briggs, and C. M. Trudinger (2020), Higher than expected CO_2 fertilization inferred from leaf to global observations, *Global Change Biology*, *26*(4), 2390–2402, doi:10.1111/gcb.14950.

Klein Goldewijk, K. (2001), Estimating global land use change over the past 300 years: The HYDE Database, *Global Biogeochem. Cycles*, *15*(2), 417–433.

Klein Goldewijk, K., A. Beusen, G. Van Drecht, and M. De Vos (2011), The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, *Global Ecology and Biogeography*, *20*(1), 73–86, doi:10.1111/j.1466-8238.2010.00587.x.

Liu, S. J., H. I. Wu, R. L. Lytton, and P. J. Sharpe (1990), Aerodynamic sheltering effects of vegetative arrays on wind erosion: A numerical approach, *Journal of Environmental Management*, *30*(3), 281–294.

Van Loon, A. F. et al. (2016), Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches, *Hydrol. Earth Syst. Sci.*, *20*(9), 3631–3650, doi:10.5194/hess-20-3631-2016.

Webb, N. P., and C. Pierre (2018), Quantifying anthropogenic dust emissions, *Earth's Future*, *6*(2), 286–295, doi:10.1002/2017EF000766.

Williams, A. P. et al. (2013), Temperature as a potent driver of regional forest drought stress and tree mortality, *Nature Climate Change*, *3*, 292–297, doi:10.1038/nclimate1693.

Some specific concerns are as follows:

Line 65: Given the focus of the manuscript on land use and vegetation change as a driver of changing dust emissions, the introduction would benefit from inclusion of a review paragraph/synthesis of the types of vegetation and the trajectories of these ecosystems across the southwest today. This is likely to have important implications for trends in dustiness, with pervasive vegetation changes influencing surface aerodynamics and wind erosivity. The authors might also comment on the likely sensitivity of these vegetation communities to elevated CO_2. See for example references within:

Bestelmeyer et al., 2018. The Grassland-Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management. Bioscience 68, 678-690.

Edwards et al., 2019. Climate change impacts on wind and water erosion on US rangelands. Journal of Soil and Water Conservation. Vol. 74, 405-418. doi:10.2489/jswc.74.4.405.

We have revised the introduction and now cite these recommended papers.

Lines 49-55: "Southwestern North America is covered by desert grassland, perennial grassland, savanna, desert scrub, and grassy shrublands or woodlands (McClaran and Van Devender, 1997). In recent decades, a gradual transition from grasslands to shrubland has been observed across much of this region, with increased aridity, atmospheric CO_2 enrichment, and livestock grazing all possibly playing a role in this trend (Bestelmeyer et al., 2018). Future climate change may further prolong this transition, especially since shrubs fare better than grasses under a climate regime characterized by large fluctuations in annual precipitation (Bestelmeyer et al., 2018; Edwards et al., 2019)."

Lines 311-314. "As predicted by previous studies (Bestelmeyer et al., 2018; Edwards et al., 2019), C_3 perennial grasses (C_3gr) in this case decrease across a large swath extending from Arizona through Mexico, showing the impacts of warmer temperatures and reduced precipitation, as well as (for Mexico) land use change."

We have added a discussion on the sensitivity of vegetation to elevated CO_2 as:
Lines 59-62: "On the other hand, elevated CO_2 concentrations in the future atmosphere could increase photosynthesis and decrease transpiration of some vegetation species, allowing for more efficient water use and enhancing growth (Poorter and Perez-Soba, 2002; Polley et al., 2013)."

Lines 170-172: "The different PFTs in LPJ-LMfire respond differently to changing CO_2, with CO_2 enrichment preferentially stimulating photosynthesis in woody vegetation and C_3 grasses compared to C_4 grasses (Polley et al., 2013)."

Line 110: How important is fire in the study area, if at all for the changes under investigation? Supporting references would help.

The LPJ-LMfire model considers the impact of wildfire on vegetation, which could be significant under a warmer and drier climate.

We now add more explanations.

Lines 141-145: "In addition, lightning strike densities decrease by ~0.006 strikes km^{-2} d^{-1} over Arizona in RCP4.5, but increase by the same magnitude in this region in RCP8.5 (Li et al., 2020). Lightning strikes play a major role for wildfire ignition in this region, while wildfires may influence landscape succession (e.g., Bodner and Robles, 2017)."

Lines 172-179: "Wildfire in LPJ-LMfire depends on lightning ignition, and the simulation considers multiday burning, coalescence of fires, and the spread rates of different vegetation types. The effects of changing fire activity on vegetation cover are then taken into account (Pfeiffer et al., 2013; Sitch et al., 2003; Chaste et al., 2019). Li et al., 2020 predicted a ~50% increase in fire-season area burned by 2100 under scenarios of both moderate and intense future climate change over the western United States. However, the effects of changing fire on vegetation cover are insignificant in the grass and bare ground-dominated ecosystems of the desert Southwest, where the low biomass fuels cannot support extensive spread of fires."

Lines 314-316: "Increased fire activity also likely plays a role in the simulated decreases of forest cover and C_3 grasses for RCP8.5 in southern Arizona, where fires together with drought may have affected landscape succession (Williams et al., 2013; Bodner and Robles, 2017)."

Line 125: It would be helpful if the authors can define what they mean by vegetation structure. Is this purely geometric (e.g., height, width of plants), or does this include spatial patterns in landscapes?

We now clarify.

Lines 163-164: "Here 'vegetation structure' refers to vegetation types and the spatial patterns in landscapes."

Line 157: The authors use an estimate of fractional vegetation cover to linearly account for vegetation effects which are predominantly lateral and non-linear for saltation flux and dust emission. While working within the constraints of the DEAD model, the authors should recognize the limitations of this approach and implications for the sensitivity of the model to vegetation change and accuracy of its representation of dust emission responses.

We now clarify this limitation, as also described above.

Lines 253-256: "The scheme assumes that the vertical flux of dust is proportional to the horizontal saltation flux, which in turn depends on surface friction velocity and the aerodynamic roughness length Z_0. As recommended by Zender et al., 2003, and consistent with Fairlie et al., 2007 and Ridley et al., 2013, we uniformly set Z_0 to 100 μm across all dust candidate grid cells."

Lines 440-443: "In addition, as recommended by Zender et al., 2003, we apply a globally uniform surface roughness Z_0 in the model, which means that the impact of changing vegetation conditions on friction velocity is not taken into account. Future work could address this weakness by varying friction velocity according to vegetation type."

Line 161: How representative are these classes of vegetation communities across the southwest? How do they relate to actual patterns of vegetation? For reference, the authors might look at NRCS ecological site descriptions across the study area.

As mentioned above, we now better describe present-day vegetation in this region.

Lines 49-50: "Southwestern North America is covered by desert grassland, perennial grassland, savanna, desert scrub, and grassy shrublands or woodlands (McClaran and Van Devender, 1997)."

Lines 196-198: “The present-day land use in the LUH dataset is taken from the HYDE database v3.1 (Goldewijk, 2001; Goldewijk et al., 2010), which in turn is based on array of sources, including satellite observations and government statistics.”

Lines 241-244: “Of these nine PFTs, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 grasses dominate the region, with temperate needleleaf evergreen having the highest LAI in spring. This mix of vegetation type is consistent with observations (e.g., McClaran and van Devender, 1997).”

Please also see the validation of the modeled VAI as described above and in the Supplement (Lines 26-41) and Figures S4 and S5.

Line 166: Although, during the first half of spring in the desert southwest, C_3 shrubs (e.g., Prosopis glandulosa) may not have leaves such that the main aerodynamic effect is provided by branches and stems. It would be instructive to link actual plant phenology in the study area to what is/is not represented in the vegetation model.

What the reviewer requests would be challenging to carry out in this model study, but we do now acknowledge this shortcoming.

Lines 45-48 (Supplement): “We acknowledge, however, that with only nine PFTs, LPJ-LMfire cannot capture the phenology of all plant species, which could in turn introduce error into our dust calculations. Still, the relatively good match of modeled springtime VAI with that observed is encouraging.”

Line 174: How did the authors parameterize the drag partition scheme and represent land use change effects in the dust model? In DEAD, these are represented through the MB95 drag partition scheme, with aerodynamic roughness lengths (z0) assigned to land cover classes. As dust emission is a lateral process, z0 and the drag partition should have a larger effect on dust emission than fractional cover via VAI. If z0 was not changed consistently with the fractional cover of vegetation, the model would represent an inconsistent vegetation effect and would likely not capture the nature of dust emission responses to the examined scenarios.

As mentioned on the previous page, we apply a uniform aerodynamic roughness length Z_0, and we acknowledge this limitation in the Discussion. See lines 250-253 and lines 440-443 in the revised main text.

Line 180: Do the authors mean saltation, or dust emission? Although a general term, dust shouldn’t be saltating.

Fixed.

Line 250-253: “Following Ridley et al., 2013, we characterize subgrid-scale surface winds as a Weibull probability distribution, which allows saltation even when the grid-scale wind conditions are below some specified threshold speed.”

Line 192: Can the authors describe the implications of not changing wind speed? Would you anticipate wind speed changes in response to regional vegetation (roughness) change and changes in synoptic meteorology?

We now clarify the implications of not considering changing winds in the future simulation.

Lines 145-148: "Finally, future surface wind speeds do not change significantly under RCP4.5, but increase slightly by ~4% across southwestern North America under RCP8.5 by 2100 (not shown). The increasing winds in RCP8.5 will influence the spread of fires in our study, but will not affect the simulated dust fluxes directly, as described in more detail below."

Lines 270-272: "In other words, we neglect the direct effects of future changes in wind speeds on dust mobilization, allowing us to focus instead on the indirect effects of changing vegetation on dust."

Lines 443-447: "Finally, our study focuses only on the effect of changing vegetation on dust mobilization and does not take into account how changing wind speeds or drier soils in the future atmosphere may more directly influence dust. Given the slight increase in monthly mean winds in RCP8.5 by 2100, future dust emissions in this scenario could be underestimated."

Line 201: Discussion point - what about changes in seasonality due to changes in plant phenological changes due to species change and change in the timing of warming and precipitation? This is partially addressed in the results, but would benefit from further discussion linked to actual plant communities.

Lines 316-319: "We also investigate trends in LAI for different months in spring from the present day to 2100. We find that the greatest percentage decreases in TeBS and C_3 grasses occur in May, consistent with the largest decreases in precipitation in that month (not shown)."

Line 235: The effect of vegetation on dust emission shouldn't be reduced to growth as it is the kinds and proportions of vegetation in the landscape that influence surface aerodynamic roughness and spatial patterns of dust emission. These changes aren't represented in the model, but do need to be addressed by the authors.

As mentioned above, we now amended the text.

Lines 430-440. "Other uncertainties in our study can be traced to the dust simulation. The different vegetation types in our model are quantified as fractions of gridcells, which have relatively large spatial dimensions of ~50 km × 60 km. This means the model cannot capture the spatial heterogeneity of land cover, and the aerodynamic sheltering effects of vegetation on wind erosion are neglected, as they are in most 3-D global model studies. Such sheltering could play a large role in dust mobilization (e.g., Liu et al., 1990). New methods involving satellite observations of surface albedo promise to improve understanding of the effects of aerodynamic sheltering on dust mobilization, at least for the present-day (Chappell and Webb, 2016; Webb and Pierre, 2018). Implementation of aerodynamic sheltering in simulations of future climate regimes would need to account for fine-scale spatial distributions of vegetation."

Line 246: Can the authors define what they mean by desertification, and how this differs to the vegetation changes (grass-shrub transitions) that have already occurred over much of this region? e.g., for reference see Bestelmeyer, B.T., Okin, G.S., Duniway, M.C., Archer, S.R., Sayre, N.F., Williamson, J.C., Herrick, J.E., 2015. Desertification, land use, and the transformation of global drylands. Frontiers in Ecology and the Environment 13, 28-36.

We have removed this reference to desertification.

Line 269: What conditions would make CO_2 of limited importance? Can the authors explain and expand on this in the Discussion? Will CO_2 be the main driver of vegetation change, or are other factors likely to be more important/have been important in the past that are likely to influence future trends? (e.g., vegetation state transitions driven in part by land management, not just land use)

First, in the Introduction, as discussed above, we have described in more detail the main factors driving dust concentrations.

In the Discussion, we now clarify the uncertainties in the effects of CO_2 fertilization.

Lines 414-423: "In summary, we find that as atmospheric CO_2 levels rise vegetation growth is enhanced and dust mobilization decreases, offsetting the impacts of warmer temperatures and reduced rainfall, at least in some areas. These results are consistent with evidence that CO_2 fertilization is already occurring in arid or semiarid environments like southwestern North America (Donohue et al., 2013; Haverd et al., 2020). In such environments, water availability is the dominant constraint on vegetation growth, and the recent increases in atmospheric CO_2 may have reduced stomatal conductance and limited evaporative water loss. The effects of CO_2 fertilization on vegetation growth are uncertain, however, and may be attenuated by the limited supply of nitrogen and phosphorus in soil (Wieder et al., 2015). These nutritional constraints vary greatly among different PFTs (Shaw et al., 2002; Nadelhoffer et al., 1999)."

Lines 453-462: "Given the many uncertainties, it is challenging to gauge which of the three factors investigated here – climate impacts on vegetation, CO_2 fertilization, or land use change – will play the dominant role in driving future changes in dust emissions and concentrations. This study thus brackets a range of possible dust scenarios for the southwestern North America, with the simulation without CO_2 fertilization placing an upper bound on dust emissions. In the absence of increased CO_2 fertilization, our work suggests that vegetated cover will contract in response to the warmer, drier climate, exposing bared ground and significantly increasing dust concentrations by 2100. In this way, dust enhancement could impose a potentially large climate penalty on $PM_{2.5}$ air quality, with consequences for human health across much of southwestern North America."

Line 278: It would help for the authors to expand on this point about wind as my understanding is that wind speeds were not adjusted for climate changes in the scenarios/ simulations.

We now clarify.

Lines 364-369: “As Figure 3 implies, land use along the ANM border contributes to the increased dust emissions in that area, by up to ~0.7 kg m^{-2} mon^{-1}. Climate change impacts on natural vegetation, however, account for the bulk of the modeled increases in dust emissions in this scenario, by as much as ~1.2 kg m^{-2} mon^{-1} (Figure 2). The modeled wind fields, which are the same in all scenarios, transport the dust from source regions, leading to the enhanced concentrations across much of the domain, as seen in Figure 4.”

Line 280: Again, it would be good if the authors can be specific about both vegetation change and land use change. For example, what is the changing land use in west Texas in this scenario?

We have added Figure S8 to show changes in land use under future climate. We further clarify. Lines 370-371: “We find that dust concentrations decrease only in a limited area in western Texas due to decreased pasture (Figures 3 and S9).”

Line 298: I agree with this statement about the importance of robust representation of both future vegetation changes and the sensitivity of dust emissions to these changes. However, I question whether this need has actually been addressed in the present study. See my major concerns above relating to: 1) description of changes lacking detail and grounding in actual vegetation and land use changes occurring across the southwest, and 2) physical representation of vegetation in the dust model ignores the major effect of vegetation on dust emission (lateral process) and the interactions with vegetation changes that are likely to occur.

As described above, we have attempted to address these issues in our revision. We repeat some of the revised text below.

1. Grounding our study in actual vegetation and land use changes.

Lines 49-55: “Southwestern North America is covered by desert grassland, perennial grassland, savanna, desert scrub, and grassy shrublands or woodlands (McClaran and Van Devender, 1997). In recent decades, a gradual transition from grasslands to shrubland has been observed across much of this region, with increased aridity, atmospheric CO_2 enrichment, and livestock grazing all possibly playing a role in this trend (Bestelmeyer et al., 2018). Future climate change may further prolong this transition, especially since shrubs fare better than grasses under a climate regime characterized by large fluctuations in annual precipitation (Bestelmeyer et al., 2018; Edwards et al., 2019).”

Lines 311-314: “As predicted by previous studies (Bestelmeyer et al., 2018; Edwards et al., 2019), C_3 perennial grasses (C_3gr) in this case decrease across a large swath extending from Arizona through Mexico, showing the impacts of warmer temperatures and reduced precipitation, as well as (for Mexico) land use change.”

Lines 414-418: “In summary, we find that as atmospheric CO_2 levels rise vegetation growth is enhanced and dust mobilization decreases, offsetting the impacts of warmer temperatures and reduced rainfall, at least in some areas. These results are consistent with evidence that CO_2 fertilization is already occurring in arid or semiarid environments like southwestern North America (Donohue et al., 2013; Haverd et al., 2020).”

2. Representation of all the effects of vegetation on dust emissions.

Lines 431-438: "The different vegetation types in our model are quantified as fractions of gridcells, which have relatively large spatial dimensions of ~50 km × 60 km. This means the model cannot capture the spatial heterogeneity of land cover, and the aerodynamic sheltering effects of vegetation on wind erosion are neglected, as they are in most 3-D global model studies. Such sheltering could play a large role in dust mobilization (e.g., Liu et al., 1990). New methods involving satellite observations of surface albedo promise to improve understanding of the effects of aerodynamic sheltering on dust mobilization, at least for the present-day (Chappell and Webb, 2016; Webb and Pierre, 2018)."

Lines 440-443: "In addition, as recommended by Zender et al. (2003), we apply a globally uniform surface roughness Z_0 in the model, which means that the impact of changing vegetation conditions on friction velocity is not taken into account. Future work could address this weakness by varying friction velocity according to vegetation type."

Lines 448-453: "Within these limitations, our study quantifies the potential impacts of changing land cover and land use practices on dust mobilization and fine dust concentration over the coming century in southwestern North America. Our work builds on previous studies focused on future dust in this region by (1) more accurately capturing the transport of dust from source regions with a dynamical 3-D model, (2) considering results with and without CO_2 fertilization, and (3) including the impact of land use trends."

In sum, although we have not been able to "close the book" on future dust emissions over the southwestern North America, our work provides an increment of progress and highlights a new threat to human health in the face of climate change.

Line 312: I think the emphasis on CO_2 perhaps oversimplifies the controls. These dryland systems are largely water, not nutrient, limited. But not only cover - this will also be C_3 vs C_4 dominance and so the proportions and kinds of vegetation on these landscapes will influence responses to elevated CO_2. Vegetation state changes today and into the future (influenced to some degree by CO_2) are likely to have a far greater effect on the structure and cover of protective roughness.

As described above, we now more strongly acknowledge the limitations of this study, in particular the neglect of the variation of surface roughness lengths for different vegetation types. We also comment on the effect of climate change on C_3 grasses in the model.

Lines 311-314: "As predicted by previous studies (Bestelmeyer et al., 2018; Edwards et al., 2019), C_3 perennial grasses (C_3gr) in this case decrease across a large swath extending from Arizona through Mexico, showing the impacts of warmer temperatures and reduced precipitation, as well as (for Mexico) land use change."

Response of dust emissions in southwestern North America to 21st century trends in climate, CO_2 fertilization, and land use: Implications for air quality

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Abstract. Climate models predict a shift toward warmer and drier environments in southwestern North America over the 21st century. The consequences of climate change for dust mobilization and concentrations are unknown, but could have large implications for human health, given connections between dust inhalation and disease. Here we drive a dynamic vegetation model (LPJ-LMfire) with future scenarios of climate and land use, and link the results to a chemical transport model (GEOS-Chem) to assess the impacts of land cover on dust mobilization and fine dust concentrations (defined as dust particles less than 2.5 microns in diameter) on surface air quality. In the most extreme warming scenario (RCP8.5), we find that surface temperatures in southwestern North America during the season of greatest dust emissions (March, April, and May) warm by 3.3 K and precipitation decreases by nearly 40% by 2100. These conditions lead to vegetation dieback and an increase in dust-producing bare ground. Enhanced CO_2 fertilization, however, offsets the modeled effects of warming temperatures and rainfall deficit on vegetation in some areas of the southwestern United States. Considering all three factors in RCP8.5 scenario, dust concentrations

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Deleted: in the most extreme warming scenario (RCP8.5) in spring (March, April, and May), the season of greatest dust emissions decrease over Arizona and New Mexico in spring by the late 21st century due to greater CO_2 fertilization and a more densely vegetated environment, which inhibits dust mobilization. Along Mexico's northern border, dust concentrations increase as a result of land use intensification. In contrast, when CO_2 fertilization is not considered in the RCP8.5 scenario, vegetation cover declines significantly across most of the domain by 2100, leading to widespread increases in fine dust concentrations, especially in southeastern New Mexico (up to ~2.0 µg m^{-3} relative to the present day) and along the border between New Mexico and Mexico (up to ~2.5 µg m^{-3}). Our results have implications for human health, especially for the health of the indigenous people who make up a large percentage of the population in this region.

Deleted: Considering all factors in the most extreme future warming scenario, we find decreasing trends of fine dust emissions over Arizona and New Mexico but increasing emissions along Mexico's northern border in the late-21st century during springtime, the season of maximum dust emissions. These trends result from more densely vegetated environments in the arid southwestern U.S. under future climate, but sparser vegetation in northern Mexico. The two main drivers of dust trends in this region – CO_2 fertilization and land use intensification – play opposing roles, with the first driver enhancing vegetation and thus decreasing dust in the southwestern U.S. and the second driver increasing dust in northern Mexico. In the absence of CO_2 fertilization, the RCP8.5 scenario places an upper bound on increases in dust, with elevated concentrations widespread over the southwestern North America by 2100 in spring, especially in southeastern New Mexico (up to ~2.0 µg m^{-3}) and along the border between New Mexico and Mexico (up to ~2.5 µg m^{-3}).

1 Introduction

The arid and semi-arid regions of the southwestern United States and northwestern Mexico are characterized by large concentrations of soil-derived dust particles in the lower atmosphere, especially in spring (Hand et al., 2016). By causing respiratory and cardiovascular diseases, fine dust particles – i.e., those particles with diameter less than 2.5 microns – can have negative effects on human health (Tong et al., 2017; Meng and Lu, 2007; Gorris et al., 2018). A key question is to what extent climate change and other factors will influence future dust concentrations in this region, which we define here as southwestern North America. In this study, we use a suite of models to predict the future influence of three factors – climate change, increasing atmospheric CO_2 concentrations, and land use change – on land cover in this region, and assess the consequences for dust mobilization and dust concentrations.

Wind speed and vegetation cover are two key factors that determine soil erodibility and dust emissions. Wind gusts mobilize dust particles from the earth's surface, while vegetation constrains dust emissions by reducing the extent of bare land and preserving soil moisture (Zender et al., 2003). The high temperatures and reduced soil moisture characteristic of drought play an important role in dust mobilization, since loss of vegetative cover during drought increases soil erosion (Archer and Predick, 2008; Bestelmeyer et al., 2018).

Southwestern North America is covered by desert grassland, perennial grassland, savanna, desert scrub, and grassy shrublands or woodlands (McClaran and Van Devender, 1997). In recent decades, a gradual transition from grasslands to shrubland has been observed across much of this region, with increased aridity, atmospheric CO_2 enrichment, and livestock grazing all possibly playing a role in this trend (Bestelmeyer et al., 2018). Future climate change may further prolong this transition, especially since shrubs fare better than grasses under a climate regime characterized

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Deleted: A key question is to what extent climate change will influence future dust concentrations in the desert Southwest. While climate models predict a warmer and drier environment in this region through the 21st century (Seager and Vecchi, 2010; MacDonald, 2010; Stahle, 2020; Prein et al., 2016; Williams et al., 2020), elevated CO_2 concentrations could enhance vegetation growth (Poorter and Perez-Soba, 2002; Polley et al., 2013). Land use practices in the future will likely also influence the propensity of dust storms.

by large fluctuations in annual precipitation (Bestelmeyer et al., 2018; Edwards et al., 2019). Climate models predict a warmer and drier environment in southwestern North America through the 21st century, with more frequent and severe drought (Seager and Vecchi, 2010; MacDonald, 2010; Stahle, 2020; Prein et al., 2016; Williams et al., 2020). Such conditions would decrease vegetative cover and allow for greater dust mobilization. On the other hand, elevated CO_2 concentrations in the future atmosphere could increase photosynthesis and decrease transpiration of some vegetation species, allowing for more efficient water use and enhancing growth (Poorter and Perez-Soba, 2002; Polley et al., 2013). Land use practices, e.g., farming and ranching, industrial activities including mining, and urban sprawl, have changed dramatically over the southwestern North America in recent decades, with Arizona and New Mexico showing decreasing cropland area and northern Mexico experiencing increasing pasture area (Figure S1). Future land use practices could also influence the propensity for dust mobilization by disturbing crustal biomass (e.g., Belnap and Gillette, 1998).

Moved down [1]: To investigate the potential effects of climate change, increasing CO_2 concentrations, and future land use practices on dust mobilization in southwestern North America, we couple a dynamic vegetation model (LPJ-LMfire) to a chemical transport model (GEOS-Chem) and perform a series of experiments in scenarios of future environmental conditions.

Previous studies have investigated the relative importance of climate, CO_2 fertilization, and/or land use in present-day and future dust emissions and concentrations, sometimes with contradictory results. For example, Woodward et al., 2005 predicted a tripling of the global dust burden by 2100 relative to the present day, while other studies suggested a decrease in the global dust burden (e.g., Harrison et al., 2001, Mahowald and Luo, 2003 and Mahowald et al., 2006). These estimates of future dust emissions depended in large part on the choice of model applied, as demonstrated by Tegen et al., 2004.

In southwestern North America, a few recent studies examined statistical relationships between observed present-day dust concentrations and meteorological conditions or leaf area index (LAI). Hand et al., 2016 found that fine dust concentrations in spring in this region correlated with the Pacific Decadal Oscillation (PDO), indicating the importance of large-scale climate patterns in the mobilization and transport of regional fine dust. Tong et al., 2017 further determined that the observed 240% increase in the frequency of windblown dust storms from 1990s to 2000s in the southwestern United States was likely associated with the PDO. Similarly, Achakulwisut et al., 2017 found that the 2002–2015 increase in average March fine dust concentrations in this region was driven by a combination of positive PDO conditions and phase of the El Nino-Southern Oscillation. More recently, Achakulwisut et al., 2018 identified the Standardized Precipitation-Evapotranspiration Index as a useful indicator of present-day dust variability. Applying that metric to an ensemble of future climate projections, these authors predicted increases of 26-46% in fine dust concentrations over the U.S. Southwest in spring by 2100. In contrast, Pu and Ginoux, 2017 found that the frequency of extreme dust days decreases slightly in spring in this region due to reduced extent of bare ground under 21st century climate change.

These regional studies relied mainly on statistical models that relate local and/or large scale meteorological conditions to dust emissions in southwestern North America. Pu and Ginoux, 2017 also considered changing LAI in their model, but these dust-LAI relationships were derived from a relatively sparse dataset, casting some uncertainty on the results (Achakulwisut et al., 2018). In this study, we investigate the effects of climate change, increasing CO_2 fertilization, and future land use practices on vegetation in southwestern North America, and we examine the response of dust mobilization due to these changes in vegetation. With regard to climate, we examine whether a shift to warmer, drier conditions by 2100 enhances dust mobilization in this region by reducing vegetation cover and exposing bare land. To that end, we couple the LPJ-LMfire dynamic vegetation model to the chemical transport model GEOS-Chem to study vegetation dynamics and dust mobilization under different conditions and climate scenarios, allowing consideration of

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Deleted: we couple a dynamic vegetation model (LPJ-LMfire) to a chemical transport model (GEOS-Chem) and perform a series of experiments in scenarios of future environmental conditions.W several factors driving future dust mobilization in the southwestern North America. We focus on fine dust particles in springtime (March, April, and May), because it is the season of highest dust concentrations in the southwestern U.S. (Hand et al., 2017). Given the deleterious impacts of airborne dust on human health, our dust projections under different climate scenarios have value for understanding the full array of potential consequences of anthropogenic climate change.

2 Methods

We examine dust mobilization in southwestern North America, here defined as 25°N – 37°N, 100°W – 115°W (Figure 1), during the late-21[st] century under scenarios of future climate and land use based on two Representative Concentration Pathways (RCPs). RCP4.5 and RCP8.5 capture two possible climate trajectories over the 21[st] century, beginning in 2006. RCP4.5 represents a scenario of moderate future climate change with gradual reduction in greenhouse gas (GHG) emissions after 2050 and a radiative forcing at 2100 relative to pre-industrial values of +4.5 W m^{-2}, while RCP8.5 represents a more extreme scenario with continued increases in GHGs throughout the 21[st] century and a radiative forcing of +8.5 W m^{-2} at 2100. For each RCP, we investigate the changes in vegetation for three cases: 1) an all-factor case that includes changes in climate, land use, and CO_2 fertilization; 2) a fixed-CO_2 case that includes changes in only climate and land use; and 3) a fixed-land use case that includes changes in only climate and CO_2 fertilization.

We use LPJ-LMfire, a dynamic global vegetation model, to estimate changes in vegetation under future conditions (Pfeiffer et al., 2013). Meteorology to drive LPJ-LMfire is taken from the Goddard Institute for Space Studies (GISS) climate model (Nazarenko et al., 2015). Using the GEOS-Chem emission component (HEMCO), we then calculate dust emissions based on the LPJ-

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generated vegetation area index (VAI) for all scenarios. We apply the resulting dust emissions to the global chemical transport model GEOS-Chem to simulate the distribution of fine dust across the southwestern North America.

2.1 GISS Model E

Present-day and future meteorological fields for RCP4.5 and RCP8.5 are simulated by the GISS Model E climate model (Nazarenko et al., 2015), configured for Phase 5 of the Coupled Model Intercomparison Project (CMIP5; https://esgf-node.llnl.gov/search/cmip5/, last accessed on 17 July 2020). The simulations cover the years 1801 to 2100 at a spatial resolution of 2° latitude x 2.5° longitude. Changes in climate in the GISS model are driven by increasing greenhouse gases. In RCP4.5, CO_2 concentrations increase to 550 ppm by 2100; in RCP8.5 the CO_2 increases to 1960 ppm ((Meinshausen et al., 2011).

Under RCP4.5, the GISS model predicts a slight increase of 0.45 K in springtime mean surface temperatures and an increase in mean precipitation by ~17% over the southwestern North America by the 2100 time slice (2095-2099), relative to the present day (2011-2015). In contrast, under RCP8.5, the 5-year mean springtime temperature increases significantly by 3.29 K by 2100 and mean precipitation decreases by ~39%. The spatial distributions of the changes in temperature and precipitation by 2100 under RCP8.5 are presented in the Supplement (Figure S2). In addition, lightning strike densities decrease by ~0.006 strikes km^{-2} d^{-1} over Arizona in RCP4.5, but increase by the same magnitude in this region in RCP8.5 (Li et al., 2020). Lightning strikes play a major role for wildfire ignition in this region, while wildfires may influence landscape succession (e.g., Bodner and Robles, 2017). Finally, future surface wind speeds do not change significantly under RCP4.5, but increase slightly by ~4% across southwestern North America under RCP8.5 by 2100

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Moved down [3]: Under RCP4.5, the GISS model predicts a slight increase of 0.45 K in springtime mean surface temperatures and an increase in mean precipitation by ~17% over the southwestern North America by the 2100 time slice (2095-2099), relative to the present day (2011-2015). Under RCP8.5, the 5-year mean springtime temperature increases significantly by 3.29 K by 2100 and mean precipitation decreases by ~39%. The spatial distributions of the changes in temperature and precipitation by 2100 under RCP8.5 are presented in the Supplement (Figure S1).

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(not shown). The increasing winds in RCP8.5 will influence the spread of fires in our study, but will not affect the simulated dust fluxes directly, as described in more detail below. Compared to those from other climate models, the GISS projections of climate change in southwestern North America are conservative (Ahlström et al., 2012; Sheffield et al., 2013), implying that our predictions of the impact of climate change on dust mobilization may also be conservative.

In our study, we do not specifically track drought frequency under future climate, as the definition of drought is elusive (Andreadis et al., 2005; Van Loon et al., 2016). Nonetheless, the meteorological conditions predicted in the RCP8.5 scenario for 2100 align with previous studies projecting increased risk of drought in this region (e.g., Williams et al., 2020), and as we shall see, such conditions, in the absence of CO_2 fertilization, result in decreased vegetation and greater dust mobilization.

2.2 LPJ-LMfire

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LPJ-LMfire is a fork of the LPJ dynamic vegetation model (Sitch et al., 2003) that includes a process-based representation of fire (Pfeiffer et al., 2013). Input to LPJ-LMfire includes meteorological variables, soil characteristics, land use, and atmospheric CO_2 concentrations, and the model then simulates the corresponding vegetation structure, biogeochemical cycling, and wildfire at a spatial resolution of 0.5° latitude x 0.5° longitude. Here "vegetation structure" refers to vegetation types and the spatial patterns in landscapes.

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More specifically, LPJ-LMfire simulates the impacts of photosynthesis, evapotranspiration, and soil water dynamics on vegetation structure and the population densities of different plants functional types (PFTs). The model considers the coupling of different ecosystem processes, such as the interactions between CO_2 fertilization, evapotranspiration, and temperature, as well as the competition among different PFTs for water resources (e.g., precipitation, surface runoff, and drainage). The different PFTs in LPJ-LMfire respond differently to changing CO_2, with CO_2 enrichment preferentially stimulating photosynthesis in woody vegetation and C_3 grasses compared to C_4 grasses (Polley et al., 2013). Wildfire in LPJ-LMfire depends on lightning ignition, and the simulation considers multiday burning, coalescence of fires, and the spread rates of different vegetation types. The effects of changing fire activity on vegetation cover are then taken into account (Pfeiffer et al., 2013; Sitch et al., 2003; Chaste et al., 2019). Li et al., 2020 predicted a ~50% increase in fire-season area burned by 2100 under scenarios of both moderate and intense future climate change over the western United States. However, the effects of changing fire on vegetation cover are insignificant in the grass and bare ground-dominated ecosystems of the desert Southwest, where the low biomass fuels cannot support extensive spread of fires.

For this study we follow Li et al., 2020, in linking meteorology from GISS-E2-R to LPJ-LMfire in order to capture the effects of climate change on vegetation. Meteorological fields from the GISS model include monthly mean surface temperature, diurnal temperature range, 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. Monthly mean lightning strike density, calculated using the GISS convective mass flux and the empirical parameterization of Magi, 2015, is also applied to LPJ-LMfire. To downscale the 2° x 2.5° GISS meteorology to finer resolution for LPJ-LMfire, we calculate the 2010-2100 monthly anomalies relative to the average over the 1961-1990 period, and then add these anomalies to an observationally based climatology (Pfeiffer et al., 2013). LPJ-LMfire then simulates the response of natural vegetation to the 21st century trends in these meteorological fields and to increasing CO_2. We apply the same changes in CO_2 concentrations as those applied to the GISS model.

We overlay the changes in natural land cover with future land use scenarios from CMIP5

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(LUH; Hurtt et al., 2011; http://tntcat.iiasa.ac.at/RcpDb/, last accessed on 17 July 2020). These scenarios include land used for crops, ranching (rangeland), and urban areas, all of which result in reduction in aboveground biomass, an increase in herbaceous relative to woody plants, and an increase in the extent of bare ground. The present-day land use in the LUH dataset is taken from the HYDE database v3.1 (Goldewijk, 2001; Goldewijk et al., 2010), which in turn is based on array of sources, including satellite observations and government statistics. In RCP8.5, the extent of crop- and rangeland cover increases by ~30% in Mexico but decreases by 10-20% over areas along Mexico's northern border in the U.S. (Hurtt et al., 2011). Only minor changes in land use practices by 2100 are predicted under RCP4.5 (Hurtt et al., 2011).

We perform global simulations with LPJ-LMfire on a 0.5° x 0.5° grid for the two RCPs from 2006-2100, and analyze results over southwestern North America, where dust emissions are especially high. For each RCP we consider the effects of changing climate on land cover, as well as the influence of land use change and CO_2 fertilization. The LPJ-LMfire simulations yield monthly timeseries of the leaf area indices (LAI) and fractional vegetation cover (σ_v) for nine plant functional types (PFTs): tropical broadleaf evergreen, tropical broadleaf raingreen, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, boreal needleleaf evergreen, and boreal summergreen trees, as well as C_3 and C_4 grasses. We further discuss the LPJ-LMfire present-day land cover in the Supplement.

2.3 VAI calculation

Vegetation constrains dust emissions in two ways: 1) by competing with bare ground as a sink for atmospheric momentum, which results in less drag on erodible soil (Nicholson et al., 1998; Raupach, 1994); and 2) by enhancing soil moisture through plant shade and root systems (Hillel, 1982). Here we implement the dust entrainment and deposition (DEAD) scheme of Zender et al.,

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Changes in climate, land use, and CO_2 fertilization all play important roles in vegetation structure, which then in turn affects dust mobilization. RCP4.5 and RCP8.5 capture two possible climate trajectories over the 21st century, beginning in 2006. RCP4.5 represents a scenario of moderate future climate change with a radiative forcings at 2100 relative to pre-industrial values of +4.5 W m^{-2}, while RCP8.5 represents a more extreme scenario with +8.5 W m^{-2} at 2100. We probe the impacts of future meteorology on changes in vegetation type and vegetation density (vegetation area index, hereafter: VAI) using the LPJ-LMfire following three conditions: 1) the all-factor scenario which includes changes in climate, land use, and CO_2 fertilization; 2) the fixed-CO_2 scenario which includes changes in only climate and land use; 3) the fixed-land use scenario which includes changes in only climate and CO_2 fertilization. The GISS-E2-R meteorology used here covers the years 1801 to 2100 at a spatial resolution of 2° latitude x 2.5° longitude. To downscale the GISS meteorology to finer resolution for LPJ-LMfire, we calculate the 2010-2100 monthly anomalies relative to the average over the 1961-1990 period, and then add these anomalies to an observationally based climatology at 0.5° latitude x 0.5° longitude (Pfeiffer et al., 2013). Compared to other climate models, the GISS model yields a conservative prediction of climate change in southwestern North America (Ahlström et al., 2012; Sheffield et al., 2013), which could result in conservative predictions of the impact of climate change on dust mobilization.¶

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2003 to compute a size-segregated dust flux, which includes entrainment thresholds for saltation, moisture inhibition, drag partitioning, and saltation feedback. The scheme assumes that vegetation suppresses dust mobilization by linearly reducing the fraction of bare soil exposed in each grid cell:

$$A_m = (1 - A_l - A_w)(1 - A_s)(1 - A_V) \qquad (1),$$

where A_l is the fraction of land covered by lakes, A_w is the fraction covered by wetlands, A_s is the fraction covered by snow, and A_V is the fraction covered by vegetation.

For this study, we use VAI as a metric to represent vegetation because it includes not only leaves but also stems and branches, all of which constrain dust emission. VAI is used to calculate A_V in equation (1) through

$$A_V = \min\,[1.0, \min(VAI, VAI_t)\,/VAI_t] \qquad (2),$$

where VAI_t is the threshold for complete suppression of dust emissions, set here to 0.3 m^2 m^{-2} (Zender et al., 2003; Mahowald et al., 1999).

To compute the dust fluxes, we need to convert LAI from LPJ-LMfire to VAI. VAI is generally defined as the sum of LAI plus stem area index (SAI). Assuming immediate removal of all dead leaves, the fractional vegetation cover, σ_v, can be used to represent SAI for the different PFTs (Zeng et al., 2002). Given that the threshold VAI_t for no dust emission is relatively low (0.3 m^2 m^{-2}), leaf area dominates stem area in the suppression of dust mobilization in the model. In areas where LAI is greater than SAI, we therefore assume that SAI does not play a role in controlling dust emissions, and we set LAI equivalent to VAI. We also assume that C_3 and C_4 grasses have zero stem area to avoid overestimating VAI during the winter and early spring when such grasses are dead. Based on the method of Zeng et al., 2002, with modifications, we calculate VAI in each grid cell as

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$$VAI = \max\left(\sum_{PFT=1}^{9} LAI, \sum_{PFT=1}^{7} \sigma_v\right) \quad (3)$$

where LAI is for the nine PFTs from LPJ-LMfire, and σ_v is for just seven PFTs, with σ_v for C_3 and C_4 grasses not considered. Of the nine PFTs, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C_3 grasses dominate the region, with temperate needleleaf evergreen having the highest LAI in spring. This mix of vegetation type is consistent with observations (e.g., McClaran and Van Devender, 1997).

2.4 Calculation of dust emissions

Dust emissions are calculated offline in the DEAD dust mobilization module within the Harvard-NASA Emissions Component (HEMCO). We feed into the DEAD module both the VAI generated by LPJ-LMfire and meteorological fields from the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) at a spatial resolution of 0.5° latitude x 0.625° longitude (Gelaro et al., 2017). Dust emission is nonlinear with surface windspeed. Following Ridley et al., 2013, we characterize subgrid-scale surface winds as a Weibull probability distribution, which allows saltation even when the grid-scale wind conditions are below some specified threshold speed. The scheme assumes that the vertical flux of dust is proportional to the horizontal saltation flux, which in turn depends on surface friction velocity and the aerodynamic roughness length Z_0. As recommended by Zender et al., 2003, and consistent with Fairlie et al., 2007 and Ridley et al., 2013, we uniformly set Z_0 to 100 µm across all dust candidate grid cells.

With this model setup, we calculate hourly dust emissions for two five-year time slices for each RCP and condition, covering the present day (2011-2015) and the late-21st century (2095-2099). Dust emissions are generated for four size bins with radii of 0.1 – 1.0 µm, 1.0 – 1.8 µm, 1.8 – 3.0 µm, 3.0 – 6.0 µm. These dust emissions are then applied to GEOS-Chem. Calculated present-day VAI and fine dust emissions are shown in Figure S3, and we compare modeled VAI with that

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observed in Figures S4 and S5.

2.5 GEOS-Chem

We use the aerosol-only version of the GEOS-Chem chemical transport model (version 12.0.1; http://acmg.seas.harvard.edu/geos/). For computational efficiency, we apply monthly mean oxidants archived from a full-chemistry simulation (Park et al., 2004). To isolate the effect of changing dust mobilization on air quality over the southwestern North America, we use present-day MERRA-2 reanalysis meteorology from NASA/GMAO (Gelaro et al., 2017) for both the present-day and future GEOS-Chem simulations. In other words, we neglect the direct effects of future changes in wind speeds on dust mobilization, allowing us to focus instead on the indirect effects of changing vegetation on dust. For each time slice, we first carry out a global GEOS-Chem simulation at 4° latitude x 5° longitude spatial resolution, and then downscale to 0.5° x 0.625° via grid nesting over the North America domain. In this study, we focus only on dust particles in the finest size bin (i.e., with radii of 0.1 – 1.0 µm), as these are most deleterious to human health. We compare modeled fine dust concentrations over southwestern North America for the present-day against observations from the IMPROVE network in Figures S6-S7.

3 Results

3.1 Spatial shifts in springtime vegetation area index

Figure 1 shows large changes in the spatial distribution of modeled springtime VAI in the southwestern North America for the three cases under both RCPs by 2100. In RCP4.5, the distributions of changes in VAI are similar for the all-factor and fixed-land use cases. Strong enhancements (up to ~2.5 m^2 m^{-2}) extend across much of Arizona, especially in the northwestern

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corner. The model exhibits moderate VAI increases in most of New Mexico and in the forest regions along the coast of northwestern Mexico. We find decreases in modeled VAI (up to ~ -1.6 $m^2 m^{-2}$) in the southwestern corner of New Mexico, to the east of the coastal forests in Mexico and in the forest regions near the Mexican border connecting with southern Texas. The similarity between the all-factor and fixed land use cases indicates the relatively trivial influence of land use change on vegetation cover in RCP4.5, compared to the effects of climate change and CO_2 fertilization. For the fixed-CO_2 case, western New Mexico and northern Mexico show greater decreases in VAI, indicating how CO_2 fertilization in the other two cases offsets the effects of the warmer and drier climate on vegetation in this region. Figure S8 further illustrates the strong positive impacts that CO_2 fertilization has on VAI.

Compared to RCP4.5, the RCP8.5 scenario shows larger changes in climate, CO_2 concentrations, and land use by 2100 (Figure 1). The net effects of these changes on vegetation are complex. As in RCP4.5, Arizona experiences a strong increase in VAI in the all-factor and fixed-land use cases, but now this increase extends to New Mexico. In contrast to RCP4.5, modeled VAI decreases in the northern Sierra Madre Occidental (Mexico) in the all-factor case for RCP8.5. In the fixed-land use case, however, the VAI decrease in northern Mexico is nearly erased, indicating the role of vegetation/forest degradation caused by land use practices in this area (Figure S9). For the fixed-CO_2 case for RCP8.5, VAI decreases in nearly all of southwestern North America, except the northeastern corner of Arizona and the northwestern corner of New Mexico.

To better understand the changes in VAI, we examine changes in LAI, which represents the major portion of VAI, for the four dominant plant functional types (PFTs) in this region. For example, decreases in LAI in the fixed-CO_2 case under RCP8.5 are dominated by the loss of temperate broadleaf evergreen (TeBE) and temperate broadleaf summergreen (TeBS) (Figure S10).

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Temperate needleleaf evergreen (TeNE) shows areas of increase in the northern part and south of Texas in this scenario, while both TeBE and TeBS show increases in northern Arizona and New Mexico. In other areas, TeBS reveals strong decreases, especially in southern Arizona and Mexico. As predicted by previous studies (Bestelmeyer et al., 2018; Edwards et al., 2019), C_3 perennial grasses (C_3gr) in this case decrease across a large swath extending from Arizona through Mexico, showing the impacts of warmer temperatures and reduced precipitation, as well as (for Mexico) land use change. Increased fire activity also likely plays a role in the simulated decreases of forest cover and C_3 grasses for RCP8.5 in southern Arizona, where fires together with drought may have affected landscape succession (Williams et al., 2013; Bodner and Robles, 2017). We also investigate trends in LAI for different months in spring from the present day to 2100. We find that the greatest percentage decreases in TeBS and C_3 grasses occur in May, consistent with the largest decreases in precipitation in that month (not shown).

In summary, we find that the warmer and drier conditions of the future climate strongly reduce vegetation cover by 2100, especially in RCP8.5. In addition, CO_2 fertilization and land use practices further modify future vegetation, but in opposite ways, as illustrated by Figure S8. Under a warmer climate, higher CO_2 concentrations facilitate vegetation growth everywhere in the southwestern North America, with larger VAI increases occurring over Arizona and New Mexico. Combined changes in land use are greater under RCP8.5 than RCP4.5, with large increases in RCP8.5 across Mexico but only modest changes in Arizona, New Mexico, and Texas (Figure S9). The increases in Mexico result in the fragmentation of forested landscapes and decrease VAI, especially in coastal forest regions and along the border with the United States.

3.2 Spatial variations in spring fine dust emissions

Unlike the widespread changes in VAI, future changes in fine dust emissions are

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concentrated in a few arid areas, including: 1) the border regions connecting Arizona, New Mexico, and northern Mexico (ANM border), 2) eastern New Mexico, and 3) western Texas (Figure 2). In RCP4.5, slight increases in fine dust emission (up to ~0.3 kg m^{-2} mon^{-1}) are simulated in the ANM border in all the three cases. In contrast, fine dust emissions decrease by up to ~ -1.0 kg m^{-2} mon^{-1} in eastern New Mexico and western Texas in RCP4.5 due to warmer temperatures and increasing VAI. Consistent with the modest changes in VAI (Figure 1), the three cases in RCP4.5 do not exhibit large differences, with only the fixed-CO_2 case showing slightly greater increases in dust emissions along the ANM border and in western Texas. In RCP8.5 in the all-factor case, spring fine dust emissions increase slightly by up to ~ 0.4 kg m^{-2} mon^{-1} along the ANM border, but decrease more strongly in western Texas by up to ~ -1.4 kg m^{-2} mon^{-1} (Figure 2). In contrast, with fixed CO_2 the sign of the change in dust emissions reverses, with significant emissions increases along the ANM border and in New Mexico. The area with decreasing emissions in western Texas also shrinks in the fixed CO_2 case. These trends occur due to the climate stresses, e.g., warmer temperatures and decreased precipitation, that impair the growth of temperature broadleaf trees and C_3 grasses. In this case, such stresses are not offset by CO_2 fertilization (Figure S10).

Figure 3 shows more vividly the opposing roles of CO_2 fertilization and projected land use change in southwestern North America. In RCP8.5, changing CO_2 fertilization alone promotes vegetation growth and dramatically reduces dust mobilization by up to ~ -1.2 kg m^{-2} mon^{-1}. Figure 3 also reveals that land use trends are a major driver of increased dust emissions along the ANM border and western Texas in RCP8.5, as crop- and rangelands expand in this region and temperature broadleaf trees decline (Hurtt et al., 2011). Similarly, the expansion of rangelands in northern Mexico in RCP8.5 reduces natural vegetation cover there (Hurtt et al., 2011), contributing to the increase of fine dust emissions by up to ~0.7 kg m^{-2} mon^{-1}.

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3.3 Spring fine dust concentrations under the high emission scenario

Our simulations suggest that fine dust emissions will increase across arid areas in southwestern North America under RCP8.5, but only if CO_2 fertilization is of minimal importance (Figure 2). To place an upper bound on future concentrations of fine dust in this region, we apply only the fixed-CO_2 emissions to GEOS-Chem at the horizontal resolution of 0.5° x 0.625°. Given the large uncertainty in the sensitivity of vegetation to changing atmospheric CO_2 concentrations (Smith et al., 2016), we argue that this approach is justified.

Results from GEOS-Chem in the fixed-CO_2 case for RCP8.5 show that the concentrations of spring fine dust are significantly enhanced in the southeastern half of New Mexico and along the ANM border, with increases up to ~2.5 µg m^{-3} (Figure 4). The model also yields elevated dust concentrations over nearly the entire extent of our study region by 2100. As Figure 3 implies, land use along the ANM border contributes to the increased dust emissions in that area, by up to ~0.7 kg m^{-2} mon^{-1}. Climate change impacts on natural vegetation, however, account for the bulk of the modeled increases in dust emissions in this scenario, by as much as ~1.2 kg m^{-2} mon^{-1} (Figure 2). The modeled wind fields, which are the same in all scenarios, transport the dust from source regions, leading to the enhanced concentrations across much of the domain, as seen in Figure 4. We find that dust concentrations decrease only in a limited area in western Texas due to decreased pasture (Figures 3 and S9).

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4 Discussion

We apply a coupled modeling approach to investigate the impact of future changes in climate, CO_2 fertilization, and land use on dust mobilization and fine dust concentration in southwestern North America by the end of the 21st century. Table 1 summarizes our findings for

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the two RCP scenarios and three conditions – all-factor, fixed CO_2, and fixed land use – in spring, when dust concentrations are greatest. We find that in the RCP8.5 fixed-CO_2 scenario, in which the effects of CO_2 fertilization are neglected, VAI decreases by 26% across the region due mainly to warmer temperatures and drier conditions, yielding an increase of 58% in fine dust emission averaged over the southwestern North America. In addition, we find that the increase in fine dust emission in northern Mexico is mainly driven by the increases in the extent of cropland and pasture cover in this area, signifying the crucial role of land use practices in modifying dust mobilization.

Our findings of decreasing VAI with future climate change are consistent with observed trends in vegetation during recent droughts in this region. For example, Breshears et al., 2005 documented large-scale die-off of overstory trees across southwestern North America in 2002-2003 in response to short-term drought accompanied by bark beetle infestations. Similarly, during a multi-year (2004-2014) drought in southern Arizona, Bodner and Robles, 2017 found that the spatial extent of both C_4 grass cover and shrub cover decreased in the southeastern part of that state.

The 58% increase predicted in this study in fixed-CO_2 RCP8.5 scenario is larger than the 26-46% future increases in fine dust for this region predicted by the statistical model of Achakulwisut et al., 2018. That study relied solely on predictions of future regional-scale meteorology and did not take into account the change in vegetation, as we do here. In contrast, the statistical model of Pu and Ginoux, 2017 estimated a 2% decrease in the springtime frequency of extreme dust events in the Southwest U.S., driven mainly by reductions in bare ground fraction and wind speed. Like Pu and Ginoux, 2017, we also find that dust emissions decrease across a broad region of the Southwest when CO_2 fertilization is taken into account, as shown in Figure 2. Pu and Ginoux, 2017 relied on limited data for capturing the sensitivity of dust event frequency to

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We further find that consideration of CO_2 fertilization can mitigate the effects of changing climate and land use on dust concentrations in southwestern North America. The all-factor and fixed-land use simulations both yield decreases of ~20% in mean dust emissions compared to the early 21st century. In the IPCC projections, CO_2 reaches ~550 ppm by 2100 under RCP4.5 and ~1960 ppm under RCP8.5 (Meinshausen et al., 2011). Correspondingly, in the RCP4.5 scenario for 2100, CO_2 fertilization enhances VAI by 30% in the all-factor case compared to the fixed-CO_2 case (1.07 m^2m^{-2} vs. 0.79 m^2m^{-2}); in RCP 8.5, the 2100 enhancement is 64% (1.11 m^2m^{-2} vs. 0.55 m^2m^{-2}), as shown in Table 1. These enhancements further decrease fine dust emissions by 21% under RCP4.5 and 78% under RCP8.5, compared to the present day. Except along the ANM border and a few other areas, trends in land use have only minor impacts on dust mobilization under the two RCPs in southwestern North America.

In summary, we find that as atmospheric CO_2 levels rise vegetation growth is enhanced and dust mobilization decreases, offsetting the impacts of warmer temperatures and reduced rainfall, at least in some areas. These results are consistent with evidence that CO_2 fertilization is already occurring in arid or semiarid environments like southwestern North America (Donohue et al., 2013; Haverd et al., 2020). In such environments, water availability is the dominant constraint on vegetation growth, and the recent increases in atmospheric CO_2 may have reduced stomatal conductance and limited evaporative water loss. The effects of CO_2 fertilization on vegetation growth are uncertain, however, and may be attenuated by the limited supply of nitrogen and

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Understanding the drivers in historic dust trends has sometimes been challenging (Mahowald and Luo, 2003; Mahowald et al., 2002), making it difficult to validate dust mobilization models. A further drawback of our approach is that the LPJ-LMfire model is driven by meteorological fields from just one climate model, GISS-E2-R. Given that the GISS model yields a conservative prediction of climate change in the southwestern North America compared to other models (Ahlström et al., 2012; Sheffield et al., 2013), our predictions of the impact of climate change on dust mobilization may also be conservative. Other uncertainties in our study can be traced to the dust simulation. The different vegetation types in our model are quantified as fractions of gridcells, which have relatively large spatial dimensions of ~50 km × 60 km. This means the model cannot capture the spatial heterogeneity of land cover, and the aerodynamic sheltering effects of vegetation on wind erosion are neglected, as they are in most 3-D global model studies. Such sheltering could play a large role in dust mobilization (e.g., Liu et al., 1990). New methods involving satellite observations of surface albedo promise to improve understanding of the effects of aerodynamic sheltering on dust mobilization, at least for the present-day (Chappell and Webb, 2016; Webb and Pierre, 2018). Implementation of aerodynamic sheltering in simulations of future climate regimes would need to account for fine-scale spatial distributions of vegetation. In addition, as recommended by Zender et al., 2003, we apply a globally uniform surface roughness Z_0 in the model, which means that the impact of changing vegetation conditions on friction velocity is not taken into account. Future work could address this weakness by varying friction velocity according to vegetation type. Finally, our study focuses only on the effect of changing vegetation on dust mobilization and does not take into account how changing windspeeds

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or drier soils in the future atmosphere may more directly influence dust. Given the slight increase in monthly mean winds in RCP8.5 by 2100, future dust emissions in this scenario could be underestimated.

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Within these limitations, our study quantifies the potential impacts of changing land cover and land use practices on dust mobilization and fine dust concentration over the coming century in southwestern North America. Our work builds on previous studies focused on future dust in this region by (1) more accurately capturing the transport of dust from source regions with a dynamical 3-D model, (2) considering results with and without CO_2 enhancement, and (3) including the impact of land use trends. Given the many uncertainties, it is challenging to gauge which of the three factors investigated here – climate impacts on vegetation, CO_2 fertilization, or land use change – will play the dominant role in driving future changes in dust emissions and concentrations. This study thus brackets a range of possible dust scenarios for the southwestern North America, with the simulation without CO_2 fertilization placing an upper bound on dust emissions. In the absence of increased CO_2 fertilization, our work suggests that vegetated cover will contract in response to the warmer, drier climate, exposing bared ground and significantly increasing dust concentrations by 2100. In this way, dust enhancement could impose a potentially large climate penalty on $PM_{2.5}$ air quality, with consequences for human health across much of southwestern North America.

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Our finding of the potential for an increased dust burden in the future atmosphere has special relevance for environmental justice in this region, where much of the current population is of Native American and/or Latino descent. For example, in New Mexico, 10% of the population is Native American and 50% identifies as either Hispanic or Latino. By some measures, New

Mexico has also one of highest poverty rates of the United States (https://www.census.gov/quickfacts/NM, last accessed on August 20, 2020).

Code and data availability

GEOS-Chem model codes can be obtained at http://acmg.seas.harvard.edu/geos. LPJ-LMfire model codes can be obtained at https://github.com/ARVE-Research/LPJ-LMfire. IMPROVE datasets are available online at http://vista.cira.colostate.edu/improve. Any additional information 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.

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Figures and tables

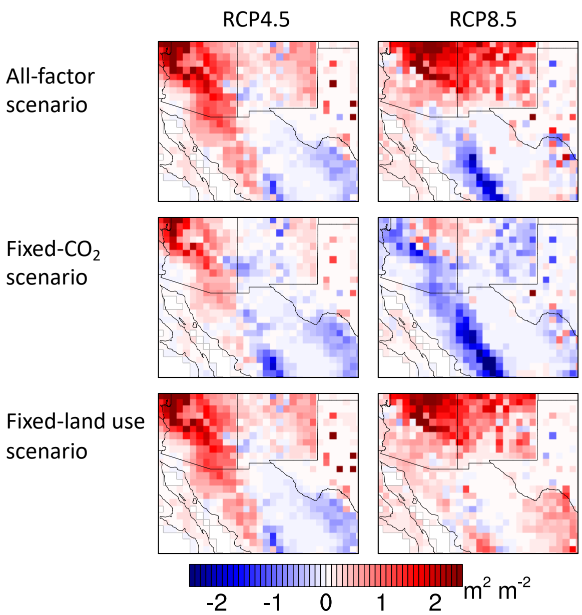

Figure 1. Simulated changes in spring averaged monthly mean vegetation area index (VAI) in southwestern North America under the three conditions for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The All-factor case (top row) includes the effects of climate, CO_2 fertilization, and land use on vegetation. Only climate and land use are considered in the Fixed-CO_2 case (middle), and only climate and CO_2 fertilization are considered in the Fixed-land use case (bottom). Results are from LPJ-LMfire.

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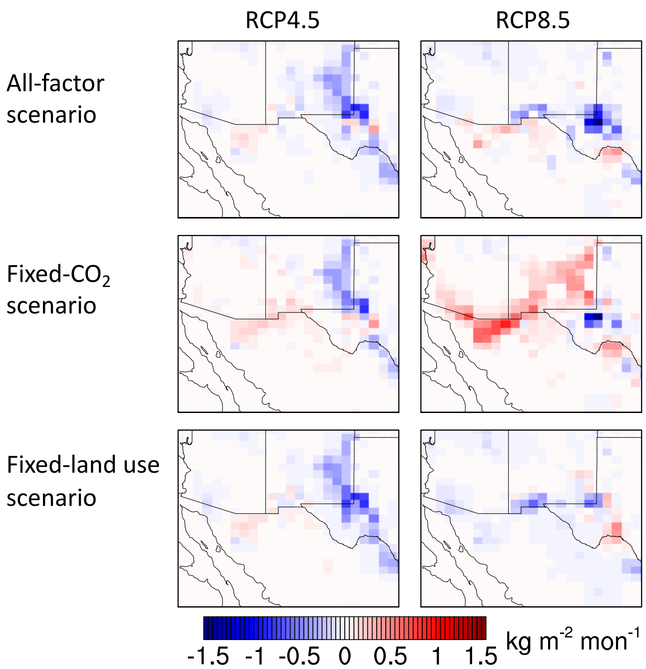

Figure 2. Simulated changes in spring averaged monthly mean dust emission in southwestern North America under the three conditions for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The top row shows results for the all-factor condition, the middle row is for the fixed-CO_2 condition, and the bottom row is for the fixed-land use condition. Cases are as described in Figure 1. Results are generated offline using the GEOS-Chem emission component (HEMCO).

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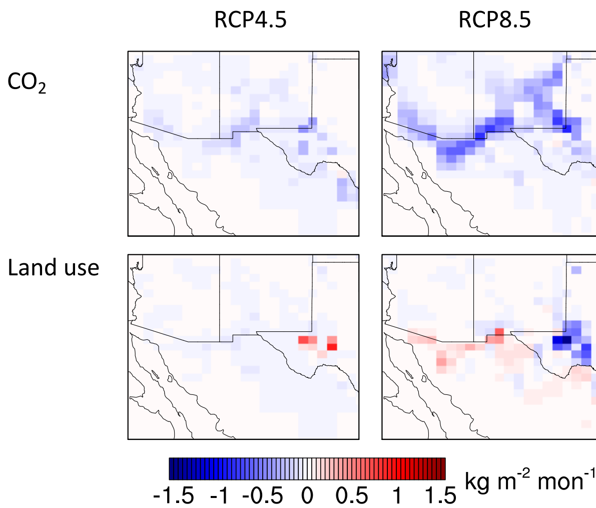

Figure 3. Contributions of CO_2 fertilization and land use change to changing dust emissions in spring in southwestern North America for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The top row shows the response of dust emission to only CO_2 fertilization and the bottom row shows the response to only trends in land use. Results are generated offline using the GEOS-Chem emission component (HEMCO).

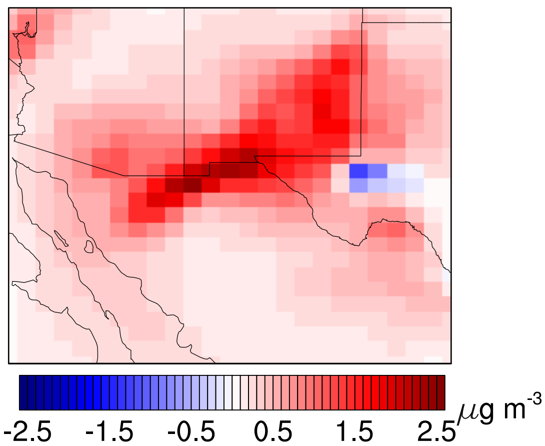

Figure 4. Simulated changes in springtime mean concentrations of fine dust over southwestern North America for the RCP8.5 fixed-CO_2 case, in which the effects of CO_2 fertilization are neglected. Changes are between the present day and 2100, with five years representing each time period. Results are from GEOS-Chem simulations at 0.5° x 0.625° resolution.

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Table 1. Averaged spring vegetation area index (VAI) and fine dust emission in southwestern North America for the present-day and future for two scenarios (RCP4.5 and RCP8.5) and three cases. The all-factor case includes changes in climate, land use, and CO_2 fertilization; the fixed-CO_2 case includes changes in only climate and land use; and the fixed-land use case includes changes in only climate and CO_2. The rows labeled "2100-2010, %" give the percentage changes in VAI and fine dust emissions between the present day and future, with positive values denoting increases in the future.

		VAI[b], $m^2\ m^{-2}$			Fine dust emission[b], $kg\ m^{-2}\ mon^{-1}$		
		All-factor	**Fixed CO_2**	**Fixed land use**	**All-factor**	**Fixed CO_2**	**Fixed land use**
RCP4.5	**2010**[a]	0.75±0.26	0.71±0.24	0.75±0.26	0.10±0.07	0.11±0.08	0.10±0.07
	2100[a]	1.07±0.48	0.79±0.34	1.07±0.48	0.08±0.04	0.10±0.05	0.08±0.04
2100-2010, %		**42**	**12**	**42**	**-25**	**-4**	**-26**
RCP8.5	**2010**[a]	0.80±0.27	0.75±0.24	0.75±0.24	0.09±0.04	0.09±0.05	0.09±0.04
	2100[a]	1.11±0.71	0.55±0.33	0.55±0.33	0.07±0.04	0.14±0.09	0.07±0.06
2100-2010, %		**38**	**-26**	**52**	**-20**	**58**	**-16**

[a]Each time slice represents 5 years (i.e., 2011-2015 represents the 2010 time slice and 2095-2099 represents the 2100 time slice); [b]Values are spring (MAM) averages over southwestern North America.

Supplementary material

Response of dust emissions in southwestern North America to 21st century trends in climate, CO_2 fertilization, and land use: Implications for air quality

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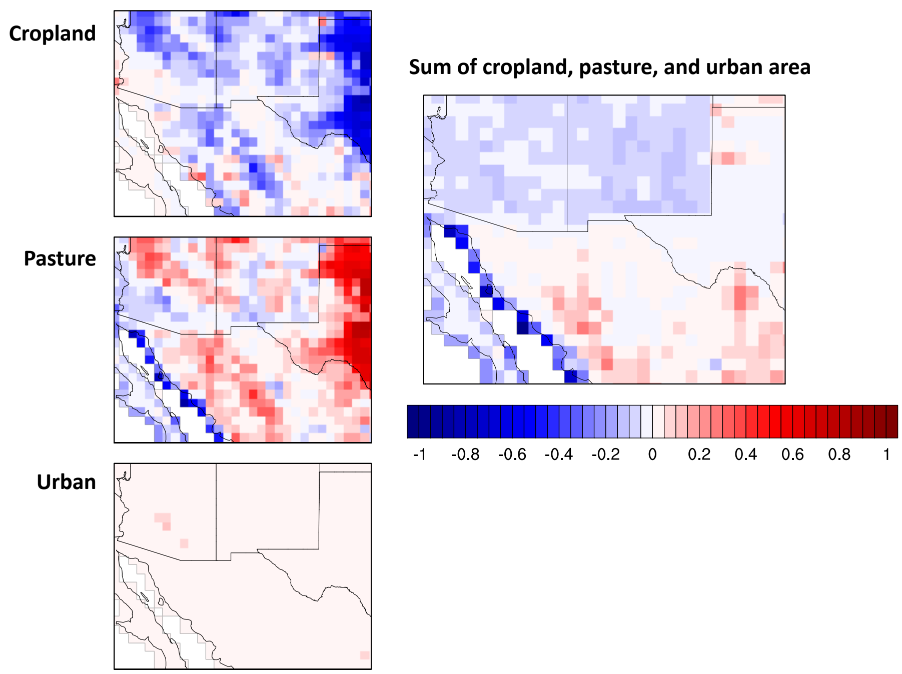

Figure S1. Changes in land use fraction in southwestern North America from 1990 to 2015. Future land use scenarios applied follow CMIP5. Land use types of cropland, pasture, and urban area are plotted on the left, and the sum of these three types is plotted on the right.

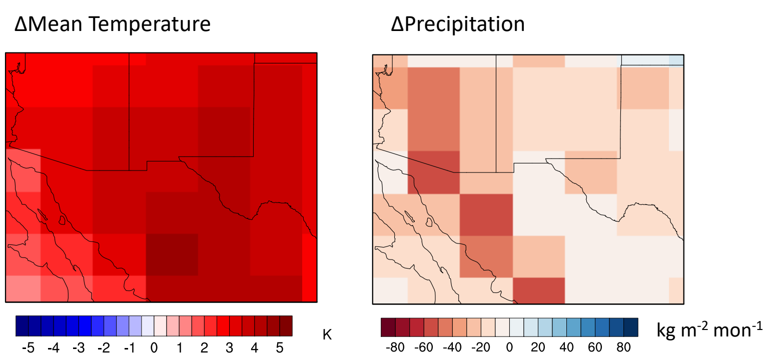

Figure S2. GISS-E2-R simulated spring averaged monthly mean temperature and precipitation in southwestern North America for RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The color bar is reversed for precipitation, with redder colors indicated drier conditions.

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Evaluation of dust emissions based on LPJ-LMfire

Figure S3 shows the simulated present-day (2011-2015) distribution of vegetation area index (VAI) over southwestern North America. Values are derived from LAI generated by the LPJ-LMfire dynamic vegetation model, as described in the main text. We find relatively high VAI values in central Arizona, northern New Mexico, northern Texas, and northwestern Mexico, but near-zero VAI in the arid regions of western Texas and along the northern Mexico border. Figure S4 compares the differences in springtime VAI generated by LPJ-LMfire for the present day and that derived from 1-km reflectance data from the Advanced Very High Resolution Radiometer (AVHRR, Bonan et al., 2002). This satellite-based VAI is the default dataset in the DEAD module (Zender et al., 2003). The differences between these two VAI datasets are mostly small, within ±1

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m^2 m^{-2}, across southwestern North America, giving us confidence in the performance of LPJ-LMfire. In addition, we categorize the LPJ-LMfire simulated land cover types as trees and shrubs, grasses, and barren land (Figure S5). The high-dust emission region shown in Figure S3 is dominated by grass ecosystems and barren land, roughly consistent with observed land cover shown in the photos of four locations (southwest New Mexico, southeast New Mexico, west Texas, and northern Chihuahua state, Mexico) selected from the principle dust-producing regions in our study (Figure S5).

The dominant plant functional types in LPJ-LMfire in the southwestern North America include temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and C3 perennial grass, roughly consistent with observed, present-day vegetation types (McClaran and Van Devender, 1997). We acknowledge, however, that with only nine PFTs, LPJ-LMfire cannot capture the phenology of all plant species, which could in turn introduce error into our dust calculations. Still, the relatively good match of modeled springtime VAI with that observed is encouraging.

Figure S3 also shows the distribution of dust emissions for the present-day RCP4.5 scenario, with especially high emissions simulated over those areas with near zero VAI. We apply these emissions to GEOS-Chem and evaluate the resulting fine dust concentrations using ground-based measurements from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network (Malm et al., 2004). Hand et al., 2016 used the observed iron content from IMPROVE as a proxy for fine dust concentrations, and approximated soil-derived $PM_{2.5}$ as $PM_{2.5}$-Iron/0.058. IMPROVE dust observations are made every three days, and we show the spatial or temporal median of these observations as outliers are common in the dataset, and GEOS-Chem is unlikely to capture the extreme dust events. For model validation, we rely on the RCP8.5 results

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for 2011-2015, which yields nearly identical results as RCP4.5. GEOS-Chem tracks fine dust with a diameter range of 0.2-2.0 µm, while the IMPROVE approximation yields dust concentrations with diameter less than 2.5 µg m^{-3}. This disparity may hinder the model comparison with observations.

Figure S6 compares the spatial distribution of GEOS-Chem springtime dust concentrations with observations, and Figure S7 examines the temporal variability of modeled and observed dust averaged over the region. In general, the model captures both the observed spatial and temporal variability, though GEOS-Chem underestimates dust at a few sites in Arizona. This underestimate could be a result of abundant mountain vegetation simulated by LPJ that alleviates dust generation from persistently arid or desert regions. The 2011-2015 timeseries of observed and modeled dust (Figure S7) reveals that GEOS-Chem exhibits a smaller seasonal variation of 0.2-3.1 µg m^{-3}, compared with the observed range of 0.2-8.1 µg m^{-3}. Overall, we find that the present-day simulations reasonably reproduce observed fine dust over southwestern North America.

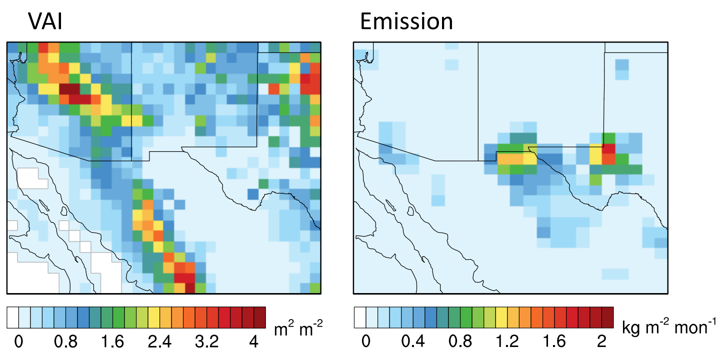

Figure S3. Present-day (2011-2015) spring averaged VAI and fine dust emissions for the RCP8.5 fixed-CO_2 case in southwestern North America, in which CO_2 fertilization is neglected. VAI results are from LPJ-LMfire. Dust emissions are generated offline using the GEOS-Chem emission component (HEMCO).

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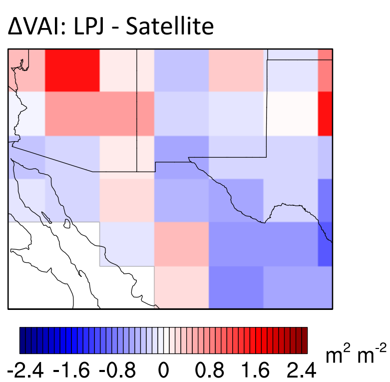
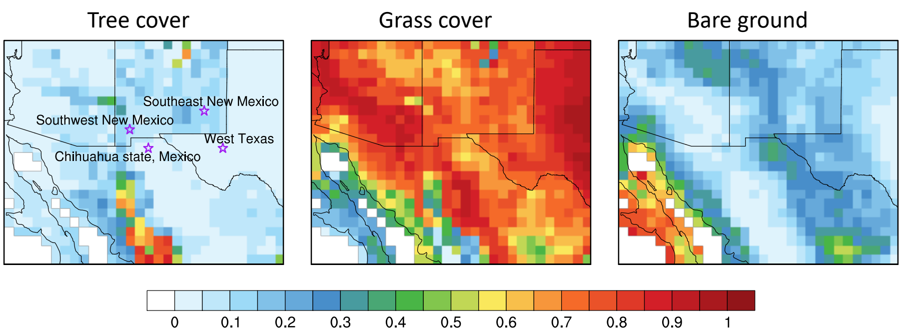


Figure S4. Differences between springtime VAI simulated by LPJ-LMfire and that derived from 1-km satellite data in southwestern North America. The LPJ-LMfire results are the mean 2011-2015 values from the RCP8.5 fixed-CO_2 case; satellite-derived VAI are from Bonan et al. (2002).



103.25°W 31.25°N (West Texas)
LPJ: 0.3% trees/shrubs, 74.9% grass, 24.8% unvegetated


The Degree Confluence Project, 2011


Google Street View, 2013


The Degree Confluence Project, 2011

104.25°W 33.25°N (Southeast New Mexico)
LPJ: 0.5% trees/shrubs, 73.4% grasses, 20.1% unvegetated


The Degree Confluence Project, 1999


Google Street View, 2013


Google Street View, 2013

108.25°W 32.25°N (Southwest New Mexico)
LPJ: 12.7% trees/shrubs, 73.3% grasses, 14.0% bare ground

Google Street View, 2014 | The Degree Confluence Project, 2014 | The Degree Confluence Project, 2014

107.25°W 31.25°N (Chihuahua state, Mexico)
LPJ: 2.4% trees/shrubs, 65.3% grasses, 32.2% bare ground

The Degree Confluence Project, 2005 | Google Street View, 2019 | Google Street View, 2018

Figure S5. Top panels show mean fractional land cover of trees, grasses, and barren land averaged over 2006-2015, as simulated by LPJ-LMfire. Purple stars on the top lefthand panel mark four selected locations that are broadly representative of vegetation within the principle dust-producing regions in our study, with photographs of each location shown below. Latitude and longitude values listed above each row of photographs denote the center of the LPJ-LMfire gridcell, and the corresponding photographs are all taken within the area encompassed by the 0.5° × 0.5° gridcell.

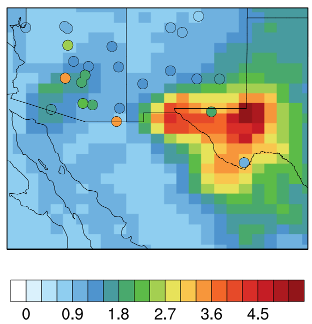


Figure S6. Spring fine dust concentration. Circles represent ground-based observations from the IMPROVE network, shown as the medians at each site over 2011-2015. The colored background is from GEOS-Chem simulations with the present-day (2011-2015) fine dust emissions for the RCP8.5 fixed-CO_2 case at 0.5° x 0.625° spatial resolution.

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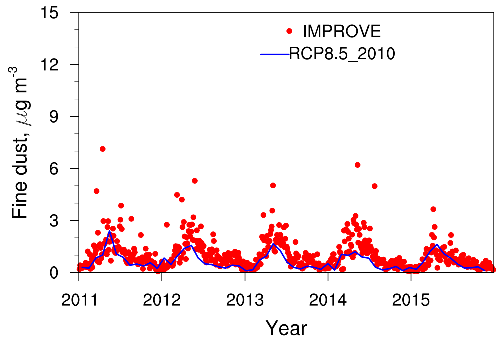

Figure S7. Seasonal cycle of GEOS-Chem simulated and IMPROVE observed fine dust concentrations, shown as the medians over southwestern North America from 2011 to 2015. The red dots represent the median of IMPROVE observations taken over all sites in the region at each measurement timestep. IMPROVE has a measurement frequency of every three days. The solid line shows GEOS-Chem simulated variations at 0.5° x 0.625° resolution for the 2010 time slice for the RCP8.5 fixed-CO_2 case.

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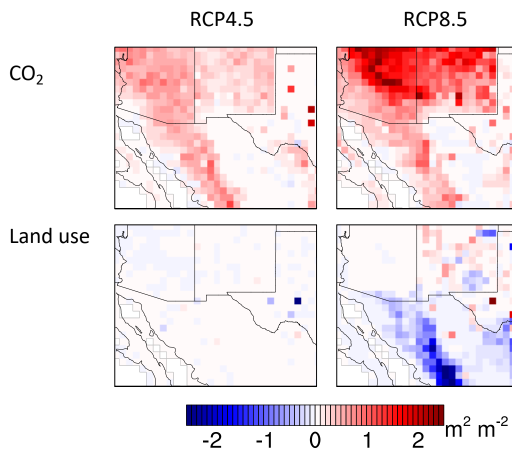

Figure S8. Contributions of CO_2 fertilization and land use to changes in VAI in spring in southwestern North America for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The top row is for CO_2 fertilization, and the bottom row is for land use trends. Results are from LPJ-LMfire.

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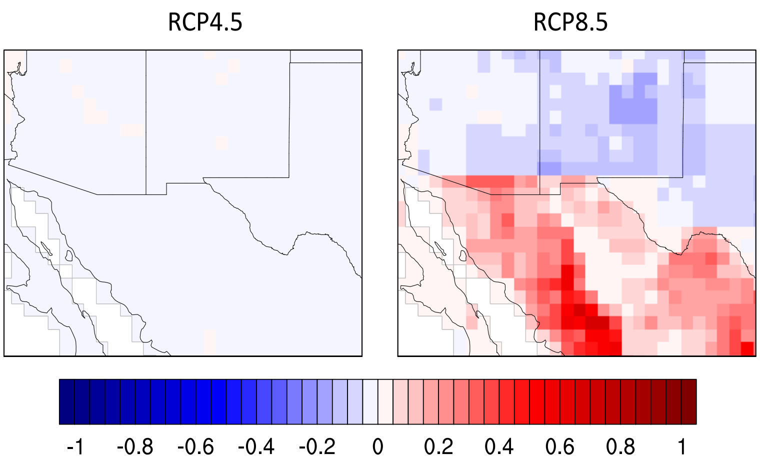

Figure S9. Changes in yearly averaged land use fraction in southwestern North America for RCP4.5 and RCP8.5 between the present day and 2100, with five years representing each time period. Future land use scenarios applied follow CMIP5. Land use plotted here is the sum of cropland, pasture, and urban area.

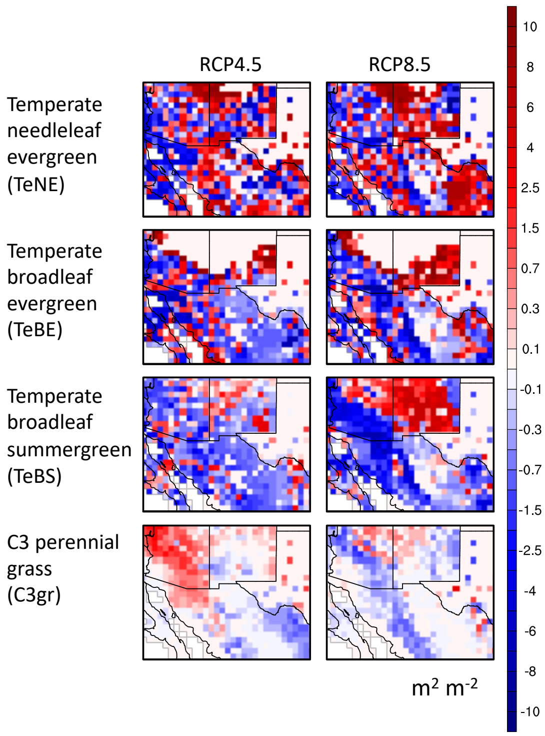

Figure S10. Simulated changes in springtime averaged LAI for the four dominant plant functional types (PFTs) in southwestern North America under RCP4.5 and RCP8.5 for the fixed-CO_2 condition, in which CO_2 fertilization is neglected. Changes are between the present day and 2100, with five years representing each time period. For clarity, the increments in the color bar are unevenly distributed. Results are from LPJ-LMfire.

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