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Projected Effects of Climate and Development on California Wildfire Emissions through 2100

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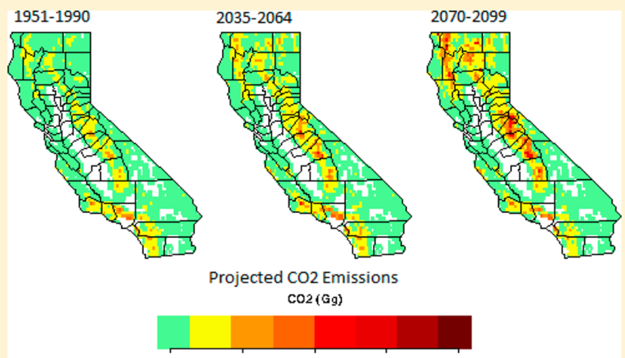
Supporting Information

ABSTRACT: Changing climatic conditions are influencing large wildfire frequency, a globally widespread disturbance that affects both human and natural systems. Understanding how climate change, population growth, and development patterns will affect the area burned by and emissions from wildfires and how populations will in turn be exposed to emissions is critical for climate change adaptation and mitigation planning. We quantified the effects of a range of population growth and development patterns in California on emission projections from large wildfires under six future climate scenarios. Here we show that end-of-century wildfire emissions are projected to increase by 19−101% (median increase 56%) above the baseline period (1961−1990) in California for a medium-high temperature scenario, with the largest emissions increases concentrated in northern California. In contrast to other measures of wildfire impacts previously studied (e.g., structural loss), projected population growth and development patterns are unlikely to substantially influence the amount of projected statewide wildfire emissions. However, increases in wildfire emissions due to climate change may have detrimental impacts on air quality and, combined with a growing population, may result in increased population exposure to unhealthy air pollutants.



INTRODUCTION

Fire is a disturbance that affects many terrestrial ecosystems around the globe. Through emissions from biomass combustion and alteration of land surface properties, fire results in feedbacks that influence the climate system.[1,2] Additionally, climatic changes in the form of increasing temperature and altered precipitation regimes affect fire frequency.[3,4] In some regions, climate feedbacks to fire frequency and extent have the potential to substantially reduce the fire rotation (i.e, time required to burn an area equal to the area of interest), resulting in novel vegetation assemblages.[5]

Humans have been deliberately using fire to alter natural systems for millennia.[1] More recently, human actions related to ignition and suppression have been exerting bottom-up controls on fire by altering the amount of biomass available to fuel fire. Top-down climatic controls also have the potential to alter size, severity, and frequency of fire and can function independently of or interact with bottom-up controls.[6,7] In the presence of these climatic and anthropogenic controls, annual global fire emissions were estimated to range from 1.5−2.8 Pg C year^{-1} from 1997 to 2009,[8] equivalent to approximately 17−32% of 2008 global emissions from fossil fuel combustion and cement production [U.S. Department of Energy, http://cdiac.ornl.gov/trends/emis/glo.html]. The relative contribution of both anthropogenic and climatic controls on fire activity has varied with time, and future projections suggest that the primary driver of global fire activity will shift from human activities to temperature during the 21st century.[9] At regional scales, increases in the size and frequency of large fires have been linked to trends in spring and summer temperature in recent decades.[4,5]

While globally temperature may become a dominant influence on fire as the climate warms, it is unclear how patterns of development will influence fire frequency at regional and local scales. Westerling et al.[10] have shown that population growth in California can simultaneously have both positive and negative effects on fire frequency. Increases in fire frequency likely stem from human presence, providing additional ignition sources, while decreases stem from reductions in vegetation

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caused by development, along with potentially increased suppression efforts. The net effect of these conflicting influences varies across California, depending on the characteristics of a given region and how development reduces the vegetated area in which wildfire can exist.[6] Potential synergies between climate and human development patterns on fire frequency and extent have implications both for feedbacks to the climate system and for human health because of the range of combustion products from fire.[11] Thus, understanding how climate and development will alter fire frequency, size, and severity is essential for both climate change mitigation through terrestrial carbon sequestration and societal adaptation to changes in air quality, risk of structure loss, and potential deterioration of ecosystem services.

Previous work has examined how the interaction of climate scenarios and different spatial population growth trajectories may affect wildfire patterns[10] and risk of structure loss within California.[12] This paper draws on those modeled changes in wildfire frequency to expand the range of impacts considered. Specifically, it extends consideration of climate and development-driven wildfire impacts on the human population by providing spatially explicit scenarios for wildfire emissions and discussion of the potential impacts on regional air quality and human exposure to pollutants. This paper also includes a range of burn severities to represent the interaction between biomass density and burn fraction on wildfire emissions.

■ METHODS

The wildfire emissions projections produced by this work rely on several upstream modeling efforts. Earlier work[12] linked spatially explicit projections for housing expansion with current land cover data to produce spatially explicit population and vegetation cover projections. These population and vegetation projections were combined with impacts of different downscaled climate change scenarios on simulated hydrology[13] and used as inputs to a spatially explicit statistical model of monthly wildfire frequency and burned area on a 1/8° latitude/longitude grid, as described by Westerling et al.[10] Lastly, for the research reported here we combined the spatially explicit wildfire patterns with scenarios for biomass loading as inputs to the Fire Inventory from NCAR (FINN) modeling framework,[14] which estimates emissions of greenhouse gases (CO_2, CH_4), reactive trace gases, and particulate matter (PM) as a function of the total biomass at a given location, the fraction of biomass that is burned, and an emission factor for each emission species. A brief description of previously published steps and data sources are provided here for context.

Scenarios for future housing expansion were obtained from the U.S. EPA Integrated Climate and Land Use Scenarios (ICLUS).[15] ICLUS scenarios provided an intermediate case along with high and low growth trajectories intended to correspond with A2 and B1 scenarios in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES),[16] with population and land cover co-varied. These three base scenarios were expanded on in the process of aggregating from a 100 m scale to an 1/8° grid cell to match the spatial scale of other inputs to the statistical fire model.[17] Specifically, three different scenarios were considered for how new development expanded into existing vegetation, interacted with two different definitions of the wildland-urban interface (i.e., the development density above which wildfires do not occur).[10,17] For reference, we also considered constant population scenarios with population and development footprint fixed at their 2000 values.[17]

The downscaled climate projections used as inputs to the fire modeling came from three global climate models (GCMs; CNRM CM3, GFDL CM2.1, NCAR PCM) for two global GHG emission scenarios, representing a medium-high (A2) and a low (B1) global emissions trajectory.[16] The specific GCMs used were selected on the basis of their ability to represent historical climate in California, the availability of daily temperature and precipitation model output, and their ability as a set to span a broad range of future climate scenarios.[13]

Future large wildfire probabilities and burned areas were simulated as a function of hydrology and climate, human population, and land-surface characteristics by applying models described in refs 10, 17, and 18 to a comprehensive set of climate and development scenarios.[17] Vegetated area and population values were developed from ICLUS scenarios as described above, while temperature and precipitation were derived from the downscaled GCM runs and used to drive the Variable Infiltration Capacity hydrologic model to simulate water and energy balances, yielding variables such as evapotranspiration, moisture deficit, and relative humidity.[10,17,19]

For each 1/8° grid cell, logistic regression models were used to estimate the probability of large wildfire occurrence for two fire size categories (>200 ha and <8500 ha, and >8500 ha) by month on a 1/8° latitude/longitude grid over California for three 30-year periods: 1961−1990, 2035−2064, and 2070−99. These models incorporate semiparametric smooth functions[20] such as piecewise polynomial and thin plate spline transformations to model nonlinear responses and interactions, as described in Preisler and Westerling.[21] The probability of fire occurrence is a nonlinear function of climate and hydrologic variables, population, and land surface characteristics that include fractional area with vegetation cover and topography.[10,18] The expected number of fires per grid cell is by definition the sum of the probabilities of fire occurrence over a given time period. Generalized Pareto distributions fit to historic fire sizes above a threshold (200 and 8500 ha) were used to generate expected fire sizes conditional on a large fire occurring.[10] These fire size thresholds were identified in previous work[18] as differentiating the different relationships between fire size and land surface characteristics. Expected burned area is then the product of the expected number of fires in each size category and the expected fire sizes in each category. Expected burned area was multiplied by normalized emissions to generate expected emissions for each scenario.

Given the range of biomass densities within a given grid cell and the effect of biomass density on emissions, it is necessary to account for spatial variation in biomass. To capture the range of potential future emissions, fire projections for each 1/8° grid cell were applied to vegetation in three scenarios: a <u>low</u> case that concentrated burned areas in the fuels with the lowest biomass of a grid cell and assumed that mixed severity fire regimes burned with low severity; a <u>high</u> case that concentrated burned areas in the fuels with the highest biomass in a grid cell and assumed mixed severity fire regimes burned at high severity; and an <u>intermediate</u> case that distributed burned area proportionally across vegetation types currently occupying a given grid cell and assumed mixed severity fire regimes burned at medium severity.

Biomass, or fuel loading, in each grid cell was assigned using the LANDFIRE product fuel loading map (www.landfire.gov) for California. The classifications of Existing Vegetation Cover from LANDFIRE were reassigned to five general vegetation categories: grasslands, shrublands, forests at elevations less than 5500′, forests located at elevations between 5500′ and 7500′, and forests located at elevations above 7500′ (Supplementary Table S1). The fraction of each of these five general vegetation classes was calculated for each grid cell, and the fraction of biomass that would be burned under low, moderate, and severe fires was assigned on the basis of observations reported in prior publications (Supplementary Table S2). Emission factors for greenhouse gases, reactive trace gases, and particulate matter were assigned to each general vegetation class (Supplementary Table S3). Following Wiedinmyer and Hurteau,[22] fire severity is assumed to impact the amount of biomass burned only; emission factors are kept constant.

Normalized emissions (g m^{-2}) for the three fire regimes (low, moderate, and severe) were assigned on the basis of the assigned biomass loading and the consumption (Supplementary Table S2) and the emission factor for the general ecosystems of the FINN model[2] (Supplementary Table S3). The results include emissions estimates of greenhouse gases (CO_2, CH_4), reactive trace gases, and particulate matter (PM) as a function of the total biomass for each 1/8° grid cell, the fraction of biomass that is burned, and the emission factor for each emission species.[22]

Our results clearly rely on the interaction of a great number of scenarios and assumptions from a number of different modeling efforts. Given this, it would be imprudent to make any claims to predictive power for any given model run. Rather, our goal is to explore the range of possible outcomes consistent with the variety of plausible scenarios we have captured. We do this both by considering spatial patterns of emissions across scenarios and by summarizing the total emissions aggregated across the state. Individual spatial depictions capture one particular scenario from each of the model components described above (e.g., climate, land use development assumptions, fire severity assumptions). The statewide statistics and bar plots we present capture changes for the whole state, with the statistics summarizing the outcomes over all modeled scenarios. In this sense, they should not be viewed as probabilistic distributions or confidence intervals, but their ranges are informative regarding what robust conclusions can be drawn, and the distribution is informative to the extent that input scenarios are considered to have approximately uniform weights. Attempts at probabilistic weighting of the input scenarios would alter the distributions of the summary statistics but not the ranges.

■ RESULTS AND DISCUSSION

The greatest increase in wildfire emissions is projected to occur in the Sierra Nevada and in the Klamath-Siskiyou regions of northern California, areas largely under federal management and unavailable for development. These regions are primarily forested and are some of the most carbon-dense areas in the state.[23] Notably, this variation in carbon-density causes the pattern of increased emissions to be different from the patterns of increased burned area shown in Westerling et al.,[10] which found that burned area increased 36−74% across the state by 2085. Our results are consistent with the range of emissions estimated by Wiedinmyer and Hurteau[22] from 2001 to 2008 for California. They found annual CO_2 emissions from wildfire ranging from 6.0 to 54.5 Tg, whereas interquartile ranges for CO_2 in this study range from 10.7 to 19.6 Tg (Table 1). Across the state, by mid-century under both the B1 and A2 scenarios and by late-century under the B1 scenario, total estimated wildfire emissions ranged from a 4% decrease to a 55% increase, with a median increase of 24% compared to the historical period (1961−1990). By 2100 under the A2 scenario, total emissions increased by 19−101% from the historical period, with a median increase of 56% (Table 1, Supplementary Table S5). In contrast to other measures of wildfire impacts (e.g., risk of structural loss), the specific population growth/development scenario yielded relatively little influence over emissions, which holds true across all of the emitted species considered (Figure 1, Supplementary Table S5). This result is largely due to the fact that development is projected to occur in less carbon-dense areas (e.g., chaparral, grassland) and growth in future fire emissions are largely concentrated in forested, publicly owned areas that are unavailable for development.

Table 1. Interquartile Ranges for Selected Simulated Emissions (Gg)[a]

	scenarios		
constituents	1970	2050 B1 and A2; 2085 B1	2085 A2
CO_2	10700−12200	13300−15800	16500−19600
CO	564−665	718−871	917−1110
CH_4	25.7−30.7	33.1−40.4	42.7−51.9
TPM[b]	107−124	134−161	169−201
organic C	51.7−60.8	65.6−79.4	83.6−101
black C	3.42−3.97	4.29−5.10	5.41−6.46

[a]Simulations include all ICLUS scenarios, but not constant population scenarios (year 2000). For a complete summary of emissions constituents see Supplementary Table S4. [b]PM2.5, SO_2, OC, and BC are included in total particulate matter (TPM).

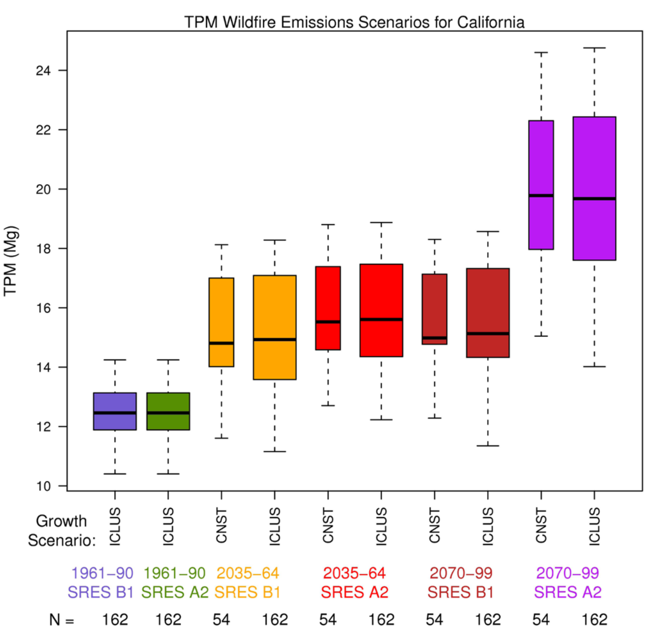

Figure 1. Projected total particulate matter (TPM) aggregated over the state of California, averaged for historical (1961−1990), mid-century (2035−2064), and late-century (2070−2099) time periods for both projected population growth (ICLUS) and population held constant at year 2000 levels (CNST) and SRES B1 and A2 emission scenarios.

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To account for the spatial variability in the distribution of vegetation within each grid cell, we included low, intermediate, and high burn severity scenarios. As expected, concentrating wildfire activity in areas with different biomass levels available for combustion influenced emission quantities. While median total particulate matter values increased with severity, there was generally a much larger difference between the low scenario and the intermediate and high scenarios (Figure 2). By late-century, the range of total particulate matter emissions exceeded that of the historical period (1961−1990) for the intermediate and high severity scenarios.

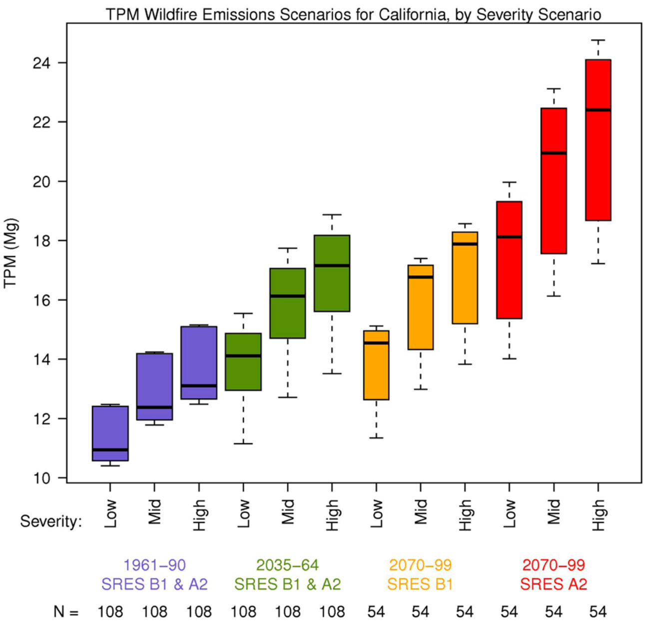

Figure 2. Projected total particulate matter emissions over the historical (1961−1990), mid-century (2035−2064), and late-century (2070−2099) time periods by burn severity. Low severity equals wildfire activity being aggregated in low biomass portions of each grid cell. Mid severity distributes wildfire activity across biomass types within each grid cell and assumes mixed severity fire. High severity aggregates wildfire activity in the highest biomass portions of each grid cell and assumes high severity fire.

Our results suggest that climate is the larger driving force behind the projected wildfire emissions increases, compared to population growth and development patterns. Consequently, decisions affecting population and development patterns within the state may be expected to have little influence over projected fire emissions in California. However, regardless of their source, the resulting increases in future fire and emissions pose significant societal adaptation challenges. Biomass burning results in the emission of several criteria air pollutants and their precursors, including particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NO_x). Biomass burning also emits non-methane organic compounds (NMOC) that, together with NO_x, can react to form the criteria pollutant ozone.[24] Current estimates of fine PM, CO, NO_x and NMOC from biomass burning in California are significant compared to emissions from other sources. When compared to reported annual estimates of anthropogenic emissions for 2008 (as reported by the U.S. EPA National Emissions Inventory, http://www.epa.gov/ttnchie1/net/2008inventory.html), annually averaged biomass burning emissions calculated using the FINN default model for 2005−2010 for the state of California were equivalent to 18%, 2%, 21%, and 34% for CO, NO_x, NMOC and PM2.5, respectively. For large fire years, the emissions from biomass burning can equate to much more. For 2008, the biomass burning emissions in California for CO and NMOC were equivalent to 58% and 66%, respectively, of the reported anthropogenic emissions. Biomass burning emitted 10% more fine PM than anthropogenic sources.

Our results show PM, NMOC, and NO_x emissions are projected to increase over the historical period, regardless of the emission scenario modeled (Figure 2, Supplementary Table S5), and while their relative contribution will depend on the changes of anthropogenic emissions over this time period, they are likely to significantly affect the emissions inventory of the state.

The greater pollutant emissions estimates have impacts on air quality and could potentially yield an increase in the number of days exceeding U.S. ambient air quality standards, which regulate the atmospheric concentrations of criteria air pollutants. The quantification of the impact of biomass burning on air quality in California is challenging, due to the episodic nature of fire emissions and the nonlinear atmospheric chemical and physical processes that affect emissions and air quality, which are not modeled as part of this study. However, several studies have shown impacts from fires on air quality in California. For example, Singh et al.[25] observed the highest ozone concentrations during an aircraft observational study over California in urban plumes that had been mixed with wildfire emissions. Cisneros et al.[26] report exceedences in the coarse PM standard in the San Joaquin Valley during a large fire event in 2002. Pfister et al.[24] have shown that large fires in both northern and southern California caused exceedences in the ozone standard in California during the fall of 2007. During this study, the emissions from wildfire in the Sierra Nevada directly impacted the San Joaquin Valley air basin.[24] The San Joaquin Valley air basin, one of the most populous in the state, is projected to experience large population growth and has a high probability of exceeding air quality standards for ground-level ozone.[27] Projected increases in emissions of air pollutants coupled with population projections for this air basin under both B1 and A2 climate scenarios for late-century suggest that an additional 1.5−5.5 million people may be impacted by degraded air quality (Figure 3). This potential presents a significant challenge for climate change adaptation.

Degraded air quality has the potential to impact society beyond direct health effects. California is a multibillion dollar agricultural producer.[28] While experimental evidence shows a CO_2 fertilization effect on crop production, increased ozone has been shown to result in substantial yield losses.[29] Similarly, increasing ozone levels have been attributed to reduced forest productivity.[30,31] Coupled with the direct effects of wildfire on forests, air quality impacts could negatively impact the substantial greenhouse gas mitigation benefits provided by forests in California.

The results of this research must be considered in the context of the limitations of the modeling approaches involved. A key determinant of the probability of large wildfires is the availability of biomass to burn, which can be impacted by climatic conditions. Forest disturbances enhanced by climate change, such as insect outbreaks,[32−34] may alter the availability of biomass for combustion. Projected increases in large fire frequency and limited vegetation recovery resulting from changes in climate may preclude the persistence of forests in some regions they currently occupy, leading to replacement

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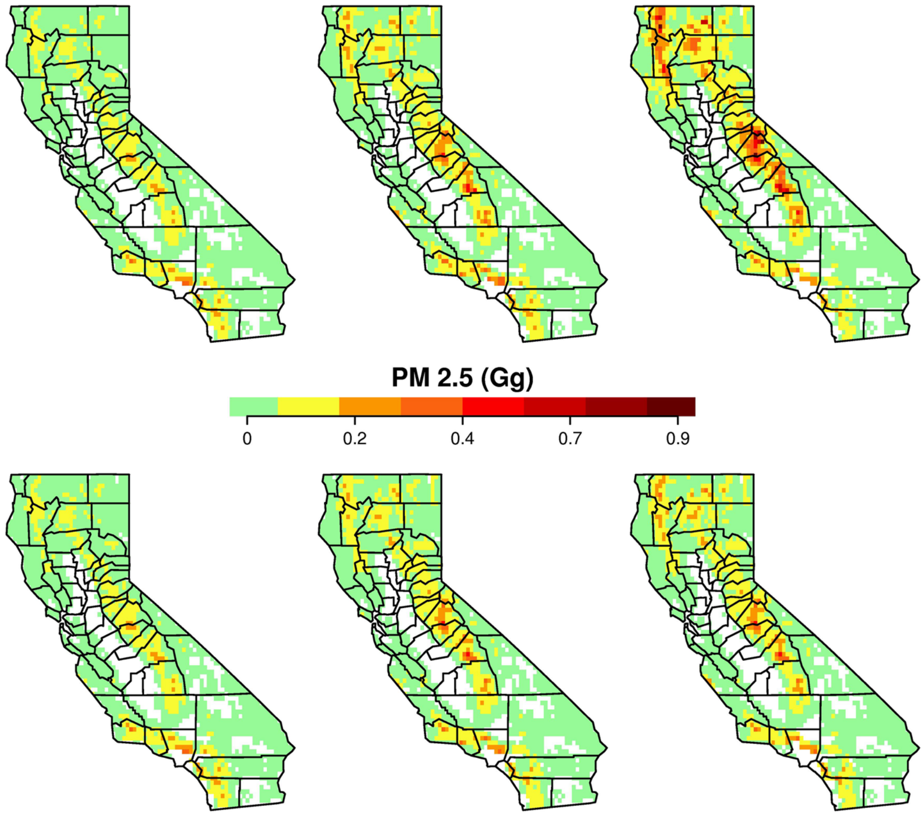

Figure 3. Projected 2.5 μm particulate matter (PM2.5) emissions over the historical (1961−1990), mid-century (2035−2064), and late-century (2070−2099) time periods for the A2 (top) and B1 (bottom) emission scenarios from GFDL.

with less carbon-dense ecosystems with different fire regimes and different capacities for carbon uptake.[5,35] Alteration of the vegetation to a less carbon-dense type following a wildfire event could also impact subsequent wildfire size and the resulting emissions per unit area. Additionally, the interaction between changing climate and vegetation has the potential to alter the amount of biomass available for combustion prior to an initial fire event. Climatic controls on vegetation productivity could limit biomass availability in some cases (e.g., prolonged drought), which may be compensated by the fertilization effects of increasing atmospheric carbon dioxide concentration.[36,37] These factors represent sources of uncertainty to future emissions projections.

Many of California's most carbon-dense vegetation types are fire-adapted.[38] The increase in large fire probability projected for the state may not be outside the range of historical fire frequency. However, the current state of many of these fire-adapted systems is substantially altered as a result of landscape fragmentation and fire-exclusion.[6,7,35] Efforts to adapt to changing climate and projected increases in large fire frequency are likely going to require the restoration of fire as a natural process in these systems.[35] Restoration of fire will require societal trade-offs, i.e., fire emissions versus altered wildfire risk, but the costs to society, such as air quality impacts, must be considered in the context of inaction. Wiedinmyer and Hurteau[22] found that emissions from prescribed fires are typically lower than those from wildfires burning the same area. While the cumulative emissions over time may be greater,[39] emissions from prescribed fire can be managed more effectively than those of wildfire to reduce the short-term impacts on air quality.

In general, climate−vegetation−fire interactions are characterized by numerous feedbacks that are only partially understood; in some cases even the sign of these feedbacks is not known. Future research is therefore needed to improve planning capabilities for societal adaptation to the changes in air quality that may result from jointly altered fire and climate regimes around the world.

■ ASSOCIATED CONTENT

Supporting Information

Vegetation information, emissions factors, and emission scenario descriptions. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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