SECTION 9.3

WILDFIRES

(March 2023)

EMISSION INVENTORY SOURCE CATEGORY
Natural (Non-Anthropogenic) Sources / Wildfires

EMISSION INVENTORY CODES (CES CODES) AND DESCRIPTION

930-934-0200-0000 (90035) Wildfires - All Vegetation

METHODS AND SOURCES

This source category provides emission estimates from wildfires. Wildfires burn a variety of vegetation communities comprised of variable plant sizes, ages, and spatial distribution. Wildfires are caused by a variety of natural and human activities including lightning strikes, arson, equipment use, and escaped prescribed burns, though the most frequent documented ignition cause is "unknown." Unlike managed fires, such as agricultural burning and prescribed fires, wildfires are suppressed by fire fighting agencies. Wildfires do not include prescribed burns or Wildland Fire Use (WFU). A prescribed burn is a fire ignited by a planned management action whereas a WFU is a naturally ignited lightning fire that is managed for resources benefit.

OVERVIEW OF ESTIMATION METHODOLOGY

Wildfire emissions are estimated using the First Order Fire Effects Model (FOFEM 6.7, Lutes 2020) in batch processing mode, and a custom geoprocessing tool (Emission Estimation System, EES) developed for CARB by researchers at UC Berkeley (Clinton et al. 2006, 2003; Scarborough 2014; Scarborough et al. 2001). Coded in the Python programming language, the current EES serves as a pre- and post-processor to FOFEM [(1)].

(1) FOFEM is a fuel consumption and smoke production model developed by USDA – Forest Service, Rocky Mountain Research Station, Missoula Fire Laboratory. The FOFEM model determines pre-burn fuel loading, fuel mass consumed, and emissions generated per acre burned.

The pre-processor module of the EES performs geoprocessing tasks in a Geographic Information System (GIS). It overlays wildfire perimeters (polygons) from a geodatabase maintained by the California Department of Forestry and Fire Protection (CALFIRE) Fire and Resource Assessment Program (FRAP)(CALFIRE 2022) on to a 30 meter pixel resolution raster layer of California vegetation "fuel beds" (Ottmar et al. 2007, LANDFIRE 2019). The pre-processor tabulates the fuel bed types and their corresponding area extent, retrieves fuel moisture and fuel loading values, and creates a batch input file FOFEM can read. For each fuel bed FOFEM calculates the mass of fuel consumed and corresponding emissions, based on fuel moisture condition. A post-processor module in EES scales the per unit area fuel bed emissions from FOFEM to total emission based on the area extent of each fuel bed within the fire perimeter, and provides estimates for additional pollutants NH_3, N_2O, and Total Non-Methane Hydrocarbons (TNMHC). This approach was used to calculate emissions for wildfires that occurred in 2000 – 2021, and will be used for subsequent annual updates.

EMISSION ESTIMATION METHODOLOGY

Activity Data - Wildfire Perimeters. Wildfire perimeters and ignition dates are provided by the FRAP geodatabase. Updated annually by FRAP, the dataset represents the most comprehensive interagency wildfire geodatabase available for California.

The FRAP geodatabase contains wildfire perimeters mapped principally by federal land management agencies, CALFIRE, and cooperating state and local agencies. Wildfires often span jurisdictions, and multiple agencies will coordinate suppression efforts. FRAP reconciles submitted geodata to produce final extent fire perimeters. Fire perimeters may over-generalize the area burned, by not delineating unburned "islands" within the final perimeter, which is common in large-area wildfires.

In the worked example below, a wildfire was selected from a set of wildfires reported for 2002 in the FRAP fire history geodatabase.

Emission Factors and Pollutants. FOFEM calculates emissions for PM_{10}, $PM_{2.5}$, CO, CH_4, CO_2, NO, and SO_2, while the EES post-processor module includes emissions of N_2O, NH_3, and TNMHC. Emission factors for PM_{10}, $PM_{2.5}$, CO_2, CH_4 and CO are functions of combustion efficiency and the flaming and smoldering phases of biomass burning under different fuel moisture conditions (Table A, reproduced from Lutes 2012). The post- processor module in the EES adds emission estimates for NH_3, N_2O and TNMHC using an emission ratio approach (Lobert et al. 1991). The approach is based on the observation that emissions correlate with CO or CO_2 depending on whether the compound evolves primarily in the flaming or smoldering phase of combustion. CARB converts the FOFEM NO output to conventional NO_2 based on molecular weight ratios. CARB TOG and ROG estimates are based on the model's estimates for CH_4 and TNMHC.

$NOx = NO * NO_2 (MW 46) / NO (MW 30) = NO * 1.533$

$TOG = (CH_4 + TNMHC) * 2$

ROG = TOG * FROG (Reactive Fraction)

For a more detailed explanation of emission factors, consult the references.

Table A. FOFEM emission factors in grams/kg of fuel consumed. FOFEM assumes flaming combustion efficiency (FCE) equals 0.97 and smoldering combustion efficiency (SCE) equals 0.67.

Pollutant	Flaming Phase	Flaming Phase	Smoldering Phase	Smoldering Phase
	Formula	**Multiplier**	**Formula**	**Multiplier**
$PM_{2.5}$	67.4 – (FCE x 66.8)	2.604	67.4 – (SCE x 66.8)	22.644
CH_4	42.7 – (FCE x 43.2)	0.796	42.7 – (SCE x 43.2)	13.756
CO	961 – (FCE x 984)	6.520	961 – (SCE x 984)	301.720
CO_2	FCE x 1833	1778.01	SCE x 1833	1228.11
PM_{10}	PM2.5 x 1.18	3.07272	PM2.5 x 1.18	26.71992
NO	3.2	3.2	0	0
SO_2	1.0	1.0	1.0	1.0

Fuel Loading and Fuel Consumption. The Fuel Characteristics Classification System (FCCS) raster layer (LANDFIRE 2019) spatially represents fuel beds, with each 30-meter resolution pixel labelled with an FCCS fuel bed identifier. Each fuel bed (vegetation community type) is represented by nine fuel components: duff; litter; 0 - ¼ inch (“1-hour”), ¼ -1 inch (“10-hour”), 1-3 inch (“100-hour”), and 3+ inch (“1000-hour”) diameter dead woody fuels; herbaceous; shrub; and canopy fuels. Duff consists of partially decomposed organic material of the forest floor and lies beneath the litter layer. Litter is comprised of fallen twigs, cones, needles, and leaves covering the surface. The hour nomenclature for dead woody fuels represent the time it takes for woody fuels to respond to changes in humidity. Thousand-hour fuels are sub-divided into sound and rotten fractions (percent), with size categories of 3-6 inch, 6-9 inch, 9-20 inch, and greater than 20-inch diameter. FOFEM provides for prescribing the weight distribution among the four size classes of 1000-hour fuels. For 1000-hour fuels CARB staff used FOFEM default settings for sound and rotten fractions and an even weight distribution. The category “Herbaceous” represents grasses and herbaceous vegetation that comprise forest understory and the dominant plant types of other vegetation communities, such as grasslands. Shrubs are woody plants of relatively low height. Two components define tree canopy fuels: canopy branch wood (lateral branches along a tree trunk that lead to the canopy) and canopy foliage (leaves or needles).

A FOFEM look-up table contains fuel loading values for each FCCS fuel bed and corresponding fuel components. Component fuel loadings are defined in units of tons per acre. Combustion efficiency and fuel consumption determine the emissions from burned fuel. Fuel consumption is the mass (tons) of fuel consumed by fire. FOFEM uses the Burnup model (Albini et al. 1997, 1995) to predict consumption of woody fuels. FOFEM uses a decision tree based on inputs for Region, Season, and Cover Group to determine which algorithms are used to estimate consumption of grasses/herbaceous vegetation, shrubs, and duff. In general, FOFEM assumes that fire consumes 100% of litter. FOFEM assumes full consumption for grasses and herbaceous vegetation, except in springtime. Tree canopy fuel consumption is a FOFEM input parameter (percent) prescribed by the user. CARB staff applied a default canopy consumption rate of 29% for wildfires (Miller et al. 2009). In the Burnup model, the spatial arrangement of fuel components also regulates the combustion process. FOFEM therefore defines an input called Fuel Category (Natural, Slash, or Piles), to be prescribed by the user. CARB staff use the Natural fuel category for wildfires.

Thousand-Hour Fuel Moisture. Moisture conditions for dead woody fuels and duff are assigned based on reported National Fire Danger Rating System Thousand-Hour (NFDR-TH) fuel moisture values. The NFDR-TH moisture value input to FOFEM affects both fuel consumption and combustion efficiency. The proportions of CO and CO_2 released from fuel consumption define combustion efficiency. Combustion efficiency is related to the portions of consumption that occur in the flaming and smoldering phases of fire. Efficient combustion is associated with dry fuel conditions, with a large portion of fuel consumption occurring in the flaming phase. Conversely, when fuels are moist, the majority of fuel consumption occurs in the less efficient smoldering phase. FOFEM provides an option for setting moisture values for the 10-hour and duff fuel components based on NFDR-TH values.

NFDR-TH values vary spatially and temporally. CARB staff use geospatially explicit statewide year- and month-specific NFDR-TH rasters to assign realistic fuel moisture values for each wildfire. A series of geoprocessing steps are used to create NFDR-TH moisture rasters from georeferenced weather station data reported by the federal Wildland Fire Assessment System (WFAS 2019) and by the gridMET system (Abatzoglu 2013, gridMET 2022).

Fuel Characterization Classification System (FCCS) map. The FCCS layer is a 30-meter pixel resolution raster developed from LANDSAT imagery and ground-based vegetation surveys and periodically updated by the federal LANDFIRE consortium (LANDFIRE 2019). For California, FCCS maps over 70 fuel bed types representing categories of forests, woodlands, grasslands, shrub lands, wetlands and sparsely vegetated lands.

TEMPORAL INFORMATION

In the CALFIRE geodatabase, fire perimeters (polygons) represent the final spatial extent of a wildfire. Therefore, emission estimates based on the final extent of a fire represent cumulative emissions rather than momentary emissions. Spatially explicit NFDR-TH fuel moistures are month averages specific to the year of the fire.

ASSUMPTIONS AND LIMITATIONS

- The CALFIRE-FRAP geodataset contains information submitted by cooperating federal, state, and local agencies, therefore accuracy and consistency can vary by location and year. FRAP data is updated annually and represents the most comprehensive geospatially explicit wildfire dataset available.
- Default FCCS fuel loading values used in FOFEM represent typical conditions. Real-world fuel loads change with time.
- FOFEM assumes 100% of the burn area experiences fire.
- NFDR-TH moisture values for each wildfire are based on the year-specific month-average value of a pixel corresponding to the ignition start date and the centroid of the wildfire polygon. Real-world fuel moistures vary with fuel component, elevation, slope, aspect, and meteorological conditions (Holden and Jolly 2011).

CHANGES IN METHODOLOGY

Emission estimation methods reflect use of FOFEM version 6.7, LANDFIRE FCCS fuels rasters, year- and month-specific NFDR-TH fuel moisture rasters created from GIS data, and the EES processor.

EXAMPLE CALCULATION

In the example below, FOFEM was used to estimate PM_{10} emissions for the Plum fire that occurred in El Dorado County in November 2002. The pre-processor module of EES overlaid the Plum fire perimeter (retrieved from the CALFIRE-FRAP geodatabase) on the FCCS vegetation fuel beds raster, and tabulated fuel bed types, loadings, and their areas. The Plum fire footprint was 1,762 acres, including 14.4 acres of urban/developed land, and encompassed ten natural vegetation types (Figure 1, Tables 1 and 2). There are no FCCS fuel bed types for urban/developed land. Of the ten FCCS fuel beds present, FCCS fuel beds 7 and 16 comprised most of the overall fuel load within the fire perimeter (Table 2). Table 3 displays model results for fuel consumption and PM_{10} emissions by FCCS fuel bed. Litter, herbaceous, 1-hour, and 10-hour fuels exhibit nearly complete consumption. Thousand-hour fuels exhibit variable consumption across FCCS fuel beds, averaging 35 to 40 percent. FOFEM assumed 70 percent consumption for duff across all fuel beds. Overall, the model estimated approximately 58,000 tons of fuel consumption, with over 60 percent represented by FCCS fuel bed 7. The bulk of PM_{10} emissions are associated with the smoldering phase of combustion. FCCS fuel beds 7 and 16 contributed approximately 80% to total PM_{10} emissions (1,124 tons) associated with the Plum fire.

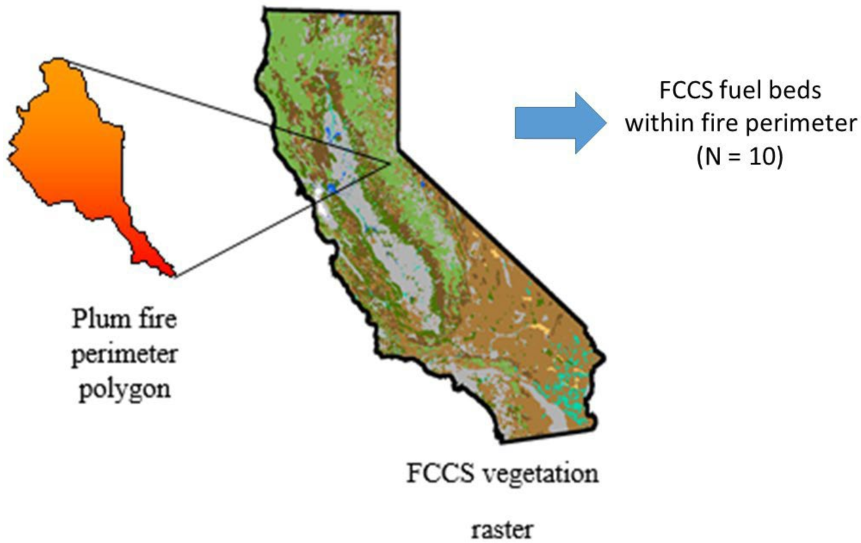

Figure 1. Schematic diagram of FCCS vegetation fuels tabulation.

Table 1. FCCS vegetation types (fuel beds) located within the Plum fire perimeter.

FCCS ID	FCCS fuel bed name
4	Douglas fir-Ceanothus forest
5	Douglas fir-White fir forest
7	Douglas fir-Sugar pine-Tanoak forest
14	California Black oak woodland
15	Jeffrey pine-Red fir-White fir-Greenleaf manzanita-Snowbrush forest
16	Jeffrey pine-Ponderosa pine-Douglas fir-Black oak forest
37	Ponderosa pine-Jeffrey pine forest
44	Scrub oak chaparral shrubland
46	Chamise chaparral shrubland
60	Sagebrush shrubland

Table 2. FOFEM inputs. Plum Fire fuel loading and other parameters.

FCCS fuel bed ID		4	5	7	14	15	16	37	44	46	60
Area (acres)		102.1	138.7	917.0	16.7	55.1	465.0	42.0	4.7	1.3	5.3
Fuel Component		Load (tons/acre)									
1-HR	0 - ¼”	0.2	0.5	1	0.25	0.08	0.3	0.1	0.5	0.5	0
10-HR	¼ - 1”	0.3	1.6	3.2	0.5	0.7	1.4	1	0.25	1	0
100-HR	1 - 3”	3.8	3.3	1.9	0.9	0.23	1.8	1.5	0.25	1	0
1000-HR	3-6” Sound	0	2.15	0.3	0.625	0.875	0.4	0.6	0	0	0
	6-9“ Sound	0	2.15	0.3	0.625	0.875	0.4	0.6	0	0	0
	9-20”Sound	0	8.9	0.7	0	5	2.5	2.5	0	0	0
	>20” Sound	0	3.4	1.7	0	6	0	0	0	0	0
	3-6” Rotten	6	0.4	2.45	0	0.25	0.35	0.3	0	0	0
	6-9” Rotten	6	0.4	2.45	0	0.25	0.35	0.3	0	0	0
	9-20”Rotten	7	1.6	5.4	0	2	2.5	2.5	0	0	0
	>20” Rotten	4.5	0.6	14.2	0	2	0	0	0	0	0
	Litter	2.27	4.98	1.27	1.87	2.49	2.65	0.76	4.65	0.3	0.11
	Duff	11	13.17	19.21	2.64	55.48	11.44	22.1	0.6	3.12	0
	Herbaceous	0.6	0.21	0.02	0.1	0.05	0.2	0.31	0	0	0.2
	Shrub	5.91	2.98	0.87	0.29	6.41	1.93	3.1	9.82	12.23	0.97
Canopy	Foliage	3.01	16.78	15.44	15.71	11.51	6.7	6.93	0	0	0
	Branchwood	0.75	4.19	3.86	3.93	2.88	1.68	1.73	0	0	0

Region	Pacific West
Season	Fall
Fuel Category	Natural
Crown Consumption	29%

Cover Group	FCCS ID
Ponderosa	16, 37
Shrub Group	44, 46
Sagebrush Group	60

Fuel Moisture	Percent
NFDR-TH	14
10-HR	10
Duff	40

Table 3. Model output. Plum Fire fuel consumption and PM_{10} emissions.

FCCS fuel bed ID		4	5	7	14	15	16	37	44	46	60
Fuel component		tons									
Litter	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	231.7	690.5	1164.7	31.2	137.2	1,232.2	31.9	21.7	0.4	0.59
1-HR	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	20.4	69.3	917.0	4.2	4.4	139.5	4.2	2.3	0.7	0
10-HR	Post-fire	0	0	0	0	0	0	0	0.1	0	0
	Consumed	30.6	221.8	2,934.6	8.3	38.6	651.0	42.0	1.1	1.3	0
100-HR	Post-fire	0	0	0	6.2	0	0	0	0.7	0.5	0
	Consumed	387.9	457.6	1,742.4	8.8	12.7	837.0	63.0	0.4	0.8	0
1000-HR Sound	Post-fire	0	1,515.5	1,815.8	17.9	307.4	1,129.9	86.1	0	0	0
	Consumed	0	786.2	935.4	3.0	395.0	404.5	69.3	0	0	0
1000-HR Rotten	Post-fire	860.5	185.8	10,940.4	0	50.7	813.7	47.9	0	0	0
	Consumed	1,538.4	230.2	11,527.3	0	197.2	674.2	82.3	0	0	0
Duff	Post-fire	374.6	608.7	5,869.1	14.7	1,019.1	1,771.6	309.5	0.9	1.4	0
	Consumed	748.3	1,217.4	11,747.4	29.4	2,037.2	3,547.9	618.5	1.9	2.8	0
Herbaceous	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	61.2	29.1	18.3	1.7	2.8	93.0	13.0	0	0	1.07
Shrubs	Post-fire	240.9	165.0	321.0	2.0	141.0	358.0	52.1	9.1	3.3	0.53
	Consumed	362.4	248.2	476.9	2.8	212.1	539.4	78.1	36.7	13.1	4.64
Canopy foliage	Post-fire	218.5	1,651.4	10,050.9	186.0	450.1	2,213.4	206.6	0	0	0
	Consumed	88.8	675.2	4,108.4	76.1	184.0	902.1	84.4	0	0	0
Canopy branchwood	Post-fire	65.3	496.4	3,026.3	56.1	135.5	669.6	62.1	0	0	0
	Consumed	11.2	84.6	513.5	9.5	23.1	111.6	10.5	0	0	0
Emissions		tons									
PM10	Flaming	2.3	6.3	33.0	0.4	1.7	10.7	0.7	0.2	0.0	0.02
	Smoldering	72.9	70.6	677.2	1.3	71.8	150.9	23.4	0.1	0.2	0.02
	Total	75.2	77.0	710.3	1.7	73.5	161.6	24.1	0.3	0.2	0.03

GLOSSARY

BURNUP. A model within FOFEM designed to calculate consumption of large-diameter dead woody fuels.

CALFIRE. California Department of Forestry and Fire Protection.

EES. Emissions Estimation System. CARB's pre- and post-processor to FOFEM.

FCCS. Fuel Characterization and Classification System. A federal system for characterizing and mapping vegetation fuels.

FCE. Flaming Combustion Efficiency. The proportion of carbon released as CO2 during the flaming phase of combustion.

FOFEM. First Order Fire Effects Model. Federal model designed to estimate vegetation fuel consumption and emissions associated with biomass burning.

FRAP. Fire and Resource Assessment Program. CALFIRE's research program.

GIS. Geographic Information System. Software designed for modeling and analysis of spatial data.

gridMET. A dataset of daily high-spatial resolution surface meteorological data covering the contiguous US.

LANDFIRE. Landscape Fire and Resource Planning Tools. A federal consortium providing landscape-scale geospatial products to support fire planning, management, and analysis.

LANDSAT. A federal program acquiring satellite imagery of Earth. LANDSAT products support natural resources mapping, monitoring, planning, and research.

NFDR-TH. National Fire Danger Rating System – Thousand Hour. A moisture parameter for large-diameter dead woody fuels (e.g. logs, branches).

RAWS. Remote Automated Weather Stations. A network of weather stations in remote locations operated cooperatively by federal land and fire management agencies and the National Interagency Fire Center.

SCE. Smoldering Combustion Efficiency. The proportion of carbon released as CO2 during the smoldering phase of combustion.

TNMHC. Total Non-Methane Hydrocarbons. Carbon and hydrogen-containing gases emitted by biomass combustion, other than CH4.

WFAS. Wildland Fire Assessment System. A federal clearinghouse of historical, real-time and forecast products on fire weather, fuel conditions, and fire potential.

WFU. Wildland Fire Use. Lightning-ignited fires managed (not suppressed) for resource benefit.

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