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Quantification of pollutants emitted from very large wildland fires in Southern California, USA ☆

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Abstract

This study investigates the efficacy of the first order fire effects model (FOFEM) implemented in a geographic information system for wildland fire emissions estimation. The objective of the study was to quantify the source and composition of smoke and emissions from wildland fires that burned 235,267 ha in Southern California, USA, in October 2003. From inputs of vegetation, fuel model data, weather condition data, and fire perimeters, the model produces estimates of ten pollutant species (10 and 2.5 μm particulates, carbon dioxide, carbon monoxide, methane, non-methane hydrocarbons, ammonia, nitrous oxide, oxides of nitrogen, sulfur dioxide) from ten fuel categories (duff, litter, woody debris in three size classes, herbs, shrubs, tree regeneration, live branch-wood and live foliage). From the Southern California fires, the model estimated over 5 million metric tons (megagrams) of total pollutant emissions over several days. These emissions include over 457,000 tons of carbon monoxide, over 6 million tons (approximately 6 Tg) of carbon dioxide, and over 46,000 tons of particulates. Fuels that contributed the most mass to the fire emissions were predominantly shrubs and duff.

Keywords: GIS; Pollution; FOFEM; Smoke; Air quality; Modeling; Carbon cycle; Fire; Emissions; Carbon dioxide; Particulates

1. Introduction

During recent Southern California fires, observers witnessed darkened skies and massive plumes of smoke billowing out of the burning hills in Los Angeles, Ventura, San Bernadino and San Diego counties, California, USA. Certainly anyone living or traveling in these areas experienced first hand the emissions that filled the skies, threatened public health and contributed thousands of tons of pollutants to the atmosphere. Other research has

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☆ *Capsule*: This study investigates the use of models that accept measurable spatial inputs to estimate the type, quantity and source of airborne emissions from wildfires, data necessary to atmospheric modelers, air quality regulators and forest managers.

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shown that these types of events can have impacts at a continental scale (Conrad and Ivanova 1997; Fearnside, 2000; Wotowa and Trainer, 2000; Dennis et al., 2002; Amiro et al., 2001), intercontinental scale (Forster et al., 2001; Spichtinger et al., 2001; Fromm and Servranckx, 2003; Spichtinger-Rakowsky and Forster, 2004) and affect air quality at locations distant from the source (Bravo et al., 2002; Davies and Unam, 1999). The recent southern California fires provide a case study type context in which to estimate the environmental effects of episodic, catastrophic disturbances. Our initial hypothesis was that these fires can, over a relatively short period of time (days), contribute a significant mass of emissions to the atmosphere and local airbasin.

The objective of this study was to quantify the mass of emissions and qualify the source of the emissions from these fires. To do so, we implemented a spatially based emissions estimation system (EES) using both spatial and non-spatial inputs (Clinton et al., 2003). A geographic information system (GIS) organized the spatial data and served as a modeling environment. The EES was created as a method for the California Air Resources Board (CARB) to obtain more accurate, spatially resolved emission estimates for wildland fire events. The resultant fire emission estimates are suitable for incorporation to emission inventories for the State of California. The EES was designed to be a significant improvement over the simple method of using generalized "emission factors" in the manner described by the United States Environmental Protection Agency (EPA) document, AP-42 (http://www.epa.gov/ttn/chief/ap42/index.html). Emission estimation of wildfires is complicated by temporal variability in combustion (Ward and Hardy, 1991), spatial variability in fuels (Burgan et al., 1998; Keane et al., 2001), and spatio-temporal variability in fuel conditions (Bradshaw et al., 1984). This study attempts to overcome these sources of uncertainty in emission estimates through the incorporation of additional spatial data to the estimation process and the use of an expanded set of emission factors.

The fires we investigated burned in late October of 2003, consuming 235,267 ha (581,356 acres) before they were contained and ultimately extinguished. Fanned by the dry, Easterly Santa Ana winds, they burned through a wide variety of vegetation, in both wildland and residential areas. The locations of the Southern California fires are mapped as seven separate incidents in Fig. 1. To place these fires in context, the US National

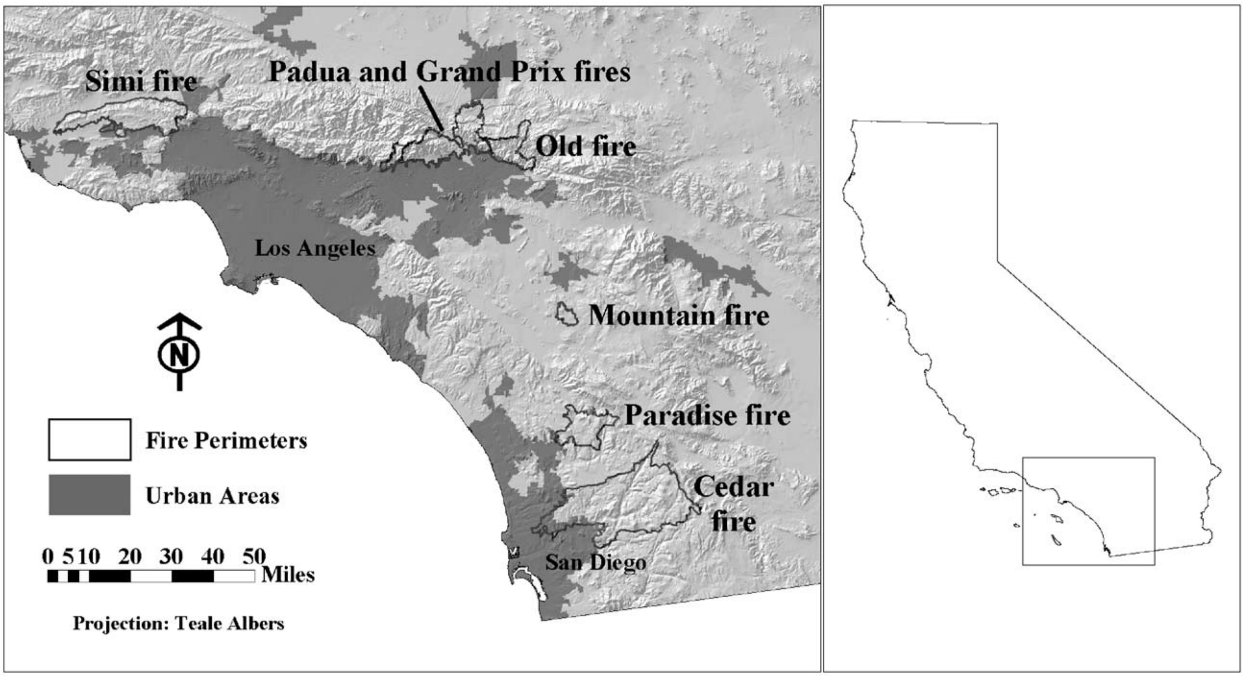

Fig. 1. Map of the Southern California wildfires. The frame on the left shows the fires draped over a hillshade for topographic context. The frame on the right shows the region of State of California, USA in which the fires burned.

Interagency Fire Center (http://www.nifc.gov/stats/index.html) estimates 1,887,090 ha (4,663,081 acres) of average annual burn area, nationally for the 1993–2002 period. Average number of fires over the same period is reported as 101,575. Clearly, these are significant fire events in terms of recent fire activity in the US and represent a significant share of wildland burning at a national level.

2. Methods

We used the USDA Forest Service First Order Fire Effects Model version 4.0 (FOFEM, Reinhardt et al., 1997), adapted to run in a GIS, to assess the fuels that contributed to the fires, the combustion amount and efficiency, and the resultant emissions (see Clinton et al. (2003) for a complete model description). The EES consists of the adapted FOFEM model as well as spatial and non-spatial inputs. The following describes the structure of the EES, also diagrammed in Fig. 2:

1. *A fire perimeter map*: This establishes the spatial extent of the burn area. It can be decomposed temporally (into daily perimeters, for example) if those data exist.
2. *A spatial fuels, vegetation or land cover map*: This map should contain vegetation types that can be linked to the FOFEM fuel model library in order to determine pre-burn fuel loadings in terms of tons per acre.
3. *A fuel model look-up table*: This relational database table contains characteristic loadings in several fuel categories and a link to the vegetation type map that establishes the loadings to be used for each vegetation type.
4. *An emission factor lookup table*: This table consists of emission factors (in pounds of pollutant per ton of fuel consumed; all units have been converted for this paper) for ten fuel types and three moisture regimes.
5. User defined parameters of fuel moisture, seasonality and fuel loadings.

We obtained a fire perimeter map from the USGS GeoMAC (Geospatial Multi-Agency Coordination, http://geomac2.cr.usgs.gov) program via the California Air Resources Board (ARB). The attributes of these data indicate that all perimeters were obtained with GPS except the Paradise fire, which was digitized. The perimeters were delineated based on fire progression up to 31 October 2003. These perimeters are typically acquired at various times during fire progression by collecting GPS locations by helicopter, over the active fire boundary. The geospatial fire perimeter data is contributed to the GeoMAC program and thence distributed to other agencies. We used these data to calculate area burned estimates and as input to the EES, described below.

We used the California Gap Analysis Project (GAP) landcover map as the vegetation input (Davis et al., 1998). California's GAP coverage is comprised of over 21,000 polygons, aggregated into over 200 natural community types. The minimum mapping unit is 1 ha. Each GAP polygon is comprised of up to three vegetation assemblages or types (primary, secondary, and tertiary), with each type comprising a fraction of the total polygon

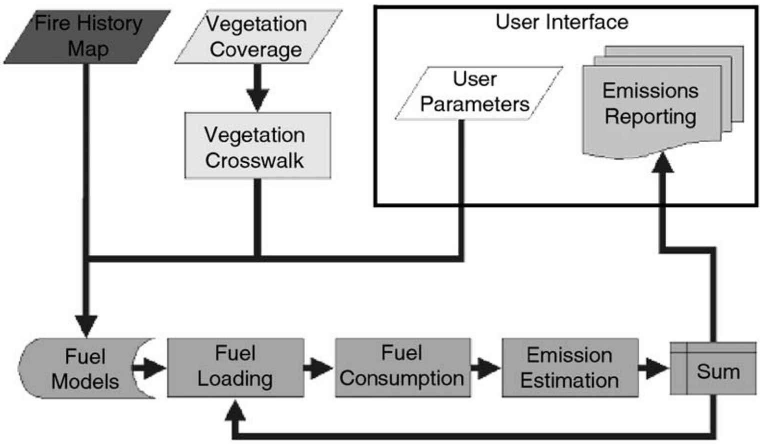

Fig. 2. Flow chart of the emissions estimation system (EES).

area. We used the primary, secondary and tertiary vegetation types as inputs to the model. We estimated area of each type by using the proportion of total vegetation attributes multiplied by the total area of each polygon. If the polygon intersected the fire perimeter polygon, the model clipped it and computed the area for each clipped polygon. We created a fuel model lookup table by cross-walking vegetation types in the system employed by FOFEM (Society of American Foresters types, Eyre, 1980) to the California Natural Diversity Database (CNDDB) vegetation classification system employed by GAP. This resulted in the assignment of a fuel model to each vegetation type mapped in the GAP land cover product. The model accepts input from any spatial vegetation input, provided a crosswalk that links the vegetation types to the internal database of fuel models.

We used the fuel models incorporated to FOFEM v.4.0 to determine fuel loading. This set of fuel models was created through a review of measured fuel loading in a wide variety of representative ecosystems. Each fuel model contains a vegetation description and fuel loads (in terms of mass per unit area) for duff, litter, woody debris in three size classes, herbs, shrubs, tree regeneration, live branchwood and live foliage. These empirically determined amounts can be adjusted from the FOFEM input parameters (typical, light, heavy) in order to modify the default fuel mass per area in each of the fuel categories. FOFEM algorithms determine the consumption of these fuels.

The emission factor lookup table is derived from tables in the FOFEM documentation that describe, for each moisture regime and each fuel category, the proportion of combustion in flaming and smoldering phases and the combustion efficiency in each phase (see Table 1). The choice of the "moisture conditions" input parameter (wet, moderate, dry) affects the proportion of flaming to smoldering combustion and the combustion efficiency within each phase. The emission factors are computed as weighted averages of these two phases of combustion and thus vary by the choice of the moisture conditions parameter. FOFEM 4.0 contained emission factors for PM_{10}, $PM_{2.5}$ and CO, for each fuel

Table 1

Combustion efficiency, proportion of flaming (F) and smoldering (S) combustion phases, and emission factors by fuel category and moisture regime (wet, moderate, dry)

Fuel category	Combustion efficiency		Combustion proportion					
			Wet		Moderate		Dry	
	F	*S*	*F*	*S*	*F*	*S*	*F*	*S*
Litter, wood 0–1 in	0.95	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Wood 1–3 in	0.92	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Wood 3 + in	0.92	0.76	0.50	0.50	0.70	0.30	0.80	0.20
Herb, shrub, regen	0.85	0.00	1.00	0.00	1.00	0.00	1.00	0.00
Duff	0.90	0.76	0.50	0.50	0.40	0.60	0.40	0.60
Canopy fuels	0.85	0.00	1.00	0.00	1.00	0.00	1.00	0.00
CO_2 emission factors								
Litter, wood 0–1 in			3482.7		3482.7		3482.7	
Wood 1–3 in			3372.7		3372.7		3372.72	
Wood 3 + in			3079.4		3196.8		3255.408	
Herb, shrub, regen			3116.1		3116.1		3116.1	
Duff			3042.8		2991.5		2991.456	
Canopy fuels			3116.1		3116.1		3116.1	
CO emission factors								
Litter, wood 0–1 in			52.4		52.4		52.4	
Wood 1–3 in			111.4		111.4		111.4	
Wood 3 + in			268.9		205.8		174.4	
Herb, shrub, regen			249.2		249.2		249.2	
Duff			288.6		316.1		316.1	
Canopy fuels			249.2		249.2		249.2	

The CO and CO_2 emission factors derive from Ward and Hardy (1991, Eqs. (4) and (5)), respectively.

category and each moisture regime. We added CO_2 emissions based on Ward and Hardy (1991, Eq. (5)). We added other pollutants based on emission ratios to either CO_2 or CO, depending on whether the pollutant is better correlated with flaming or smoldering combustion. The emission factor lookup table thus contains emission factors for each moisture regime and six fuel categories (live fuels are aggregated) for a total of 18 emission factors for each pollutant.

For the user defined parameters, we used FOFEM default values with the exception of the NFDR-TH (Thousand Hour fuel moisture, Bradshaw et al., 1984) value. This parameter, computed from local meteorological data, describes the moisture percent (in terms of equilibration time to local environmental conditions) of fuels that are approximately 20 cm diameter. In FOFEM, this parameter is used to determine fuel consumption (in terms of proportion of pre-burn fuel load, determined from the fuel models). For the NFDR-TH value, we used averaged daily grids of fuel moisture for October 2000 (provided by the US Forest Service Wildland Fire Assessment System, http://www.fs.fed.us/land/wfas/) and the model automatically chose the average value of moisture under the centroids of the fire perimeter polygons. We defined the input parameters to the EES as follows:

- *fuel category*: "Natural" (as opposed to piled or lopped and scattered logging slash);
- *dead fuel adjustment factor*: "Typical";
- *fire intensity*: "Extreme";
- *moisture conditions*: "Dry";
- *will this fire burn tree crowns*: "Yes";
- *tree crown biomass burning*: "Typical";
- *herbaceous density*: "Typical";
- *shrub density*: "Typical";
- *tree regeneration density*: "Typical";
- *NFDR-TH moisture percent*: "Automatic".

To process these data for fuel consumption and emissions, we used algorithms published in the FOFEM 4.0 users' manual (Reinhardt et al., 1997). We coded these equations into Avenue, the ArcView 3 × scripting language, to be able to process multiple fires over multiple cover types iteratively. The fuel consumption and emissions generation modules of the FORTRAN based FOFEM are thus implemented in the GIS. We checked model output against the command line version of FOFEM to validate these coding efforts and insure that our model was producing results consistent with the off-the-shelf version of the FOFEM software.

The flow of the EES is shown in Fig. 2. For each fire, the EES determines the fuel moisture and area of each vegetation type that is consumed. Fuel models linked to the vegetation types are used to determine pre-burn fuel load in each fuel category. Consumption in each vegetation type and each fuel category is computed according to the NFDR-TH value and the algorithms shown by Reinhardt et al. (1997). Based on the consumption, emissions in each fuel category are computed using the emission factor lookup table and the moisture conditions input. The results are then summarized by each fuel type, in each vegetation type, in each fire.

We processed the seven fire perimeters (see Fig. 1) to produce reports of emissions and pre-burn fuel conditions. The EES determines the emissions based on the parameters defined above, the amounts of each vegetation type (linked to a fuel model) in each fire, and the average NFDR-TH value in each fire. The data are summarized below.

3. Results

The fires contained 48 cover types in the primary, secondary or tertiary vegetation types. These cover types are indicated in Table 2 along with pre-burn, average fuel load and total fuel load estimated for all the fires. The data have been sorted by total contribution to the fuel loading over all the fires. Shrub dominated ecosystems, including coastal sage scrub and sclerophyllous chaparral are the most ubiquitous ecosystems in the burn areas we analyzed. We excluded several cover types from this tabulation that we considered to have no fuels. These include some desert types, some urban types, and bare land. The EES does not compute any emissions from these land cover types.

The various land covers contributed fuels in a variety of categories. These categories, designated through the fuel models used by FOFEM, represent various size classes as well as both live and dead vegetation. The estimated pre-burn loadings, by fire, are shown in Table 3. The "shrubs" and "duff" categories contribute the most mass to the pre-burn fuel loadings for all the fires. Some fires do not have any "canopy branchwood" or "canopy foliage." While the fires may have contained live, arboreal vegetation, the cover types were not linked to fuel models that contained these fuel categories, or the minimum mapping unit of the vegetation input was

Table 2
Cover types contained within the Southern California fires according to the GAP vegetation dataset

Covertype description	Average load	Total load
Hoary-leafed chaparral	28.25	741,697.96
Northern mixed chaparral	28.25	589,859.08
Interior live oak chaparral	28.25	450,796.68
Scrub oak chaparral	28.25	415,110.47
Semi-desert chaparral	28.25	385,323.73
Bigcone spruce-canyon oak forest	119.26	378,231.69
Chamise chaparral(chamisal)	28.25	292,631.53
Montane ceanothus chaparrals	28.25	234,025.38
Southern mixed chaparral	28.25	210,017.34
Coulter pine forest	45.28	206,765.21
Westside ponderosa pine forest	45.28	157,384.91
Diegan coastal sage scrub	6.25	143,513.45
Venturan coastal sage scrub	6.25	132,365.48
Southern california white fir forest	140.78	122,358.15
Dense engelmann oak woodland	15.02	107,432.25
Buck brush chaparral	28.25	92,469.93
Black oak forest	15.02	78,513.95
Sierran mixed conifer forest	164.99	62,150.30
Upper sonoran manzanita chaparral	28.25	36,668.10
Jeffrey pine forest	102.67	35,297.87
Redshank chaparral	28.25	27,468.90
Coast live oak forest	15.02	22,349.23
Non-native grassland	1.41	17,838.59
Mojavean pinyon juniper woodland	37.88	15,569.13
Coastal sage-chapparal scrub	6.25	15,211.25
Mixed montane chaparral	28.25	15,208.72
Jeffrey pine-fir forest	164.99	14,606.76
Riversidean sage scrub	6.25	14,505.25
Mule fat scrub	28.25	8828.27
Knobcone pine forest	97.18	8077.03
Coast live oak woodland	15.02	5781.08
Canyon live oak forest	15.02	5651.46
Southern california subalpine forest	140.78	2795.16
Misc. cover types	15.02	2534.66
Southern coast live oak riparian forest	15.02	1939.27
Big sagebrush scrub	6.25	1155.90
Mojave riparian forest	15.02	1154.06
White Alder riparian forest	15.02	899.46
Southern cottonwood-willow riparian	15.02	433.69
Mesic north slope chaparral	28.24	271.00

Pre-burn average fuel loads (metric tons/hectare) and total pre-burn loads (metric tons) for each type are shown in the columns to the right.

too large to resolve small pockets of this type of vegetation. As an example, the data show over 1.4 million metric tons (or megagrams, hereafter simply "tons") of fuel prior to burning in the area of the Grand Prix fire. Just under half that total was in shrub or chaparral fuels.

The fires generated a significant amount of emissions. Table 4 shows the estimated amount of particulate and gaseous emissions to be produced by the fires. While the magnitude of total pollutants emitted varies by fire, in response to total fire size and types of land cover burned, the distribution of the emissions is approximately constant between the pollutant categories. The data show, for example, over 457,000 tons of carbon monoxide and over 6 million tons (approximately 6 Tg) of carbon dioxide emissions from the fires. Over 46,000 tons of particulates entered the atmosphere as a result of the burning. Lesser masses of other pollutants were emitted from the fires.

The source of these emissions, in terms of fuel component, is shown in Table 5. The most abundant fuel sources are contributing the most to the emissions. This table indicates that shrubs and duff were major sources of emissions, with wood over 3 in in diameter and canopy foliage representing distant third and fourth places, respectively.

4. Discussion

For the purpose of comparison, we have computed average values of fuel loading and emission factors for the case study reported here. The average fuel loading is 21.5 tons ha^{-1} over the entire burn area and 23.6 tons ha^{-1} when land covers with zero fuel models (bare rock, urban, agriculture, for example) are excluded. These values are intermediate to the loads reported by Hoelzemann et al. (2004) for North American "savanna and grasslands" (9.47 tons ha^{-1}) and "temperate forest." The values are logical due to the fact that the vast majority of cover types burned by these fires consist of chaparral and shrub dominated ecosystems (Table 2). They are also comparable to the pre-burn fuel loads of the National Fire Danger Rating System (NFDRS) fuel models, as described by Leenhouts (1998). As mentioned above, the emission factors used here are contained within a lookup table that has distinct emission factors for three moisture regimes and six fuel types. In terms of dimensionless emission factors (mass emission per mass consumed fuel), the emission factors represented in the lookup table are almost all (with very slight exceptions) within the ranges reported by Andrae and Merlet (2001). For example, the average CO_2 emission factor used here (corresponding to the "dry" moisture regime) is 1.611 while Andrae and Merlet (2001, Table 1, savanna and grassland) report 1.613 ± 95. The equivalent comparison for CO is 0.096 (used here) and 0.065 ± 0.02

Table 3
Fuel loading by category and fire

Fuel component	Padua	Paradise	Old	Mountain	Grand Prix	Simi	Cedar	Total
Canopy branchwood	281.234	0.000	5335.887	0.000	35,608.958	0.000	10,980.634	52,206.71
Canopy foliage	485.063	0.000	23,554.063	0.000	76,582.960	0.000	77,472.322	178,094.41
Duff	18,800.953	78,071.474	103,554.405	11,953.298	330,003.620	50,133.047	462,016.945	1,054,533.74
Herbs	870.061	5953.223	4009.727	1720.574	11,028.243	33,525.931	39,900.687	97,008.45
Litter	4417.384	24,909.475	21,355.639	3297.125	43,584.674	20,805.331	137,283.620	255,653.25
Regen	13.451	259.537	617.027	0.000	1898.772	136.321	3127.436	6052.55
Shrubs	85,655.358	291,224.656	283,345.596	66,167.073	563,995.480	311,355.401	1438,525.438	3,040,269.00
Wood 0–1 in	85.329	2595.375	3435.410	0.000	10,841.101	1363.213	21,303.145	39,623.57
Wood 1–3 in	103.407	0.000	3397.034	0.000	13,413.470	0.000	10,990.810	27,904.72
Wood 3 + in	1566.166	0.000	31,313.556	0.000	191,687.875	0.000	78,978.355	303,545.95
Total	112,278.406	403,013.740	479,918.345	83,138.070	1,278,645.152	417,319.245	2,280,579.392	5,054,892.35

These data represent pre-burn conditions. Units in metric tons (megagrams).

Table 4
Pollutant mass (metric tons) by category and fire

Pollutant	Padua	Paradise	Old	Mountain	Grand Prix	Simi	Cedar	Total
PM_{10}	1030.802	3584.428	4475.526	779.226	11,944.540	4121.633	20,511.311	46,447.465
$PM_{2.5}$	874.879	3042.921	3797.415	661.440	10,138.099	3499.408	17,407.271	39,421.433
CO	10,214.294	35,346.327	44,141.520	7724.407	117,429.992	40,720.124	201,567.765	457,144.428
CH_4	408.554	1413.070	1765.780	308.998	4698.132	1629.506	8060.910	18,284.948
TNMHC	714.762	2473.654	3088.588	540.562	8220.465	2850.325	14,106.254	31,994.609
NH_3	101.921	352.226	440.430	77.135	1173.986	407.569	2014.409	4567.677
N_2O	17.475	62.921	77.736	13.339	212.995	74.176	362.156	820.797
NO_X	306.024	1086.726	1355.933	230.930	3676.862	1240.400	6312.225	14,209.099
SO_2	94.396	336.222	418.583	71.335	1132.707	384.111	1947.853	4385.208
CO_2	129,553.834	460,255.097	573,885.211	97,795.271	1,555,972.625	525,810.551	2,672,727.063	6,015,999.6514

Abbreviations as follows: 10 μm particulates (PM_{10}), 2.5 μm particulates ($PM_{2.5}$), carbon monoxide (CO), methane (CH_4), total non-methane hydrocarbons (TNMHC), ammonia (NH_3), nitrous oxide (N_2O), oxides of nitrogen (NO_X), sulfur dioxide (SO_2).

Table 5
Relative contribution of fuel components to total emissions (metric tons)

Fuel type	PM_{10}	$PM_{2.5}$	CO	CH_4	TNMHC	NH_3	N_2O	NO_X	SO_2	CO_2	Total
Branchwood	328	278	3252	130	228	33	6	96	30	40,670	45,174
Canopy foliage	2235	1897	22,191	888	1554	223	39	656	202	277,480	307,485
Duff	9256	7857	96,242	3849	6738	966	124	2153	662	910,805	1,038,773
Herbs	1214	1029	12,086	485	842	114	17	350	106	151,139	167,504
Litter	1194	1019	6700	259	463	73	59	1050	330	445,175	456,446
Regeneration	47	38	452	18	32	5	0	14	5	5658	6390
Shrubs	28,990	24,604	287,892	11,524	20,154	2872	495	8508	2626	3,599,901	3,987,689
Wood 0–1 in	166	142	934	36	66	8	8	147	45	62,098	63,775
Wood 1–3 in	127	108	1010	40	71	10	4	72	23	30,587	32,175
Wood 3 + in	2889	2451	26,384	1055	1847	264	69	1164	358	492,486	529,089
Total	46,447	39,421	457,144	18,285	31,995	4568	821	14,209	4385	6,016,000	6,633,275

(Andrae and Merlet, 2001). Using the averages reported above, this study shows approximately 2.2656 tons CO emissions per hectare. This is comparable to the 4.5 tons CO per hectare used for boreal forest (Wotowa and Trainer, 2000; Forster et al., 2001) considering that emissions from forest should be at least double what is reported here due to higher per hectare fuel loads.

The capacity of the EES to estimate emissions and fuel loading is constrained by the quality of the inputs. The number and quality of the fuel models in the "library" (lookup table) affect the accuracy of the emissions estimates. Since the fuel models are compiled from a wide variety of empirical data, there is a need for additional research to model fuel distributions in a broad range of ecosystems. The vegetation map also impacts the estimates. The minimum mapping unit will constrain the ability to characterize and model fire effects in heterogeneous ecosystems with an average patch size smaller than the minimum mapping unit. The spatial resolution of the NFDR-TH input affects model output for similar reasons. To assess the relative sensitivity of the EES to various inputs, we performed extensive sensitivity testing of the EES by varying both spatial and non-spatial inputs and comparing model outputs (though we did not perform this analysis over the project area, the results are generalizeable). We found that the largest change in emission estimates resulted from varying the NFDR-TH input by 10%. Changes in default fuel loadings, crown burning, and moisture regime had a lesser effect. This finding suggests that the resolution and accuracy of the spatial NFDR-TH input is important to obtaining accurate emissions estimates. The model could be improved by a spatial query of NFDR-TH input value for each vegetation type, rather than each fire. Additionally, a higher resolution NFDR-TH grid, derived from data closer to the time of fire occurrence, would also add confidence to the emission estimates. By varying the spatial vegetation input (for comparison to GAP, we used the CalVeg coverage, available from the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program, http://frap.cdf.ca.gov/data/frapgisdata/select.asp), we found that the emission contribution of less dominant ecosystems (meadows within a forest matrix, for example) was higher when a higher resolution vegetation input was used. Therefore, the choice of vegetation input is more critical to emission estimates for highly heterogeneous or fragmented landscapes.

Model results indicate the importance of duff and shrubs to the air quality effects of large fires. Clearly, these were catastrophic fire events that burned, for the most part, in chaparral and other shrub dominated ecosystems. Of the 5,054,892 tons of fuel in these systems prior to the fires, over 4,094,000 tons were in shrubs and duff (Table 3). Upon consumption, these shrub and duff fuels were converted to over 5 million tons of emissions (Table 4), mostly carbon dioxide, but including lesser amounts of carbon monoxide, particulates, and other chemical components of what is usually referred to as "smoke." These results seem to reinforce the notion that wildland management designed to minimize fire effects (such as atmospheric pollution) should allocate effort to ecosystem type based on proportion of ultimate fire effect. Potential strategies to mitigate wildfire impacts will benefit from the investigation of management options in shrub-dominated ecosystems in order to reduce risk.

Emissions of compounds which play roles in ozone formation were also significant: oxides of nitrogen and total non-methane hydrocarbons totaled 14,209 and 31,995 tons, respectively, over all fuel categories. These results highlight the significance of wildfire effects on air quality and other resources. This is especially true as the emissions were contributed to local airbasins on the temporal scale of days. The magnitude of the emission mass must also be considered in terms of their rate of delivery to the airbasin when considering the local air quality impact.

We are not aware of any definitive way to validate these types of emission estimates. Measurements of smoke plumes above active fires can be extended to produce empirically based emission factors (Cofer et al., 1991), but these studies are also dependent on a long list of assumptions (which may or may not be valid) necessary to compute the emission factors. Additionally, biomass burning is distributed spatially and temporally. Thus, in situ measurements of a large fire, taken at a point, will measure emissions that derive from multiple spatial locations and a combination of combustion phases, all mixed together. Laboratory studies are necessary abstractions of actual field conditions and are also of marginal utility in terms of validation. Comparison to other published data that use various approaches to estimate the same phenomena is therefore the most viable approach to validation of these estimates. The correlation of measured air quality to estimated emissions (Bravo et al., 2002) or transport model output (with estimated emissions as input) provides some limited statistical evidence of valid emission estimates. We hope the estimates we report here can be useful in future studies that seek to explore trends in air quality data collected at or near the time of the southern California fires.

The advantage of the EES described here is the ability to estimate emissions using multiple fuel model, fuel moisture, and combustion environment inputs. The system can therefore estimate emissions at the spatial resolution that results from the geographic intersection of these inputs. With this setup, it is possible to identify the source of emissions from ecosystem components, rather than homogenous grid cells. Due to the continuous nature of the NFDR-TH input, there exist unlimited possible values for fuel loading, consumption and resultant emissions for unique input combinations. The EES is also modular and scalable. The fire perimeter polygons, vegetation polygons, and NFDR-TH grid can be replaced with other geographic inputs, in raster or vector format, to estimate emissions at global scales, or more localized spatial scales in daily or hourly increments. The look-up tables, including the vegetation crosswalk, fuel models, and emission factors are similarly replaceable. The consumption engine (currently FOFEM 4.0) can also be swapped with later releases of FOFEM or some other fire model.

5. Conclusions

Spatially based emissions estimation models allow the incorporation of geographic information about fuel distribution and condition as measured inputs. When combined with empirically derived fuel models, the source and composition of wildland fire emissions can be estimated and quantified. The resolution of the emission estimates is only constrained by the resolution of the inputs, meaning that emissions could be estimated on an hourly basis over small areas, given the requisite input data of fuel loading and moisture. This information could be beneficial for air quality management, mitigation of wildland fire environmental effects, and identification of wildland fire emission signatures by air monitoring instruments.

Modeling used for fire effects analysis and planning would benefit from a more comprehensive set of inputs. This enhancement of input quality could be achieved through the creation of a wide array of fuel models as a fuels "library," arranged by ecosystem. There is also potential for remotely sensed data or information derived from remote sensing to be used in the mapping of fuels directly. Maps of real-time fuel moisture (NFDR-TH) would also be beneficial to the study of wildfire emissions and could be used directly as input to the EES. More research is needed to create the detailed spatial data necessary for effective modeling, understanding and management of this growing dilemma in the arid West.

The validation of modeling emissions from large fire events is still an outstanding issue. It is difficult to isolate the effects of such disturbances due to their violent, uncontrollable nature, the size of the disturbance, and the dynamic of the event. Indeed, a State of Emergency was declared in California during the burning of the fires considered in this study. In this context, detailed ground surveys that measure actual consumption, laboratory combustion experiments, and analysis of air quality measurements from the fire proximity could be combined to form a circumstantial validation of model output. These validation efforts are an outstanding research need.

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