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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. However, the projected dust trends under climate change are sometimes contradictory. Here we link a dynamic vegetation model (LPJ-LMfire) to a chemical transport model (GEOS-Chem) to assess the impacts of future changes in climate, CO_2 fertilization, and land use practices on dust mobilization, and to investigate the consequences for surface air quality. 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

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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}).

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1 Introduction

Dust storms in the arid southwestern United States and northwestern Mexico (here defined as southwestern North America) entrain large quantities of soil-derived fine dust particles into the lower atmosphere and have negative effects on human health including causing respiratory and cardiovascular diseases (Tong et al., 2017; Meng and Lu, 2007; Gorris et al., 2018). Wind and vegetation cover are key factors that determine soil erodibility and dust emissions, with wind gusts mobilizing dust particles from the earth's surface and vegetation constraining dust emissions by reducing bare land and preserving soil moisture (Zender et al., 2003). 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), elevated CO_2 concentrations could enhance vegetation growth (Poorter and Perez-Soba, 2002). Land use practices in the future will likely also influence the propensity of dust storms. 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 investigated the relative importance of climate, CO_2 fertilization, and 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 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.

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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 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 land under 21st century climate change.

These previous 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 examine the response of dust mobilization due to climate-induced changes in vegetation, increasing CO_2 fertilization, and land use practices across the 21st century. 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,

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allowing consideration of many factors driving future dust mobilization in the southwestern North America. We focus on springtime (March, April, and May), because it is the season of highest dust concentrations in the southwestern U.S. (Hand et al., 2017).

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-21st century under future climate and land use based on two Representative Concentration Pathways (RCPs). RCP4.5 represents a moderate pathway with gradual reduction in greenhouse gas (GHG) emissions after 2050, while RCP8.5 assumes continued increases in GHGs throughout the 21st century. To estimate changes in vegetation under future meteorological conditions, we use LPJ-LMfire, a dynamic global vegetation model that accounts for the effects of land use and fire on vegetation structure (Pfeiffer et al., 2013). Present-day and future meteorological fields, including surface temperature and precipitation, are simulated by the Goddard Institute for Space Studies (GISS) Model E climate model, and these are fed into LPJ-LMfire. For each RCP, we investigate the changes in vegetation following three scenarios: 1) an all-factor scenario that includes changes in climate, land use, and CO_2 fertilization; 2) a fixed-CO_2 scenario that includes changes in only climate and land use; and 3) a fixed-land use scenario that includes changes in only climate and CO_2 fertilization. Using the GEOS-Chem emission component (HEMCO), we calculate dust emissions based on the LPJ-generated vegetation area index (VAI) in different scenarios. We then apply these dust emissions and the global chemical transport model GEOS-Chem to simulate the distribution of fine dust across the southwestern North America at a spatial resolution of 0.5° latitude x 0.625° longitude. For each RCP, the LPJ-LMfire simulation covers the period 2006-2100 continuously, with

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monthly resolution. For computational reasons, we limit our GEOS-Chem simulations to two time-slices centered on the early and late 21st century, with each time slice covering 5 continuous years (2011-2015 and 2095-2099). We apply present-day meteorology to both time slices in GEOS-Chem, which allows us to focus on the effect of changing land cover on dust mobilization. More information is in the Methods section, including validation of the GEOS-Chem dust simulation for the present-day.

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).

2.1 LPJ-LMfire

LPJ-LMfire is driven by gridded climate, soil, land use fields, and atmospheric CO_2 concentrations, and simulates vegetation structure, biogeochemical cycling, and wildfire. The model takes into account the effects of fire activity on vegetation cover (Pfeiffer et al., 2013; Sitch et al., 2003). As described in Li et al., 2020, the model depends on a suite of meteorological anomalies from GISS-E2-R (Nazarenko et al., 2015) for RCP4.5 and RCP8.5: 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. Future land use scenarios applied follow CMIP5. In RCP8.5, the extent of cropland

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and pasture 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). 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.

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.

2.2 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); 2) and 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., 2003 to compute a size-segregated dust flux, which includes entrainment thresholds for saltation, moisture inhibition, drag partitioning, and saltation feedback. It calculates the vertical dust flux as proportional to the horizontal saltation flux, and allows seasonally devegetated regions to mobilize dust. The DEAD dust scheme assumes that vegetation suppresses dust by linearly reducing A_m, the fraction of bare soil exposed in each grid cell:

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

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

$$A_V = \min\left[1.0, \min(VAI, VAI_t)\,/VAI_t\right] \quad (2),$$

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

LPJ-LMfire calculates the monthly 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. Assuming immediate removal of all dead leaves as in Sellers et al., 1996, σ_v can be used

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to represent stem area index (SAI) for different PFTs (Zeng et al., 2002). VAI is generally defined as the sum of the LAI plus SAI. As the threshold VAI_t for no dust emission is relatively low (i.e., 0.3 m^2 m^{-2}), leaf area has a dominant suppression effect on dust mobilization. In areas where LAI is greater than SAI, we assume that SAI does not play a role in controlling dust emissions and that LAI is equivalent to VAI. We also assume that C_3 and C_4 grasses have zero stem area to avoid overestimating VAI during the non-growing season when such grasses are dead. Based on the method of Zeng et al., 2002, with modifications, we calculate VAI in each grid cell as

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

where LAI and σ_v are from LPJ-LMfire.

2.3 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 MERRA-2 meteorology 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 dust saltation even when the grid-scale wind conditions are below some specified threshold speed. 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 S2.

2.4 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 time slices. In other words, we do not take into account changes in wind speeds in our simulations. 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 S3-S4.

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 scenarios under both RCPs by 2100. In RCP4.5, the distributions of changes in VAI are similar for the all-factor and fixed-land use scenarios. Strong enhancements (up to ~2.5 m^2 m^{-2}) occur in the National Forests and Parks extending from the northwestern to southeastern corners of Arizona. 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 two scenarios indicates the relatively trivial

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influence of land use change on vegetation cover in RCP4.5. For the fixed-CO_2 scenario, western New Mexico and northern Mexico show greater decreases in VAI, indicating the role of CO_2 fertilization in balancing the effects of climate change on vegetation in this region. We also find scattered decreases in VAI in western Texas in this scenario. CO_2 fertilization has strong positive impacts on VAI (Figure S5).

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 scenarios, but now this increase extends to New Mexico. In contrast to RCP4.5, modeled VAI decreases in the coastal forest areas in northern Mexico in the all-factor RCP8.5 scenario. In the fixed-land use scenario, however, the VAI decrease in northern Mexico is nearly erased, indicating the role of vegetation/forest degradation caused by land use practices (Figure S5). For the fixed-CO_2 scenario in 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 can 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 scenario under RCP8.5 are dominated by the degradation of temperate broadleaf evergreen (TeBE) and temperate broadleaf summergreen (TeBS) (Figure S6). 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 shows strong decreases, especially in southern Arizona and Mexico. C3 perennial grass (C3gr) makes only a minor contribution to the VAI decreases in this scenario, but this degradation plays an important role in dust mobilization.

As summarized in the Supplement (Figure S5), CO_2 fertilization and land use practices modify future vegetation cover in opposite ways. 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. Projected land use practices – which include agriculture, human settlement, and urban sprawl – result in habitat loss and the fragmentation of forested landscapes. These trends in land use decrease VAI, especially in RCP8.5 in the coastal forest regions of Mexico and along the northeastern border of Mexico south of Texas.

3.2 Spatial variations in spring fine dust emissions

Unlike the widespread changes in VAI, future changes in fine dust emissions are 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 scenarios, indicating desertification of the southern semi-arid highlands between the Sonoran and Chihuahuan deserts. 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 scenarios in RCP4.5 do not exhibit large differences, with only the fixed-CO_2 scenario showing slightly greater increases in dust emissions along the ANM border and in western Texas. In RCP8.5 in the all-factor scenario, 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 this scenario. These trends occur due to the

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climate stresses on temperature broadleaf trees and C3 grasses that are not counteracted in this scenario by CO_2 fertilization (Figure S5).

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 shows that land use trends are a major driver of dust emissions along the ANM border and western Texas. Again in RCP8.5, the land use scenario shows abandonment of crop- and rangelands in this region, curtailing dust emissions (Hurtt et al., 2011). However, the projection of rangeland expansion in northern Mexico in RCP8.5 reduces natural vegetation cover in this region (Hurtt et al., 2011), contributing to the increase of fine dust emissions by up to ~0.7 kg m^{-2} mon^{-1}.

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 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. While anthropogenic land use serves as a major driver of the dust increases along the ANM border, climate change accounts for the bulk of these increases, with winds transporting the enhanced dust across much of the region. We find that dust decreases

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in this scenario only in a limited area in western Texas due to changing land use (Figure 3).

4 Discussion

We apply a coupled modeling approach to investigate the impact of future changes in climate, CO_2 fertilization, and anthropogenic land use on dust mobilization and dust concentration in southwestern North America by the end of the 21st 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 to warmer temperatures and drier conditions, yielding an increase of 58% in fine dust emission averaged over the southwestern North America. Specifically, 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. The 58% increase predicted in this study is larger than the 26-46% future increases in fine dust for this region predicted by the statistical model of Achakulwisut et al., 2018. In contrast, the statistical model of Pu and Ginoux, 2017 estimated a decrease by ~2% in the springtime frequency of extreme dust events in the Southwest U.S., driven by reductions in bare ground fraction and wind speed. Differences between our study and these two previous ones highlight the importance of robust representation of both future vegetation changes and the sensitivity of dust emissions to these changes. The study of Achakulwisut et al., 2018 did not consider the climate effect on vegetation, while that of Pu and Ginoux, 2017 relied on limited data for capturing the sensitivity of dust to land cover in this region. Neither study considered changes in land use.

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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, CO_2 fertilization enhances VAI by 30% by 2100 under RCP4.5 and 64% under RCP8.5. 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.

Our study suggests that CO_2 fertilization plays a major role in modifying vegetation cover and, in some regions, reverses the sign of future dust emission trends from positive to negative by 2100. However, there is large uncertainty in quantifying the sensitivity of vegetation to ambient CO_2, with at least one study suggesting that models may overestimate this sensitivity (Smith et al., 2016). One reason for this uncertainty is incomplete understanding of the nutrient constraints on plant growth (Wieder et al., 2015), which vary greatly among different PFTs (Shaw et al., 2002; Nadelhoffer et al., 1999). Additionally, 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. Finally, our study

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focuses only on the effect of changing vegetation on dust mobilization and does not take into account how changing windspeeds may also influence dust.

Within these limitations, our study quantifies the potential impacts of climate change and land use practices on dust mobilization over the coming decades. For example, if the effects of CO_2 fertilization on vegetation growth are attenuated by nutrient constraints, our work suggests a potentially large climate penalty on air quality, with consequences for human health by 2100 across much of southwestern North America.

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

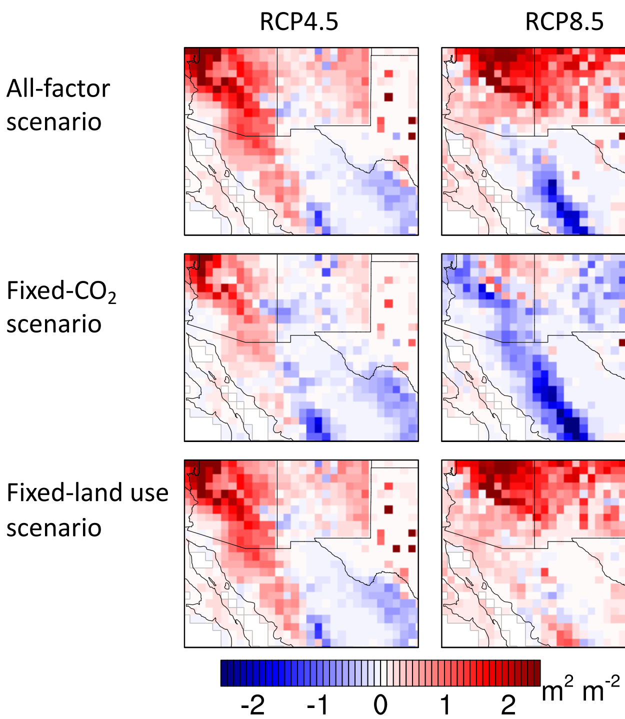

Figure 1. Simulated changes in spring averaged monthly mean vegetation area index (VAI) in southwestern North America under the three conditions for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The All-factor scenario (top row) includes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

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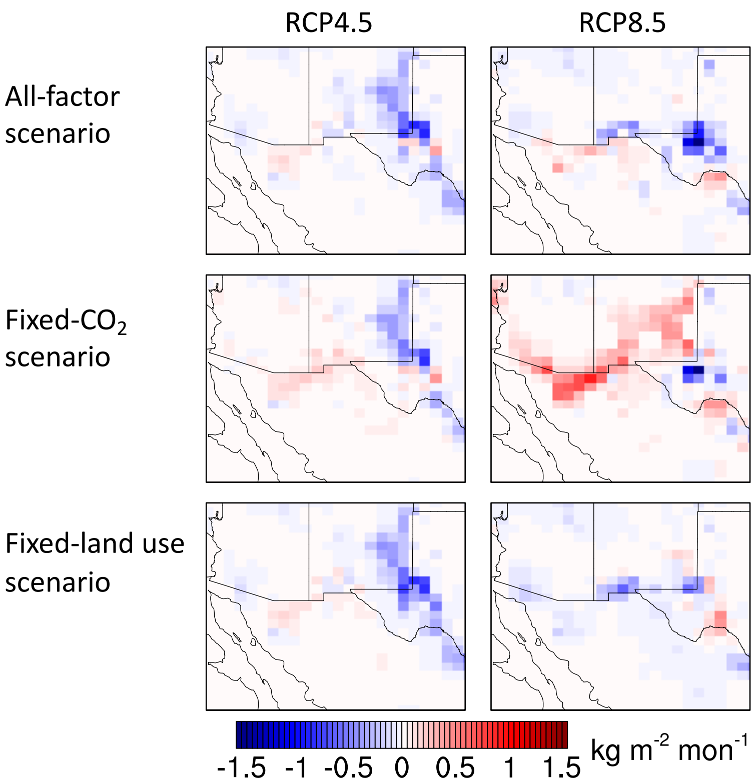

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495 **Figure 2.** Simulated changes in spring averaged monthly mean dust emission in southwestern
496 North America under the three conditions for RCP4.5 and RCP8.5. Changes are between the
497 present day and 2100, with five years representing each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

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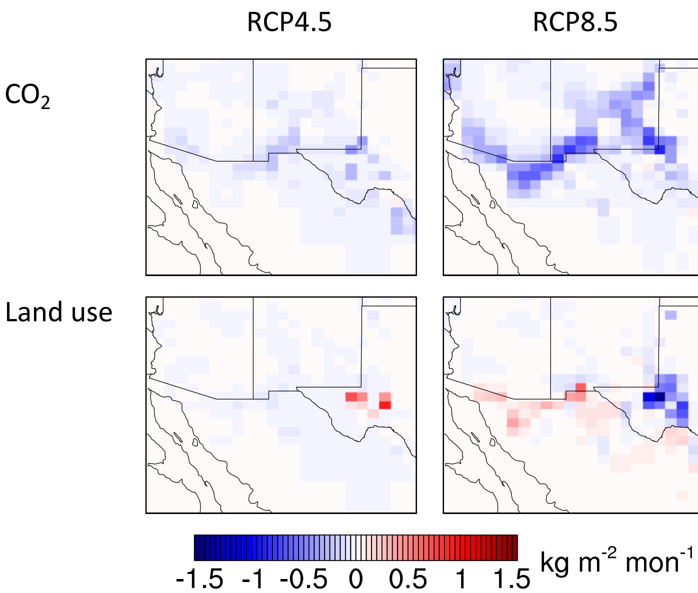

Figure 3. Contributions of CO_2 fertilization and land use change to changing dust emissions in spring in southwestern North America for RCP4.5 and RCP8.5. Changes are between the present day and 2100, with five years representing each time period. The top row shows the response of dust emission to only 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).

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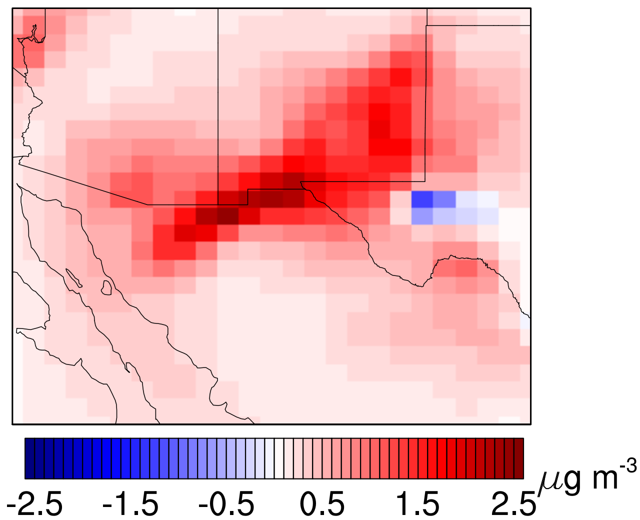

Figure 4. Simulated changes in springtime mean concentrations of fine dust over southwestern North America for the RCP8.5 fixed-CO_2 scenario, in which the effects of CO_2 fertilization are neglected. Changes are between the present day and 2100, with five years representing each time period. Results 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.

		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; [b]Values are spring (MAM) averages over southwestern North America.