Science of the Total Environment 907 (2024) 167960

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Estimating annual GHG and particulate matter emissions from rural and forest fires based on an integrated modelling approach

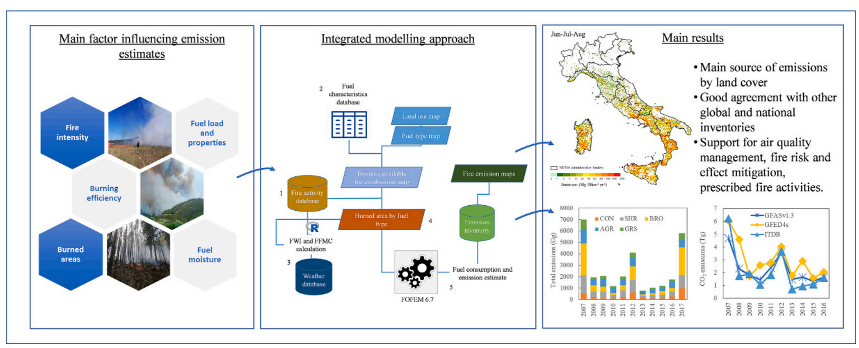
Carla Scarpa [a], Valentina Bacciu [a,b,*], Davide Ascoli [c], Josè Maria Costa-Saura [d,b,e], Michele Salis [a], Costantino Sirca [d,b], Marco Marchetti [f,g], Donatella Spano [d,b]

[a] National Research Council, Institute of BioEconomy (CNR-IBE), 07100 Sassari, Italy
[b] EuroMediterranean Center on Climate Change (CMCC) Foundation, Impact on Agriculture, Forest, and Ecosystem Services (IAFES) Division, 07100 Sassari, Italy
[c] University of Torino, Department of Agricultural, Forest and Food Sciences, 10095 Grugliasco, Italy
[d] University of Sassari, Department of Agriculture Sciences, 07100 Sassari, Italy
[e] National Biodiversity Future Center, Palazzo Steri, Piazza Marina 61, 90133 Palermo, Italy
[f] University of Study of Molise, Department of Biosciences and Territory, 86090 Pesche, Italy
[g] Fondazione Alberitalia ETS, Via Isola Capaccio 77, 47018 Santa Sofia, Italy

HIGHLIGHTS

- Accurate input data and consumption model to estimate fire emissions
- The produced database and maps highlight the main source of emissions by land cover.
- Good agreement with other global and national inventories
- Integrated modelling improves fire emission estimates and reduces uncertainties.
- Results can be integrated into decision support systems and fire mitigation policies.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paulo Pereira

Keywords:
Fire emission
Integrated approach
Fuel consumption
Burning efficiency
Greenhouse gas and particulate matter

ABSTRACT

Rural and forest fires represent one of the most significant sources of emissions in the atmosphere of trace gases and aerosol particles, which significantly impact carbon budget, air quality, and human health. This paper aims to illustrate an integrated modelling approach combining spatial and non-spatial inputs to provide and enhance the estimation of GHG and particulate matter emissions from surface fires using Italy as a case study over the period 2007–2017. Three main improvements characterize the approach proposed in this work: (i) the collection and development of comprehensive and accurate data inputs related to burned area; (ii) the use of the most recent data on fuel type and load; and (iii) the modelling application to estimate fuel moisture, burning efficiency, and fuel consumption considering meteorological factors and combustion phases. On average, Italy's GHG and particulate matter emissions were 2621 Gg yr^{-1}, ranging from a minimum of 772 Gg yr^{-1} in 2013 to a maximum of 7020 Gg yr^{-1} in 2007. Emissions from fire disturbances in broadleaf forests, shrublands, and agricultural fuel types account for about 76 % of the total. Results were compared with global and national

* Corresponding author at: National Research Council, Institute of BioEconomy (CNR-IBE), 07100 Sassari, Italy.
E-mail addresses: carla.scarpa@ibe.cnr.it (C. Scarpa), valentina.bacciu@ibe.cnr.it (V. Bacciu), d.ascoli@unito.it (D. Ascoli), jmcostasaura@uniss.it (J.M. Costa-Saura), michele.salis@ibe.cnr.it (M. Salis), cosirca@uniss.it (C. Sirca), marchettimarco@unimol.it (M. Marchetti), spano@uniss.it (D. Spano).

https://doi.org/10.1016/j.scitotenv.2023.167960
Received 18 June 2023; Received in revised form 18 October 2023; Accepted 18 October 2023
Available online 20 October 2023

inventories and showed good agreement, especially considering CO_2 and particulate matter. The approach of this study added confidence in emission estimates, and the results can be utilized in decision support systems to address air quality management and fire impact mitigation policies.

1. Introduction

Natural and anthropogenic fires play a key role in the terrestrial carbon cycle and are an important source of emissions in the atmosphere of greenhouse gases (GHG), carbon monoxide, carbonaceous aerosols, and an array of other gases (including NMVOC) and particulates (Adame et al., 2018; Akagi et al., 2011; Miranda et al., 2008; Van Der Werf et al., 2010). A recent study on global fire emissions modelling (including forest, peat, grassland and shrubland, and cropland fires) estimated the global average for 2002–2020 to be 2.1 ± 0.2 Pg C yr^{-1} (Van Wees et al., 2022). According to Yue and Gao (2018), forest fires account for 37.8 % of the total emissions from natural sources and 16.9 % of total natural and anthropogenic emissions. The massive release of trace gases and aerosol particles can have a significant impact on local, regional, global carbon budget and climate change (Dintwe et al., 2017; Larkin et al., 2020; Liu et al., 2019) through three mechanisms (direct, indirect, and semi-direct radiative forcing) that can interact with solar radiation, clouds, atmospheric structure, circulation, and energy exchange on the ground (e.g., Kaskaoutis et al., 2011; Lohmann and Feichter, 2005). Furthermore, as emissions are transported through the atmosphere, they contribute to air degradation (e.g., Burke et al., 2021; Tang et al., 2022), reducing visibility, generating or raising unhealthy conditions (e.g., particulate matter or toxic products level) (Analitis et al., 2012; Dorman and Ritz, 2014; Xu et al., 2021), and also reacting with other gases, such as ozone (e.g., Bourgeois et al., 2021; Xu et al., 2021). Exposure to smoke pollution due to forest fires, especially the so-called mega-fires (Linley et al., 2022), can have a significant impact on citizens, also for prolonged time (e.g., Augusto et al., 2020; Tarín-Carrasco et al., 2021), and on personnel involved in firefighting operations, from the infliction of burns and eye irritation from smoke, up to the loss of lives (e.g., Adetona et al., 2016; Cascio, 2018; Gianniou et al., 2016; Oliveira et al., 2020). By promoting the frequency of days characterized by hot and dry conditions (Jia et al., 2019), future climate is expected to play an increasing role in the intensity and frequency of extreme fire events and prolonging fire season length (e.g., Dupuy et al., 2020; Patacca et al., 2023), and thus fire emissions.

Quantifying fire emissions is then a key activity to predict regional air quality during large fires, evaluate potential emission reductions from mitigation strategies (e.g., Alcasena et al., 2021), use prescribed burning while complying with air quality regulations (e.g., Hyde et al., 2017), obtain greenhouse gas reporting (e.g., United Nations Framework Convention on Climate Change (UNFCCC)), and understand global climate effects (Larkin et al., 2020; Yi and Bao, 2016). It requires the combination of multiple and interdependent factors and intertwining different scientific fields and models (Drury et al., 2014). Over the last decades, several studies focused on estimating fire emissions of many gaseous and particulate species through several approaches, basically relying on the model developed by Seiler and Crutzen (1980) and Penman et al. (2003). This model combines information on burned area, biomass available to burn, combustion factor (also called combustion completeness or burning efficiency), and emission factors for different species and vegetation types. However, large uncertainties remain at both spatial and temporal scales due to the representation of input resolution and variability (e.g., Van Wees and Van Der Werf, 2019; Carter et al., 2020; Liu et al., 2020; Wiedinmyer et al., 2023). A growing body of literature introduced new advances in modelling and measurement efforts to improve the estimation of fire emissions, mainly through experimental measurements of emissions factors (e.g., Andreae, 2019; Selimovic et al., 2019; Van Der Werf et al., 2017; Vicente et al., 2013; Wiggins et al., 2021), the development of fuel consumption models (Larkin et al., 2020; Monteiro et al., 2014; Urbanski et al., 2018), the application of satellite instruments (e.g., Giglio et al., 2018; Ramo et al., 2021; Van Wees et al., 2022; Wiedinmyer et al., 2023) and their integration with a large number of national and local datasets (e.g., Larkin et al., 2020), and the application of biogeochemical models and satellite observations to better estimate biomass loading (e.g., Di Giuseppe et al., 2021; Shiraishi et al., 2021; Van Der Werf et al., 2017). In Europe, several studies focused on different aspects of fire impacts on the atmosphere, from fire emission reporting (e.g., Barbosa Ferreira et al., 2009; Rosa et al., 2011) to air quality issues at national (e.g., Martins et al., 2012; Miranda et al., 2009; Monteiro et al., 2014) and local levels (e.g., Bo et al., 2020; Di Carlo et al., 2015). Among these, a few studies tackled the factors limiting the reliability of fire emission estimates, as for instance improving land and vegetation characteristics (vegetation type burned, fuel load assessment) (e.g., Martins et al., 2012; Rosa et al., 2011), or fire characteristics (burned area, fuel load consumption, burning efficiency) (e.g., Chiriacò et al., 2013; Monteiro et al., 2014), or emission factors (e.g., Fernandes et al., 2022). Thus far, however, no inventory considered all the limiting factors in a comprehensive approach, proposing high spatial resolution data for a large scale and for a long period of time, of utmost importance for (among others) addressing international initiatives and commitments (Chuvieco et al., 2019), air quality modelling and forecasting (Urbanski et al., 2011; Martins et al., 2012; Monteiro et al., 2022), and planning fuel treatments (Alcasena et al., 2021; North and Hurteau, 2011; Wiedinmyer and Hurteau, 2010).

In this paper, we present an integrated methodology at high resolution, providing and improving the estimation of trace gases and particulate matter from surface fires, also qualifying the source of emission, using the spatial forest and rural fire database from Italy as a case study (period 2007–2017). The methodology takes into consideration the main source of uncertainties in emission estimates (e.g., accuracy of fire perimeters, combustion completeness, vegetation load and characteristics (Martins et al., 2012; Ottmar et al., 2008; Schultz et al., 2008) combining a fire emissions model with accurate spatial and non-spatial inputs related to fire disturbance, vegetation, and weather conditions. The main improvements from previous methods are: (i) the development of a high-accuracy burned area geographical dataset; (ii) the use of the most recent data on fuel type and fuel load based on an updated field measurement database; (iii) a more precise estimation of burning efficiency and fuel consumption considering fuel moisture and properties, meteorological factors, and different combustion phases through modelling application.

Finally, following Larkin et al. (2020), Rosa et al. (2011), Urbanski et al. (2018), and Wiedinmyer et al. (2023), we compared our approach against available inventories at the global and national levels to evaluate convergence, assess differences identifying primary sources of variability in existing datasets and methods, and validate our estimates.

2. Material and methods

The methodology applied to calculate emissions is based on the modelling framework developed by Bacciu et al. (2011, 2012). The framework integrates spatial and non-spatial inputs (Fig. 1). It requires (1) collecting and combining information related to individual fire events, (2) classifying land cover in fuel types and obtaining data on vegetation available to burn according to input parameters of the consumption model (i.e., fuel load by size classes) by fuel type; (3) extracting the burned area by fuel type at each fire site, (4) estimating fuel moisture using as a proxy the Fine Fuel Moisture Code index (FFMC)

(Van Wagner, 1987) associated to each fire event, and (5) modelling fuel consumption and emissions through the application of FOFEM 6.7 (First Order Fire Effects Model) (Reinhardt, 2003; Reinhardt et al., 1997; Lutes, 2013). The methods to obtain all information and to reach each step are described in the following sections.

2.1. Fire activity data

The fire activity information needed is the day of occurrence, the location, and the georeferenced polygon of each fire event. Developing a coherent fire dataset for Italy was a significant effort in preparing this work. We collected and then collated daily georeferenced fire perimeters from 2007 to 2017 according to their geographical provenance. For most Italian regions, data were acquired from the former Italian Forest Service (actually Carabinieri CUFAA). Data from three autonomous regions (Sardinia, Sicily, and Friuli Venezia Giulia) were gathered from the respective Regional Forest Services, through the following sources: https://www.sardegnageoportale.it/index.html, https://sifweb.regione.sicilia.it/portalsif/home/, https://eaglefvg.regione.fvg.it/eagle/main.aspx?configuration=guest (last access on 5 October 2023). Daily fire perimeters were unavailable for the autonomous region of Valle d'Aosta and the two autonomous provinces of Trento and Bolzano (Trentino Alto Adige region). For this reason, these regions were not included in our study. However, it is noteworthy that, according to the European Forest Fire Information System (EFFIS) annual reports (available at https://effis.jrc.ec.europa.eu/reports-and-publications/annual-fire-reports, last access 29 August 2023), Trentino Alto Adige and Valle d'Aosta accounted for only 0.05 % of the Italian burned area (wooded and non-wooded) for the period 2008–2017.

The final dataset minimum mapping unit is 0.01 ha. Indeed, fire perimeters are typically acquired by collecting GPS locations (by walking or helicopter) over the fire boundaries. The dataset comprises about 81,000 fire ignitions and a total burned area of about 10,200 km^2, which represent about 3.23 % of the Italian surface.

2.2. Fuel type and loading

The fuel type and biomass available for combustion (fuel loading) for each fire event were determined using a combination of satellite imagery products and recently published data. To spatialize fuel types, we aggregated Corine Land Cover Classes (CLCC), level IV (ISPRA, 2010), minimum mapping unit 25 ha, into sixteen classes across Italy according to crosslinks with the fuel classification proposed by Ascoli et al. (2020) (Fig. 2 and Table 1) and related quantitative data. Indeed, Ascoli et al. (2020) harmonized more than 600 quantitative fuel samples carried out over the last decade in alpine, temperate, and Mediterranean vegetation types and including duff, litter, herbaceous, shrub, and downed woody fuel loadings by size classes (1h,10h,100h) grouped into surface fuelbeds representing the principal fuel types in Italy crosslinked to CLCC classes (see Table 1 in Ascoli et al., 2020). Since data related to agriculture (including arable lands, permanent crops, stable meadows, and heterogeneous agricultural areas) were not available in Ascoli et al. (2020), fuel data for this fuel type were derived from Rosa et al. (2011). For some fuel type classes (i.e., CTMG, PTB, MEB, RV, see "Fuel type code" in Table 1), data on duff load were missing or not representative in Ascoli et al. (2020). Thus, we filled the gaps using the information on similar fuel classes from the Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007; Sandberg et al., 2001). FCCS describes fuelbed categories through six horizontal strata (i.e., canopy, herbs and grasses, woody dead material, litter, and duff or ground fuels) and their properties to determine how fires will burn and consume them (Ottmar, 2014). In particular, the association with the FCCS classes was conducted through a meticulous photographic evaluation of each FCCS class with the sixteen Italian fuel types. Finally, the fuel types were

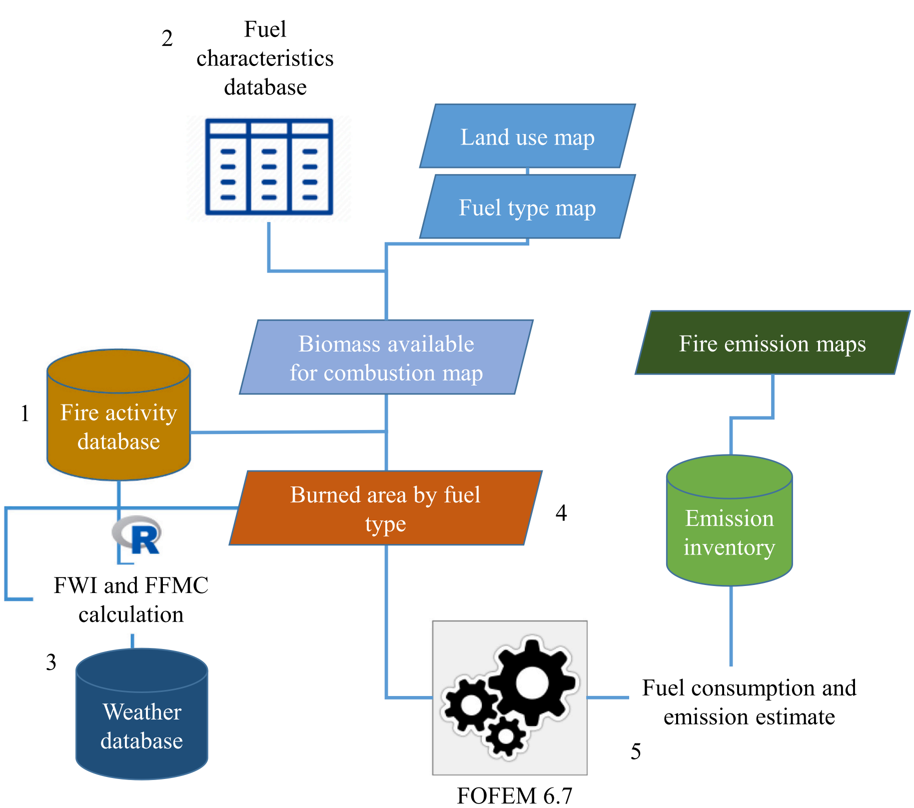


Fig. 1. Flow chart of the integrated approach to estimate fuel consumption and emissions (adapted from Bacciu et al., 2011, 2012). The numbers represent the different phases of the process according to the main text description. The parallelograms represent input-output data (including maps), while cylinders represent geospatial knowledge bases.

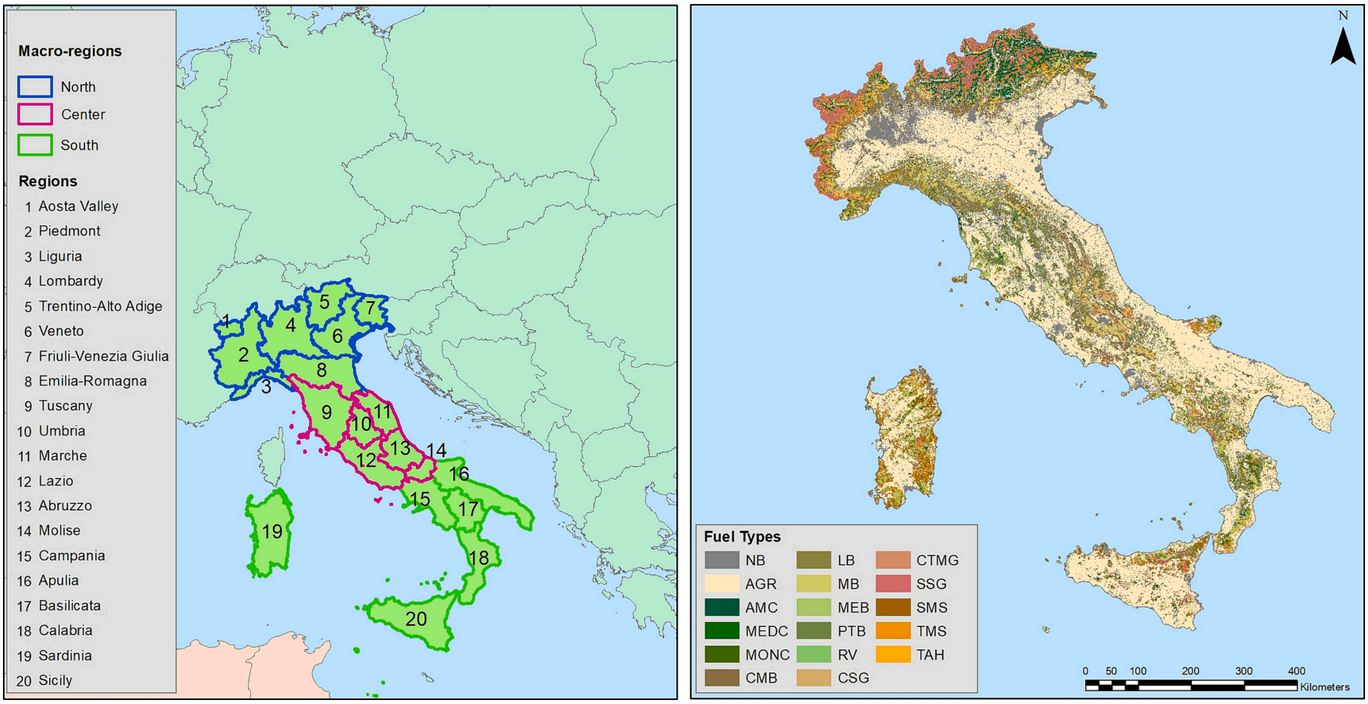


Fig. 2. Location of the study area (Italy) in the Euro-Mediterranean region and division into regions and macro-regions (on the left panel); map of fuel types in Italy, based on our elaboration from Ascoli et al. (2020) (on the right panel). NB – not burnable; AGR – Agriculture; AMC - Alpine and Mediterranean short-needled conifer litter; MEDC - Mediterranean long-needled conifer understory with shrubs; MONC - Montane long-needled conifer understory with shrubs; CMB - Compact mesophytic broadleaved litter; LB - Long broadleaved litter; MB - Montane beech litter; MEB - Mediterranean evergreen broadleaved litter; PTB - Porous Thermophilous broadleaved litter; RV - Riparian vegetation; CSG - Continuous short grassland; CTMG - Continuous tall Mediterranean grassland; SSG - Sparse and very short grassland; SMS - Short Mediterranean shrublands and heathlands; TMS - Tall Mediterranean shrublands and heathlands; TAH - Temperate and Alpine heathlands.

Table 1
Fuel types, based on our elaboration from Ascoli et al. (2020), associated with the Corine Land Cover Classes (level II, III and IV), percentage of their burned area over the total of the analyzed period, and characterization of their mean fuel load (Mg ha^{-1}) by fuel component.

Surface fuel group	Fuel type	Fuel type code	Corine LCC	% of burned area over total	Duff	Litter	Dead (1h, 10h, 100h)	Live	
								herb	shrub
Conifers understory (CON)	Alpine and Mediterranean short-needled conifer litter	AMC	3123	0.1 %	39.36	2.36	6.47	0.29	0.05
	Mediterranean long-needled conifer understory with shrubs	MEDC	3121	3.7 %	32.83	4.31	8.04	0.88	7.87
	Montane long-needled conifer understory with shrubs	MONC	3122, 3124, 3125	2.0 %	23.92	1.11	12.73	1.33	2.05
Broadleaves understory (BRD)	Long broadleaved litter	LB	3114	2.2 %	35.69	2.52	8.98	0.21	1.87
	Montane beech litter	MB	3115	1.1 %	35.06	1.88	5.97	0.21	0.03
	Compact mesophytic broadleaved litter	CMB	2241, 3113, 3117	5.1 %	33.07	2.18	9.01	0.60	1.02
	Porous Thermophilous broadleaved litter	PTB	3112	6.8 %	39.87	1.73	4.74	0.86	0.65
	Mediterranean evergreen broadleaved litter	MEB	3111	3.4 %	10.81[a]	2.25	6.95	0.44	3.32
	Riparian vegetation	RV	3116	0.3 %	35.39[a]	0.49	4.09	1.40	1.53
Heathlands & Shrublands (SHR)	Tall Mediterranean shrublands and heathlands	TMS	3231	7.0 %	11.65	5.33	8.89	1.35	16.35
	Short Mediterranean shrublands and heathlands	SMS	3232	9.9 %	6.89	2.26	5.18	1.90	6.20
	Temperate and Alpine heathlands	TAH	322	1.1 %	3.18	2.35	2.35	0.38	5.77
Natural Grassland (GRS)	Continuous short grassland	CSG	3211	2.3 %	23.70	0.28	0.31	3.74	0.03
	Continuous tall Mediterranean grassland	CTMG	3211	4.4 %	11.60[a]	3.96	3.96	12.26	–
	Sparse and very short grassland	SSG	3212	10.6 %	2.83[a]	0.08	0.15	2.10	0.21
Agriculture (AGR)		AGR	211, 212, 22, 23, 24	40 %	0.22	–	5.10[b]	2.5[b]	1.86[b]

[a] Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007; Sandberg et al., 2001).
[b] Rosa et al. (2011).

aggregated into five surface fuel groups: Conifers understory (CON), Broadleaves understory (BRD), Heathlands & Shrublands (SHR), Natural Grasslands (GRS), Agriculture (AGR) (Table 1). This study did not include canopy fuels because of the lack of information concerning crown fire occurrence or a reliable model for canopy fuel consumption. Indeed, the fire database only provides data on the burned area, and the fuel consumption model (see Section 2.4) does not predict whether a crown fire will occur or canopy fuels will be consumed. It simply requires the user to estimate the proportion of the stand affected by crown fire (Keane and Lutes, 2020). Given these limitations, we excluded canopy fuel consumption from the analysis. However, crown fires in Italy occur mainly in the Mediterranean and montane pine fuel types, which represent 5.7 % of the total burned area (Table 1), and on average, the stand-replacing area over the entire burned area in Italy is 1.7 % (Elia et al., 2022).

Finally, we intersected the fuel type map with the fire perimeter layers to identify the amount of burned area within each fuel type class at each fire event.

2.3. Fuel moisture scenarios

Combustion efficiency, that is the fuel consumption amount, partly depends on the fuel moisture conditions during the fire. To estimate fuel moisture conditions for each fire event, we used the Fine Fuel Moisture Code (FFMC) as a proxy. FFMC is one of six indices composing the Canadian Fire Weather Index (FWI) (Van Wagner, 1987), and is a numeric rating (inversely proportional) of the moisture content of litter and other cured fine fuels. It is computed using four weather inputs: precipitation accumulated over 24 h (P), instantaneous temperature (T), relative humidity (H), and wind speed (W), generally taken at noon local standard time. Weather data were gathered from the Era-Interim Reanalysis product (http://apps.ecmwf.int/) at a grid resolution of 0.125° and at 12:00 UTC, considering 24 h accumulated values for precipitation and instantaneous values for the other variables. FWI and the FFMC subcode were then calculated using the function implemented on the R package *fireDanger* (Santander Meteorology Group, 2017).

The daily FFMC values were associated with each fire event. Then four thresholds (25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles) were calculated, with the aim of grouping fire events based on their fuel moisture conditions, distinguishing between five classes (wet, medium, dry, very dry, and extreme). Finally, a dead fuel moisture content value (FMC) for duff, 10h, and 1000h fuel was assigned for each fuel type within an FFMC group based on literature data information (Pellizzaro et al., 2007a, 2007b) (Table 2).

2.4. Fuel consumption and emission model

FOFEM 6.7 (Reinhardt, 2003; Reinhardt et al., 1997; Lutes, 2013) was used to estimate fuel consumption and fire emissions. The model requires fuel load by fuel component (duff, litter, three size classes of woody debris, herbs, shrubs, and live tree live branches and foliage) and fuel moisture inputs for 10h and 1000h downed woody and duff. FOFEM integrates extensive fuel data derived from the literature (e.g., Ottmar et al., 2007; Prichard et al., 2013), but users can customize the input data parameters according to local fuel loads and moisture conditions.

FOFEM employs BURNUP, a process-based model of heat transfer and burning rates (Albini et al., 1995; Albini and Reinhardt, 1995, 1997; Lutes, 2013; Reinhardt and Dickinson, 2010), to calculate the consumption of downed woody fuel and litter; the consumption of other fuels is predicted using a variety of empirical equations and rules of thumb. In particular: (i) duff consumption is estimated through different algorithms (e.g., Brown et al., 1985; Harrington, 1987; Hough, 1978; Reinhardt, 1991); (ii) shrub consumption depends on the season and type of shrub, but generally is assumed to be in the range 60 %–80 %; (iii) almost 90 %–100 % of herbaceous fuel is consumed; (iv) canopy fuel consumption requires the user to estimate the proportion of the stand affected by crown fires, and then FOFEM applies this proportion to the canopy foliage and one-half of the canopy branches. Furthermore, in 2001 the BURNUP model was modified to provide separate estimates of flaming and smoldering consumption (Finney, 2001). In turn, the model allows emission factors (Ward et al., 1993) to be applied separately to the fuel consumed in each phase. Finally, total emissions of $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, NO_X, and SO_2 are calculated as the sum of the emissions calculated separately from the two fuel consumption phases.

In this study, the quantitative characteristics of fuel components for each fuel type based on the data provided in Table 1, derived from Ascoli et al. (2020), were used as fuel load inputs, while fuel moisture values for 10-h, 1000-h, and duff were derived from the conditions presented in Table 2.

Table 2
Fuel moisture content value associated with fuel moisture conditions and dead fuel strata used for simulating fuel consumption.

Fuel moisture conditions	Dead fuel moisture content value (FMC) (%)		
	Duff	10h	1000h
WET	130	16	50
MEDIUM	90	13	40
DRY	75	11	30
VERY-DRY	40	9	25
EXTREME	20	7	15

2.5. Comparison with other inventories

To evaluate the results of our modelling framework, we compared the burned area and the emission estimates obtained in this work (ITDB) with those obtained from the Italian National Emission Inventory (IT NIR, 2022) and two global fire emission inventories, GFASv1.3 (Kaiser et al., 2012) and GFED4s (Van Der Werf et al., 2017), calculating the relative percentage difference (RPD) and the correlation coefficient (*r*).

The IT NIR (2022) is the national GHG emission inventory compiled and communicated annually by the Higher Institute for Environmental Protection and Research (ISPRA) under the UNFCCC. IT NIR report provides a detailed analysis of the annual source and sink category emission estimates and trends (and the models behind them) and common reporting format (CRF) tables. The inventory includes the assessment of GHG and particulate matter emissions from forest, cropland, and grassland fires. Land use categories are defined according to the IPCC protocols (IPCC, 2006). It is noteworthy to mention that the grassland land use category includes all grazing land, natural grassland and other wooded land that does not meet the forest definition (as shrublands). The approach used to calculate non-CO_2 emission from fires is based on the method developed by Bovio (2007), who estimated forest fire damage and related biomass loss in Italy based on two main factors: the fire intensity and the type of forest vegetation affected by the fire. The approach was implemented by Chiriacò et al. (2013), who proposed scorch height to represent fire intensity.

The Global Fire Assimilation System (GFASv1.3) calculates biomass burning emissions at daily time step on a global 0.1° × 0.1° grid from 2003 to 2016. The emissions have been calculated by assimilating Fire Radiative Power (FRP) observations from the MODIS instruments onboard the Terra and Aqua satellites; the combustion rate is subsequently calculated with land cover-specific conversion factors, while the emission factors have been compiled from a literature survey. Instead, the Global Fire trace gas and aerosol emissions (GFED4s) calculates biomass burning emissions at monthly time step on a global 0.25° × 0.25° grid from 1997 to 2016. Fire activity, including small fires and vegetation productivity, was derived from satellite information (e.g., Giglio et al., 2013; Randerson et al., 2012), while trace gas and aerosol emissions are based on Akagi et al. (2011) as well as Andreae and Merlet (2001). Furthermore, GFED4s fire emission data are available for three sectors: 1) agricultural waste burning, 2) temperate forest, and 3) savanna, grassland, and shrubland fires. The two global databases served as benchmark for evaluating fire emissions estimates from prognostic models (IPCC, the Carbon Project) or as a validation tool for other estimation methods (e.g., Hantson et al., 2016; Urbanski et al., 2018).

In this study, we obtained the three databases from the following sources (last access on 15 June 2023): IT NIR, 2022 http://emissioni.sina.isprambiente.it/inventario-nazionale/, GFASv1.3 https://eccad3.sedoo.fr/data, and GFED4s https://www.globalfiredata.org/.

3. Results

3.1. Spatial and temporal characteristics of fire activity

From 2007 to 2017, fire activity in Italy showed a high inter-annual variability (Fig. 3a). The annual average burned area was about 92,900 ha. The maximum number of fires per year occurred in 2007, 2012, and 2011 (11,530, 9226, and 9200, respectively), accounting for 37 % of the total fires of the analyzed period under investigation. In contrast, the maximum recorded burned area occurred in 2007, 2017, and 2012 (about 226,800, 173,500, and 137,700 ha, respectively), corresponding to 53 % of the total burned area in the study period. 2007 and 2017 had the highest FFMC average annual values (74.8 and 76.1, respectively). Additionally, FFMC average annual values for each region diverged from northern to southern Italy, ranging from a maximum of 81.5 and 80.8 for Sardinia and Calabria in 2017, respectively, to a minimum of 59.5 and 59.6 for Lombardy and Piedmont in 2014. Overall, in the southern regions, a large percentage of the burned area (72 %) occurred under the "dry", "very dry", and "extreme" fuel moisture scenarios according to FFMC values. In the central regions, the burned area occurring under "extreme" fuel moisture scenarios represented about 40 % of the total burned area in that part of Italy. In the northern regions, the largest percentage of the burned area occurred under "wet" and "medium" fuel moisture scenarios (66 % and 22 %, respectively).

As far as the contribution of the five fuel groups to the burned area is concerned, AGR (agriculture) was the most affected, accounting for about 40 % of the total burned area (about 405,700 ha), whereas CON (conifers understory) represented the group less affected by fire (about 58,500 ha), accounting for 6 % of the total area burned. More in-depth, under the SHR (heathlands & shrublands) macro-category (18 % over the total), SMS and TMS contributed 10 % and 7 % of the total burned area, while under the GRS (natural grassland) fuel group (17 % over the total), SSG contributed 11 %. PTB and CMB were the BRD (broadleaves understory) classes that contributed the most (7 % and 5 %, respectively) to the total burned area.

The monthly distribution of burned area, broken down by fuel group, is plotted in Fig. 3b. At the national level, the burned area had mainly an unimodal distribution, with peaks in July and August (accounting for 70 % of the total burned area). The months with the least burned area were December and February, with 5100 and 6600 ha burned, respectively. Additionally, Fig. 3b showed that the group AGR had the highest area burned during summer and autumn, accounting for 33 % and 6 % of the total. During summer, SHR and BRD accounted for 14 % of the total burned area. Under these two fuel groups, the fuel types most affected by fire during the summer were SMS (8 %) and PTB (5 %), respectively. On the other hand, in summer, CON contributed 5 % of the total burned area, with 3 % due to fuel type MEDC.

3.2. Spatial and temporal distribution of emissions

The total and the monthly distributions of surface fire emissions released over 2007–2017, broken down by fuel group, are plotted in Fig. 4. Total fire emissions (considering PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_x and SO_2) during 2007–2017 were estimated at 28,830 Gg. Average total emissions were 2621 Gg yr^{-1}. As observed for burned areas, the most significant years in terms of emissions were 2007 (7020 Gg), 2017 (5788 Gg), and 2012 (4096 Gg). These years accounted for about 60 % of the total emissions for the studied period. The minimum emission values

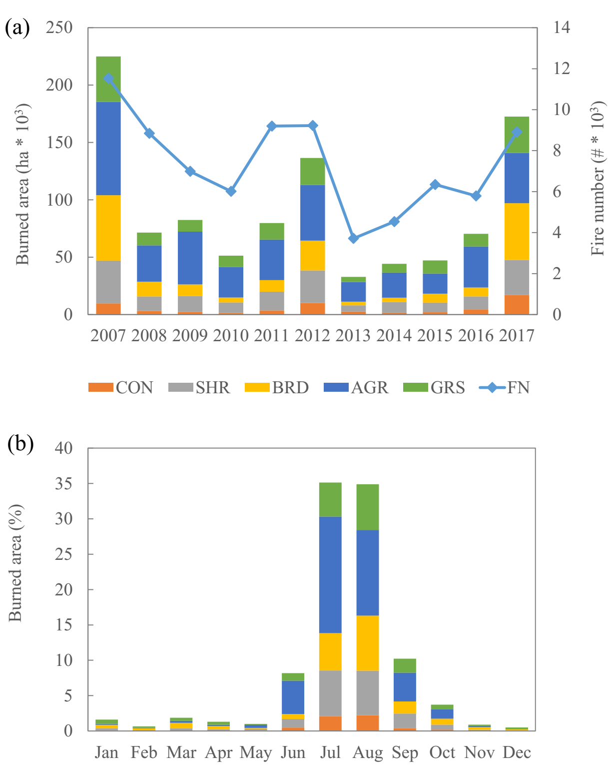


Fig. 3. (a) Annual burned area (ha * 10^3) and fire number (#*10^3) and (b) monthly distribution of burned area (%) broken down by fuel groups over the 2007–2017 study period. CON: conifers understory; BRD: broadleaves understory; SHR: heathlands & shrublands; GRS: Natural Grassland; AGR: agriculture; FN: fire number.

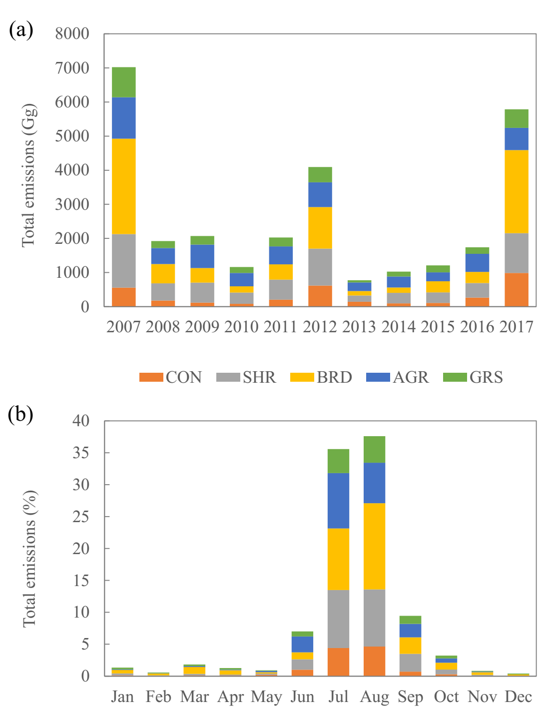


Fig. 4. (a) Annual fire emissions (Gg) and (b) monthly distribution of fire emissions (%) broken down by fuel groups over 2007–2017. CON: conifers understory; BRD: broadleaves understory; SHR: heathlands & shrublands; GRS: Natural Grassland; AGR: agriculture.

Table 3
Average estimated trace gases and particulate matter fire emissions (Gg yr^{-1}) per fuel type for the period from 2007 to 2017. The description of fuel type codes is shown in Table 1.

Fuel group	Fuel type code	PM_{10}	$PM_{2.5}$	CH_4	CO	CO_2	NO_x	SO_2
Conifers (CON)	AMC	0.060	0.051	0.031	0.663	3.840	0.002	0.003
	MEDC	2.12	1.80	1.05	22.48	184.54	0.170	0.126
	MONC	1.24	1.05	0.631	13.74	71.87	0.029	0.054
Broadleaves (BRD)	LB	1.22	1.03	0.612	13.21	88.55	0.063	0.063
	MB	0.571	0.484	0.291	6.33	32.70	0.013	0.025
	CMB	2.96	2.51	1.49	32.23	205.95	0.137	0.149
	PTB	4.67	3.96	2.38	51.91	262.28	0.091	0.197
	MEB	0.937	0.795	0.467	9.97	78.71	0.070	0.054
	RV	0.179	0.152	0.092	2.00	9.18	0.002	0.007
Heathlands & Shrublands (SHR)	TMS	1.89	1.60	0.850	16.94	341.02	0.497	0.209
	SMS	1.88	1.59	0.889	18.51	238.12	0.299	0.153
	TAH	0.056	0.048	0.022	0.40	16.42	0.027	0.010
Natural Grassland (GRS)	CSG	0.651	0.553	0.331	7.14	42.77	0.026	0.031
	CTMG	0.967	0.821	0.434	8.64	178.12	0.263	0.109
	SSG	0.505	0.426	0.247	5.09	58.91	0.065	0.037
Agriculture (AGR)	AGR	1.64	1.39	0.606	10.48	533.78	0.910	0.331
Total		21.54	18.26	10.42	219.75	2346.75	2.66	1.56

were observed in 2013 (772 Gg). Table 3 summarizes the average annual emissions of trace gases and particulate matter for the different fuel groups and type categories. BRD, SHR, and AGR were the primary sources of emissions, accounting for about 76 % of the total (31 %, 24 %, and 21 %, respectively). Under BRD fuel group, PTB and CMB contributed the most to total emissions (12 % and 9 %, respectively). As far as SHR is concerned, TMS fuel type was less affected by fires than SMS, although contributing to 14 % in terms of total emissions. MEDC and CTMG (pertaining to CON and GRS fuel groups, respectively) contributed to the 8 % and 7 %, respectively. August and July were the most significant months for emissions, accounting for 38 % and 36 % of the total.

We compared the total emissions in proportion to the burned area by fire for each fuel group, fuel type, season, and administrative region. On average, CON released the highest emissions per burned hectare, 56.3 Mg ha^{-1}, ranging from 53.2 Mg ha^{-1} in 2013 to 61.1 Mg ha^{-1} in 2012. BRD and SHR released, on average, a comparable amount of emissions per burned hectare (44.0 and 37.5 Mg ha^{-1}), while GRS and AGR were about half (18.7 and 14.9 Mg ha^{-1}), although the last one represented the group most affected by fires. MEDC (under the CON group) was the fuel type with the highest average emission (61.38 Mg ha^{-1}), followed by TMS and LB (under the SHR and BRD groups), emitting 55.32 and 49.45 Mg ha^{-1}, respectively, and by CTMG (under the GRS group), releasing 46.21 Mg ha^{-1}. On the opposite, SSG (GRS group) was the fuel type with the lowest average emission per burned hectares (6.6 Mg ha^{-1}), followed by TAH (SHR group, 17.21 Mg ha^{-1}).

Fig. 5 shows the average fire emissions over the period 2007–2017, at a seasonal level, using hexcells with 10,000 ha cell size. The geographic distribution of emissions varied considerably by region and season. In the northern regions, the percentage of emissions reached up to 6 %; in contrast, southern regions contributed to 80 % of the total pollutants emitted. The largest amount of pollutants was released in the Southern regions most affected by fires, namely Sicily, Calabria, and Sardinia, with about 6700, 5600, and 4000 Gg emitted. 2.3 % of total emissions occurred in the winter months and were largely limited to the northern regions (1.5 % over the total). Most central (12.7 %) and southern (67 %) emissions occurred in summer. Southern regions also contributed to the 10.4 % emission over the total in autumn.

Furthermore, normalizing the total emissions per burned area at the regional level, the results showed that the Marche region (East Central Italy) presented the highest emission value (46.7 Mg ha^{-1}) despite its small contribution to the total burned area for the analyzed period (6530 ha, 0.64 %). Also, Campania (Southern Italy) and Umbria (Central Italy) regions showed high emission values, 39.1 and 35.8 Mg ha^{-1}, respectively. The lowest emissions per hectare were in Sardinia (20.7 Mg ha^{-1}), where fires mainly occurred under the AGR group (73 % over the total burned area in the region).

3.3. Comparison with other inventories

Next, we compared the results of this study (ITDB) with data from other inventories: the Italian National Emission Inventory (IT NIR, 2022) and two global fire emission inventories, GFASv1.3, and GFED4s. National annual emissions ($PM_{2.5}$, PM_{10}, CH_4, and CO from IT NIR and CO_2 from GFASv1.3 and GFED4s) compared with ITDB are plotted in Fig. 6. The statistical comparison is provided in Table 4. Overall, the year-to-year pattern variability between inventories was consistent, and ITDB data were well correlated with the analyzed inventories (especially with IT NIR and GFASv1.3). In terms of mean relative percentage difference, ITDB was in good agreement with IT NIR $PM_{2.5}$ and PM_{10} estimates and with GFASv1.3 CO_2 estimates. On the other hand, as far as CH_4 and CO annual averages are concerned, IT NIR estimates were three and four times larger than ITDB (Fig. 6b).

4. Discussion

The main aim of this paper was to present an integrated methodology at high resolution to estimate trace gases and particulate matter from rural and forest fires using the Italian burned area from 2007 to 2017 as a case study. The approach aimed to contribute to advancements in the state-of-the-art knowledge and approaches on fire emissions in Italy and Europe. Thus, a strong effort was put into the collection of detailed input data and the integration with fuel consumption and emission models to reduce the main uncertainties, such as burned area (e.g., Ramo et al., 2021; Van Wees and Van Der Werf, 2019), fuel load available for combustion (e.g., Fernandes et al., 2022; Wiedinmyer et al., 2023), and emission and combustion factors (e.g., Rosa et al., 2011; Chiriacò et al., 2013).

In Italy, from 2007 to 2017, the burned area displayed high inter-annual variability. The three most significant years in terms of burned areas, as well as in terms of FFMC average values, were observed in 2007, 2017, and 2012. During these severe years, fires affected mainly agricultural (in 2007 and 2012) and broadleaves (in 2017) fuel groups. Over the study period, considering the whole country, the most impacted fuel groups were agricultural (40 % of the total burned area), shrubland and grassland (35 %), and broadleaves (19 %), in agreement with the findings of Mancini et al. (2017). Southern regions, characterized by a typical Mediterranean climate and being the most fire-prone, profoundly influenced this distribution: fires affected mainly agricultural (45 %), shrubland and grassland (35 %), and broadleaves (15 %) fuel groups. Other studies observed a positive relationship between agricultural and shrubland land uses and fire occurrence in

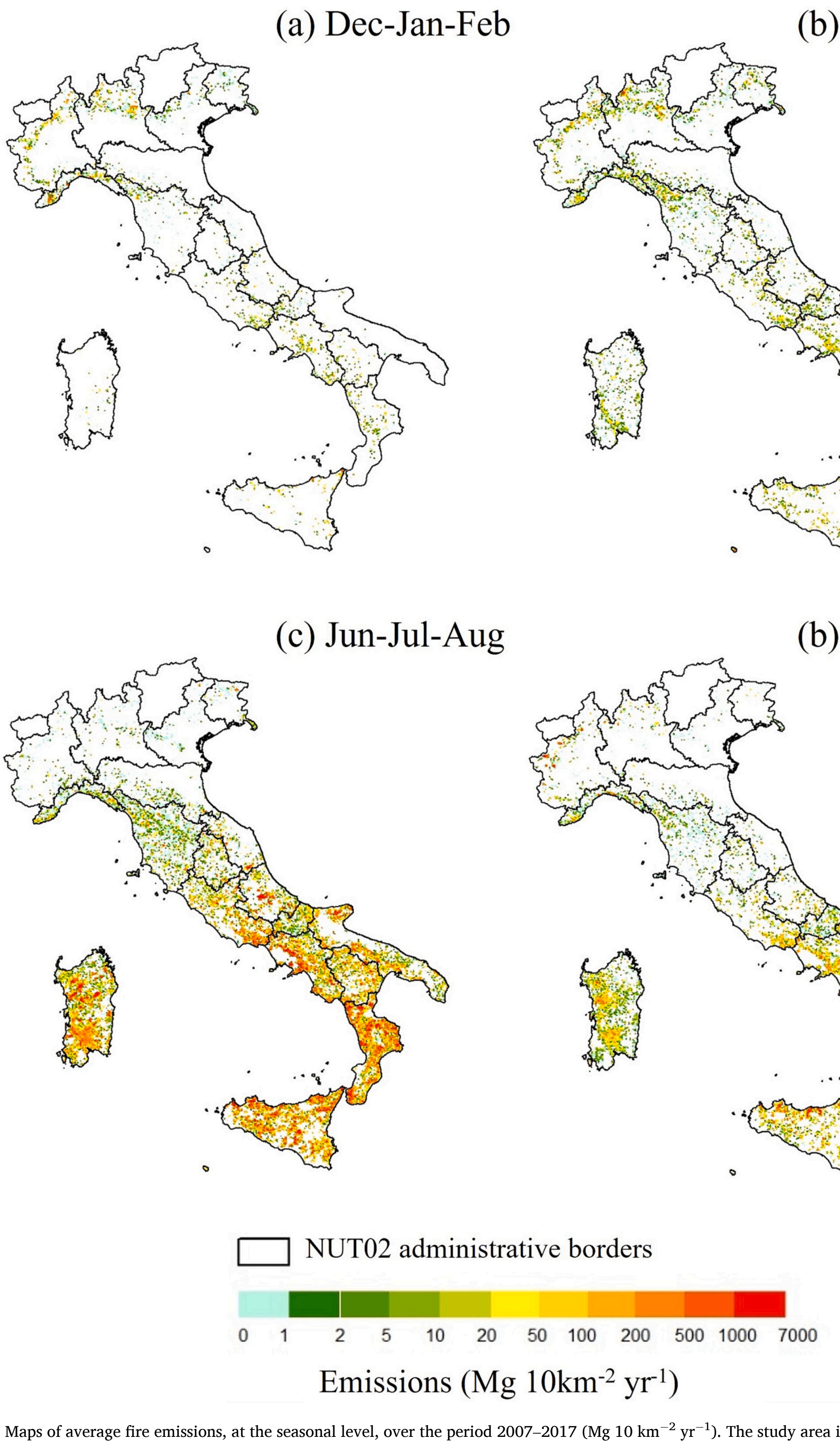


Fig. 5. Maps of average fire emissions, at the seasonal level, over the period 2007–2017 (Mg 10 km^{-2} yr^{-1}). The study area is divided in 10,000-ha hexcells. White areas represent locations without fires.

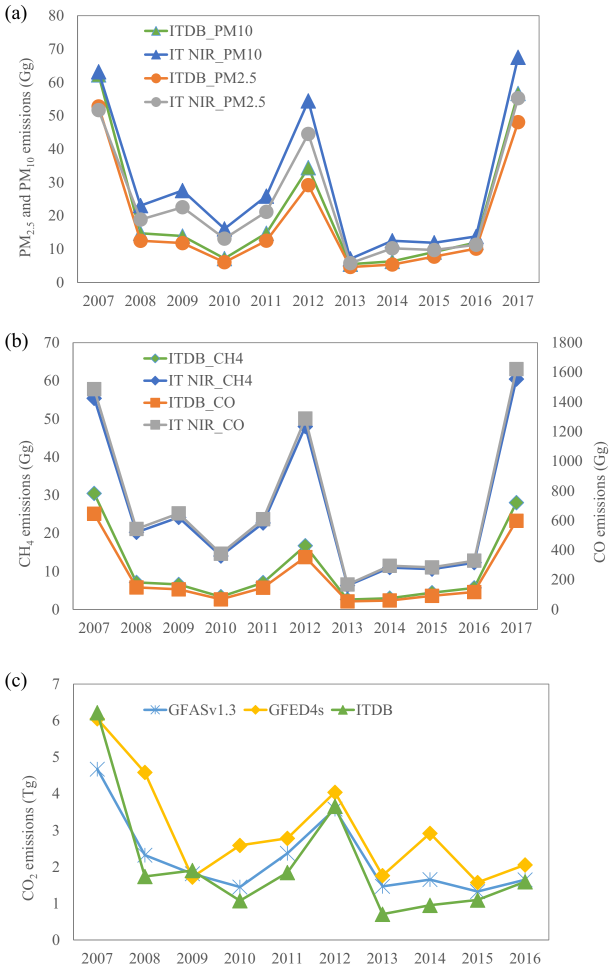


Fig. 6. (a) Annual $PM_{2.5}$ and PM_{10} and (b) CH_4 and CO released in Italy according to the results obtained in this study (ITDB) and the Italian National Emission Inventory (IT NIR, 2022) for the period 2007–2017; (c) Annual CO_2 released in Italy according to the results obtained in from this study (ITDB) and the two global inventories GFASv1.3 and GFED4s for the period 2007–2016,

Table 4
Statistics (relative percentage difference (RPD) and correlation coefficient (r)) of annual chemical species emissions from fires between the results obtained in this study (ITDB), the Italian National Emission Inventory (IT NIR, 2022), and the two global inventories GFASv1.3 and GFED4s,

Species	Databases	Period	Mean RPD[a]	Min RPD	Max RPD	r
$PM_{2.5}$	ITDB vs IT NIR	2007–2017	−31 %	−26 %	−8 %	0.96
PM_{10}			−27 %	−22 %	−5 %	
CH_4			−85 %	−83 %	−66 %	
CO			−104 %	−103 %	−86 %	
CO_2	ITDB vs GFASv1.3	2007–2016	−7 %	−61 %	28 %	0.96
	ITDB vs GFED4s		−37 %	−76 %	3 %	0.82

[a] Relative percentage difference (RPD) $= \frac{X1 - Y2}{\left(\frac{X1 + Y2}{2}\right)}*100$, where X1 represents the chemical species emitted by the DB produced in this study at the annual level during the period analyzed, Y2 is the chemical species emitted by the national or global inventories, and r is the correlation coefficient.

Mediterranean ecosystems (e.g., D'Este et al., 2020; Moreira et al., 2011). Indeed, in these areas, agricultural and pastoral fires are a common practice to, on the one hand, rejuvenate the crops and pastures (Ascoli and Bovio, 2010; García-Ruiz et al., 2020) and, on the other hand, to reverse shrubland encroachment due to the reduced grazing pressure and abandonment of agro-pastoral lands (e.g., Ascoli et al., 2021; Malandra et al., 2018). It is noteworthy to highlight that the progressive abandonment of agro-pastoral lands in central and southern Italy, with the inherent variations in fuel load and continuity, is leading to a reduction in fire occurrence, which could be counterbalanced by an increased likelihood of significant and fast-spreading events (Ascoli et al., 2021; Salis et al., 2022; Spadoni et al., 2023). On the contrary, in northern regions, fire occurring in agricultural areas dropped 7 %, reaching 51 % in shrubland and grassland areas and 33 % in broadleaves areas.

On average, this study estimated 2621 Gg yr^{-1} of particulate and GHG emissions, reflecting the large burned area annual variability. Overall, the primary sources of emissions were represented by broadleaf forests, shrublands, and agriculture, accounting for about 76 % of the total. However, due to its fuel load, the conifer fuel group showed the highest emissions per burned hectare; on the contrary, grassland and agricultural fuel groups released one-third of GHG and particulate matter.

The estimates presented in this work showed a good correlation with those reported for a coincident period by the IT NIR (2022) and the two global inventories GFASv1.3 and GFED4s in Italy. Particulate matter emissions from IT NIR were in very good agreement with the results of this study in terms of variability and mean percentage difference. On the other hand, CH_4 and CO emissions from IT NIR were higher than our estimates, even though the total burned area in our study was about 19 % higher. Comparing the CO_2 emissions from this study with those estimated by the two global inventories, it is possible to observe that the year-to-year variability was consistent between different inventories. IT NIR and GFED4s also allowed the possibility to explore emission estimate differences according to three main vegetation covers (grassland, forest, and cropland in the first database, savannah, forest, and agriculture in the second one). To compare the datasets, we aggregated ITDB data (burned area and emissions) according to IT NIR, 2022 and GFED4s vegetation covers. Specifically, we collated fuel type classes on CON and BRD fuel groups to obtain one "forest" category, while fuel type classes pertaining to GRS and SHR were aggregated into a "grassland" category to be coherent with IT NIR, 2022, and a "savannah" category to be in line

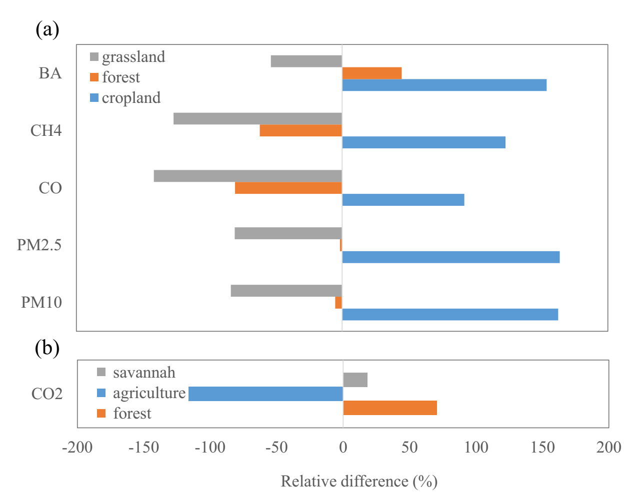


Fig. 7. (a) Percentage difference in PM_{10}, $PM_{2.5}$, CH_4, CO, and burned area (BA) between ITDB and IT NIR for three vegetation cover (grassland, forest, and cropland) over the period 2007–2017; (b) percentage difference in CO_2 emissions between ITDB and GFED4s for three sectors (savannah, forest, agriculture) over the period 2007–2016.

with GFED4s. Fig. 7a provides the ITDB to IT NIR percentage difference over the analyzed period for the burned area (BA) and PM_{10}, $PM_{2.5}$, CH_4, and CO, while Fig. 7b plots the ITDB to GFED4s percentage difference for CO_2. The ITDB to IT NIR percentage difference for the forest component ranged from −2 % to −5 % considering both PM_{10} and $PM_{2.5}$, while it increased from −62 % to −81 % considering CH_4 and CO, respectively. ITDB estimates were also lower than IT NIR regarding grassland (ranging from −81 % for $PM_{2.5}$ to −142 % for CO). On the other hand, ITDB estimates were higher than IT NIR regarding the cropland cover. It is interesting to point out that the ITDB to IT NIR percentage difference for burned area presented a different sign regarding the forest cover (45 %) and a different magnitude regarding grassland cover (−54 %). The comparison of ITDB fire emission estimates according to the three GFED4s vegetation classes (Fig. 7b) highlighted that the main average percentage difference could be attributed to agricultural burning (which also includes agricultural waste burning). For the savannah sector (also including grassland and shrubland), the difference was, on average, about 18 %, while ITDB estimated a 70 % mean increase for the forest sector compared to GFED4s during 2007–2016.

Overall, the discrepancies among the inventories, particularly evident if we consider the vegetation types, were due to the different input data and methodologies applied to estimate the emissions. For example, as far as emission factors are concerned, IT NIR and ITDB shared similar values for PM_{10} and $PM_{2.5}$ (11 g kg^{-1} and 9 g kg^{-1} vs. 13.3 g kg^{-1} and 11.3 g kg^{-1}, respectively), while CO and CH_4 emission factors used on average in this study were about the half of those applied by IT NIR. The case of the forest component, estimating lower but still similar PM emissions for a larger burned area (percentage difference 45 %) and comparable emission factors, suggested that other factors, such as fuel load availability and variability across regions and vegetation types, or the approach to calculate combustion completeness, can have a higher influence on the final emission estimates.

Besides the inventories analyzed in Section 3.3, other research efforts focused on estimating CO_2 emissions from forest fires in Italy (Table 5), with results comparable to this work. On average, this study estimated 2347 Gg CO_2 yr^{-1}, from a minimum of 704 Gg CO_2 yr^{-1} in 2013 to a maximum of 6218 Gg CO_2 yr^{-1} in 2007. Bovio (1996) estimated an annual average of CO_2 ranging between 2600 and 4400 Gg yr^{-1} based on the 1977–1991 fire database, regional parameters of vegetation types, and combustible biomass adopted from Anderson (1982) fuel models. Two other studies (Narayan et al., 2007; Vilén and Fernandes, 2011), aimed at exploring the prescribed burning potential in terms of fire emission reduction and impacts on total CO_2 emissions, estimated an annual average of 2009 Gg yr^{-1} for the period 1999–2003 and 5816 Gg yr^{-1} for the period 1980–2008, respectively. The differences found among the results of the present study and the other inventories analyzed are attributable to several factors, such as burned area (including differences in burned vegetation type and study periods), biomass data, combustion, and emission factors, as well as the methodology applied.

Using a fuel dataset providing quantitative characteristics of fuel beds in grasslands, shrublands, broadleaved, and coniferous forests of Italy's Alpine, temperate, and Mediterranean regions is an important asset of this paper. While other studies and inventories applied data referring to fuel models (e.g., Monteiro et al., 2014), or derived from dynamic vegetation models (as in GFED4s, e.g., Van Wees et al., 2022; Van Wees and Van Der Werf, 2019; Van Der Werf et al., 2017) or for a few fuel component deriving from local (e.g., Chiriacò et al., 2013; Fernandes et al., 2022; IT NIR, 2022) or global datasets (e.g., Vilén and Fernandes, 2011), the survey applied in this study covered a broad range of bioclimatic regions and vegetation types. Furthermore, it also covered the wide range of fuel components (from duff to downed woody), providing data not yet available in the Global Forest Resources Assessment or the Italian National Forest Inventory (used in the IT NIR, 2022), such as duff, grass, and shrub biomass, crucial for carbon loss estimation (Ascoli et al., 2020). Recently, Kennedy et al. (2020) highlighted the sensibility of the two combustion phases to specific fuel components, i. e., litter loading during the flaming phase and duff loading during the smoldering, suggesting that reducing the uncertainty in litter and duff layers loading across different vegetation types is advisable.

Another element of improvement in this paper is represented by estimating fuel moisture, burning efficiency, and fuel consumption considering meteorological factors at the fire event spatio-temporal scale and different combustion phases through modelling application. For example, the IT NIR approach relies on the damage level information based on the scorch height of forest typologies affected by fires to assess the fraction of biomass consumed in a fire event. This metric is highly uncertain due to a subjective post-fire estimate by the fire personnel, and in some cases, and especially for the five autonomous regions (including the most fire-affected areas of Sardinia and Sicily), these data are not available; thus, a gap-filling procedure is applied (IT NIR, 2022). Chiriacò et al. (2013) reported that, in Italy, scorch heights have been assessed and stored in a geodataset, although it required a quite demanding operational effort. On the other hand, GFASv1.3 applied a conversion factor that links the Fire Radiative Power (FRP) to dry matter combustion rate for several land cover classes, while GFED4s integrated satellite-based severity metric (including tree mortality and a vegetation destruction index) from Rogers et al. (2015). Bovio (1996) estimated the biomass available for combustion per vegetation type, also considering several management systems whose application produces a biomass growth different from the original conditions. Narayan et al. (2007) and Vilén and Fernandes (2011) applied the approach of Seiler and Crutzen (1980), even though with some differences in the main assumptions. For example, burning efficiency was taken as 50 % of the aboveground biomass in Narayan et al. (2007). Vilén and Fernandes (2011) adjusted this value to 75 % for canopy biomass and 90 % for litter and deadwood. Martins et al. (2012) and Fernandes et al. (2022) applied a burning efficiency value of 80 % for shrubs and 25 % for forests.

Overall, the combustion factor is statically determined for specific fuel components or based on data related to fire activity, which is often challenging to collect. In fact, combustion completeness is determined by several factors, including the fuel component's moisture content, which depends on meteorological factors (spatially and temporally

Table 5
Comparison between the CO_2 emissions from Italian fires estimated in this study and those obtained in previous works. The table also summarizes study period, applied approach, input data, and annual burned area for each work.

Literature cited	Period analyzed	Approach	Burned Area product	Fuel load source	Fuel Canopy loading data	Burned area (ha yr^{-1})	Emissions (Gg yr^{-1})
This work	2007–2017	Integrated modelling approach	Italian Forest Service	Field observations	N	92,900	2347
Bovio et al. (1996)	1977–1991	Product of the level of damage, EF, BA	Italian Forest Service	Fuel models	Y	143,261	2600–4400
Narayan et al. (2007)	1999–2003	Seiler & Crutzen approach	Literature	Literature	Y	76,891	2009
Vilen and Fernandes (2011)	1980–2008	IPCC guidelines and Seiler&Crutzen approach	Italian Forest Service	Literature	Y	118,022	5816

changing) (e.g., Yi and Bao, 2016). Thus, in the present study, we improved the assessment of combustion completeness as a function of FFMC, therefore considering fuel properties and meteorological factors, and implicitly, fire behavior, as Amiro et al. (2001) suggested and as also applied by Monteiro et al. (2014). Furthermore, the integration of the FOFEM modelling system, which implies the process-based BURNUP model to predict fire intensity and fuel consumption, provides a number of advantages: (i) it reflects the scientific knowledge of the underlying dynamics; (ii) it is found to be robust to be applied in different systems and under different conditions (Hoffman et al., 2018); and (iii) it is recognized to provide a better estimate of consumption efficiency and different release rates of chemical compounds through the determination of combustion efficiency of woody and non-woody properties during the two combustion phases (Ottmar, 2014). However, as suggested by Kennedy et al. (2020), the complexity of process-based models such as FOFEM requires more input data and a complex model assessment that would include validation against observed fuel consumption and associated emissions and sensitivity analysis to understand better how the model structure coupled with parameter uncertainty propagates prediction uncertainty (e.g., Lutes, 2013).

Further work to mitigate uncertainty in emissions estimates will be related to integrating emission factors (EF) specific to Mediterranean vegetation. Indeed, in this study, we applied FOFEM default EF, which are combustion-phase dependent for fuel consumed (Ward et al., 1993). IT NIR uses EMEP/EEA (2009) EF, while GFED4s uses a list of EF based on Akagi et al. (2011), as well as Andreae and Merlet (2001), specific for different types of biomass burning. Although, the values used in this study are in the same range of variation of IT NIR and GFED4s as far as particulate matters and CO_2, respectively, are concerned. In particular, EF CO_2 used in this study ranges between 1228 and 1778 g kg^{-1} of flaming and smoldering phases, while GFED4s applies as EF CO_2 1637 g kg^{-1} for temperate forest, 1686 g kg^{-1} for savannah, and 1710 g kg^{-1} for chaparral. A similar range of average values is also reported by Fernandes et al. (2022), who collected data from experimental forest fires under different vegetation types (i.e., from a minimum of 1398 g kg^{-1} for oak, chestnut, and cork oak to a maximum of 1585 g kg^{-1} for other hardwoods). Bovio (1996) applied EF CO_2 ranging from 900 to 1500 g kg^{-1}, while Narayan et al. (2007) used a value of 1569 g kg^{-1} taken from Andreae and Merlet (2001), and Vilén and Fernandes (2011) applied a range from 1627 g kg^{-1} for conifers to 1393 g kg^{-1} for broadleaves (based on Carvalho et al., 2007).

The proposed integrated modelling approach represents a framework that could have multiple implications in fire-related issues, at different scales and for different purposes, as well as the resulting data and maps. As far as the overall approach is concerned, it is worth noting that the effort in reducing bias in fire emission estimates is an aspect of extreme relevance in the context of GHG reporting (McGlynn et al., 2022). Indeed, to estimate CO_2 and non-CO_2 biomass burning emissions, the IPCC provides a three-Tier approach (IPCC, 2006), within which the most detailed Tier 3 relies on sophisticated modelling based also on accurate country-specific dataset. In this sense, the integration of a fire emission model with accurate data inputs represents a step forward in fulfilling the higher level of accuracy requirements (Chiriacò et al., 2013; Volkova et al., 2019). As regards the output data obtained by this study, the overall fire emission estimates can be disaggregated down to the single fire event level, by combustion phase and by fuel type, thus supporting different requests. Besides the contribution to a total state-wise annual inventory addressing international initiatives and commitments (Volkova et al., 2019), our data can also be useful to evaluate the impact of extreme wildfires on national carbon loss (de Groot et al., 2007; de Groot et al., 2009) and GHG balance (e.g. Bacciu et al., 2018), as well as to air quality modelling and management (e.g., Carter et al., 2020; Martins et al., 2012; Monteiro et al., 2022). Furthermore, both the proposed approach and the resulting data and maps can support and provide valuable information for wildland fire and smoke management programs (Hardy et al., 2001; Prichard et al., 2020), such as better understanding and planning of smoke reduction techniques in the framework of prescribed burning programs (Long et al., 2022; Miller et al., 2019; Prichard et al., 2020) or evaluating whether and to what extent reduced carbon sequestration from fuel treatments could be mitigated by avoided emissions of large wildfires (Ager et al., 2010; Alcasena et al., 2021; Salis et al., 2016). The identification of the fire emission hot spot locations and the main fuel types contributing to fire emission is also crucial in strategic fire management planning to develop, monitor, and evaluate emission reduction strategy for carbon mitigation (Bacciu et al., 2018; Herbert et al., 2022; Phillips et al., 2022) and health risk reduction (Cascio, 2018; Stephens et al., 2020). Finally, coupling the proposed integrated approach with forest management scenarios or future climate would offer valuable insights toward the long-term evaluation of fire management on mitigating smoke impacts from wildfires, opportunities for adaptation, and costs and benefits for carbon mitigation (e.g., Bacciu et al., 2021; Elder et al., 2022; Long et al., 2022).

5. Conclusions

Any effort to decarbonize the economy, mitigate, and adapt to the climate crisis will be partial if, at the global level, we will not consider the role of fires in greenhouse gases and particulate emissions. This study aimed to contribute toward this objective by proposing an integrated approach that combines a fire emissions model with spatial and non-spatial inputs related to forest and rural fire disturbance, vegetation, and weather conditions to provide and improve the estimate of trace gases and particulate matter from fires, using Italy as a case study. To reduce bias in predicting and quantifying fire emissions' source and composition and achieve realistic estimates, the development and survey of comprehensive and accurate data inputs, primarily related to fire activity and fuel type and loading, was emphasized. Furthermore, using a modelling approach, fuel moisture, burning efficiency, and fuel consumption were estimated considering meteorological factors and different combustion phases.

In Italy, fire disturbance in broadleaf forests, shrublands, and agricultural fuel types is the primary source of emissions, accounting for about 76 % of the total. On the other hand, the conifer fuel group released the highest amount of emissions per burned hectare due to its relevant fuel load. Overall, emissions are strongly seasonal and heavily concentrated in summer, although the high-detail spatial approach allowed us to identify the most affected areas during the other seasons.

The use of appropriate spatial and non-spatial data integrated with a process-based fuel consumption and fire emission model contributed to advancing current knowledge on fire emission, emphasizing the uncertainty elements involved in this type of estimation. Due to the lack of monitored or measured field campaigns emission data, the results of the present study were compared to the emission estimations of specific chemical species with the Italian National Emission Inventory and two global inventories at the annual level. Although the estimates of this work are conservative with respect to the other analyzed inventories due to differences in terms of burned area, biomass data, combustion, and emission factors, the comparison showed a good agreement, especially considering particulate matter and CO_2.

The outputs and the derived smoke emission maps provided by this study can be helpful for emission source models coupled with dispersion models and decision support systems, crucial for air quality management, mitigation of wildland fire environmental effects, and assisting decision-makers in prescribed fire activities.

Further steps to mitigate uncertainties in emission estimates will be taken by integrating emission factors specific to Mediterranean vegetation, collecting field measurements, and integrating new approaches to define combustion completeness, especially for canopies, and then performing a comprehensive model assessment (including validation and sensitivity analysis).

CRediT authorship contribution statement

Carla Scarpa: Methodology, Writing – original draft, Writing – review & editing, Data curation, Formal analysis. **Valentina Bacciu:** Conceptualization, Methodology, Writing – review & editing, Formal analysis. **Davide Ascoli:** Methodology, Writing – review & editing. **Josè Maria Costa-Saura:** Writing – review & editing, Data curation. **Michele Salis:** Methodology, Writing – review & editing. **Costantino Sirca:** Writing – review & editing, Supervision. **Marco Marchetti:** Writing – review & editing. **Donatella Spano:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Data availability

Data will be made available on request.

Acknowledgements

This work was carried out within Carla Scarpa's PhD course on Agricultural Science, Curriculum of Agrometeorology and Ecophysiology of Agricultural and Forestry Systems, at the Agricultural Department of the University of Sassari (XXXII cycle). Carla Scarpa has also been supported by the FirEUrisk project 2021–2024 (grant no. 101003890). José Maria Costa Saura has been supported by the National Biodiversity Future Center - NBFC project funded under the National Recovery and Resilience Plan (NRRP) (project code CNS00000033) through a research position contract. The Authors would thank the two anonymous reviewers and the Editor for providing thoughtful and detailed comments, and for helping to improve the final version of this work.

References

Adame, J.A., Lope, L., Hidalgo, P.J., Sorribas, M., Gutiérrez-Álvarez, I., del Águila, A., Saiz-Lopez, A., Yela, M., 2018. Study of the exceptional meteorological conditions, trace gases and particulate matter measured during the 2017 forest fire in Doñana Natural Park, Spain. Sci. Total Environ. 645, 710–720. https://doi.org/10.1016/j.scitotenv.2018.07.181.

Adetona, O., Reinhardt, T.E., Domitrovich, J., Broyles, G., Adetona, A.M., Kleinman, M. T., Ottmar, R.D., Naeher, L.P., 2016. Review of the health effects of wildland fire smoke on wildland firefighters and the public. Inhal. Toxicol. https://doi.org/10.3109/08958378.2016.1145771.

Ager, A., Finney, M., McMahan, A., Cathcart, J., 2010. Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. Nat. Hazards Earth Syst. Sci. 10, 2515–2526. https://doi.org/10.5194/nhess-10-2515-2010.

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D., Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmos. Chem. Phys. 11, 4039–4072. https://doi.org/10.5194/acp-11-4039-2011.

Albini, F.A., Reinhardt, E.D., 1995. Modeling ignition and burning rate of large woody natural fuels. Int. J. Wildland Fire 5, 81–91. https://doi.org/10.1071/WF9950081.

Albini, F.A., Reinhardt, E.D., 1997. Improved calibration of a large fuel burnout model. Int. J. Wildland Fire 7, 21–28. https://doi.org/10.1071/WF9970021.

Albini, F.A., Brown, J.K., Reinhardt, E.D., Ottmar, R.D., 1995. Calibration of a large fuel burnout model. Int. J. Wildland Fire 5, 173–192. https://doi.org/10.1071/WF9950173.

Alcasena, F., Rodrigues, M., Gelabert, P., Ager, A., Salis, M., Ameztegui, A., Cervera, T., Vega-García, C., 2021. Fostering carbon credits to finance wildfire risk reduction forest management in Mediterranean landscapes. Land 10, 1104. https://doi.org/10.3390/land10101104.

Amiro, B.D., Stocks, B.J., Alexander, M.E., Flannigan, M.D., Wotton, B.M., 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire 10, 405–413. https://doi.org/10.1071/WF01038.

Analitis, A., Georgiadis, I., Katsouyanni, K., 2012. Forest fires are associated with elevated mortality in a dense urban setting. Occup. Environ. Med. 69, 158–162. https://doi.org/10.1136/oem.2010.064238.

Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior, Research Paper INT-122 U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. https://doi.org/10.2737/INT-GTR-122.

Andreae, M.O., 2019. Emission of trace gases and aerosols from biomass burning – an updated assessment. Atmos. Chem. Phys. 19, 8523–8546. https://doi.org/10.5194/acp-19-8523-2019.

Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Glob. Biogeochem. Cycles 15, 955–966. https://doi.org/10.1029/2000GB001382.

Ascoli, D., Bovio, G., 2010. Tree encroachment dynamics in heathlands of north-west Italy: the fire regime hypothesis. IForest 137–143. https://doi.org/10.3832/ifor0548-003.

Ascoli, D., Vacchiano, G., Scarpa, C., Arca, B., Barbati, A., Battipaglia, G., Elia, M., Esposito, A., Garfì, V., Lovreglio, R., Mairota, P., Marchetti, M., Marchi, E., Meytre, S., Ottaviano, M., Pellizzaro, G., Rizzolo, R., Sallustio, L., Salis, M., Sirca, C., Valese, E., Ventura, A., Bacciu, V., 2020. Harmonized dataset of surface fuels under Alpine, temperate and Mediterranean conditions in Italy. A synthesis supporting fire management. IForest 13, 513. https://doi.org/10.3832/IFOR3587-013.

Ascoli, D., Moris, J.V., Marchetti, M., Sallustio, L., 2021. Land use change towards forests and wooded land correlates with large and frequent wildfires in Italy. Ann. Silvicult. Res. 46 https://doi.org/10.12899/ASR-2264.

Augusto, S., Ratola, N., Tarín-Carrasco, P., Jiménez-Guerrero, P., Turco, M., Schuhmacher, M., Costa, S., Teixeira, J., Costa, C., 2020. Population exposure to particulate-matter and related mortality due to the Portuguese wildfires in October 2017 driven by storm Ophelia. Environ. Int. 144, 106056 https://doi.org/10.1016/j.envint.2020.106056.

Bacciu, V., Salis, M., Pellizzaro, G., Arca, B., Duce, P., Spano, D., 2011. Carbon loss and greenhouse gas emission from extreme fire events occurred in Sardinia, Italy. In: AGU Fall Meeting Abstracts, 447 (San Francisco, 5–9 December 2011). 2011AGUFM.B23C0447B.

Bacciu, V., Pellizzaro, G., Salis, M., Arca, B., Duce, P., Spano, D., 2012. Estimating vegetation fire emissions from Sardinian wildland fires (2005–2009). In: Spano, D., Bacciu, V., Salis, M., Sirca, C. (Eds.), Modelling Fire Behaviour and Risk. Nuova Stampa Color Publisher, Muros, Italy, pp. 34–40. ISBN: 978-88-904409-7-7.

Bacciu, V., Scarpa, C., Ascoli, D., Salis, M., Sirca, C., Marchetti, M., Spano, D., 2018. Extreme fire events in summer 2017 accounted for a large portion of carbon loss and national greenhouse gas emissions in Southern Italy. In: Proceedings of the "IV National Congress of Silviculture". Torino (Italy) 5–9 Nov 2018. Accademia Italiana di Scienze Forestali, Firenze, Italy, p. 312 ([in Italian] ISBN 978-88-87553-24-6).

Bacciu, V., Hatzaki, M., Karali, A., Cauchy, A., Giannakopoulos, C., Spano, D., Briche, E., 2021. Investigating the climate-related risk of forest fires for Mediterranean islands' blue economy. Sustainability 13 (18), 10004. https://doi.org/10.3390/su131810004.

Barbosa Ferreira, P., Camia, A., Kucera, J., Libertà, G., Palumbo, I., San-Miguel-Ayanz, J., Schmuck, G., 2009. Assessment of forest fires impact and emissions in the European Union based on the European forest fire information system. In: Bytnerowicz, A., Arbaugh, M., Riebau, A., Andersen, C. (Eds.), Wildland Fires and Air Pollution. Elsevier, Amsterdam (The Netherlands), pp. 197–208. JRC49086. https://doi.org/10.1016/S1474-817700008-9.

Bo, M., Mercalli, L., Pognant, F., Cat Berro, D., Clerico, M., 2020. Urban air pollution, climate change and wildfires: the case study of an extended forest fire episode in northern Italy favoured by drought and warm weather conditions. Energy Rep. 6, 781–786. https://doi.org/10.1016/j.egyr.2019.11.002.

Bourgeois, I., Peischl, J., Andrew Neuman, J., Brown, S.S., Thompson, C.R., Aikin, K.C., Allen, H.M., Angot, H., Apel, E.C., Baublitz, C.B., Brewer, J.F., Campuzano-Jost, P., Commane, R., Crounse, J.D., Daube, B.C., DiGangi, J.P., Diskin, G.S., Emmons, L.K., Fiore, A.M., Gkatzelis, G.I., Hills, A., Hornbrook, R.S., Gregory Huey, L., Jimenez, J. L., Kim, M., Lacey, F., McKain, K., Murray, L.T., Nault, B.A., Parrish, D.D., Ray, E., Sweeney, C., Tanner, D., Wofsy, S.C., Ryerson, T.B., 2021. Large contribution of biomass burning emissions to ozone throughout the global remote troposphere. Proc. Natl. Acad. Sci. U. S. A. 118 https://doi.org/10.1073/PNAS.2109628118/-/DCSUPPLEMENTAL.

Bovio, G., 1996. Stima della biomassa bruciata e della CO_2 prodotta da incendi boschivi in Italia. Schweizerische Zeitschrift fuer Forstwesen 147, 281–292.

Bovio, G., 2007. Method for forest fire damage level assessment based on detectable effects. In: Ciancio, O., Corona, P., Marinelli, M., Pettenella, D. (Eds.), Evaluation of Forest Fire Damages in Italy. Accademia Italiana di Scienze Forestali, Firenze, Italy, pp. 85–95.

Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D., 1985. Predicting Duff and Woody Fuel Consumed by Prescribed Fire in the Northern Rocky Mountains (No. Res. Pap. INT-337). Ogden, UT.

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., Wara, M., 2021. The changing risk and burden of wildfire in the United States. PNAS 118 (2), e2011048118. https://doi.org/10.1073/pnas.2011048118.

Carter, T.S., Heald, C.L., Jimenez, J.L., Campuzano-Jost, P., Kondo, Y., Moteki, N., Schwarz, J.P., Wiedinmyer, C., Darmenov, A.S., Da Silva, A.M., Kaiser, J.W., 2020. How emissions uncertainty influences the distribution and radiative impacts of smoke from fires in North America. Atmos. Chem. Phys. 20, 2073–2097. https://doi.org/10.5194/ACP-20-2073-2020.

Carvalho, A., Martins, V., Miranda, A.I., Borrego, C., 2007. Forest fire emissions under climate change: An air quality perspective. In: UNISDR, FAO, European Commission (Eds.), 4th International Wildland Fire Conference. Sevilla, Spain.

Cascio, W.E., 2018. Wildland fire smoke and human health. Sci. Total Environ. 624, 586. https://doi.org/10.1016/J.SCITOTENV.2017.12.086.

Chiriacò, M.V., Perugini, L., Cimini, D., D'Amato, E., Valentini, R., Bovio, G., Corona, P., Barbati, A., 2013. Comparison of approaches for reporting forest fire-related biomass loss and greenhouse gas emissions in southern Europe. Int. J. Wildland Fire 22, 730–738. https://doi.org/10.1071/WF12011.

Chuvieco, E., Mouillot, F., van der Werf, G.R., San Miguel, J., Tanase, M., Koutsias, N., García, M., Yebra, M., Padillag, M., Gitas, I., Heili, H., Hawbaker, T.J., Giglio, L., 2019. Historical background and current developments for mapping burned area from satellite Earth observation. Remote Sens. Environ. 225, 45–64. https://doi.org/10.1016/j.rse.2019.02.013.

D'Este, M., Ganga, A., Elia, M., Lovreglio, R., Giannico, V., Spano, G., Colangelo, G., Lafortezza, R., Sanesi, G., 2020. Modeling fire ignition probability and frequency using Hurdle models: a cross-regional study in Southern Europe. Ecol. Process. 9, 54. https://doi.org/10.1186/s13717-020-00263-4.

Di Carlo, P., Aruffo, E., Biancofiore, F., Busilacchio, M., Pitari, G., Dari-Salisburgo, C., Tuccella, P., Kajii, Y., 2015. Wildfires impact on surface nitrogen oxides and ozone in Central Italy. Atmos. Pollut. Res. 6, 29–35. https://doi.org/10.5094/APR.2015.004.

Di Giuseppe, F., Benedetti, A., Coughlan, R., Vitolo, C., Vuckovic, M., 2021. A global bottom-up approach to estimate fuel consumed by fires using above ground biomass observations. Geophys. Res. Lett. 48, e2021GL095452 https://doi.org/10.1029/2021GL095452.

Dintwe, K., Okin, G.S., Xue, Y., 2017. Fire-induced albedo change and surface radiative forcing in sub-Saharan Africa savanna ecosystems: implications for the energy balance. J. Geophys. Res. 122, 6186–6201. https://doi.org/10.1002/2016JD026318.

Dorman, S.C., Ritz, S.A., 2014. Smoke exposure has transient pulmonary and systemic effects in wildland firefighters. J. Respir. Med. 2014, 1–9. https://doi.org/10.1155/2014/943219.

Drury, S.A., Larkin, N.S., Strand, T.T., Huang, S., Strenfel, S.J., Banwell, E.M., O'Brien, T. E., Raffuse, S.M., 2014. Intercomparison of fire size, fuel loading, fuel consumption, and smoke emissions estimates on the 2006 tripod fire, Washington, USA. Fire Ecol. 10, 56–83. https://doi.org/10.4996/fireecology.1001056.

Dupuy, J., Fargeon, H., Martin-StPaul, N., et al., 2020. Climate change impact on future wildfire danger and activity in southern Europe: a review. Ann. For. Sci. 77, 35. https://doi.org/10.1007/s13595-020-00933-5.

Elder, M., Phillips, C., Potter, S., Frumhoff, P., Rogers, B., 2022. The costs and benefits of fire management for carbon mitigation in Alaska through 2100. Environ. Res. Lett. 17 https://doi.org/10.1088/1748-9326/ac8e85.

Elia, M., Giannico, V., Ascoli, D., Argañaraz, J.P., D'Este, M., Spano, G., Lafortezza, R., Sanesi, G., 2022. Uncovering current pyroregions in Italy using wildfire metrics. Ecol. Process. 11, 15. https://doi.org/10.1186/s13717-022-00360-6.

EMEP/EEA, 2009. EMEP/EEA Air Pollutant Emission Inventory Guidebook - 2009 (No. Technical Report No 9/2009).

Fernandes, A.P., Lopes, D., Sorte, S., Monteiro, A., Gama, C., Reis, J., Menezes, I., Osswald, T., Borrego, C., Almeida, M., Ribeiro, L.M., Viegas, D.X., Miranda, A.I., 2022. Smoke emissions from the extreme wildfire events in Central Portugal in October 2017. Int. J. Wildland Fire 31, 989–1001. https://doi.org/10.1071/WF21097.

Finney, M., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47, 219–228.

García-Ruiz, J.M., Tomás-Faci, G., Diarte-Blasco, P., Montes, L., Domingo, R., Sebastián, M., Lasanta, T., González-Sampériz, P., López-Moreno, J.I., Arnáez, J., Beguería, S., 2020. Transhumance and long-term deforestation in the subalpine belt of the central Spanish Pyrenees: an interdisciplinary approach. Catena (Amst) 195, 104744. https://doi.org/10.1016/j.catena.2020.104744.

Gianniou, N., Katsaounou, P., Dima, E., Giannakopoulou, C.E., Kardara, M., Saltagianni, V., Trigidou, R., Kokkini, A., Bakakos, P., Markozannes, E., Litsiou, E., Tsakatikas, A., Papadopoulos, C., Roussos, C., Koulouris, N., Rovina, N., 2016. Prolonged occupational exposure leads to allergic airway sensitization and chronic airway and systemic inflammation in professional firefighters. Respir. Med. 118, 7–14. https://doi.org/10.1016/j.rmed.2016.07.006.

Giglio, L., Randerson, J.T., Van Der Werf, G.R., 2013. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). Eur. J. Vasc. Endovasc. Surg. 118, 317–328. https://doi.org/10.1002/jgrg.20042.

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L., Justice, C.O., 2018. The collection 6 MODIS burned area mapping algorithm and product. Remote Sens. Environ. 217, 72–85. https://doi.org/10.1016/J.RSE.2018.08.005.

de Groot, W., Landry, R., Kurz, W., Anderson, K., Englefield, P., Fraser, R., Hall, R.J., Banfield, G., Raymond, D., Decker, V., Lynham, T., Pritchard, J., 2007. Estimating direct carbon emissions from Canadian wildland fires. Int. J. Wildland Fire 16. https://doi.org/10.1071/WF06150.

de Groot, W., Pritchard, J.M., Lynham, T.J., 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Can. J. For. Res. 39, 367–382. https://doi.org/10.1139/X08-192.

Hantson, S., Arneth, A., Harrison, S.P., Kelley, D.I., Prentice, I.C., Rabin, S.S., Archibald, S., Mouillot, F., Arnold, S.R., Artaxo, P., Bachelet, D., Ciais, P., Forrest, M., Friedlingstein, P., Hickler, T., Kaplan, J.O., Kloster, S., Knorr, W., Lasslop, G., Li, F., Mangeon, S., Melton, J.R., Meyn, A., Sitch, S., Spessa, A., van der Werf, G.R., Voulgarakis, A., Yue, C., 2016. The status and challenge of global fire modelling. Biogeosciences 13, 3359–3375. https://doi.org/10.5194/bg-13-3359-2016.

Hardy, C.C., Ottmar, R.D., Peterson, J.L., Core, J.E., Seamon, P., 2001. Smoke management guide for prescribed and wildland fire. In: PMS 420-2. NFES 1279, 2001 edition. National Wildfire Coodination Group, Boise, ID. (226 p).

Harrington, M.G., 1987. Predicting Reduction of Natural Fuels by Prescribed Burning Under Ponderosa Pine in Southeastern Arizona (No. Res. Note RM-472). Ogden, UT.

Herbert, C., Haya, B.K., Stephens, S.L., Butsic, V., 2022. Managing nature-based solutions in fire-prone ecosystems: competing management objectives in California forests evaluated at a landscape scale. Front. For. Glob. Chang. 5, 957189 https://doi.org/10.3389/ffgc.2022.957189.

Hoffman, C., Sieg, C., Linn, R., Mell, W., Parson, R., Ziegler, J., Hiers, J., 2018. Advancing the science of wildland fire dynamics using process-based models. Fire 1, 32. https://doi.org/10.3390/FIRE1020032.

Hough, W.A., 1978. Estimating Available Fuel Weight Consumed by Prescribed Fires in the South (No. Res. Pap. SE-187). Athens, GA.

Hyde, J.C., Yedinak, K.M., Talhelm, A.F., Smith, A.M.S., Bowman, D.M.J.S., Johnston, F. H., Lahm, P., Fitch, M., Tinkham, W.T., 2017. Air quality policy and fire management responses addressing smoke from wildland fires in the United States and Australia. Int. J. Wildland Fire 26, 347–363. https://doi.org/10.1071/WF16154.

IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan. ISBN 4-88788-032-4.

ISPRA, 2010. La realizzazione in Italia del progetto Corine Land Cover 2006 [The Realization in Italy of the Project Corine Land Cover 2006]. Rapporti 131/2010.

IT NIR, 2022. Italian Greenhouse Gas Inventory 1990–2020. National Inventory Report 2022. Rome.

Jia, G., Shevliakova, E., Artaxo, P., De-Docoudré, N., Houghton, R., House, J., Kitajima, K., Lennard, C., Popp, A., Sirin, A., Sukumar, R., Verchot, L., Sporre, M., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J.P., Vyas, P., Huntley, E., Malley, J., 2019. Land–climate interactions. In: Shukla, P.R., Shukla, J.R., Skea, J.E., Buendia, C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, pp. 133–206. In press.

Kaiser, J.W., Heil, A., Andreae, M.O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.J., Razinger, M., Schultz, M.G., Suttie, M., Van Der Werf, G.R., 2012. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. Biogeosciences 9, 527–554. https://doi.org/10.5194/BG-9-527-2012.

Kaskaoutis, D.G., Kharol, S.K., Sifakis, N., Nastos, P.T., Sharma, A.R., Badarinath, K.V.S., Kambezidis, H.D., 2011. Satellite monitoring of the biomass-burning aerosols during the wildfires of August 2007 in Greece: climate implications. Atmos. Environ. 45, 716–726. https://doi.org/10.1016/J.ATMOSENV.2010.09.043.

Keane, R.E., Lutes, D., 2020. First-Order Fire Effects Model (FOFEM). In: Manzello, S.L. (Ed.), Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer International Publishing, Cham, pp. 463–468. https://doi.org/10.1007/978-3-319-52090-2_74.

Kennedy, M.C., Prichard, S.J., McKenzie, D., French, N.H.F., 2020. Quantifying how sources of uncertainty in combustible biomass propagate to prediction of wildland fire emissions. Int. J. Wildland Fire 29, 793–806. https://doi.org/10.1071/WF19160.

Larkin, N.K., Raffuse, S.M., Huang, S.M., Pavlovic, N., Lahm, P., Rao, V., 2020. The comprehensive fire information reconciled emissions (CFIRE) inventory: wildland fire emissions developed for the 2011 and 2014 US National Emissions Inventory. J. Air Waste Manage. Assoc. 70, 1165–1185. https://doi.org/10.1080/10962247.2020.1802365.

Liu, T., Mickley, L.J., Marlier, M.E., DeFries, R.S., Khan, M.F., Latif, M.T., Karambelas, A., 2020. Diagnosing spatial biases and uncertainties in global fire emissions inventories: Indonesia as regional case study. Remote Sens. Environ. 237 https://doi.org/10.1016/J.RSE.2019.111557.

Liu, Z., Ballantyne, A.P., Cooper, L.A., 2019. Biophysical feedback of global forest fires on surface temperature. Nat. Commun. 10 https://doi.org/10.1038/S41467-018-08237-Z.

Linley, G.D., Jolly, C.J., Doherty, T.S., Geary, W.L., Armenteras, D., Belcher, C.M., Bliege Bird, R., Duane, A., Fletcher, M.-S., Giorgis, M.A., Haslem, A., Jones, G.M., Kelly, L. T., Lee, C.K.F., Nolan, R.H., Parr, C.L., Pausas, J.G., Price, J.N., Regos, A., Ritchie, E. G., Ruffault, J., Williamson, G.J., Wu, Q., Nimmo, D.G., 2022. What do you mean, 'megafire'? Glob. Ecol. Biogeogr. 31, 1906–1922. https://doi.org/10.1111/geb.13499.

Lohmann, U., Feichter, J., 2005. Global indirect aerosol effects: a review. Atmos. Chem. Phys. 5, 715–737. https://doi.org/10.5194/acp-5-715-2005.

Long, J.W., Drury, S.A., Evans, S.G., Maxwell, C.J., Scheller, R.M., 2022. Comparing smoke emissions and impacts under alternative forest management regimes. Ecol. Soc. 27 (4), 26. https://doi.org/10.5751/ES-13553-270426.

Lutes, D.C., 2013. First Order Fire Effects Model Mapping Tool: FOFEM Version 6.0 User's Guide. USDA Forest Service, Rocky Mountain Research Station, 66 p. URL: https://www.frames.gov/catalog/15530.

Malandra, F., Vitali, A., Urbinati, C., Garbarino, M., 2018. 70 years of land use/land cover changes in the Apennines (Italy): a Meta-analysis. Forests 9. https://doi.org/10.3390/f9090551.

Mancini, L.D., Barbati, A., Corona, P., 2017. Geospatial analysis of woodland fire occurrence & recurrence in Italy. Ann. Silvicult. Res. 41, 41–47. https://doi.org/10.12899/asr-1376.

Martins, V., Miranda, A.I., Carvalho, A., Schaap, M., Borrego, C., Sá, E., 2012. Impact of forest fires on particulate matter and ozone levels during the 2003, 2004 and 2005 fire seasons in Portugal. Sci. Total Environ. 414, 53–62. https://doi.org/10.1016/j.scitotenv.2011.10.007.

McGlynn, E., Li, S., Berger, M., Amend, M., Harper, K., 2022. Addressing uncertainty and bias in land use, land use change, and forestry greenhouse gas inventories. Clim. Chang. 170 https://doi.org/10.1007/s10584-021-03254-2.

Miller, C., O'Neill, S.M., Rorig, M., Alvarado, E., 2019. Air quality challenges of prescribed fire in complex terrain and the wildland urban interface surrounding Bend, Oregon. Atmosphere 10, 515. https://doi.org/10.3390/ATMOS10090515.

Miranda, A.I., Marchi, E., Ferretti, M., Millán, M.M., 2008. Chapter 9 forest fires and air quality issues in southern Europe. In: Bytnerowicz, A., Arbaugh, M., Riebauand, A., Andersen, C. (Eds.), Developments in Environmental Science. https://doi.org/10.1016/S1474-8177(08)00009-0.

Miranda, A.I., Borrego, C., Martins, H., Martins, V., Amorim, J.H., Valente, J., Carvalho, A., 2009. Forest fire emissions and air pollution in southern Europe. In: Chuvieco, E. (Ed.), Earth Observation of Wildland Fires in Mediterranean Ecosystems. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-01754-4_12.

Monteiro, A., Corti, P., San Miguel-Ayanz, J., Miranda, A.I., Borrego, C., 2014. The EFFIS forest fire atmospheric emission model: application to a major fire event in Portugal. Atmos. Environ. 84, 355–362. https://doi.org/10.1016/j.atmosenv.2013.11.059.

Monteiro, A., Gama, C., Osswald, T., Fernandes, A.P., Miranda, A.I., 2022. Estimating the impact on air quality of the Portuguese 2017 forest fires with the new APIFLAME model. Environ. Sci. Proc. 17 (1), 29. https://doi.org/10.3390/environsciproc2022017029.

Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., Bilgili, E., 2011. Landscape–wildfire interactions in southern Europe: implications for landscape management. J. Environ. Manag. 92 (10), 2389–2402. https://doi.org/10.1016/j.jenvman.2011.06.028.

Narayan, C., Fernandes, P.M., van Brusselen, J., Schuck, A., 2007. Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto protocol. For. Ecol. Manag. 251, 164–173. https://doi.org/10.1016/J.FORECO.2007.06.042.

North, M.P., Hurteau, M.D., 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. For. Ecol. Manag. 261, 1115–1120. https://doi.org/10.1016/j.foreco.2010.12.039.

Oliveira, M., Delerue-Matos, C., Pereira, M.C., Morais, S., 2020. Environmental particulate matter levels during 2017 large forest fires and megafires in the center region of Portugal: a public health concern? Int. J. Environ. Res. Public Health 17. https://doi.org/10.3390/ijerph17031032.

Ottmar, R.D., 2014. Wildland fire emissions, carbon, and climate: modeling fuel consumption. For. Ecol. Manag. 317, 41–50. https://doi.org/10.1016/J.FORECO.2013.06.010.

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the fuel characteristic classification system — quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37, 2383–2393. https://doi.org/10.1139/X07-077.

Ottmar, R.D., Miranda, A., Sandberg, D.V., 2008. Chapter 3 characterizing sources of emissions from wildland fires. Dev. Environ. Sci. 8 https://doi.org/10.1016/S1474-8177(08)00003-X.

Patacca, M., Lindner, M., Lucas-Borja, M.E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G.-J., Nagel, T.A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M.Z., Schelhaas, M.-J., 2023. Significant increase in natural disturbance impacts on European forests since 1950. Glob. Chang. Biol. 29, 1359–1376. https://doi.org/10.1111/gcb.16531.

Pellizzaro, G., Cesaraccio, C., Duce, P., Ventura, A., Zara, P., Pellizzaro, G., Cesaraccio, C., Duce, P., Ventura, A., Zara, P., 2007a. Relationships between seasonal patterns of live fuel moisture and meteorological drought indices for Mediterranean shrubland species. Int. J. Wildland Fire 16, 232–241. https://doi.org/10.1071/WF06081.

Pellizzaro, G., Duce, P., Ventura, A., Zara, P., 2007b. Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. Int. J. Wildland Fire 16, 633–641. https://doi.org/10.1071/WF05088.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003. Definitions and Methodological Options to Inventory Emissions From Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types. Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-004-9.

Phillips, C.A., Rogers, B.M., Elder, M., Cooperdock, S., Moubarak, M., Randerson, J.T., Frumhoff, P., 2022. Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management. Sci. Adv. 8, eabl7161. https://doi.org/10.1126/sciadv.abl7161.

Prichard, S., Andreu, A., Eagle, P., Swedin, K., Sandberg, D.V., Ottmar, R.D., Eberhardt, E., 2013. Fuel characteristic classification system version 3.0: technical documentation. In: USDA Forest Service - General Technical Report PNW-GTR.

Prichard, S., O'Neill, S.M., Eagle, P., Andreu, A.G., Drye, B., Dubowy, J., Urbanski, S., Strand, T.M., 2020. Wildland fire emission factors in North America: synthesis of existing data, measurement needs and management applications. Int. J. Wildland Fire 29 (2), 132–147. https://doi.org/10.1071/WF19066.

Ramo, R., Roteta, E., Bistinas, I., van Wees, D., Bastarrika, A., Chuvieco, E., van der Werf, G.R., 2021. African burned area and fire carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. Proc. Natl. Acad. Sci. U. S. A. 118 https://doi.org/10.1073/PNAS.2011160118.

Randerson, J.T., Chen, Y., Van Der Werf, G.R., Rogers, B.M., Morton, D.C., 2012. Global burned area and biomass burning emissions from small fires. Eur. J. Vasc. Endovasc. Surg. 117 https://doi.org/10.1029/2012JG002128.

Keane, R.E., Brown, J.K., Turner, D.L., 1991. Duff consumption from prescribed fire in the US and Canada: a broadly based empirical approach. In: Reinhardt, E.D. (Ed.), 11th Conference on Fire and Forest Meteorology.

Reinhardt, E.D., 2003. Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. In: 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress.

Reinhardt, E.D., Dickinson, M.B., 2010. First-order fire effects models for land management: overview and issues. Fire Ecol. 6, 131–142. https://doi.org/10.4996/fireecology.0601131.

Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. First Order Fire Effects Model: FOFEM 4.0, User's Guide. Gen. Tech. Rep. INT-GTR-344, 65. US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, p. 344. https://doi.org/10.2737/INT-GTR-344.

Rogers, B.M., Soja, A.J., Goulden, M.L., Randerson, J.T., 2015. Influence of tree species on continental differences in boreal fires and climate feedbacks. Nat. Geosci. 8, 228–234. https://doi.org/10.1038/ngeo2352.

Rosa, I.M.D., Pereira, J.M.C., Tarantola, S., 2011. Atmospheric emissions from vegetation fires in Portugal (1990–2008): estimates, uncertainty analysis, and sensitivity analysis. Atmos. Chem. Phys. 11, 2625–2640. https://doi.org/10.5194/acp-11-2625-2011.

Salis, M., Arca, B., Alcasena, F., Arianotsou, M., Bacciu, V., Duce, P., Duguy, B., Koutsias, N., Mallinis, G., Mitsopoulos, I., Moreno, J.M., Pérez, J.R., Rodriguez, I., Xystrakis, F., Zavala, G., Spano, D., 2016. Predicting wildfire spread and behavior in Mediterranean landscapes. Int. J. Wildland Fire 25 (10), 1015–1032. https://doi.org/10.1071/WF15081.

Salis, M., Del Giudice, L., Jahdi, R., Alcasena-Urdiroz, F., Scarpa, C., Pellizzaro, G., Bacciu, V., Schirru, M., Ventura, A., Casula, M., Pedes, F., Canu, A., Duce, P., Arca, B., 2022. Spatial patterns and intensity of land abandonment drive wildfire hazard and likelihood in Mediterranean agropastoral areas. Land 11, 1942. https://doi.org/10.3390/LAND11111942.

Sandberg, D.V., Ottmar, R.D., Cushon, G.H., 2001. Characterizing fuels in the 21st century. Int. J. Wildland Fire 10, 381–387. https://doi.org/10.1071/wf01036.

Santander Meteorology Group, . fireDanger: Fire Weather Index Calculation. URL. https://github.com/SantanderMetGroup/fireDanger. r package version 1.0.1.

Schultz, M.G., Heil, A., Hoelzemann, J.J., Spessa, A., Thonicke, K., Goldammer, J.G., Held, A.C., Pereira, J.M.C., van Het Bolscher, M., 2008. Global wildland fire emissions from 1960 to 2000. Glob. Biogeochem. Cycles 22. https://doi.org/10.1029/2007GB003031.

Seiler, W., Crutzen, P.J., 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Clim. Chang. 2, 207–247. https://doi.org/10.1007/BF00137988.

Selimovic, V., Yokelson, R.J., McMeeking, G.R., Coefield, S., 2019. In situ measurements of trace gases, PM, and aerosol optical properties during the 2017 NW US wildfire smoke event. Atmos. Chem. Phys. 19, 3905–3926. https://doi.org/10.5194/acp-19-3905-2019.

Shiraishi, T., Hirata, R., Hirano, T., 2021. New inventories of global carbon dioxide emissions through biomass burning in 2001–2020. Remote Sens. 13 https://doi.org/10.3390/rs13101914.

Spadoni, G.L., Moris, J.V., Vacchiano, G., Elia, M., Garbarino, M., Sibona, E., Tomao, A., Barbati, A., Sallustio, L., Salvati, L., Ferrara, C., Francini, S., Bonis, E., Dalla Vecchia, I., Strollo, A., Di Leginio, M., Munafò, M., Chirici, G., Romano, R., Corona, P., Marchetti, M., Brunori, A., Motta, R., Ascoli, D., 2023. Active governance of agro-pastoral, forest and protected areas mitigates wildfire impacts in Italy. Sci. Total Environ. 890, 164281 https://doi.org/10.1016/j.scitotenv.2023.164281.

Stephens, S.L., Westerling, A.L.R., Hurteau, M.D., Peery, M.Z., Schultz, C.A., Thompson, S., 2020. Fire and climate change: conserving seasonally dry forests is still possible. Front. Ecol. Environ. 18, 354–360. https://doi.org/10.1002/fee.2218.

Tang, W., Emmons, L.K., Buchholz, R.R., Wiedinmyer, C., Schwantes, R.H., He, C., Kumar, R., Pfister, G.G., Worden, H.M., Hornbrook, R.S., Apel, E.C., Tilmes, S., Gaubert, B., Martinez-Alonso, S.E., Lacey, F., Holmes, C.D., Diskin, G.S., Bourgeois, I., Peischl, J., Ryerson, T.B., Hair, J.W., Weinheimer, A.J., Montzka, D.D., Tyndall, G.S., Campos, T.L., 2022. Effects of fire diurnal variation and plume rise on US air quality during FIREX-AQ and WE-CAN based on the multi-scale infrastructure for chemistry and aerosols (MUSICAv0). J. Geophys. Res.-Atmos. 127, e2022JD036650 https://doi.org/10.1029/2022JD036650.

Tarín-Carrasco, P., Augusto, S., Palacios-Peña, L., Ratola, N., Jiménez-Guerrero, P., 2021. Impact of large wildfires on PM10 levels and human mortality in Portugal. Nat. Hazards Earth Syst. Sci. 21, 2867–2880. https://doi.org/10.5194/nhess-21-2867-2021.

Urbanski, S.P., Hao, W.M., Nordgren, B., 2011. The wildland fire emission inventory: western United States emission estimates and an evaluation of uncertainty. Atmos. Chem. Phys. 11, 12973–13000. https://doi.org/10.5194/acp-11-12973-2011.

Urbanski, S.P., Reeves, M.C., Corley, R.E., Silverstein, R.P., Hao, W.M., 2018. Contiguous United States wildland fire emission estimates during 2003–2015. Earth Syst. Sci. Data 10, 2241–2274. https://doi.org/10.5194/essd-10-2241-2018.

Van Der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., Defries, R.S., Jin, Y., Van Leeuwen, T.T., 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). Atmos. Chem. Phys. 10, 11707–11735. https://doi.org/10.5194/acp-10-11707-2010.

Van Der Werf, G.R., Randerson, J.T., Giglio, L., Van Leeuwen, T.T., Chen, Y., Rogers, B. M., Mu, M., Van Marle, M.J.E., Morton, D.C., Collatz, G.J., Yokelson, R.J., Kasibhatla, P.S., 2017. Global fire emissions estimates during 1997-2016. Earth Syst. Sci. Data 9, 697–720. https://doi.org/10.5194/ESSD-9-697-2017.

Van Wagner, C.E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. C.E. Canadian Forestry Service, Headquarters, Ottawa. Forestry Technical Report, 35 (35 p).

Van Wees, D., Van Der Werf, G.R., 2019. Modelling biomass burning emissions and the effect of spatial resolution: a case study for Africa based on the Global Fire Emissions Database (GFED). Geosci. Model Dev. 12, 4681–4703. https://doi.org/10.5194/GMD-12-4681-2019.

Van Wees, D., Van Der Werf, G.R., Randerson, J.T., Rogers, B.M., Chen, Y., Veraverbeke, S., Giglio, L., Morton, D.C., 2022. Global biomass burning fuel consumption and emissions at 500 m spatial resolution based on the Global Fire Emissions Database (GFED). Geosci. Model Dev. 15, 8411–8437. https://doi.org/10.5194/GMD-15-8411-2022.

Vicente, A., Alves, C., Calvo, A.I., Fernandes, A.P., Nunes, T., Monteiro, C., Almeida, S. M., Pio, C., 2013. Emission factors and detailed chemical composition of smoke particles from the 2010 wildfire season. Atmos. Environ. 71, 295–303. https://doi.org/10.1016/j.atmosenv.2013.01.062.

Vilén, T., Fernandes, P.M., 2011. Forest fires in Mediterranean countries: CO_2 emissions and mitigation possibilities through prescribed burning. Environ. Manag. 48, 558–567. https://doi.org/10.1007/S00267-011-9681-9.

Volkova, L., Roxburgh, S., Surawski, N., Meyer, M., Weston, C., 2019. Improving reporting of national greenhouse gas emissions from forest fires for emission reduction benefits: an example from Australia. Environ. Sci. Pol. 94, 49–62. https://doi.org/10.1016/j.envsci.2018.12.023.

Ward, D.E., Peterson, J., Hao, W.M., 1993. An inventory of particulate matter and air toxic emissions from prescribed fires in the USA for 1989. In: Proceedings of the Air and Waste Management Association 1993 Annual Meeting. Denver, CO, p. 19.

Wiedinmyer, C., Hurteau, M.D., 2010. Prescribed fire as a means of reducing forest carbon emissions in the Western United States. Environ. Sci. Technol. 44, 1926–1932. https://doi.org/10.1021/es902455e.

Wiedinmyer, C., Kimura, Y., McDonald-Buller, E.C., Emmons, L.K., Buchholz, R.R., Tang, W., Seto, K., Joseph, M.B., Barsanti, K.C., Carlton, A.G., Yokelson, R., 2023. The Fire Inventory from NCAR version 2.5: an updated global fire emissions model for climate and chemistry applications. EGUsphere 2023, 1–45. https://doi.org/10.5194/egusphere-2023-124.

Wiggins, E.B., Andrews, A., Sweeney, C., Miller, J.B., Miller, C.E., Veraverbeke, S., Commane, R., Wofsy, S., Henderson, J.M., Randerson, J.T., 2021. Boreal forest fire CO and CH_4 emission factors derived from tower observations in Alaska during the extreme fire season of 2015. Atmos. Chem. Phys. 21, 8557–8574. https://doi.org/10.5194/acp-21-8557-2021.

Xu, L., Crounse, J.D., Vasquez, K.T., Allen, H., Wennberg, P.O., Bourgeois, I., Brown, S.S., Campuzano-Jost, P., Coggon, M.M., Crawford, J.H., DiGangi, J.P., Diskin, G.S., Fried, A., Gargulinski, E.M., Gilman, J.B., Gkatzelis, G.I., Guo, H., Hair, J.W., Hall, S. R., Halliday, H.A., Hanisco, T.F., Hannun, R.A., Holmes, C.D., Huey, L.G., Jimenez, J. L., Lamplugh, A., Lee, Y.R., Liao, J., Lindaas, J., Neuman, J.A., Nowak, J.B., Peischl, J., Peterson, D.A., Piel, F., Richter, D., Rickly, P.S., Robinson, M.A., Rollins, A.W., Ryerson, T.B., Sekimoto, K., Selimovic, V., Shingler, T., Soja, A.J., Clair, J.M.S., Tanner, D.J., Ullmann, K., Veres, P.R., Walega, J., Warneke, C., Washenfelder, R.A., Weibring, P., Wisthaler, A., Wolfe, G.M., Womack, C.C., Yokelson, R.J., 2021. Ozone chemistry in western U.S. wildfire plumes. Sci. Adv. 7, 3648. https://doi.org/10.1126/SCIADV.ABL3648.

Yi, K., Bao, Y., 2016. Estimates of wildfire emissions in boreal forests of China. Forests 7. https://doi.org/10.3390/f7080158.

Yue, X.L., Gao, Q.X., 2018. Contributions of natural systems and human activity to greenhouse gas emissions. Adv. Clim. Chang. Res. 9, 243–252. https://doi.org/10.1016/j.accre.2018.12.003.