Section 9.4
Wildland Fire Use (WFU)

(March 2023)

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

EMISSION INVENTORY CODES (CES CODES) AND DESCRIPTION

930-667-0200-0000 (95091) Wildland Fire Use (WFU)

METHODS AND SOURCES

This source category provides emission estimates from Wildland Fire Use (WFU) fires. A WFU is a naturally ignited lightning fire that public land management agencies manage for resources benefit. Hence, land management agencies currently refer to this category of wildland fire as “Fire for Resource Benefit”. In some years, land management agencies may suppress all fires, and no WFUs will be reported for those years. The emission estimation methodology described here is the same approach used to calculate emissions for the Wildfire category. The WFU emission inventory category was created in 2004.

OVERVIEW OF ESTIMATION METHODOLOGY

WFU 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)]

The pre-processor module of the EES performs geoprocessing tasks in a Geographic Information System (GIS). It overlays WFU 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

(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 smoke emissions generated per fire acre burned.

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 WFUs that occurred in 2000 – 2021 (the FRAP geodatabase reports no WFUs for years 2013 - 2018), and will be used for subsequent annual updates.

EMISSION ESTIMATION METHODOLOGY

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

The FRAP geodatabase contains WFU perimeters mapped principally by federal land management agencies, CALFIRE, and cooperating state and local agencies. WFUs sometimes span jurisdictions, and multiple agencies will coordinate management of a WFU. 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 WFU was selected from a set of WFUs reported for 2003 in the FRAP WFU 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.

$NOx = NO * NO_2 \text{ (MW 46)} / NO \text{ (MW 30)} = NO * 1.533$

$TOG = (CH_4 + TNMHC) * 2$

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		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 1% for WFUs. 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 WFU fires.

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 WFU. 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 WFU fire. 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 geodatabase 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 WFU dataset available.
- Default FCCS fuel loading values used in FOFEM represent typical conditions. Real-world fuel loads change with time.
- The 1% consumption rate for tree canopies is a default assumption.
- FOFEM assumes 100% of the burn area experiences fire.
- NFDR-TH moisture values for each WFU are based on the year-specific month-average value of a pixel corresponding to the ignition start date and the centroid of the WFU 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 Mudd WFU that occurred in Alpine County from August 31, 2003 to October 3, 2003. The pre-processor module of EES overlaid the Mudd WFU 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 Mudd WFU fire footprint encompassed 4,337 acres, including 9.6 acres of water bodies, 503 acres of barren (non-vegetated) land, and twenty natural vegetation types (Figure 1, Tables 1 and 2). Fuel bed 17 (Red fir forest) accounted for nearly 80% of the over 300,000 tons of total fuel load, and nearly 80% of total PM_{10} emissions (Table 3).

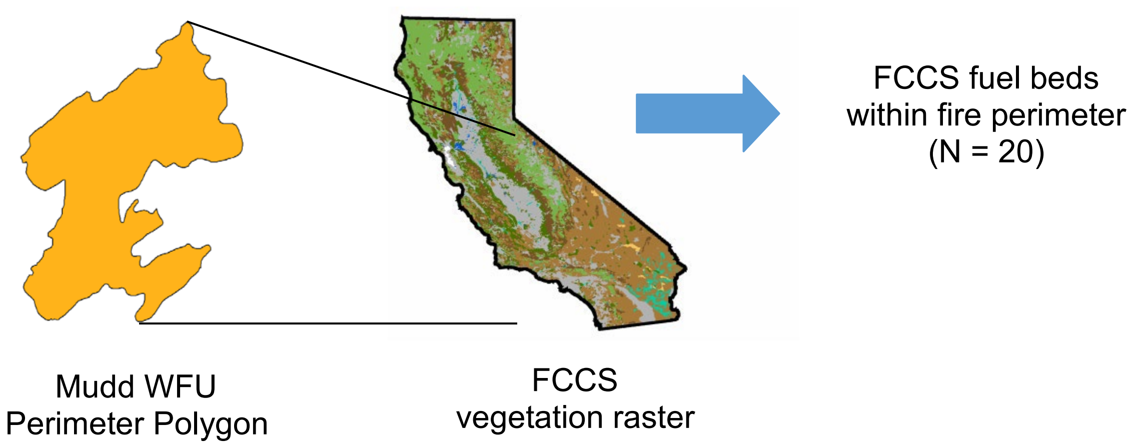

Figure 1. Schematic diagram of FCCS vegetation fuels tabulation.

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

FCCS ID	FCCS fuel bed name
1	Black cottonwood-Douglas fir-Quaking aspen riparian forest
4	Douglas fir-Ceanothus forest
5	Douglas fir-White fir forest
7	Douglas fir-Sugar pine-Tanoak forest
12	Red fir-Mountain hemlock-Lodgepole pine-White pine forest
14	California Black oak woodland
15	Jeffrey pine-Red fir-White fir-Greenleaf manzanita-Snowbrush forest
17	Red fir forest
21	Lodgepole pine forest[1]
22	Lodgepole pine forest[2]
30	Turbinella oak-Alderleaf mountain mahogany shrubland
37	Ponderosa pine-Jeffrey pine forest
41	Idaho fescue-Bluebunch wheatgrass grassland
44	Scrub oak chaparral shrubland
60	Sagebrush shrubland
63	Showy sedge-Alpine black sedge grassland
70	Subalpine fir-Lodgepole pine-Whitebark pine-Engelmann spruce forest
210	Pinyon-Utah juniper woodland
237	Vaccinium-heather shrubland
310	Greasewood shrubland

[1, 2] FCCS maps several versions of Lodgepole pine forest, each with a different fuel composition.

Table 2. FOFEM inputs. Mudd WFU fire fuel loading and other parameters.

FCCS fuel bed ID		1	4	5	7	12	14	15	17	21	22
Area (acres)		16.3	36.2	414.8	159.8	1.1	0.2	241.9	2,594.6	0.2	7.3
Fuel Component		Load (tons/acre)									
1-HR	0 - ¼”	0.2	0.2	0.5	1	0.3	0.25	0.08	0.9	0.2	0.4
10-HR	¼ - 1”	0.8	0.3	1.6	3.2	0.6	0.5	0.7	3.1	1	2.2
100-HR	1 - 3”	3.5	3.8	3.3	1.9	1.1	0.9	0.23	3	2.5	2.8
1000-HR	3-6” Sound	0.25	0	2.15	0.3	0.3	0.625	0.875	0.5	4	4.15
	6-9“ Sound	0.25	0	2.15	0.3	0.3	0.625	0.875	0.5	4	4.15
	9-20”Sound	0.5	0	8.9	0.7	4.5	0	5	1	0.5	0.7
	>20” Sound	0	0	3.4	1.7	7	0	6	1	0	0.5
	3-6” Rotten	1.5	6	0.4	2.45	0.25	0	0.25	0.5	0.35	0.4
	6-9” Rotten	1.5	6	0.4	2.45	0.25	0	0.25	0.5	0.35	0.4
	9-20”Rotten	4	7	1.6	5.4	3.6	0	2	0.8	0.2	0.5
	>20” Rotten	5	4.5	0.6	14.2	5	0	2	0	0	0.5
	Litter	1.61	2.27	4.98	1.27	3.29	1.87	2.49	4.17	0.75	0.75
	Duff	37	11	13.17	19.21	18.82	2.64	55.48	54.64	6.5	13
	Herbaceous	0.2	0.6	0.21	0.02	0.06	0.1	0.05	0.06	0.02	0.2
	Shrub	2.7	5.91	2.98	0.87	0.03	0.29	6.41	0	0	0
Canopy	Foliage	22.94	3.01	16.78	15.44	13.06	15.71	11.51	20	0.51	3.3
	Branchwood	5.74	0.75	4.19	3.86	3.26	3.93	2.88	5	0.31	0.83

FCCS fuel bed ID		30	37	41	44	60	63	70	210	237	310
Area (acres)		1.1	161.9	1.8	15.7	161.9	0.5	1.4	6.2	1.2	0.2
Fuel Component		Load (tons/acre)									
1-HR	0 - ¼”	0.1	0.1	0	0.5	0	0	0.3	0.2	0	0.1
10-HR	¼ - 1”	0.3	1	0	0.25	0	0	1.2	0.4	0	0.2
100-HR	1 - 3”	0	1.5	0	0.25	0	0	2.5	1	0	0
1000-HR	3-6” Sound	0	0.6	0	0	0	0	6	0.15	0	0
	6-9“ Sound	0	0.6	0	0	0	0	6	0.15	0	0
	9-20”Sound	0	2.5	0	0	0	0	7	0	0	0
	>20” Sound	0	0	0	0	0	0	0	0	0	0
	3-6” Rotten	0	0.3	0	0	0	0	4.35	0.1	0	0
	6-9” Rotten	0	0.3	0	0	0	0	4.35	0.1	0	0
	9-20”Rotten	0	2.5	0	0	0	0	5.5	0.2	0	0
	>20” Rotten	0	0	0	0	0	0	0	0	0	0
	Litter	0.76	0.76	0.18	4.65	0.11	0.11	1.44	0.45	0.16	0.05
	Duff	0.65	22.1	0	0.6	0	0	14.04	0.52	0	0
	Herbaceous	0.1	0.31	0.65	0	0.2	1.35	0.2	0.1	0.06	0.1
	Shrub	4.35	3.1	0	9.82	0.97	0	2.84	1.51	6.06	2.14
Canopy	Foliage	0	6.93	0	0	0	0	7.79	1.02	0	0
	Branchwood	0	1.73	0	0	0	0	1.95	0.26	0	0

Region	Pacific West
Season	Fall
Fuel Category	Natural
Crown consumption	1%

Cover Group	FCCS ID
Grass Group	41, 63
Sagebrush	60
Shrub Group	30, 44, 237, 310
White pine-Hemlock	12

Fuel moisture	Percent
NFDR-TH	10
10-HR	6
Duff	20

Table 3. Model output. Mudd WFU fire fuel consumption and PM_{10} emissions.

FCCS fuel bed ID		1	4	5	7	12	14	15	17	21	22
Fuel component		tons									
Litter	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	26.3	82.2	2065.7	203.0	3.7	0.4	602.2	10,819.6	0.1	5.5
1-HR	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	3.3	7.2	207.4	159.8	0.3	0.1	19.3	2,335.2	<0.05	2.9
10-HR	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	13.1	10.9	663.7	511.4	0.7	0.1	169.3	8,043.3	0.2	16.0
100-HR	Post-fire	0	0	0	0	0	0.1	0	0	0	0
	Consumed	57.2	137.6	1,368.9	303.7	1.2	0.1	55.6	7,783.9	0.5	20.4
1000-HR Sound	Post-fire	3.9	0	4,260.0	300.5	9.8	0.2	1,182.7	2,438.9	0.8	26.5
	Consumed	12.4	0	2,625.7	179.0	3.6	0.1	1,901.0	5,344.9	0.7	42.8
1000-HR Rotten	Post-fire	45.6	262.5	485.3	1,662.2	5.2	0	157.2	25.9	0.1	4.9
	Consumed	150.4	588.5	759.1	2,253.6	5.0	0	931.1	4,644.4	0.1	8.2
Duff	Post-fire	150.0	98.9	1,356.4	762.4	5.2	0.1	3,330.3	35,183.1	0.3	23.6
	Consumed	454.4	299.5	4,106.6	2,307.9	15.8	0.4	10,087.8	106,587.3	0.9	71.2
Herbaceous	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	3.3	21.7	87.1	3.2	0.1	<0.05	12.1	155.70	<0.05	1.5
Shrubs	Post-fire	17.6	85.5	493.6	55.9	<0.05	<0.05	619.1	0	0	0
	Consumed	26.5	128.6	742.5	83.1	<0.05	<0.05	931.1	0	0	0
Canopy foliage	Post-fire	371.0	107.9	6,889.9	2,443.8	14.4	3.5	2,754.7	51,373.6	0.1	23.8
	Consumed	3.8	1.1	70.5	24.0	0.1	<0.05	29.0	518.9	<0.05	0.2
Canopy branchwood	Post-fire	93.3	27.2	1,729.7	613.7	3.6	0.9	694.1	12,895.3	<0.05	6.1
	Consumed	0.5	0	8.3	3.2	<0.05	<0.05	2.4	51.9	0	0
Emissions		Tons									
PM10	Flaming	0.2	0.7	12.2	3.5	<0.05	<0.05	4.8	70.1	<0.05	0.1
	Smoldering	18.4	27.8	233.1	131.0	0.7	<0.05	351.7	3,297.8	0.1	3.8
	Total	18.6	28.5	245.4	134.5	0.7	<0.05	356.5	3,367.8	0.1	3.9

Table 3, continued.

FCCS fuel bed ID		30	37	41	44	60	63	70	210	237	310
Fuel component		tons									
Litter	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	0.8	123.0	0.3	72.8	17.8	0.1	2.0	2.8	0.2	<0.05
1-HR	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	0.1	16.2	0	7.8	0	0	0.4	1.2	0	<0.05
10-HR	Post-fire	0.1	0	0	0.2	0	0	0	0.4	0	<0.05
	Consumed	0.2	161.9	0	3.8	0	0	1.7	2.0	0	<0.05
100-HR	Post-fire	0	0	0	2.3	0	0	0	4.0	0	0
	Consumed	0	242.8	0	1.6	0	0	3.5	2.2	0	0
1000-HR Sound	Post-fire	0	299.5	0	0	0	0	8.6	1.7	0	0
	Consumed	0	299.5	0	0	0	0	17.8	0.2	0	0
1000-HR Rotten	Post-fire	0	145.7	0	0	0	0	2.4	2.2	0	0
	Consumed	0	356.1	0	0	0	0	17.3	0.3	0	0
Duff	Post-fire	0.2	888.6	0	2.3	0	0	4.8	0.8	0	0
	Consumed	0.5	2,688.6	0	7.0	0	0	14.7	2.4	0	0
Herbaceous	Post-fire	0	0	0	0	0	0	0	0	0	0
	Consumed	0.1	50.2	1.2	0	32.4	0.7	0.3	0.6	0.1	<0.05
Shrubs	Post-fire	1.0	200.7	0	30.7	79.3	0	1.6	3.7	1.5	0.1
	Consumed	3.9	301.1	0	123.1	79.3	0	2.4	5.6	5.9	0.4
Canopy foliage	Post-fire	0	1110.4	0	0	0	0	10.7	6.2	0	0
	Consumed	0	11.3	0	0	0	0	0.1	0.1	0	0
Canopy branchwood	Post-fire	0	278.4	0	0	0	0	2.7	1.6	0	0
	Consumed	0	1.6	0	0	0	0	<0.05	0	0	0
Emissions		tons									
PM10	Flaming	<0.05	1.5	<0.05	0.6	0.3	<0.05	<0.05	<0.05	<0.05	<0.05
	Smoldering	<0.05	100.1	<0.05	0.3	0.5	<0.05	1.5	0.2	<0.05	<0.05
	Total	<0.05	101.7	<0.05	1.0	0.8	<0.05	1.5	0.2	<0.05	<0.05

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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