Technical Documentation for Emissions Inventory of Vegetations Burned in Wildfires

Published: January 2026

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Acknowledgements

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CARB staff wish to express their appreciation to many individuals and organizations that were an integral part of developing the daily wildfire perimeter and emissions inventory. We would like to thank the following for providing their technical and scientific support:

National Aeronautics and Space Administration and University of Maryland
- Tempest McCabe, Ph.D.
- Elijah Orland
- Zebediah Becker
- Douglas Morton, Ph.D.
- Melanie Cook, Ph.D.

Development Seed
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University of California, Davis
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I. Introduction

Wildfires are a dominant source of air pollution in California, contributing large quantities of fine particulate matter ($PM_{2.5}$), ozone, and greenhouse gases to the atmosphere. Over the last two decades, wildfires on average account for the majority of $PM_{2.5}$ emissions in the statewide emission inventory, with large pulses of activity in recent years, while anthropogenic sources have gradually declined (*https://ww2.arb.ca.gov/wildfire-emissions*). Wildfire emissions can degrade air quality and pose serious risks to public health, particularly for vulnerable populations such as children, the elderly, and individuals with respiratory or cardiovascular conditions (*https://www.epa.gov/air-research/research-health-effects-air-pollution*).

The California Air Resources Board (CARB) develops and maintains emission inventories that support air quality planning, regulatory development, the tracking of emission reduction progress, and understanding the impacts of emission sources on public health. Emissions inventories are foundational to a wide range of programs, including State Implementation Plans (SIPs), which demonstrate how nonattainment areas will meet federal air quality standards (*https://ww2.arb.ca.gov/our-work/programs/california-state-implementation-plans/statewide-efforts/emissions-inventory*).

Historically, CARB's vegetation wildfire emission inventory relied on final fire perimeters and total bulk emissions estimates, which provide aggregated emissions but lack the temporal resolution needed for understanding the impact of fire on air quality. To better support exceptional event demonstrations, air quality modeling, and public health assessment, CARB developed a new daily vegetation wildfire emissions inventory that integrates satellite-derived fire perimeters, spatiotemporally aligned fuelbed and fuel moisture data, and improved modeling of smoldering emissions. The new emission inventory methodology framework provides emissions estimates at the daily scale, enabling more precise attribution of wildfire impacts on air quality and supporting a broader range of regulatory, scientific, and public health applications. The methods, performance, and implications of this new inventory are described in the sections that follow.

II. Methods

A. Overview

Past Methodology: For the last decade, CARB has estimated total bulk emissions and consumption for each wildfire included in the annually released wildfire perimeter dataset from the California Department of Forestry and Fire Protection, CAL FIRE (*https://www.fire.ca.gov/what-we-do/fire-resource-assessment-program/fire-perimeters*). For each wildfire, Fuel Characteristic Classification System (FCCS) fuelbed rasters developed under a CARB contract (University of California, Berkeley 2019) were clipped to the perimeter. The monthly average 1000-hr fuel moisture from gridMET (Abatzoglou 2013) for the ignition month was taken from the perimeter centroid. Fuelbed and fuel moisture data are used as inputs for FOFEM (Lutes 2020), which produces estimates of flaming emissions, smoldering emissions, and consumption. For more information on past methodology, see California Air Resources Board (2023).

New Methodology: To generate an inventory of *daily* wildfire emissions and consumption, CARB has modified this methodology by substituting final fire perimeters with daily fire perimeters. For each day's perimeter, FCCS fuelbeds—now sourced from LANDFIRE, which is widely used across the scientific community—are similarly clipped. For fuel moisture inputs, instead of extracting a single point estimate of 1000-hour fuel moisture from the polygon centroid, day-specific rasters are clipped to the spatial domain of an entire day's perimeter. The fuelbed and fuel moisture rasters are stacked, spatially and temporally associating fuelbeds with correct fuel moistures, improving the precision of wildfire emissions estimates. In the following sections, steps to generate daily fire perimeters and pre- and post-processing steps in the FOFEM workflow are described in more detail.

B. Daily perimeters derived from VIIRS active fire product

Most wildfires in California last one day or less, so for these fires, the CARB inventory defaults to using perimeters from the CAL FIRE dataset. For the remaining wildfires, CARB attempts to estimate daily perimeters derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) active fire product (AFP, Schroeder et al. 2014). This product detects actively burning pixels during each 12-hour satellite overpass (around 1 a.m. and 1 p.m. local time) with a 375-meter spatial resolution. As of 2022, VIIRS sensors are aboard three satellites: NOAA-20, NOAA-21, and Suomi National Polar-orbiting Partnership (SNPP). For the purposes of this methodology, AFP data from SNPP only are used, as it is the only product in the Standard Processing collection (i.e., science quality, 'Archive collection') that spans the entire time period of this inventory and has undergone additional quality assurance and quality control compared to the Near Real-Time collection (*www.earthdata.nasa.gov/faq/firms-faq*). SNPP AFP from the Standard Processing collection (VNP14IMGTML) are downloaded from the online Fire Information for Resource Management System site (*https://firms.modaps.eosdis.nasa.gov/download*).

To interpolate daily perimeters from VIIRS, CARB uses modified methods by Chen *et al.*

(2022). For each 12-hour time interval, AFP, which are formatted as spatial points, are clustered using a ball-tree algorithm (Omohundro 1989) and a nearest neighbor search (Pedregosa *et al.* 2011) for points within the same vicinity. Perimeters of these clusters are drawn using an alpha shape hull algorithm (Edelsbrunner, Kirkpatrick, and Seidel 1983), creating vectorized boundaries of discrete fire objects. As the algorithm processes each time step, fire objects may continue to be created, grow, merge with others, or stop when no new AFP are located nearby. These fire objects form the basis of the sub-daily fire progression perimeters, called Fire Events Data Suite (FEDS, Chen *et al*. 2022). The Wildfire Tracking Lab within NASA's Goddard Space Flight Center and scientists at University of California, Irvine continue to optimize FEDS in order to track fires globally (*https://earth-information-system.github.io/fireatlas/docs/*), with the latest developments available on Github (*https://github.com/Earth-Information-System/fireatlas*). To develop a daily wildfire inventory, the 12-hour FEDS perimeters are aggregated into 24-hour ones, such that the perimeters from 1 PM on day *t* are joined with those from 1 AM on day *t+1*.

While FEDS is capable of detecting fires with very high accuracy, it can also be subjected to limitations inherent to VIIRS. Namely, VIIRS may pick up high heat signatures in large smoke plumes (Zhang *et al.* 2017), leading to the presence of AFP far from the actual boundary of a fire (e.g. multiple kilometers away). Here, FEDS would overestimate the size of a fire perimeter. Furthermore, even though the 375-meter spatial resolution of VIIRS is relatively fine compared to other fire-detecting satellites, such as MODIS (1 km) or GOES (4 km), it can still be too coarse to discern the boundaries of co-occurring, nearby fires. This situation is often the case for small lightning fires and FEDS can erroneously merge independent fires together.

To address these issues, CARB has modified the FEDS algorithm by pre-filtering AFP to the final fire footprints of known wildfires. This is done using wildfire perimeters from the CAL FIRE dataset, which are buffered by 187.5-meter—equivalent to the radius of the spatial resolution of VIIRS. The FEDS algorithm then loops through each wildfire, solving the two previously mentioned issues: 1) it removes false positive AFP data, reducing the extent of overestimated fire perimeters, and 2) it prevents the merging of coinciding, close fires since each fire is independently processed. Another outcome of this approach is that it removes any non-wildfires that would have been detected by FEDS, which is beneficial for the purpose of building an emissions inventory of wildfires.

C. FOFEM emissions and consumption

CARB estimates emissions and consumption from each wildfire by providing two user-based inputs to FOFEM: 1000-hr fuel moisture data and FCCS fuelbeds. Combustion efficiency and therefore emissions are highly influenced by fuel moisture (Garg *et al.* 2021), which can vary greatly with temperature, precipitation, and relative humidity. Daily 4-km resolution rasters of 1000-hour fuel moisture are obtained from gridMET (Abatzoglou 2013) and reprojected to 30-meter resolution to align with FCCS data. FCCS fuelbeds describe the inherent physical properties of fuel that influence fire behavior and effects (Riccardi et al. 2007), capturing the structure and quantity of fuel across multiple strata (Ottmar et al. 2007).

Thousands of FCCS fuelbed classifications exist, providing detailed fuel load information for various ecological types and disturbance histories, and are accessible for download at 30-meter resolution from LANDFIRE (*www.landfire.gov/data*). Currently, LANDFIRE hosts publicly available versions of FCCS for the United States for 2001, 2014, 2016, 2020, and 2023. Each vintage corresponds to disturbances occurring through the end of the indicated year. For example, the 2023 version incorporates disturbances through December 31, 2023 (Puma 2023). The most recent version available *prior to the fire* (e.g., a fire in 2020 uses version 2016) gets used since newer versions would reflect post-fire conditions rather than pre-fire fuels. CARB acknowledges that fuelbed accuracy diminishes as time since the last update increases, and that significant step-changes in fuelbeds may occur between LANDFIRE vintages.

FOFEM also allows users to specify canopy mortality. Currently, CARB assumes 39% canopy mortality for all wildfires, which stems from a study of the Monitoring Trends in Burn Severity (MTBS) project. Eidenshink *et al.* (2007) demonstrated that of the 347 fires (7.8 million acres) surveyed in MTBS, 39% of the area burned at moderate and high severity. Future enhancements to CARB's methodology could incorporate satellite-derived fire severity to more accurately estimate canopy mortality.

While emissions for most wildfires are estimated using final fire perimeters from CAL FIRE, daily perimeters from FEDS are used instead when VIIRS detects fire activity lasting more than 24 hours. In such cases, the process as described below is repeated for each day, and emissions are quantified only for the new growth occurring on that day. Raster-based inputs are stacked, clipped to each fire perimeter, then converted to a tabular format, with the total acreage of each fuelbed–fuel moisture combination quantified. Input data is processed through FOFEM version 6.7 in "batch mode" (Lutes 2020), and the default output includes consumption of various fuel strata and emissions of PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_x[1], SO_2, separated by short-term flaming and smoldering ("flaming phase") and residual smoldering ("smoldering phase"). CARB additionally estimates pollutants NH_3, total non-methane hydrocarbons (TNMHC), N_2O, NO_2, and total organic gases (TOG) using equations derived from molecular weight relationships (Table 1). Emissions are estimated using emission factors (EFs), of which FOFEM offers two built-in options—default and "expanded" EFs. Compared to the default EFs, the expanded EFs are derived from more up-to-date research (Urbanski 2014) and distinguish between broad vegetation types, including wildfires and prescribed fires in western forests (Table 2). In past inventories, CARB used the default EFs (Table S1); the current inventory uses the expanded EFs.

[1] *Although labeled as "NOx," the FOFEM output actually represents nitric oxide (NO) only, not total nitrogen oxides (NO + NO_2). This is a common convention in fire emission models. For inventory and modeling purposes, CARB converts this NO to its NO_2-equivalent using the molecular weight ratio (46/30), consistent with standard reporting practices.*

Table 1. Empirical equations used to estimate additional pollutants.

Pollutant Equation	Notes & Reference(s)
$NH_3 = CO \times 0.01$	California Air Resources Board 2023; Lobert *et al.* 1991
$TNMHC = CO \times 0.07$	California Air Resources Board 2023; Lobert *et al.* 1991
$N_2O = CO_2 \times 0.0001394$	California Air Resources Board 2023; Lobert *et al.* 1991
$NO_2 = NO_x \times 46/30$	W. Yang, *Pers. Comms.*; California Air Resources Board 2023
$TOG = (CH_4 + TNMHC) \times 2$	W. Yang, *Pers. Comms.*; California Air Resources Board 2023

Table 2. Expanded emission factors from Urbanski (2014). Emissions from litter, herbaceous cover, shrubs, foliage, and branches are computed using the cover-specific EFs for both the flaming and smoldering phases. Emissions from fine and coarse woody debris are computed using the cover-specific EFs during the flaming phase, and the coarse wood RSC EF for the smoldering phase. Both flaming and smoldering emissions of duff are computed using the duff RSC EF. *Note*: The FOFEM 6.7 User's Guide lists EFs for NH_3 (Lutes 2020), but the default batch mode outputs do not include the pollutant. As a result, CARB speciates NH_3 according to the equation in Table 1.

Cover Type	CO_2 g/kg	CO g/kg	CH_4 g/kg	NO_x g/kg	SO_2 g/kg	$PM_{2.5}$ g/kg	PM_{10} g/kg
Southeastern Forest	1703	76	2.32	1.70	1.06	12.58	14.8
Boreal Forest	1641	95	3.38	1.00	1.06	21.50	25.4
Western Forest-Rx[1]	1598	105	4.86	2.06	1.06	17.57	20.7
Western Forest-WF[2]	1600	135	7.32	2.00	1.06	23.20	27.4
Shrubland	1674	74	3.69	2.18	0.68	7.06	8.3
Grassland	1705	61	1.95	2.18	0.68	8.51	10.0
Coarse Wood RSC[3]	1408	229	13.94	0.00	0.00	33.00	38.9
Duff RSC[3]	1371	257	7.945	0.67	1.76	35.30	41.6

[1]"Rx": Prescribed fire; [2]"WF": Wildfire; [3]"RSC": Residual smoldering component

D. Post-processing of emissions

FOFEM produces estimates of total bulk emissions, which inherently assumes that all emissions from a single day's perimeter are completely released within a 24-hour period. A distinct flaming front typically moves through fuel quickly, producing the bulk of flaming emissions early, followed by a smoldering tail (Chen *et al.* 2007). Smoldering combustion may continue well beyond the flaming front, sometimes persisting for days to weeks in organic matter or large coarse woody debris (Qin *et al.* 2022; Rein & Huang 2021). Under lower intensity burns, smoldering may decay in hours, whereas under high intensity conditions with abundant coarse fuels or deep litter and duff layers smoldering may subsist for days or even weeks (Lin *et al.* 2024; Prichard *et al.* 2022).

For fires using FEDS perimeters, smoldering emissions are empirically allocated over time for each day using VIIRS fire radiative power (FRP), which is related to fuel consumption and fire intensity (Schroeder *et al.* 2014). Within each daily perimeter x, VIIRS AFP may be detected over multiple days $t \dots T$. The partial emissions E_{xt} from perimeter x on day t are calculated by multiplying the total smoldering emissions E_x by a weights scalar w_{xt}:

$$w0_{xt} = \sum FRP_{xt} \tag{1}$$

$$w_{xt} = \frac{w0_{xt}}{\sum_t^T w0_{xt}} \tag{2}$$

$$E_{xt} = E_x \cdot w_{xt} \tag{3}$$

where $w0_{xt}$ is the sum of all FRP on day t within perimeter x, representing the raw weight (eq. 1), and w_{xt} is the normalized weight, ranging between 0 and 1 (eq. 2). The summed partial emissions from all perimeters for day t yields the adjusted smoldering emissions for that day.

To ensure that acres burned, emissions, and consumption generated from FEDS perimeters are of similar magnitude to those estimated from CAL FIRE perimeters, each quantity, y, is multiplied by a scalar φ:

$$y = \varphi \cdot \mathrm{y}_{FEDS} \tag{4}$$

$$\varphi = \frac{area_{CAL\ FIRE}}{area_{FEDS}} \tag{5}$$

such that φ adjusts for differences between the final fire size of FEDS and the CAL FIRE footprint (eq. 5).

III. Conclusion

This report presents a major update to CARB's vegetation wildfire emissions inventory, introducing an inventory with daily data that integrates satellite-derived fire perimeters, spatiotemporally aligned fuelbed and fuel moisture data, and improved modeling of smoldering emissions. Compared to previous inventories, this approach enhances temporal precision and better reflects fire activity. By providing daily estimates of wildfire activity and emissions, the inventory better supports applications such as SIPs and exceptional event demonstrations, where linking elevated pollutant concentrations to wildfire activity is important.

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