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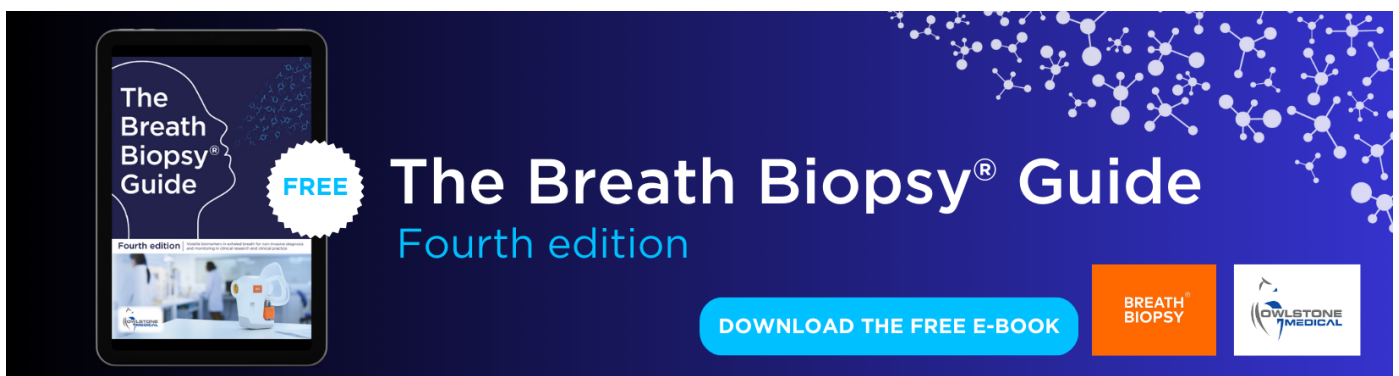
Spatial and temporal patterns of wildfire burn severity and biomass burning-induced emissions in California

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Spatial and temporal patterns of wildfire burn severity and biomass burning-induced emissions in California

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* Author to whom any correspondence should be addressed.E-mail: qxu6@ucmerced.edu**Keywords:** PM_{2.5}, trend, seasonality, megafiresSupplementary material for this article is available [online](#)**Abstract**

Wildfires are an important disturbance in the Earth system, and their emissions have regional and even global impacts on radiation, clouds, and climate. The increased frequency and magnitude of California wildfires in recent years is altering the terrestrial carbon cycle, undermining the state's efforts to reduce the Greenhouse Gases (GHGs) to confront climate change. Air quality and public health are also greatly affected by air pollution from wildfires. The severity of wildfire burns is a critical indicator of both their direct and indirect ecological and human impacts. To formulate targeted mitigation strategies, it is imperative to understand the evolving scale, location and timing of wildfire burn severity and emissions. This study analyzed spatial and temporal patterns of burn severity and emissions at 30 m resolution from large wildfires (>404 hectares) burning in California during 1984–2020 from the recently developed Wildfire Burn Severity and Emissions Inventory. Results show vegetation and severity play critical roles in controlling the spatial and seasonal distribution of emissions. California's annual burned area and emissions increased, notably in early and late parts of what once was the typical fire season, although peak wildfire burned area and emissions continue to occur in mid-Summer. Emissions and areas burned in moderate to high severity were particularly high and increasing in North Coast and Sierra Nevada forests. The 2020 fire year—with the most megafires in California history—had 15 times the annual average emissions that occurred during 1984–2015.

1. Introduction

Fire is a natural phenomenon, sparked by humans as well as natural ignitions such as lightning and other far less common ways, including volcanic activity and meteors. Fire serves an important ecological role in clearing low-growing underbrush, removing organic debris, opening the ground up to sunlight, and nourishing the soil (He *et al* 2019, McLauchlan *et al* 2020). Fire also facilitated human evolution over two million years ago when our ancestors began to control and make uses of fire. Fire and humans have then contributed together to landscape diversity. Not all fires are harmful and need to be extinguished. However, uncontrollable and destructive wildfires that burn with uncharacteristic frequency, extent, and severity due to climate change and legacies of past management can have negative impacts on nature and human

society, and are a phenomenon we have been increasingly challenged by in recent decades and expect to continue to face in the near future (Westerling 2006, 2016, 2018, Abatzoglou and Williams 2016, Williams *et al* 2019).

Fire has been a vital force in California's diverse ecosystems for millennia, such as facilitating germination of seeds for certain tree species, shaping the composition of land cover, and altering biological diversity (Van Wagtenonk 2018). Expanding development in wildland-urban interfaces, fuel accumulations from fire suppression and land use legacies over the last century, increasing temperatures, and more variable precipitation are making wildfires more catastrophic in California, with increases in total and high severity burned area in recent decades (Lutz *et al* 2011, Miller and Safford 2012, Stevens *et al* 2017, Keeley and Syphard 2019, Keyser and Westerling 2019,

Goss *et al* 2020, Swain 2021). In addition to direct damage to the environment and human systems in the wildfire burned area, wildfire severity affects emissions, which in turn can have effects on air quality, climate, and public health over a much larger area that can long outlast their flames (Reid *et al* 2016, O'Neill *et al* 2021, Wang *et al* 2021). Recent catastrophic wildfires driven by climate change and human activities also make achieving carbon neutrality more challenging in California. Air regulators and policy makers are increasingly interested in understanding the patterns of wildfire burn severity and emissions, in order to develop plans to reduce the risk of uncharacteristically severe wildfires and to mitigate emissions from wildfires.

Many studies have analyzed patterns of wildfires and fire emissions at various temporal and spatial scales. Li and Banerjee (2021) studied the spatial and temporal distributions of wildfire occurrence in California and found their frequency and total burned area increased significantly during 2000–2019 compared to 1920–1999. They also found temperature, vapor pressure deficit, grass cover, and distance to roads highly affected risks of wildfire occurrence. Chen and Jin (2022) analyzed spatial patterns of wildfire ignitions during 1992–2015 and found precipitation, slope, human settlement, and road network controlled human-caused ignitions while snow water equivalent, lightning density, and fuel amount shaped lightning-caused ignition in California. Stephens *et al* (2007) estimated annual average prehistoric fire emissions in California using a First Order Fire Effects Model by each vegetation type. They found a high amount of wildfire emissions was produced annually before the influences of Euro-American settlement on fuels and ignitions led to a period of relative fire exclusion. Estimates of modern California wildfire emissions found that they exhibited large inter-annual variability, and forests and woodlands represented the largest contributors (Jaffe *et al* 2008, Hurteau *et al* 2014, CARB 2021). Estimated daily fire emissions of CO₂ for 11 states in the western U.S.—including California—during 2001–2008 by Wiedinmyer and Hurteau (2010) indicated that emissions were elevated from July through October with the peak in August. For a medium-high temperature scenario, projected effects of climate change and development on California wildfire emissions through 2100 were projected to increase by 19%–101% over 1961–1990, with the highest increases centered in northern California forests (Hurteau *et al* 2014). Despite all the efforts, the spatiotemporal patterns of large wildfires' burn severity and emission regimes throughout California over the past four decades have not been investigated with high spatial and temporal resolution data.

Here, we take advantage of the recently available Wildfire Burn Severity and Emission Inventory

(WBSE), a retrospective inventory that was recently developed to calculate burn severity and emissions at 30 m resolution for each large wildfire observed since 1984 (Xu *et al* 2022). This study attempts to utilize the most up-to-date data to investigate the spatio-temporal patterns of burn severity and emissions from large wildfires burned in California over the period of 1984–2020 to answer the following questions: (a) How have annual and seasonal patterns of burn severity and emissions changed over the period of 1984–2020? (b) What are the spatial distribution characteristics of burn severity and emissions? (c) What are the contributions of the most extreme fire events to emissions?

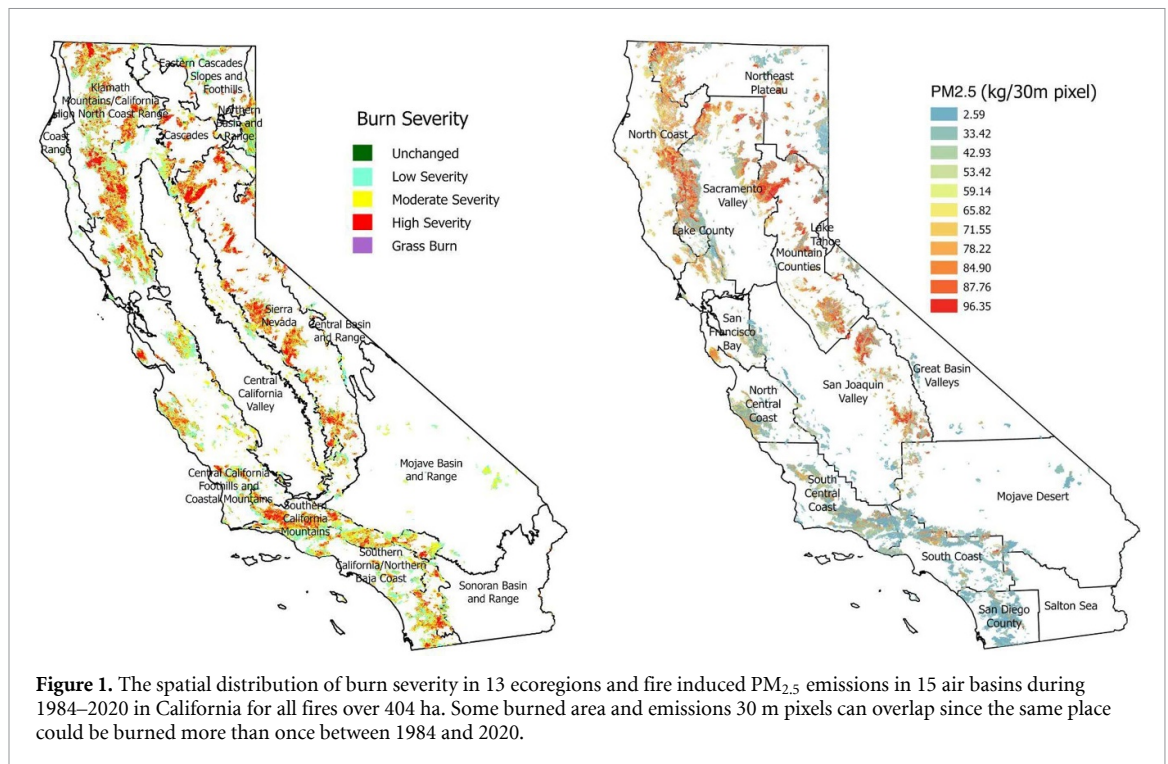
2. Data and methods

2.1. Study area

California is the third-largest state in the United States in area, bordered by the Pacific Ocean to the west, and geographically diverse. In the middle of the state lie the fertile farmlands of the Central Valley, bounded by the Sierra Nevada mountains in the east, the Coastal Mountain Ranges in the west, the Klamath Mountains in the northwest, and the Mojave Desert in the southeast. The climate of most areas in California is described as a Mediterranean climate, characterized by winter precipitation and long dry, hot summers. The natural environmental conditions make California a high fire risk area. There are currently 13 level III ecoregions (Griffith *et al* 2016) and 15 Air Basins in California that we use here for context (figure 1).

2.2. Data

The burn severity and emissions data used for this analysis are from the WBSE, a retrospective inventory that was recently developed by Xu *et al* (2022). Historical (1984–2019) remote sensing data previously used by the Monitoring Trends in Burn Severity project (MTBS) to estimate burn severity were calibrated by WBSE based on regression relationships developed by Picotte *et al* (2021) between the field-based burn severity index—the Composite Burn Index (CBI), and Landsat imagery-derived differenced normalized burn ratio (dNBR)/normalized burn ratio to produce objective, validated severity classifications at 30 m resolution. For large wildfires in 2020 recorded by the California Department of Forestry and Fire Protection (CAL FIRE), burn severity maps were also generated with a Landsat dNBR calculator developed for WBSE in order to extend the record through the very active 2020 fire season (MTBS data for comparison were not yet available for 2020). WBSE burn severity products differ from MTBS in that the spectral indices are first converted to CBI and then classified with standard thresholds other than the



subjective interpretation per fire based on the experience of MTBS analysts. The WBSE burn severity dataset was generated following the regression models developed by Picotte *et al* (2021), where the details of accuracy and evaluation of the regression models for each landcover classification were presented. There were only 12 wildfires in California during 1984–2020 that have CBI field data (collected between 1996 and 2018). Thus, the companion paper by Xu *et al* (2022) compared the WBSE dataset with the burn severity dataset from the MTBS project. Their pixel-level classification comparison indicated that around 45% of the pixels in both datasets were classified as the same burn severity. The rest generally have a higher burn severity in WBSE than do MTBS products.

WBSE calculated the amount of particulate matter (PM_{2.5}), greenhouse gases (CO₂, CH₄), and other trace gases emitted from each large wildfire (>400 ha) as a function of the area burned by severity classification, fuel consumption under low, moderate, and high severity, and emission factors for coarse vegetation types, using a modification of the Fire Inventory from NCAR (FINN) model (Wiedinmyer *et al* 2011). Fuel type was assigned to five general vegetation categories (grass, shrub, forest under 5500 feet (1676 m), forest between 5500 and 7500 feet (1676–2286 m), and forest above 7500 feet (2286 m)) using the LANDFIRE existing vegetation type (EVT) product (Rollins 2009). Fuel loadings and consumption rates for the five vegetation classes were assigned under low, moderate, and high severity.

Normalized emission factors were compiled and updated for coarse vegetation types in California ecosystems. Fire event-based emissions were estimated at 30 m resolution. The estimates agree reasonably well with global and regional emissions inventories (Xu *et al* 2022).

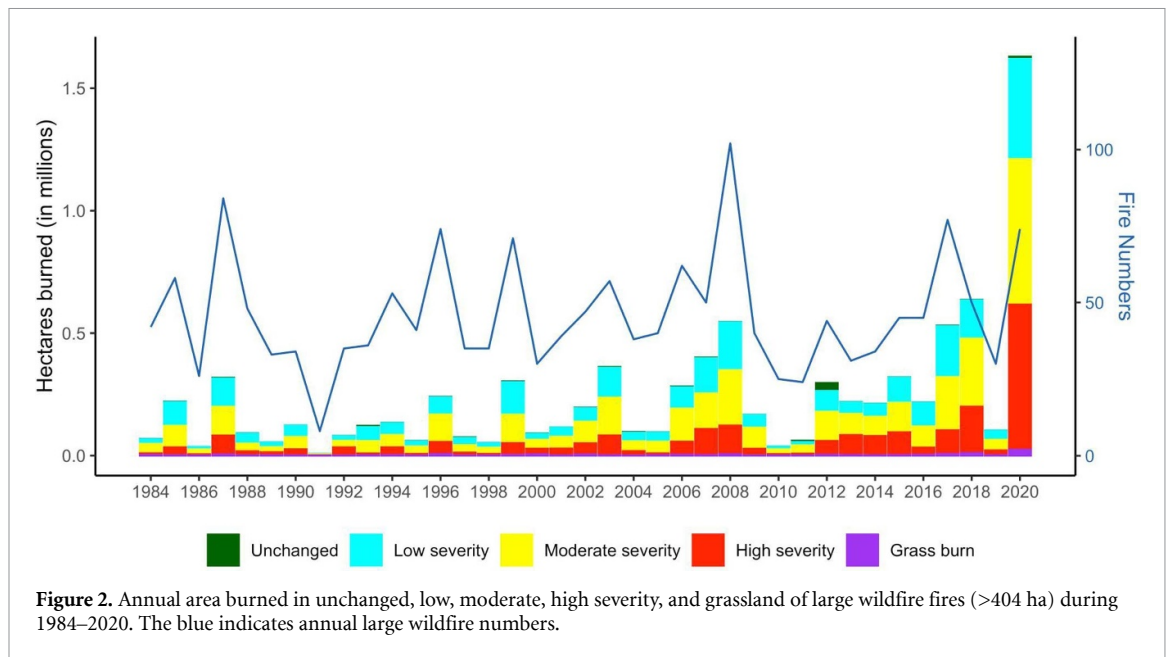
2.3. Statistical estimation of annual trends

The non-parametric Mann–Kendall test (Mann 1945, Kendall 1975) and Sen’s slope estimator (Sen 1968) were used to determine if a trend exists, and to estimate the magnitude of the changes. Non-parametric methods were considered to be effective here since they are less influenced by extremes, and do not have to meet the assumption of normality. Both methods were applied together to detect consistent increasing or decreasing trends on a variety of metrics of burn severity and emissions data (annual total burned area, annual burned area and fractions in low, moderate, and high severity, annual total emissions, and emissions from different fire severities and land covers). Results were considered significant at $p < 0.05$.

3. Results and discussions

3.1. The spatial distribution of burn severity and emissions

WBSE provides 30 m resolution burn severity and 12 types of biomass burning-induced emissions. Annual emissions of CO₂, CO, CH₄, non-methane organic compounds, SO₂, NH₃, NO, NO₂, nitrogen oxides



($\text{NO}_x = \text{NO} + \text{NO}_2$), $\text{PM}_{2.5}$, OC and BC averaged about 17.819, 0.910, 0.037, 0.263, 0.010, 0.014, 0.011, 0.011, 0.016, 0.108, 0.106, and 0.007 million tons, respectively. Annual emissions of all types are summarized in supplementary table 1. Spatial and temporal patterns of the 12 types of emissions were the same except for the scale, due to the fact that the modified FINN model calculates emissions as a function of burned area, vegetation consumption, and emission factors. We use $\text{PM}_{2.5}$ as an example to illustrate the patterns of emissions since it is a major concern due to its potential for public health impacts. The spatial distribution of burn severity and fire-induced emissions was highly heterogeneous in different ecoregions and air basins in California (figure 1). The North Coast Ranges, Southern California Mountains, and Sierra Nevada are regions of large burned areas. The spatial pattern of $\text{PM}_{2.5}$ emissions is similar to that of burned area. However, the magnitude of emissions did not resemble that of burn severity in the Southern Coast due to the fact that the dominant shrub ecosystem there emits fewer emissions compared to the forest ecosystems that are characteristic of the northern mountain regions.

3.2. Annual severity and emissions

Annual area burned from large wildfires (>404 ha) averages about 0.23 million ha, with a range of 0.008–1.63 million ha during 1984–2020. Area burned significantly increased during the past four decades at a mean annual rate of 0.07 million ha (figure 2; supplementary table 2). On average, 32%, 41% and 25% burned in low, moderate, and high severity, respectively. Area burned in grassland only accounted for 1% of total area burned. The remaining 1% of total area burned was in barren-rock/sand/clay, open

water, or perennial ice/snow, which were categorized as unchanged. Annual area burned in low, moderate, and high severity also significantly increased, but there was no significant trend in the fractions of each severity category over the available record. The year 1991 had the smallest number (8) of large wildfires while the year 2008 had the largest number (102) of large wildfires (figure 2). On average, 46 large wildfires burned each year in California. However, there is no significant trend of annual large fire numbers (supplementary table 2).

Nearly half of the area burned in low, moderate, and high severities was in shrubland before 2002 but decreased to 13% during the period of 2002–2015 (figure 3). The fraction of area burned in low elevation forests (<5500 ft) and mid elevation forests (5500–7500 ft) increased, especially in low and moderate severity, from 45% before the year of 2002 to 78% during the period of 2002–2015. During the last five years (2016–2020), shrubs and forests (at low and moderate elevation) burned an average of 26% and 54% of total area, similar to the average percentage burned during the past four decades. The high elevation forests burned only about 2% of total area during 1984–2020. However, the annual average area burned in those high elevation forests has increased about four times since 2008, greatly contributed to by megafires that burned in the year of 2020. This increase is comparable in scale to what has been previously projected for these forests in some scenarios for end-of-century climate change (Westerling 2018).

Emissions from low, moderate, and high severity burns are coupled with area burned in the corresponding severity category (figures 2 and 4). $\text{PM}_{2.5}$ emissions showed considerable inter-annual

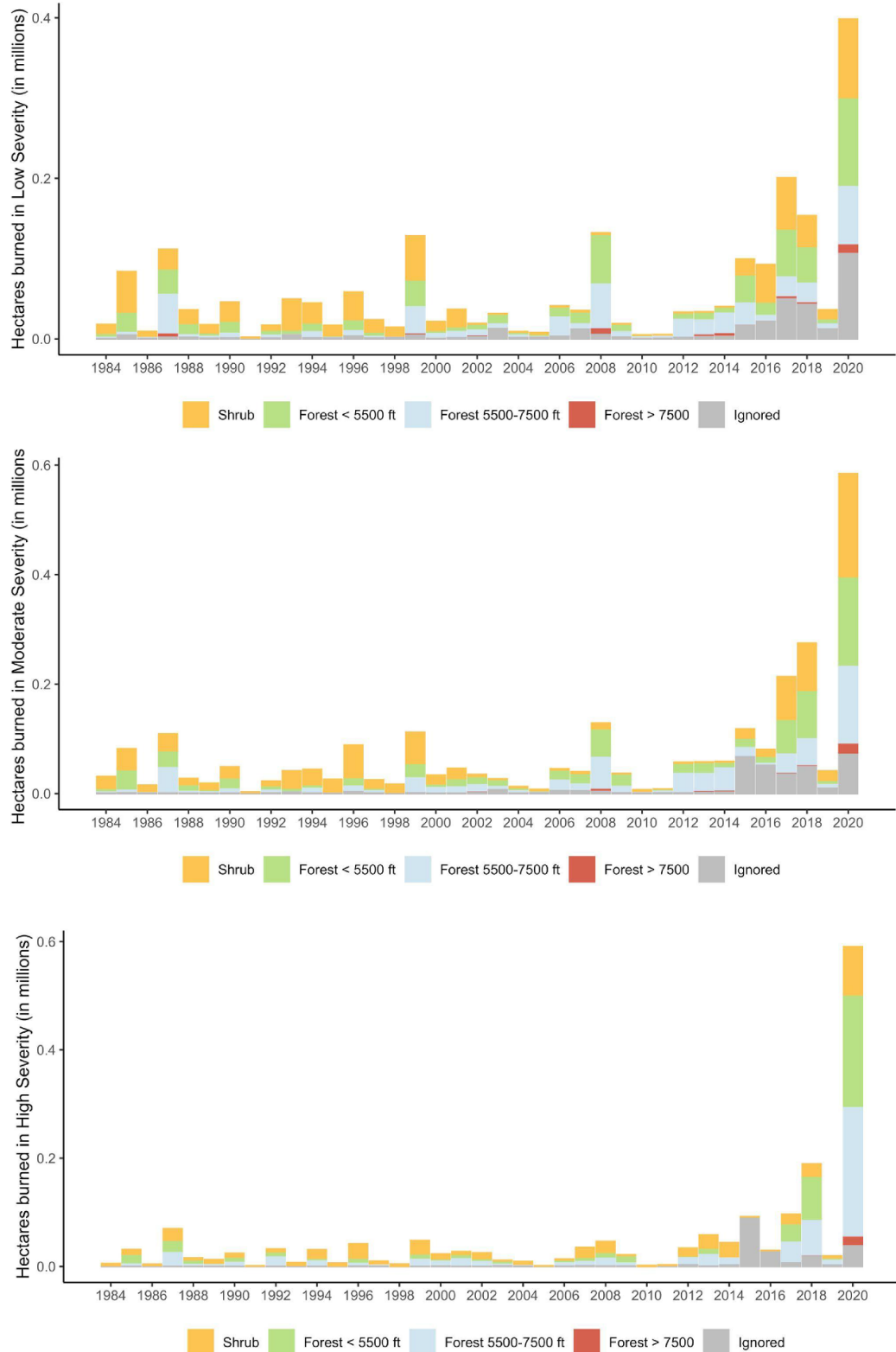
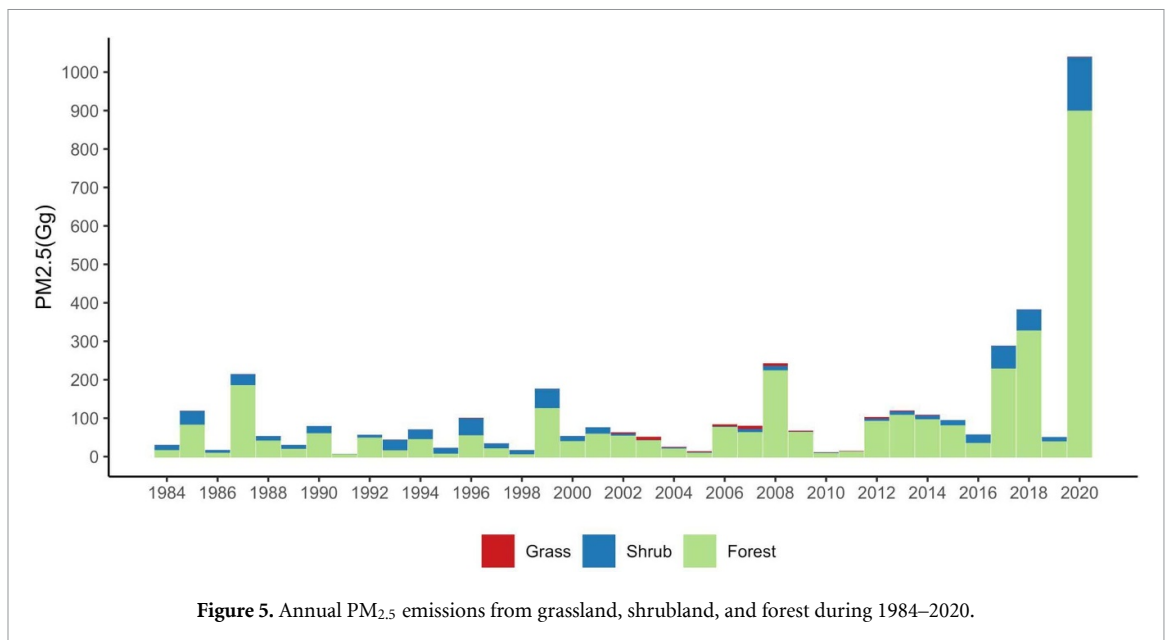
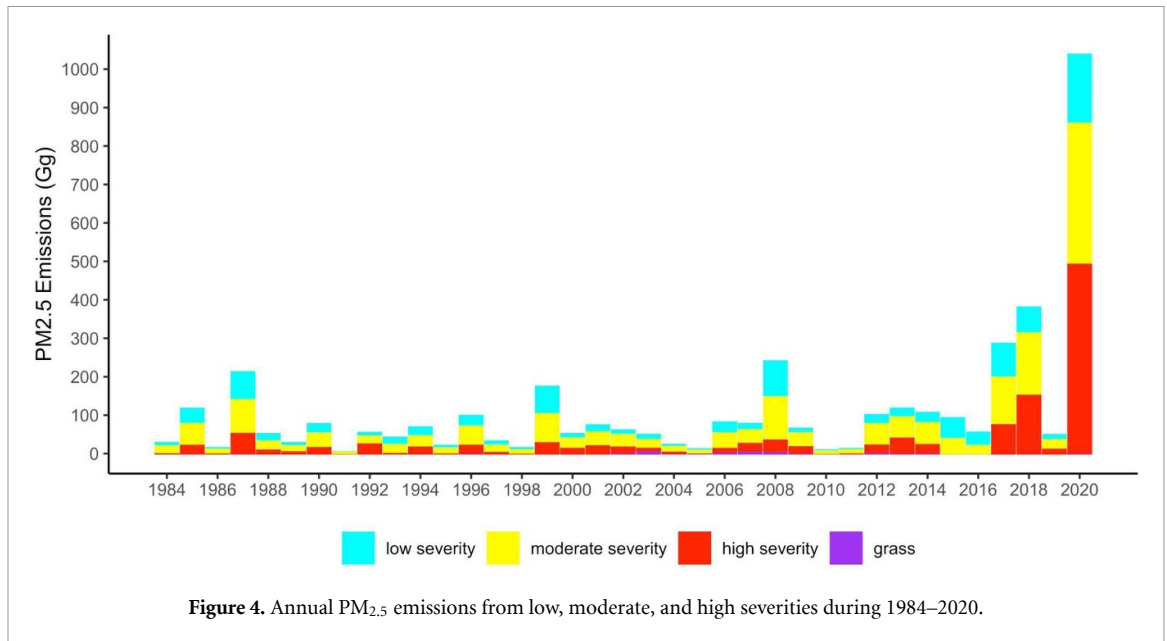


Figure 3. Annual area burned in shrub, low elevation forest (<5500 ft), moderate elevation forest (5500–7500 ft), high elevation forest (>7500 ft) in low (top), moderate (middle), and high (bottom) severity during 1984–2020. Grey bars indicated areas ignored by WBSE when classifying LANDFIRE existing vegetation type to coarse land cover types, and not classified as grass burn as the burn severity. Those areas are mainly developed or vegetation types that were not considered in the emission model.

variations, with a significant increasing trend at a mean rate of about 1.98 Gg yr⁻¹ over 1984–2020 (supplementary table 2). California’s annual PM_{2.5} emissions from large wildfires ranged between 4 and

1038 Gg yr⁻¹ during 1984–2020, with an average of 108 Gg yr⁻¹. Emissions from the last 5 years (2016–2020) are more than five times the average annual emissions during 1984–2015. California experienced



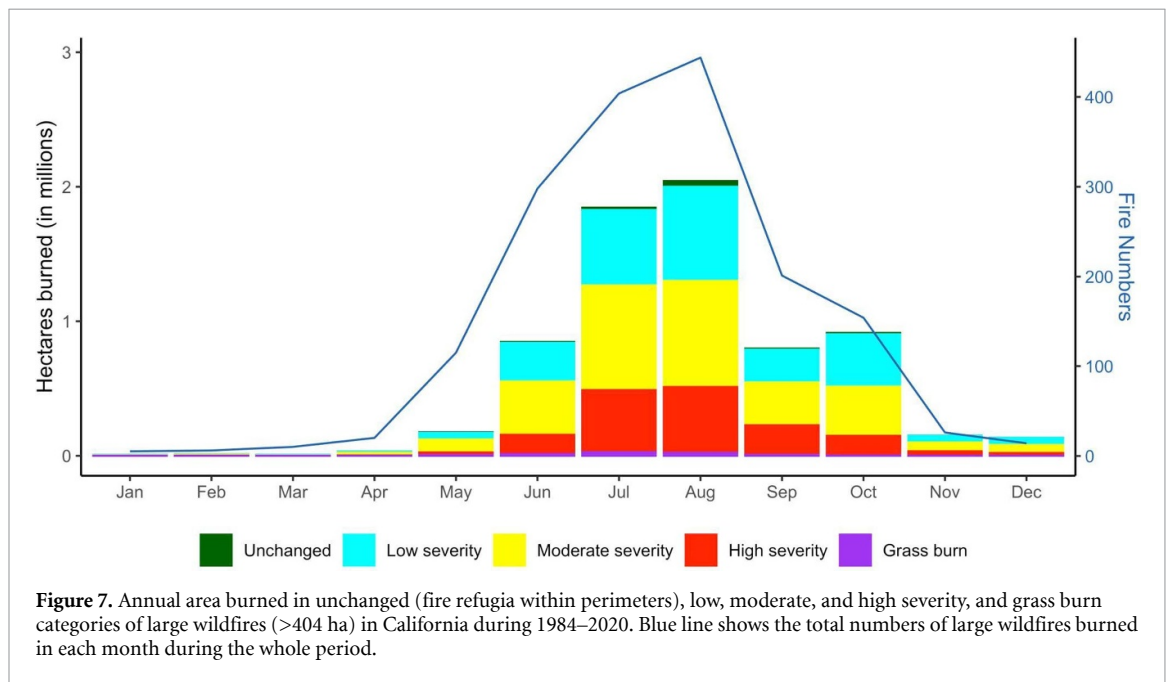
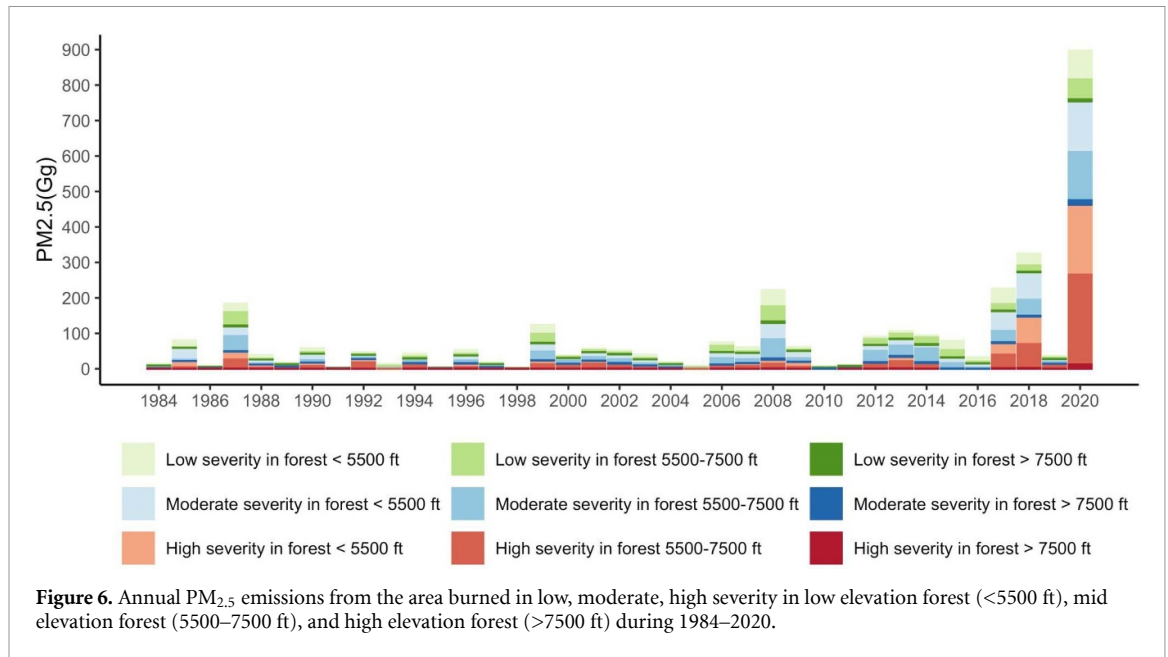
a record-breaking total area burned in large wildfires in the year of 2020, which led to 15 times the amount of annual average emissions compared to 1984–2015.

In total, 80.9%, 17.7%, and 1.4% of emissions were emitted from forests, shrublands, and grasslands, respectively. Annual area burned in forests ranged from 0.004 to 0.99 million ha, accounting for 7%–67% of total area burned, and 22%–95% of annual emissions (figure 5). There is a significant trend of a 2 Gg yr⁻¹ increase from forest over 1984–2020 (supplementary table 2). Forests, specifically low and mid elevation forests burned in moderate and high severity, are the major sources of emissions (figure 6). Emissions from moderate severity burned areas in mid elevation forests significantly increased at

0.3% per year, and accounted for 16% of total emissions during 1984–2020.

3.3. Emission seasonality

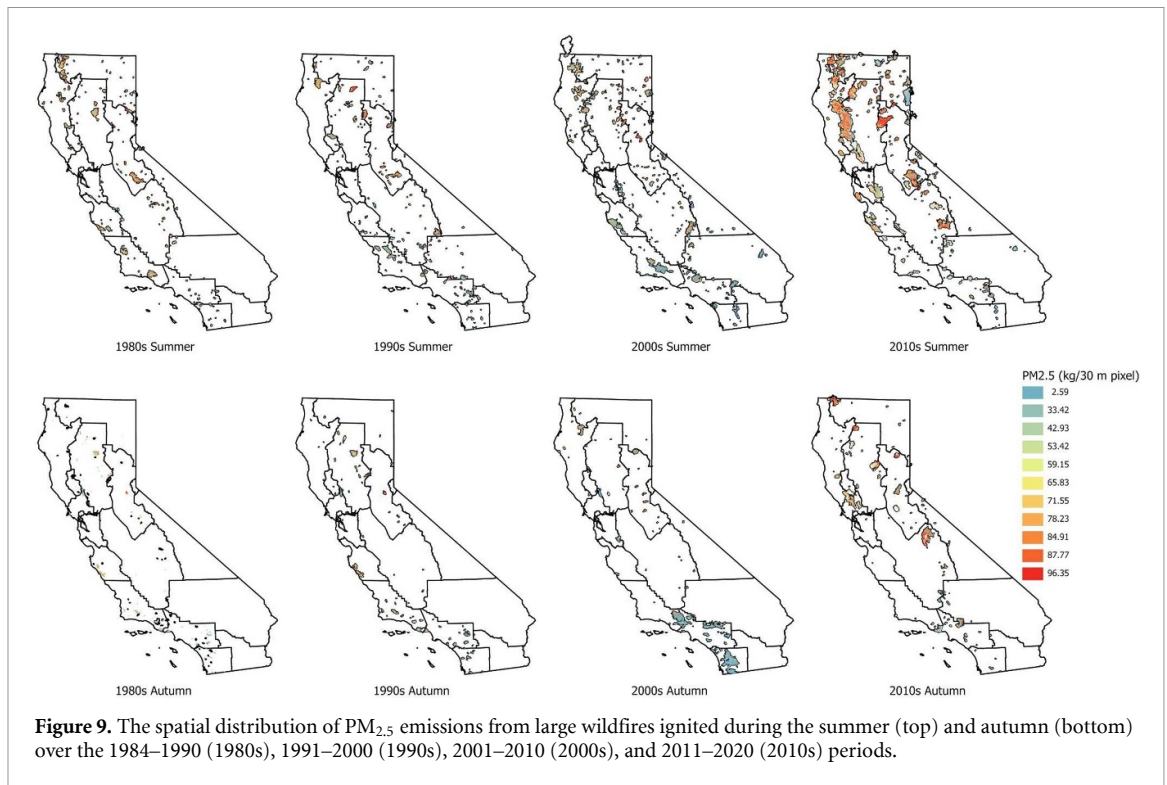
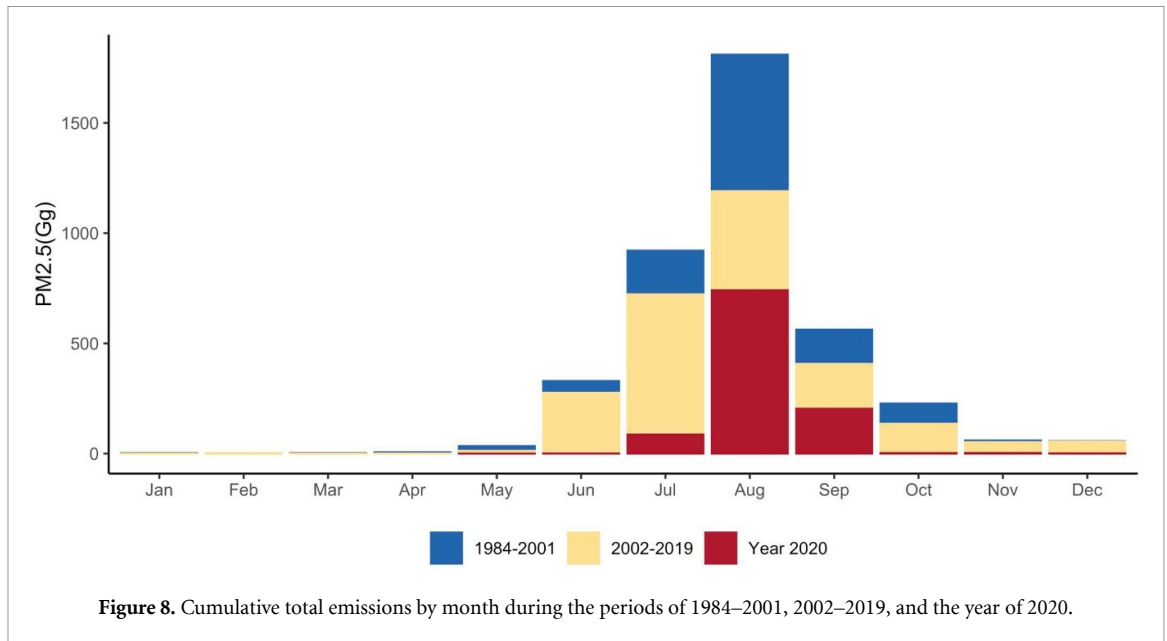
Some years wildfires burn all year round. Large wildfires burn frequently starting early summer through the end of the autumn in most parts of California (figure 7). The peak emission month was in August during 1984–2001, and then shifted to July during 2002–2019 (figure 8). The peak month was back to August in the year of 2020 with multiple megafires including the August Complex fires, North Complex fires, SCU Complex fires, and LNU Lightning Complex fires that all ignited in Northern California. The peak month emissions from this single year are at a similar magnitude to the peak month



emissions cumulated over 18 years during the 1984–2001 and the 2002–2019 periods (figure 8). While peak emissions continue to coincide with fires beginning in July or August, the scale of emissions from fires starting earlier and later in the season has increased substantially over the past two decades, with very substantial increases in June (~400%) and in October–December (~125%), comparing 2002–2020 to 1984–2001. Note, however, that fires beginning in any particular month may have some portion of their emissions occurring over subsequent months.

The seasonal distribution of emissions is also uneven across California. Figure 9 shows the spatial

distribution of PM_{2.5} emissions from large wildfires ignited in summer (June–August) and autumn (September–November) over the 1984–1990 (1980s), 1991–2000 (1990s), 2001–2010 (2000s), and 2011–2020 (2010s) periods. The peak emissions start month usually occurred in summer in Northern California, and later in Fall in the Southern California region. There was a large increase of areas burned with low emissions in the South Coast region in the summers during the 2001–2010 period. The greatest increase occurred in the summers and autumns during the 2011–2020 period in the North Coast region, areas largely in forest ecosystems under federal management. Changes were relatively small in the Great



Basin Valleys, Mojave Desert, and Salton Sea regions, which are also sometimes classified as the Southeastern Desert bioregion, which usually has low fire risks due to natural limitations on fuel availability.

The seasonal distribution of emissions from grass, shrub, and forest ecosystems is consistent with the burn patterns. The majority of emissions were from forests burning throughout the year (figure 10). The fraction of emissions from shrubland in December is higher compared to November, due to the massive 2017 Thomas wildfire that mostly burned in shrub vegetation types.

3.4. Extreme events

Extremely large wildfires, or *megafires*, are the major contributors to fire emissions. The concept of megafires has not been formally defined but most frequently characterized by size. They have been classified by fire size larger than 10 000 ha (24 710 acres) (Jones et al 2016, Stevens et al 2017) and over 40 468 ha (100 000 acres) in more recent years (Weber and Yadav 2020, Jones and McDermott 2021, Calhoun et al 2022). We defined megafires as fire size over 40 468 ha here to capture the effects of the most extreme fires. We further grouped the 1697

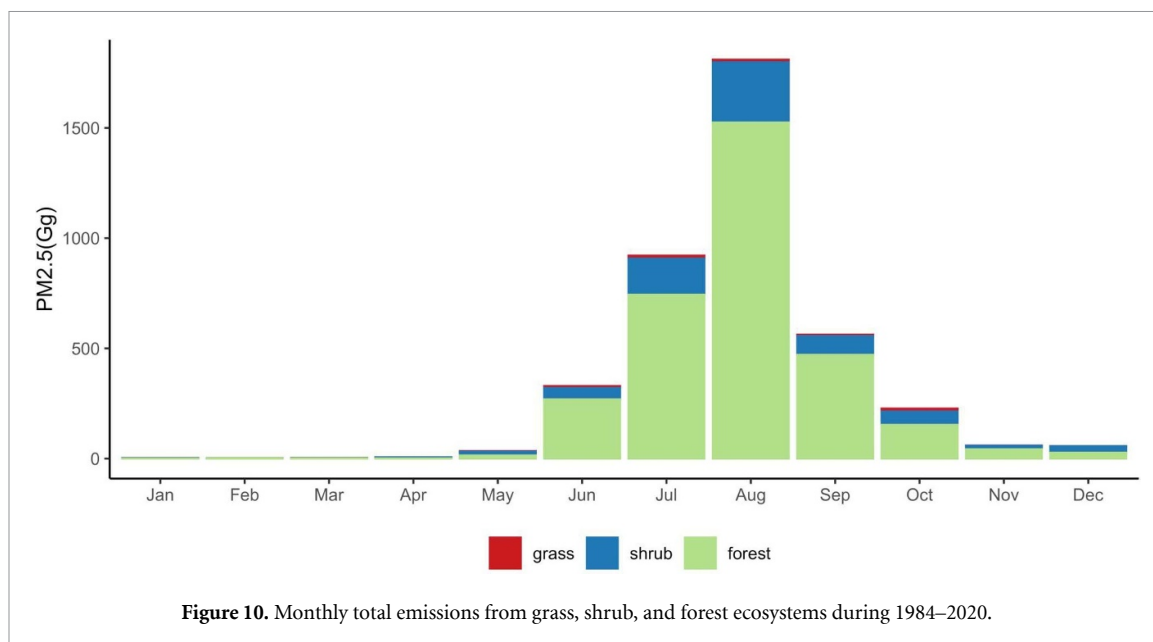


Figure 10. Monthly total emissions from grass, shrub, and forest ecosystems during 1984–2020.

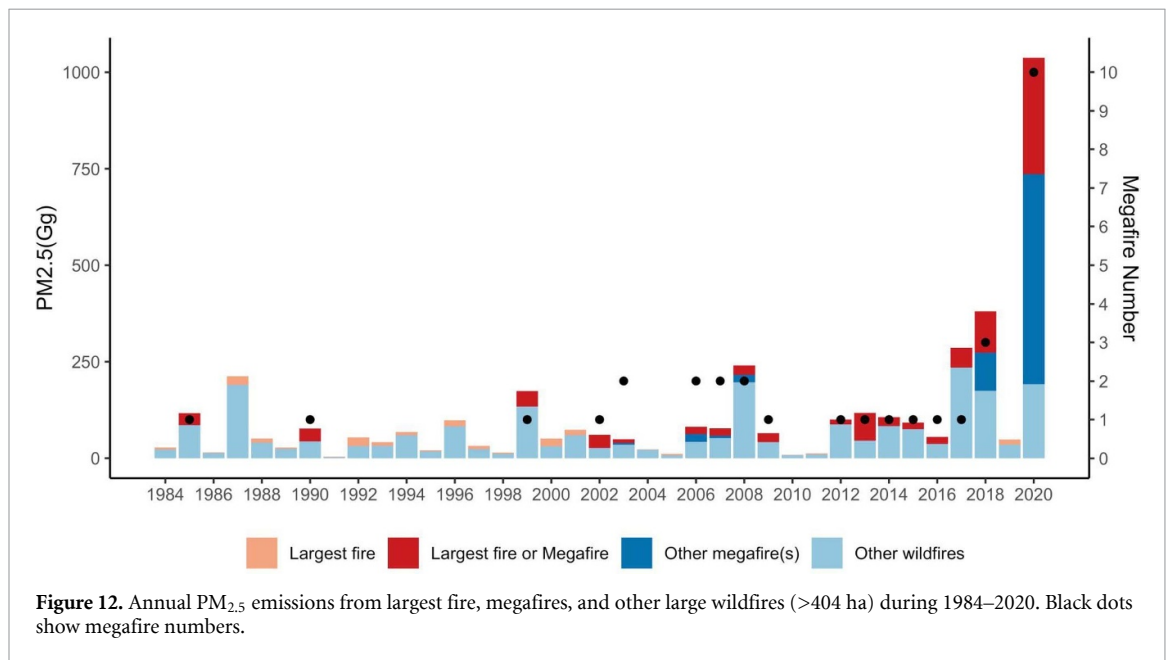
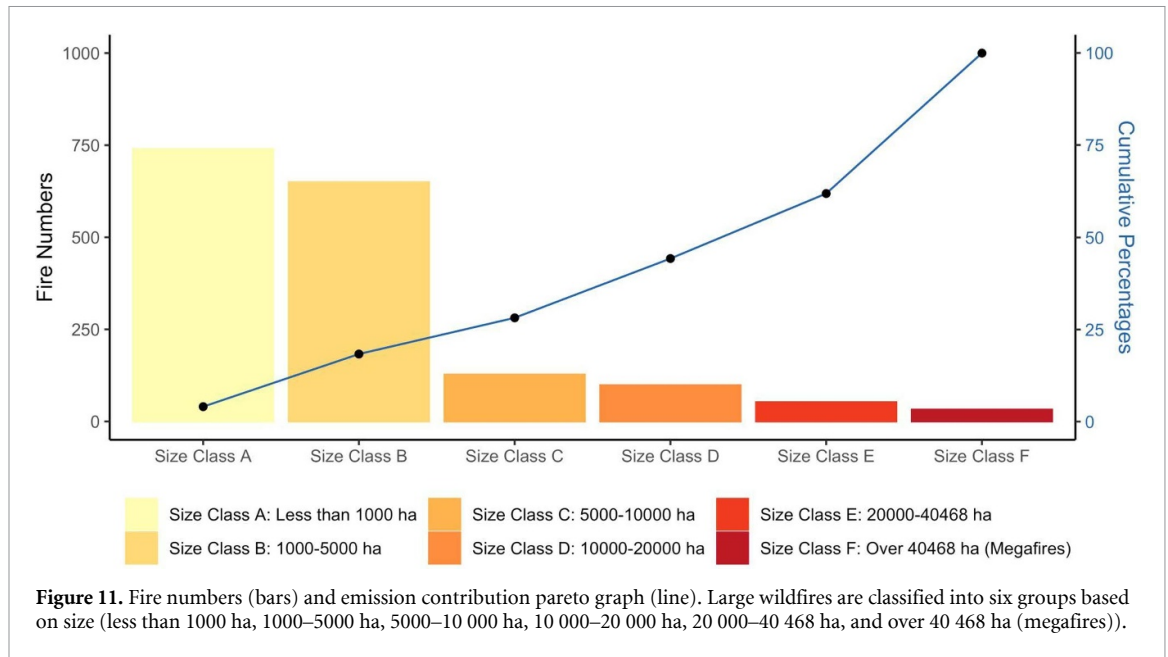
large wildfires included in the analysis into six groups based on size: less than 1000 ha, 1000–5000 ha, 5000–10 000 ha, 10 000–20 000 ha, 20 000–40 468 ha, and over 40 468 ha (with fires over 40 468 ha defined here as megafires). Figure 11 shows the numbers of fires in each size group and the cumulative percentages of emissions. The less than 1000 ha group burned with the largest number (739) of large wildfires but only accounted for 4% of total emissions. The numbers of fires decrease rapidly with increasing size class, while the emissions contribution increases with fire size. There was not much difference in the fractions of vegetation burned among size groups (supplementary figure 1). Increasing wildfire size has been the primary driver of increased emissions.

The size of the annual largest fire ranges from 0.002 million ha to 0.42 million ha with a significant increasing trend (supplementary figure 2). Those fires accounted for about 25% of the total $PM_{2.5}$ emissions (figure 12). Some years there are multiple megafires, defined here as a fire larger than 40 468 ha (100 000 acres). Those megafires (not including megafires that were also classified as the annual largest fire) contributed about 17% of the total emissions. Overall, megafires accounted for about 40% of total emissions, and 10 of the 32 total megafires burned in the year of 2020, accounting for 21% of total emissions from all large wildfires during 1984–2020.

3.5. Limitations

The models used to estimate emissions and severity were developed using different input data: fuel loadings were assigned based on the most appropriate version of LANDFIRE EVT products while burn severities were classified based on LANDFIRE Biophysical Settings (BPS) products. This resulted in

differences in land cover classification of some pixels, as discussed in Xu *et al* this issue. Emissions were calculated assuming grass burn when either EVT or BPS identified the pixel as grassland, except when a pixel is classified as barren-rock/sand/clay, open water, or perennial ice/snow in BPS. Emissions from 22% total area burned in low, moderate, or high severity were calculated as grass burn, a much larger fraction than the fraction of grass burn classified in burn severity calculations (figure 1 and supplementary figure 2). This may lead to an underestimate of the emissions since fuel consumption rates of shrubland and forest are about 12–25 times the number from grassland. The magnitude of changes in emissions varies among different types of emissions depending on emission factors. The current inventory also included 0.2% of total area burned as grass burned in emissions calculations, accounting for 0.1% of emissions. Also, about 11% of burned areas were ignored in emission calculations due to the fact that urban and some other vegetation types were not considered in the current methodology (see supplementary figure 3 for a map of burned area in different vegetation classes and ignored area). A great fraction of total area burned (on average 33% each year) were ignored in emission calculation over the 2016–2020 period, while this number only averages 5% each year during 1984–2015. The increase of emissions is still large even though we underestimate the total emission during the recent five years. This also implies that more urban ecosystems were damaged by recent wildfires. Future versions of these open-source models will seek to reconcile the vegetation types used to calculate fire severity and emissions, and to assign reasonable emissions factors to areas burned in developed areas.



4. Conclusions

Burn severity and emissions have significant implications for assessing fire effects on ecosystems. Using the data from a new wildfire burn severity and emissions inventory, we systematically assessed the temporal and spatial distribution of California’s large wildfires over the last four decades. The main conclusions from this study can be summarized as follows:

- (a) The spatial distribution of burn severity and fire-induced emissions was highly heterogeneous, with the North Coast Ranges, Southern California Mountains, and Sierra Nevada being the hot spots and main sources. The spatial pattern

- of PM_{2.5} emission is similar to that of burned area, albeit the magnitude of emissions did not resemble that of burn severity in the Southern Coast.
- (b) On average, 32%, 41%, and 25%, respectively, burned in low, moderate, and high severity. Nearly half of the areas burned in low, moderate, and high severities were shrubland before 2002. The fraction of area burned in low elevation forests (<5500 ft) and moderate elevation forests (5500–7500 ft) increased, especially in low and moderate severity, during the period of 2002–2015. During the last 5 years (2016–2020), shrub, and low and mid elevation forests burned at the average severity fractions of the past four decades.

- (c) Emissions from low, moderate, and high severity burns are coupled with area burned in the corresponding severity category. PM_{2.5} emissions averaged 108 Gg yr⁻¹ with considerable inter-annual variation, and a significant increasing trend. Emissions from the last five years (2016–2020) are more than five times the average annual emissions during 1984–2015. The year of 2020 had 15 times the amount of annual average emissions during 1984–2015.
- (d) Most emissions were emitted from forests. There is a significant increasing trend from forest emissions over 1984–2020 (supplementary table 2). Forests, specifically low and mid elevation forests burned in moderate severity, are the major sources of emissions. However, emissions from high elevation forests appear to be increasing rapidly over the last decade of the record, and this potential emerging trend merits close attention in coming years.
- (e) Large wildfires burned frequently, starting in early summer through the end of the autumn in most parts of California. The peak emissions month was in August during 1984–2001, and then shifted to July during 2002–2019. The peak month was back to August in the year of 2020 with multiple megafires that all ignited in Northern California. The seasonal distribution of emissions is also uneven across California. The peak emissions start month usually occurred in summer in Northern California, and later in fall in the Southern California region. The seasonal distribution of emissions from grass, shrub, and forest ecosystems is consistent with the burn patterns.
- (f) Extreme fires such as megafires have serious consequences for ecosystems and human society. Their impacts far exceed those of more numerous smaller fires. Extreme events corresponding to less than 2% of fires accounted for about 40% of total emissions. Megafires are also burning more high elevation forests than in previous decades.

Wildfires are a natural and necessary component of California's ecosystems, and play complex roles with biological, physical, climatic, and social elements. As a warming climate, increasing variability in precipitation, and changing land use patterns continue to alter the ecosystems that sustain fire, California will also continue to see changing patterns of wildfire severity, size, timing, location and emissions. However, understanding the changing spatio-temporal patterns of burn severity and emissions can help to facilitate management actions to mitigate the risks of uncharacteristically severe large wildfires and their impacts. The fire and emissions inventory data analyzed here are being used to calibrate models for simulating extreme fire events over a range of future

climate, development footprint, and fuels management scenarios for California's Fifth State Climate Assessment, with the goal of providing a guide to public and private resource managers, policymakers and communities undertaking adaptation and mitigation efforts.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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