UNIVERSITÀ DEGLI STUDI DI SASSARI

CORSO DI DOTTORATO DI RICERCA IN

SCIENZE AGRARIE

DIPARTIMENTO DI AGRARIA

AGROMETEOROLOGIA ED ECOFISIOLOGIA DEI SISTEMI AGRARI E FORESTALI

XXXII CICLO

TEMA DI RICERCA

ANALYSIS OF THE UNCERTAINTIES IN MODELING AND INVENTORING GREENHOUSE GASES AND PARTICULATES FROM VEGETATION BURNING FIRE EMISSIONS

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Anno Accademico 2018/2019

Summary

Abstract

Wildland fires are one of the most source of disturbances causing ecological degradation, contributing to ecosystem changes and affecting all biosphere components. They represent one of the most significant sources of emissions in atmosphere of trace gases and aerosol particles, with a significant impact on air quality, human health, operational safety, altering the carbon budget and affecting climate change. According to the equation first proposed by Seiler and Crutzen (1980), fire emission estimation use information on the amount of burned biomass, the emission factors associated with each specific chemical species, the burned area and the combustion efficiency. Still, simulating emission from forest fires is affected by several errors and uncertainties, due to the different assessment approach to characterize the various parameters involved in the equation. For example, regional assessment relied on fire-activity reports from forest services, with assumptions regarding the type of vegetation burned, the characteristics of burning, and the burned area. Over the last decades, several studies have focused on the estimation of global fire emissions of many gaseous and particulate species through the application of several methodologies. Improvements and new advances in remote sensing, experimental measurements of emission factors, fuel consumption models, fuel load evaluation, and spatial and temporal distribution of burning are a valuable help for predicting and quantifying accurately the source and the composition of fire emissions.

but despite new advances in modelling and improvement of the knowledge of fires and the connected emissions have been made, due to the use of different approaches and datasets used for fire emissions components, several uncertainties and errors still exist, and a multi-year comprehensive inventory of the fire incidence and inherent fire emissions in Italy is missing.

In this work, we first carried out a comprehensive literature of fire emission, highlighting the principal methodologies and related uncertainties. Then, we estimated the FE derived from fires that occurred in Italy during the period 2007-2017, using an integrated methodology combining a fire emissions model with spatial and non-spatial inputs related on fire characteristics, vegetation and weather conditions. Finally, through the analysis of six forest fires occurred in Italy at particular severe conditions during 2017, we evaluated

the main sources of uncertainties in the estimation of fire emissions combining two fire size information sources, and two methods for identifying fire severity and thus fuel consumption.

This study provides insight to better inform a long-standing fire incidence in Italy and the resulting effects. Our results are valuable for providing data for emissions source models coupled with dispersion models and decision support systems, crucial for air quality managements, mitigation of wildland fire environmental effects, and to assist decision makers in prescribed fire activities in order to help the development of more accurate emissions inventories at a national scale and in the framework of Kyoto Protocol reporting activities for the LULUCF (Land Use, Land Use Change and Forestry) sector.

General Introduction

Wildland fires are a disturbance process causing ecological degradation, contributing to ecosystem changes and affecting all biosphere components. The emissions of greenhouse gases and particulates derived from biomass combustion are known to be one of the main threats for the atmosphere, being associated with public health, environmental and economic problems, and affecting climate change. Recently, new advances by modelling and measurement efforts have been made in order to improve the knowledge of the effects of vegetation burning in the atmosphere and its estimation. Several studies have been conducted in the temperate zone and southern Europe in order to improve the knowledge of forest fires and the connected emissions. However, due to the use of different approaches and datasets used for fire emissions components, several uncertainties and errors are still present, and a multi-year complete inventory of the fire incidence and inherent FE in Italy is missing.

In this context, we first carried out a comprehensive literature of fire emission, highlighting the principal methodologies and the related uncertainties. Then, we estimated the FE derived from forest fires occurred in Italy during the period 2007-2017, using an integrated methodology combining a fire emissions model with spatial and non-spatial inputs related on fire characteristics, vegetation and weather conditions. Finally, we examine six large forest fires occurred in Italy (2017) as case studies for comparing alternative data sets to evaluate the main sources of uncertainties in the estimation of fire emissions; specifically, we use two fire size information sources and two approaches to define fuel moisture and combustion completeness. Finally, emissions data (trace gas and particulate) distribution for inputs combination were examined and compared.

This study provides a helpful way to a better understand fire incidence in Italy and the resulting effects. Our results are valuable for providing data for emissions source models coupled with dispersion models and decision support systems, crucial for air quality managements, mitigation of wildland fire environmental effects, and to assist decision makers in prescribed fire activities in order to help the development of more accurate emissions inventories at a national scale and in the framework of Kyoto Protocol reporting activities for the LULUCF (Land Use, Land Use Change and Forestry) sector.

Chapter 1: Overview on wildland fire emission: impacts and uncertainties

1. *Introduction*

Wildland fires play a crucial role in the release of terrestrial carbon, and are an important source of emissions in atmosphere of trace gases and aerosol particles, with a significant impact not only on air quality, human health, operational safety, but also on local, regional, global carbon budget and climate change (Miranda et al., 2014; Randerson et al., 2006; Urbanski et al., 2011).

The main chemical compounds emitted by forest fires are carbon monoxide (CO) and dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), ammonia (NH_3), non-methane hydrocarbons (NMHC), and particulate matter (PM) (Miranda et al., 2008; Ward et al., 1993; Reinhardt et al., 2001). CO_2 and CO, responsible for about 90–95% of the total carbon emitted (Andreae and Merlet 2001), are the dominant fractions released. The remaining 5–10% of carbon emitted is represented by carbonaceous aerosol (35%), nitrogen oxides (20%), and CH_4 (6%) (IPCC 2001). The fraction of carbon emitted as particulate matter ($PM_{2.5}$ and PM_{10}) is less than 5% (Reid et al., 2005). Hydrocarbons and nitrogen oxides can lead to the formation of ozone in smoke plumes, acting as short-lived climate forcing (Urbanski et al., 2011; Naeher et al., 2007; Ghan et al., 2012), while smoke aerosols affect radiation budget due to the absorption effect, influence on cloud formation and microphysical processes (Jacobson, 2014; Seinfeld et al., 2016).

Fires emit air pollutants and particulates in many regions of the world, contributing to the air degradation (Miranda et al. 1994; Schollnberger et al., 2002; Simmonds et al., 2005; Hodzic et al., 2007), representing likely the main factor affecting the interannual variability of the atmospheric composition (Shultz et al., 2008) and a source of environmental and health problems, as well as also being a source in the atmosphere for toxic products such as mercury (Friedli et al., 2009) and dioxins (EFSA, 2012).

The exposure to smoke pollution due to forest fires can have significant impact on human populations and to the personnel involved in firefighting operations, including infliction of burns and eye irritation from smoke, up to loss of lives (Coghlan, 2004, Brustet et al., 1991; Miranda et al., 1994, 2005c; Reinhardt et al., 2001; Valente et al., 2007; Ward et al., 1996).

The now evident high incidence and impacts of fires on the environment from fire emissions throughout the world started to be identified only at the end of 1970s (Seiler and Crutzen, 1980), and is now a subject of concern for a variety of people, from the decision-makers to citizens in general (Miranda et al., 2014), and leading through the last decades to an increased demand for quantification and description of fire emissions (FE). This can be attributed to several motivations, such as the need to a better knowledge on the sources of air pollution responsible for human health problems, the increased regard of governments and agencies on GHG emissions (Bell and Adams, 2009) and also the need to integrate the analysis and modelling of air quality and climate change issues (Granier et al., 2011; Urbanski et al., 2011).

Over the last decades, several studies have focused on the estimation of global fire emissions of many gaseous and particulate species through the application of several methodologies (**Errore. L'origine riferimento non è stata trovata.**). In 2001, Sandberg e t al. indicated that FE correspond to almost one fifth of the global amount of CO_2 emissions; Smith et al. (2004) estimated a 38% contribution of atmospheric CO_2 emissions from biomass burning and 62% was estimated to be caused by fossil fuel combustion. Pétron et al. (2004) estimated the contribution of biomass burning at 50% of the total surface CO emissions, whereas the contribution of surface NOx emissions has been estimated at about 15% (IPCC, 2001). Van der Werf et al. (2010) described the global contribution of fires on global amount of carbon combusted, corresponding to 22% of the global fossil emissions (the largest contribution for total emissions was related to African fires, corresponding to 49% of total emission). Wiedinmyer et al. (2011) indicated that during 2008, the contribution of biomass burning accounted for 33% of the global CO emissions.

Van der Werf et al. (2006) estimated global emissions using different detecting burned area methods on the basis of the availability of satellite information. They estimated average annual emissions per unit burned area at 2.22 kg C m^{-2} and 0.52 kg C m^{-2} for forest and herbaceous cells, respectively. They also estimated that, for the period 1997-2004, fire emissions were 4.4% of the global total carbon loss, calculated as the net flux between net primary production (NPP), heterotrophic respiration (Rh), and biomass burning. Langmann et al. (2009) estimated the annual global distribution (from 1997 to

2006) of carbon released from vegetation fires (Figure 1), deriving the data from the Global Fire Emission Database, version 2 (van der Werf et al., 2006).

Smith et al. (2014) described the anthropogenic emissions of non-CO_2 gases from peat and forest fires at 300 million t CO_2 eq yr^{-1} (on average for the period 2001-2010). Furthermore, Tubiello et al. (2014) estimated a further 200 million t CO_2 eq yr^{-1} to be added due to prescribed burning of savanna.

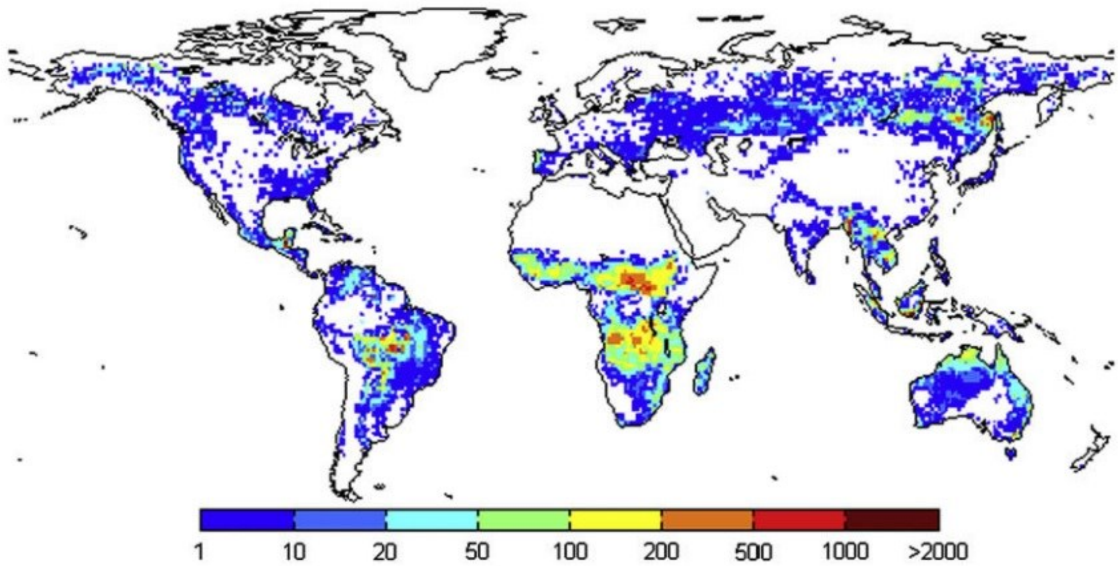

Figure 1 – Average annual emissions for the period 1997-2000 (g C m^2 $year^{-1}$). (From Langman et al., 2009)

Table 1 Description of annual global average emissions derived from several studies

Work	Period analysed	Total emissions Tg C year^{-1}	Tg CO^2 year^{-1}	Tg CO year^{-1}
Andreae and Merlet (2001)	1990s		7,864	423
Duncan et al. (2003)	1996-2000			429
Van der Werf et al. (2003)	1998-2001		7,634	
Van der Werf et al. (2004)	1997-2001			289
Hoelzemann et al. (2004)	2000	7,800	5,716	271
Ito and Penner, (2004)	2000		2,290	496
van der Werf et al. (2006)	1997-2004		8,903	433
Jain et al. (2007)	2000		7,828	502
Van der Werf et al. (2010)	1997-2009	2,000	500	
Mieville et al. (2010)	1900-2005		9,235	
Wiedinmyer et al. (2011)	2005-2010	8,039	7,330	377

Over recent decades new advances in modelling and measurement efforts have been made to improve the knowledge of effects of vegetation burning on the atmosphere, especially through new advances in satellite remote sensing data, the creation of new biogeochemical models to estimate biomass loading, experimental measurements of emissions factors and fuel consumption models. Despite this, large uncertainties related to spatially and temporally vegetation fire emissions remain.

Langmann et al. (2009) gave an overview of vegetation fire emission, their impacts on the environment and on climate, highlighting the improvement expected for the near future.

This present work builds on that review, updating the contemporary state of the research concerning emissions from forest fires. Firstly, section 2 provides information about the products from fire emissions and their impact on air pollution, air quality and climate. Section 3 presents the main approach to estimate fire emissions discussing the uncertainties related to the different contributing factors. In section 4, the main models to estimate fire consumption and smoke emissions are compared and discussed.

2. Fire products in the atmosphere

The composition and quantities of gaseous and particulate pollutants released in the atmosphere from the combustion of vegetation depends on combustion conditions and the fuel composition (Lobert and Warnatz, 1993; Andreae and Merlet, 2001). When the fuel is ignited it is subject firstly to a thermal degradation, followed by pyrolysis (Yokelson et al., 1996) and then by the phases of combustion.

While the primary component of fire emissions is CO_2 (Andreae and Merlet, 2001; Wooster et al., 2011), the smoke is a complex mixture. All components, except for CO_2 and H_2O, are generated by the incomplete combustion of the biomass, and the emissions vary in different proportions depending on the type of event. These include organic compounds containing traces gas (CO, CH_4, C_2H_6, C_2H_4), higher alkanes and alkenes (CH_3OH), higher alcohols (HCHO), and other aldehydes and organic acids (Andreae and Merlet, 2001). In addition, vegetation burning emit nitrogen-containing compounds (NO_2 + NO, N_2O, HCN), sulfur-containing compounds (e.g. SO_2), and halogen-containing compounds (e.g. CH_3Cl, CH_3Br). Yolkenson et al. (2013) identified over 200 gases in fresh smoke, the majority of which are NMOC (non-methane organic compounds). Indeed, an area of active research concerning FE is about the identification of this type of compounds, which are believed to play an important role in the formation of aerosol (Warneke et al., 2011).

Particulate matter consists mainly of organic material. Over 90% of the particulate mass is smaller than 10 µm in diameter (PM_{10}), and 2/3 of these are characterized by diameters of less than 2.5 µm ($PM_{2.5}$). Most of this particulate matter is organic aerosol (OA), black carbon (BC), and inorganic aerosols. Depending on fire type and burning conditions, the 5-20% of $PM_{2.5}$ mass can be attributed to the above mentioned last two components (Reid et al., 2005). Alves et al. (2011) indicated the need of additional studies to define presence of trace metals and water-soluble ions in particulate matter as potential tracers of biomass burning.

2.1. Air pollution, air quality, and health effects

Characteristics of wildfires, such the amount, location and the prevalent meteorological conditions, can strongly influence the atmospheric composition and thus the air quality (Langmann et al., 2009). For example, fires which occur in extreme conditions have larger burned areas, difficult to control and larger atmospheric emissions (Adame et al., 2018).

As fire emissions are transported through the atmosphere, they reduce visibility in the proximity of fires (Valente et al., 2007). Furthermore, the impacts of fire emissions on air quality span across scales, affecting trace gas and particulate matter beyond the fire activity region (Crutzen and Carmichael, 1993; Thompson et al., 1996; Miranda et al., 2009). Fire has significant impacts on regional CO pollution level. For the Mediterranean Basin, Adame et al. (2018) found that during the large fire that occurred in Doñana Natural Park (24 to 26 June 2017, Spain), CO and PM_{10} concentration at the station of Seville (70 km away from the fire) were 2,032 μgm^{-3} and 100 μgm^{-3}, respectively (Figure 2).

The interactions of CO, CH_4 and higher organic hydrocarbon compounds with nitrogen oxides lead to tropospheric ozone formation, O_3 (Wiedinmyer et al., 2006; Langmann et al., 2009), and the hydroxyl radical, OH, which represent major atmospheric oxidants. Using regional atmospheric chemistry models, WRF-Chem and EMEP MSC-W, Hodnebrog et al. (2012) demonstrated the large influence of fires occurred in southeast Europe on ozone production during the summer 2007; they showed that ozone pollution levels went up to 18 ppbv near the centre of the plume during the hottest season, as a consequence of fire impacts. On the other hand, Martins et al. (2012) examined the 2003, 2004 and 2005 fire seasons in Portugal using a numerical modelling approach and found a significant impact of forest fires on PM_{10} concentrations while on O_3 formation was not evident.

Concerning fire contribution to aerosol pollution, Bougiatioti et al. (2014) found that biomass burning from Greek islands and other Mediterranean locations in summer 2012 contributed almost half of the organic aerosol mass on the island of Crete (Figure 3). Diapouli et al. (2010) showed an increased aerosol concentration of 40-50% (on average) in Athens (Greece), due to large fires occurred in August 2010 in Russia and Ukraine. In Spain, Reche et al. (2012) demonstrated biomass burning to account, on an annual basis, for about 20% of organic carbon levels in PM_{10} and $PM_{2.5}$. Fire aerosols can also cover intercontinental scales, as have been demonstrated by Forster et al. (2001) showing with Lidar measurements discovered that fires in Canada contributed to the increase of aerosol concentration in Europe. Kaskaoutis et al. (2011) showed that the higher values of MODIS-derived Aerosol Optical Depth were attributed to the combined effect of smoke and dust aerosols for fires occurring in Greece during 2007. Alves et al. (2011), through a collection of a set of measurements (from gas-phase to the particulate-phase emissions) for fires occurred in Portugal during 2009, showed that, on average, the organic carbon concentrations were 10 times higher in $PM_{2.5}$ than in $PM_{2.5-10}$, and particulate mass was composed of 50% organic carbon. The presence of particulate pollution from forest fires is linked to weather conditions. In particular, during summer factors such as low humidity and high wind speed lead to an increase of fire occurrence with a consequently increase of dust and pollen resuspension (Coutinho et al., 2005).

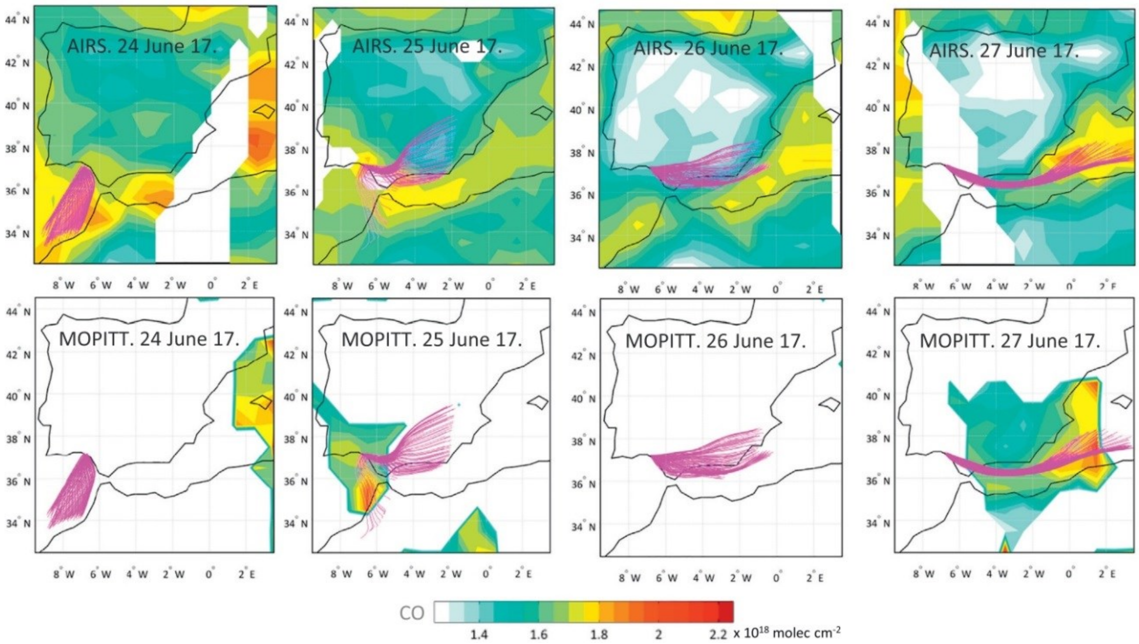

Figure 2 – 24-27 June 2017 CO columns progression obtained from two satellite detection (AIRS and MOPITT) combined with the trajectories obtained with the HYSPLIT model through ERA-Interim meteorological fields (0.125° × 0.125°). (From Adame et al., 2018).

Figure 3 – MODIS image of the Chios fire (18 August 2012) (From Bougiatioti et al., 2014)

A study conducted in the city of Porto, using the HYSPLIT model, identified the annual contribution of PM_{10} pollution from fires during 2001, 2002, and 2003, showing that they contributed 35%, 8%, and 18%, respectively (Borrego et al., 2005). Moreover, Miranda et al. (2009) showed that the Lisbon urban area on 13 September 2003 was characterized by the biggest amount of CO and PM_{10} emissions, corresponding to the same day during which 33 fires occurred, burning about 400 hectares of forest and shrublands.

Recently, Adetona et al. (2016) reviewed the fire smoke health effects in the general public through both epidemiological and experimental studies. The results highlighted that cardiovascular and/or respiratory impacts are the most relevant, especially to people affected by pre-existing diseases. Analitis et al. (2012) referred about an increased mortality due to respiratory illness associated during the fire occurrence in Athens (Greece).

Miranda et al. (2010) monitored fire-fighter exposure to gases and PM through personal portable devices during the Gestosa experimental fires (Portugal). The analysis of values acquired during the fire experiments evidenced that air pollutant concentration was beyond the limits recommended by the World Health Organization (WHO), namely for $PM_{2.5}$, CO and NO_2. Dorman and Ritz (2014) characterized the respiratory and systemic effects of smoke exposure in wildland firefighters, showing that the smoke exposure promote an inflammatory response, with a peak through the first week after exposure, diminishing within the second week.

2.2. Climate interaction

Fire emissions particles can affect atmospheric radiative transfer through three mechanisms. The first is known as “direct radiative forcing” (Charlson et al., 1992), meaning that smoke particles can impact on both shortwave and long-wave radiation through scattering and absorbing solar radiation. Second, through a mechanism called “indirect radiative forcing”, smoke particles can serve as CCNs (cloud condensation nuclei), thus modifying the microphysical, the radiative properties, the amount and the lifetime of clouds. The third mechanism is called “semi-direct radiative forcing”, and refers to the impact of radiative forcing, both direct and indirect, on the atmospheric structure, circulation, and energy exchange on the ground.

Aerosols could indirectly affect climate by increasing cloud albedo and cloud lifetime (Lohmann and Feichter, 2005). As shown by Kaskaoutis et al., 2011, CNN derived from an intense smoke plume might have important impacts on the regional climate in a limited time interval. At the same time, the absorbing aerosols could warm the atmosphere and lead to suppression of precipitation due to evaporation of clouds.

For these mentioned aspects, fire occurrence and climate are doubly related: fire emissions, with the modification of surface albedo, cause changes of the vegetation cover, which modify locally surface albedo, surface evaporation and the capacity of soil to hold water, causing feedbacks with the climate. At the same time, the variation of climate modifies fire occurrence (Langmann, 2009).

Another aspect is represented by the way fuel is consumed. On this depends the emissions of specific components, particularly greenhouse gases, black carbon and organic carbon. These emissions can affect the radiative properties of the atmosphere, leading for example to the increase of ice melting when black carbon is deposited on the ice or snow (Sand et al. 2013; Ramanathan and Carmichael, 2008; Flanner et al., 2007)

3. Quantification of forest fire emissions and uncertainty sources

The estimation of FE can be estimated from the variables area burned (BA, ha), the fuel load (F_l, t ha^{-1}, namely the amount of biomass available for burning), the combustion completeness (CC, %, the fraction of fuel consumed during burning), and the emissions factor (EF, namely the amount of specific trace gas released typical for each vegetational species). The combination of these elements is shown in the equation 1, formulated by Seiler and Crutzen (1980).

$$FE_i = BA \cdot F_i \cdot CC \cdot EF_i \qquad \text{Equation 1}$$

This method has been applied, simplified, integrated and adapted by several authors for different studies from global to local scale (e.g. Battye and Battye 2002; French et al. 2004; Narayan et al. 2007; Wiedinmyer and Neff 2007; Shultz et al. 2008; Wiedinmyer et al. 2010; Thonicke et al. 2010; Carvalho et al. 2011) and represents the basis on the estimation of FE.

Based on the assumption of Hardy et al (2001), the generation of fire emissions derived from wildland fires depends on the incomplete combustion of fuel. The component factors of the equation are considered highly correlated, indeed Shultz et al. (2008) showed the correlation between larger fuel loads and large burned areas, especially on a regional scale, but also highly uncertain. For this reason several studies have been focused on the analysis of their uncertainties.

According to Ottmar (2009a), the largest errors and uncertainties are associated with fuel load and fuel consumption (Figure 4).

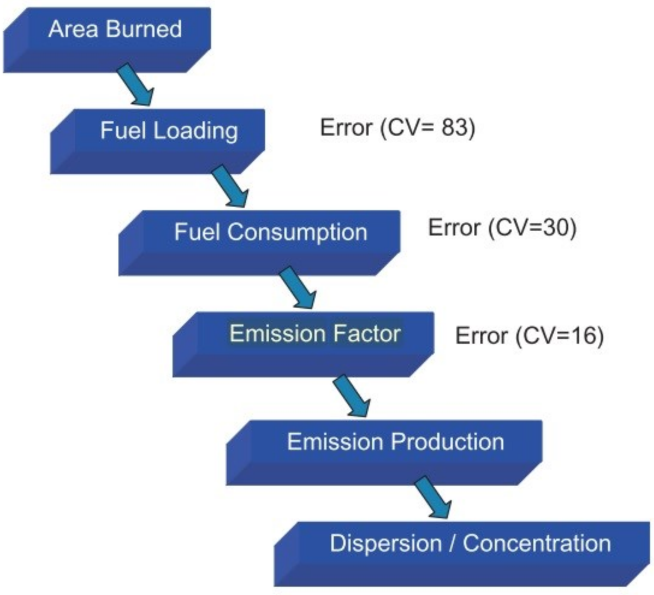

Figure 4 – Factors involved in combustion and emissions processes (CV = Coefficient of Variation). From Ottmar et al. (2009a)

In the boreal regions, most of uncertainties are related to fuel and fire conditions, because they are difficult to measure than the relative ease of mapping fire perimeters large boreal fires (French et al. 2004). Schultz et al. (2008) pointed out BA as the most limiting factor for accuracy, especially if mapping depends on satellite data coarse resolution. Rosa et al. (2011), established that the most related factors to uncertainties in FE are combustion factors and emissions factors for shrublands and grasslands. Moreover, other authors indicated BA, EF and F_l as the most related factors to uncertainties in long-term FE datasets (Battye and Battye 2002; Schultz et al. 2008; Peterson 1987; Peterson and Sandberg 1988).

Given the dissimilarities between several datasets, the discovery and representation of the variability of the above-mentioned factors is a challenge in FE inventories production (Langmann et al. 2009).

3.1. Burned area

Information about burned area (BA) supply a direct estimate of the fire size and emissions losses, all necessary to apply equation 1 (Randerson et al., 2012). Langmann et al. (2009) observed that, together with fuel load, most of the uncertainties for the estimation of vegetation FE are related to burned area. Peterson (1987) identified the relation between large systematic errors in BA evaluation and the reporting system used. Other authors examined the differences and uncertainties of BA on FE estimation using different satellite-based BA products. Particularly, Korontzi et al. (2004), which analysed three satellite spatial datasets and the connected emissions, found differences due to the BA products and to land cover type. Similarly, Al-saadi et al. (2008) showed discrepancies between biomass burning emissions estimates derived to four spatio-temporal satellite data in near real-time. Bacciu et al. (2015a), comparing different inventories of emissions from forest fires, showed that the differences between the various inventories were mainly due to the different datasets used to estimate burnt area.

Even though several burned areas and active fire datasets have been built thanks to the new advances in remote sensing, the identification of burned areas by satellite is still characterized by inaccuracy and inconsistency across the world, and is restricted to certain regions. (Langmann et al., 2009). Some limitations specific to satellite products, for example failure to acquire images, low satellite frequency over a given area or low spatial resolution, can be a source of further uncertainty.

BA mapping from satellite imagery detects the changes from a vegetated surface to another characterized by bare soil, ashes and char (Roy et al.,1999). Its precision is related to scale, which depends on the presence of mixed pixels (Boschetti et al., 2004). For example, with 500m spatial resolution MODIS data (Giglio, 2013), it can be difficult to identify small fire perimeters, which have been demonstrated to contribute about 35% of total burned area and total emissions on global scale, and considerably to the total amount of carbon emissions from tropical forest regions (Randerson et al., 2012). Moreover, the exclusion of small fires can lead to the elimination to the total burned area of prescribed or agricultural fires, derived for example from the burning of crop residues, even though their contribution is estimated to be minimal (Hawbaker and Zhu, 2012). Another difficulty related to the remote sensing mapping is the ability of the sensor to distinguish burned and unburned areas, especially if an unburned overstory canopy obstructs the detection of a burned understory (Cocke et al., 2005). Moreover, detecting data can be strongly be constrained or confused by the presence of clouds (Stroppiana et al., 2010).

Rosa et al. (2011) during a work based on the twenty years greenhouse gas estimation in Portugal, used satellite high resolution imagery data combined with field measurements, growth vegetational models and literature data for the detection of burned area. Information from National Forestry Inventory helped to distinguish more forest types than those shown by land cover maps. A study conducted by Humber et al. (2019) through an intercomparison between some global burned area products for the period 2005-2011, showed the temporal and spatial output differences in detecting area by satellites. They concluded that is necessary to standardize, validate and identify these satellite-derived burned area products, accuracies and errors, in order to allow users to access and choose the best data for other purposes.

The other method for the identification of burned area at the local level is the use of a Global Positioning System (GPS). This can be mounted on a helicopter or held by the suppression personnel who walk through the edges of the fire, in order to trace and obtain the burn perimeter. Once the perimeter has been acquired, the sequent step is the calculation of the burned area using a Geographic Information System (GIS). For this method, for which success are important the skills of the personnel involved and the precision of the available equipment, the main problems and limitation are represented by personnel safety, low visibility caused by smoke, vegetation cover and shadow effects, both for aerial and ground mapping (Kolden and Weisberg, 2007). For this reason, inaccuracy in mapping due to the roughness of the soil or to difficulties in traversing, and boundary mapping error due to the safety considerations walking near the fire perimeter, represent potential sources of error related to this method (Kolden and Weisberg, 2007), together with the heterogeneity of burning and the presence of unburned islands inside the fire perimeter which can occur with both methods (Eberhart and Woodard, 1987; Kolden and Weisberg, 2007; Kolden et al. 2012; Roman-Cuesta et al., 2009).

A study conducted by Srivastava et al. (2013) in the Fraser island of Australia, compared the two mapping methods for two decades of data. Manual mapping data was acquired by the delineation of fire perimeters on topographic maps, and afterward they may have been digitised on GIS. Results showed big differences between the two methods, with the mean fire extent derived by manual mapping three times bigger than Landsat imagery. Conversely, the mean perimeter size derived from Landsat mapping was bigger by more than eight times the manually derived data.

3.2. Fuel loading

The estimation of fuel biomass is important for fire management and the prediction of fire behavior and severity; the quantification of the combustible can be made through the integration of the estimates with observed values (Gray and Reinhardt, 2003).

Fuel load (F_l) represents the amount of fuel available in a unit area. Factors such as vegetation, climate, soil type and disturbances determine the fuel load.

Dependent on fuel type, F_l can be estimated through several techniques, such as fuel collecting and weighting (more frequent for grasses and shrubs), the biomass estimation through the combination of measurements and the application of pre-derived equations (Brown, 1974), the estimation of F_l through the use of natural photo series (Ottmar et al., 1998, Ottmar and Vihnanek, 2000a); or national classification methods like the Fuel Characteristic Class system (FCCS) developed for the United States fuelbed types

(Sandberg and Ottmar, 2001).

Fuel load dictates the amount of heat released during a fire, while the combustibility depends on the distribution, type and state of fuel. The ease of ignition depends on size, because fine fuel moisture changes more easily with weather changes, and varies between dead and live fuel, of which the latter can burn less readily due to its higher moisture content (Gambiza et al., 2005, Baeza et al., 2002). Moreover, completeness of combustion depends on moisture content (Bilgili and Saglam, 2003; Helly et al., 2003). Fuel loading is directly connected to the amount of emissions, and for this reason actions addressed to reduce the amount of fuel, such as prescribed burning, lead to the production of less emissions (Hardy et al. 2001). At the same time, large variability of fuel load among ecosystems and type of vegetation, makes F_l the largest contributor of errors connected to FE estimates (Hardy et al., 2001; Peterson, 1987; Peterson and Sandberg, 1988).

For example, Dimitrakopoulos (2002) with the aim of creating fuel models for Mediterranean vegetation types in Greece, described the high variability of fuel load ranging from 4.85 t ha^{-1} of grasslands to 53 t ha^{-1} of evergreen sclerophyllous shrublands (fuel depth: 1.5-3 m). Sağlam et al. (2008) pointed out the variability of total fuel load for some shrub species in Turkey from 10.6 t ha^{-1} to 77.2 t ha^{-1}, whereas other studies (Basanta et al., 1988; Soto et al., 1997) conducted in Atlantic gorse shrublands reported a range between 20 t ha^{-1} and 60 t ha^{-1}. Duce et al. (2012) pointed out the high fuel load variability in the Mediterranean maquis shrubland, ranging from 2.7 Mg ha^{-1} (low and sparse maquis) to 13 Mg ha^{-1} (high and dense maquis).

Other attempts of better understanding the spatial variability of fuel load has been the estimation of global FE through a satellite-driven biochemical model (van der Werf et al. 2006), or the use of a model coupled with global ecosystem dynamics, in order to explore the emissions associated to fire regimes (Thonicke et al. 2010).

Fuel load can also differ between seasons, due to the vegetation productivity, decomposition rates and fire occurrence. The variability of fuel driven by climate can improve the quality of estimates, but sometimes is related to lack of highly spatially and temporally resolved observations which leads to not fully consider its variability and use instead of a time constant fuel load (Lasslop and Kloster, 2015).

Lasslop and Kloster (2015) applied a vegetation model as a tool to investigate the influence of fuel variability on fire carbon emissions. The identification of available fuel load was the amount of modelled tree biomass and the seasonality of fraction of absorbed photosynthetic radiation obtained by satellite data-based datasets. Fuel loading variability results showed a higher reliability of the changes derived to plant functional type than that obtained by seasonal changes.

There have been many efforts to estimate the contribution on emissions of different types of vegetation. Mieville et al. (2010) estimated that the 52% of contribution on total emissions was related to savanna burning, 45% to forest fire and only 3% was related on cultivated area fires. Similar proportions were declared by Shi et al. (2015) with a work based on comparison between different CO_2 global datasets emissions.

3.3. Combustion completeness

The Combustion Completeness (CC, %), also known as Burning Efficiency or Combustion Efficiency, is the third essential component needed for the estimation of the quantity and source of emissions (Ottmar et al., 2009a; Shea et al., 1996). It is defined as the ratio of carbon released as CO_2 on the total carbon present in the fuel and represents the live or dead vegetative material pyrolyzed or combusted when a fire occurs.

CC depends on fuel type characteristics such as its moisture content, plant's age and phenology, fire characteristics such as the fire line intensity, rate of spread and flame residence time (Langmann et al., 2009; Battye and Battye, 2002; Ward D. E. et al., 1996, Rosa et al., 2011) and also on the variation of factors such as the type of vegetation, the amount of fuel available to burn (dependently on the categories of each vegetation type) and the combustion factor, specified as the amount of fuel combusted for each fuel type (Ito and Penner, 2004).

For example, the moisture content is inversely proportional to the time needed to consume fuel (Dimitrakopoulos and Papaioannou, 2001; Pellizzaro et al., 2007; Xanthopoulos and Wakimoto, 1993; Sandberg and Ottmar, 1983; Brown et al., 1991, Hoffa et al., 1999) and for this reason, seasons have an influence on CC, especially for fine than coarse ones; the compactness of the fuel bed influences its oxygenation and heat transfer, affecting the fuel continuity, both horizontal and vertical, which determines if fuels are close enough to ignite one another (Ottmar, 2014).

Moreover, the characteristics of fuel mentioned before and the environmental factors that influence CC such as wind speed, slope and seasons (Wright, 2013; Wright, 2015, Wright and Prichard, 2006) affect fire behaviour, severity, the completeness of combustion, the duration of combustion phases and consequently the resulting total greenhouse gas and aerosol emissions.

Seiler and Crutzen (1980) indicated a global average of burning efficiency of about 50%, with peaks of 75% in savanna, where drought season is longer and there is a majority of small-sized vegetation.

Detailed descriptions of CC have been provided through the description of the combustion factors based on fuel strata and moisture conditions (Hardy et al., 2001; Reinhardt et al., 1997; van der Werf et al., 2006, Martins et al., 2012).

As specified before, CC represents the fraction of carbon released from the fuel combustion in the form of CO_2, and is calculated on the basis of the composition of the gases released by fire compared to clean air composition. This is due to the fact that >90% of the carbon combusted in a fire is emitted in the form of CO_2 and CO, and <10% of carbon is released in species such as hydrocarbons and particulate carbon (Alves et al., 2011).

Biomass component	Combustion factor (%)	Reference
Litter	100	Cinnirella et al. (2007)
	59 to 92	Ormeño et al. (2009)
	90 to 100	van der Werf et al. (2006)
	93	Stephens and Finney (2002)
	50 to 70	Arora and Boer (2005)
	63	Botelho et al. (1994)
	47.6 to 86.7	De Luis et al. (2004)
	58.9 to 86.7	Fernandes et al. (2000a)
Shrubs	60	Cinnirella et al. (2007)
	50	Narayan et al. (2007)
	83	Botelho et al. (1994)
	88.4 to 95.4	Fernandes et al. (2000a)
	16 to 100	Fernandes et al. (1998)
Leaves	100	Cinnirella et al. (2007)
	80 to 100	van der Werf et al. (2006)
	70 to 80	Arora and Boer (2005)
Fine branches	50 to 65	Cinnirella et al. (2007)

Figure 5 – Combustion factor for each vegetation fuel strata of temperate ecosystems, obtained by a review of literature (from Rosa et al., 2011)

A way to evaluate CC is represented by the use of the satellite observations of fire radiative power, which has been demonstrated to be a linear relationship with fuel consumption (Wooster, 2002); however, this method can have increased uncertainties due to low spatial resolution and the related lacking in fire-detecting (Wooster et al., 2005).

Several works determined fuel consumption values on the basis of previous experiments with prescribed fuel load (Lasslop and Kloster, 2015), or through the application of combustion models built on the basis of field measurements combined with satellite-based information of tree cover and leaf area index (Ito and Penner, 2004). Strand et al. (2016) computed CC in relation to the combustion phases, called modified combustion efficiency (MCE), concerning the ratio between CO_2 and the sum of CO and CO_2 concentrations derived to previous measurements.

Recently, Chiriacò et al. (2013) evaluated the different methods used by Southern European nations to estimate the completeness of combustion in the context of the development of national greenhouse gas inventories. The Spanish approach, for example, foresees that completeness is 100% when it comes to estimating CO_2 production, and 20% in the case of non-CO_2 products (ES NIR 2011). Another approach envisages instead that the biomass fraction is obtained by multiplying the burned area (classified in forest vegetation classes) by the level of damage that is determined on the basis of the vegetation class and the height of the flame (Bovio 2007). This last method, continues Chiriacò et al. (2013), reduces the uncertainty in the estimation of the completeness of the combustion since it takes into consideration its space-time variability and seems to be promising to respond to international requests for estimating emissions from forest fires.

3.4. Emissions factor

The Emissions Factor for a chemical species x (EF_x) is the mass of a chemical species, a gas or aerosol (M_x, g), produced per amount of dry vegetation consumed by burning (M_b, kg). It is expressed in grams emitted per kg of mass burned, as explained by the Equation 2.

$$EF_x = \frac{M_x}{M_b} \qquad \text{Equation 2}$$

EF depends on the fuel type, its composition, and the chemical and physical processes that occur during the combustion of the vegetation. Particularly, because each type of vegetation differs in structure and composition, the duration of combustion phases differs between vegetation types, leading to different emissions factors, but often these characteristics are poorly determined (Andreae and Merlet, 2001; Liousse et al., 2004). Indeed, EF varies depending on the following factors: fuel type, type of fire and phases of the fire, particularly flaming or smouldering (Hardy et al., 2001).

A general trend shows that fire efficiency increases when fuel is thinner, and the increase of CO_2 emission factor lead to a decrease of emissions factors of the chemical species in reduced form (van der Werf et al., 2006). Emission factors differ between biomes (Andreae and Merlet, 2001) and seasons, probably due to the period of fire occurrence (van der Werf et al., 2006) and by water content and weather (Korontzki et al., 2003).

Typically, uncertainties related to EF are about 20-30% for the most frequently measured chemical species, such as CO, but the percentage increases for compounds or biomes that have not been sufficiently analysed (Langmann et al., 2009). For example, because CO is an indicator of smouldering combustion, its emissions factor is often used to estimate emission factors of other products of incomplete combustion (Battye and Battye, 2002); this leads to the increase of the uncertainties for these other chemical species, due to their estimation instead of their direct measurement.

The EF variability for the flaming and smouldering phases is about 16% of the total errors of the predicted emissions. This uncertainty is particularly dependent on the fuel type, combustion efficiency and the pollutant species (Peterson, 1987; Peterson and Sandberg, 1988). Ward and Hardy (1991) emphasised the advantages of considering flaming and smouldering phases, with their relative combustion efficiency, to better estimate FE. Also, Ottmar et al. (2009a) pointed out that the larger amount of FE is emitted by fires that burn primarily in smouldering combustion despite the emissions derived from fires characterised by flaming combustion, showing the importance of separating the emissions derived from these two combustion phases.

Also, a general trend consists in releasing the larger fraction of chemical oxidized species, such as CO_2 and NO_x, during the flaming phase of the fire, whereas during the smouldering stage it has been observed the release of chemical species in the reduced form, such as CO, NH_3 and non-methane volatile organic compounds (NMVOCs) (Schultz et al., 2008). Moreover, other studies showed the way to separate the two phases, through the introduction of the fractional rate of the complete combustion. They indicated that flaming phase is characterised by a combustion efficiency higher than 90%, whereas values of CE smaller than 85% point at smouldering phase (Yolkenson et al., 2007; Ward and Hardy,1991).

Since the 1980s several studies on EF, such as biomass burning experiments and field measurements, have been made for several ecosystems (Andreae and Merlet, 2001). This led to a large variety of fragmented data on several types of vegetation and ecosystems.

In 2001, Andreae and Merlet presented a set of Emissions Factors for a broad variety of chemical species emitted from biomass burning and for an assortment of vegetation involved by fire, such as savanna, grassland and tropical forest.

The majority available EF data information is from the rainforest and savanna in Africa (Lacaux et al., 1995; Hao et al., 1996; Delmas et al., 1999; Swap et al., 2003) or in Brazil (Crutzen et al. 1985; Kaufman et al., 1998; Yokelson et al., 2007).

A recent work conducted in the United States on biomass burning emissions from 71 fires compared the emissions field measurements of prescribed fires with laboratory measurements, to identify EFs of several chemical species for different vegetation types (Yokelson et al., 2013).

Conversely, despite the importance of fire in boreal zone and the temperate forest, few EF studies have been conducted, resulting in an incomplete FE data of these areas (Koppmann et al. 2005; Urbanski et al. 2009). Urbansky et al. (2009) produced a compilation of FE involving temperate, boreal and tropical geographic zones. Regarding temperate forest, data were acquired on wildland and prescribed fires, describing forest and shrubland/grassland emissions, but due to the fragmentation of available data the information were derived by United States and Canada literature data.

Information on EF in the South of Europe were obtained through the measurements of experimental fires of Mediterranean shrublands (Miranda, 2004) and the presentation of several EF for many chemical species (Miranda et al. 2005a, 2005b) and particulates, obtained from both prescribed and natural fires occurred in Portugal (Alves et al., 2010 ad 2011) at medium and severe conditions.

Figure 6 shows a comparison among several shrubland emissions factors for $PM_{2.5}$, CO, CO_2, CH_4, derived by Bacciu et al (2015a) from seven different studies, conducted for Mediterranean and US vegetation. Data concerning CO_2 are similar among databases, whereas for the $PM_{2.5}$, CO and CO_4, EFs from prescribed burning result in the lowest value.

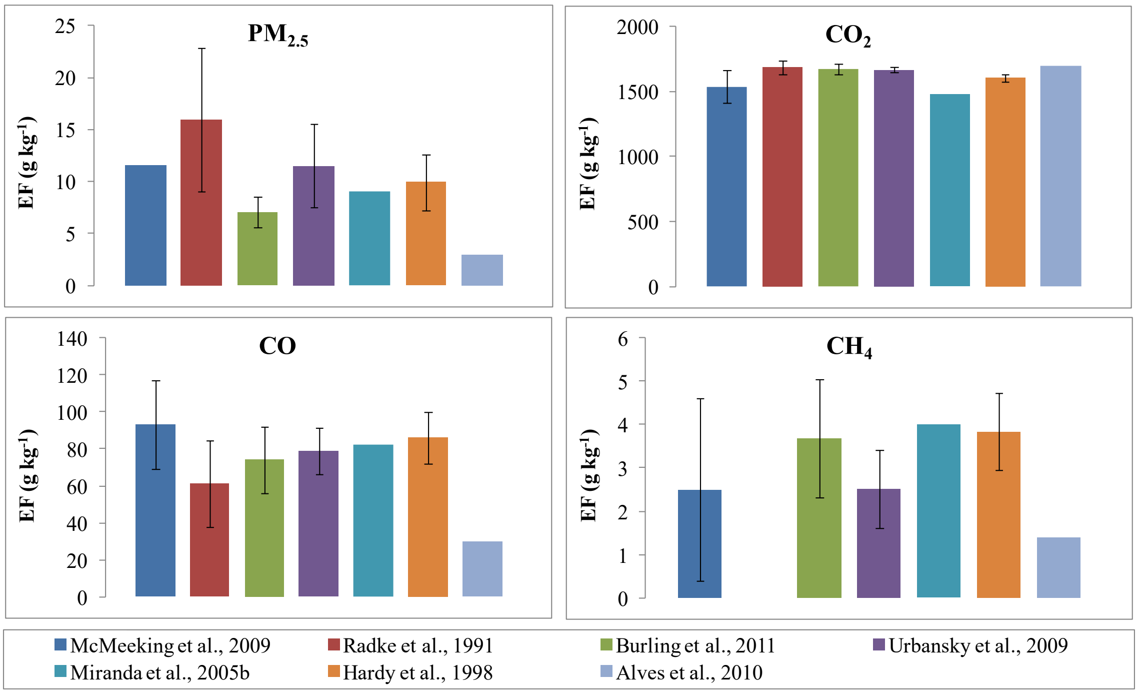

Figure 6 – Comparison between shrubland EF data derived from literature (from Bacciu et al., 2015)

4. Fuel consumption and smoke emission modelling

Combustion results in several fire effects, including direct (or first-order), such as plant injury and mortality, fuel consumption, smoke production, and soil heating, and indirect (or second-order), such as vegetation succession, fuel dynamics, erosion, air quality, and water quality (Reinhardt and Dickinson, 2010).

According to Debano et al. (1998) and Reinhardt et al. (2001), fire effect prediction models can be distinguished based on the fuel consumption modelling approach. Empirical models are based on the application of statistical relations, equations and algorithms (e.g., Brown et al. 1991; Anderson et al. 2004; Prichard et al., 2005 Hood et al. 2007). Generally, they have a simple internal architecture (Reinhardt & Dickinson 2010) that is based on the application of statistics or algorithms starting from a rather extensive database and does not explain the physical mechanisms underlying the process to be modelled. This implies greater accuracy when the models are used within the range within which they were developed, while they are considered not appropriate to be applied outside developing environment (Reinhardt & Dickinson 2010). Physical models describe in detail the heat transfer processes (Albini 1976; Campbell et al. 1995; Keane et al. 1995). They are considered the most appropriate to explore effects not directly observed and to simulate a given process in an area other than that of model development. The main disadvantages, however, lie in their intrinsic complexity and in the accuracy of their prediction, which can be low. Finally, semi-physical models result from the combination of the previous two approaches (Albini et al. 1995; Albini and Reinhardt 1995, 1997).

4.1. Main fuel consumption and emission models

Today, among the various models used to estimate fuel consumption and smoke emission, the CONSUME empirical model (Ottmar et al. 1993, Prichard et al. 2006; 2007) and FOFEM, containing the BURNUP semi-physical model, developed on the basis of improved and calibrated Burnout model (Albini et al. 1995; Albini and Reinhardt 1995; Albini and Reinhardt 1997) are the most used.

The CONSUME model relies on the Fuel Characteristic Classification System (Ottmar et al. 2007) for the assignment of the default fuel load and predicts the consumption of natural fuel or derived from forest management activities using a set of empirical formulas, general rules, and coefficient derived from field experiments (Ottmar and Sandberg, 1985; Ottmar et al., 1990). CONSUME distinguishes fuel consumption also on the basis of the combustion phases. For example, the model assumes that the material from 0 to 2.6 cm in diameter is completely consumed during the flame phase, based on a series of field observations. For larger fuel, the duration of the flame phase - and therefore the consumption of the material - is calculated through a non-linear exponential equation deriving from the observation of about fifty prescribed fire activities (Ottmar 1983).

CONSUME estimates smoke production by multiplying fuel consumption by a given emission factor based on fuel type, and the difference between piled and not piled fuels. In the first case, emissions are calculated based on soil content in the piled material (Prichard et al. 2007). The emission factors related to PM, PM_{10}, $PM_{2.5}$ for this type of fuel, divided into three classes of soil quantity, are based on emissions data collected as a result of experimental works by Hardy (1998) and Baker (2005), while the emission factors for the other pollutants (CO, CO_2, CH_4 and NMHC) are calculated by multiplying the consumed biomass during the combustion phases by a set of emission factors derived from the experimental work of Ward et al. (1989) and Hardy (1996).

BURNUP (Albini and Reinhardt 1995) is a semi-physical model of wood fuel consumption based on the heat transfer formulation and on the wood particles rate of combustion during the process (Lutes 2013). According to the developers, the wooded particles are immersed in the so called "fire environment", where the heat is transferred through convection and radiation. BURNUP model estimates the time required for the fuel particle ignition considering it as a wet cylinder and calculating its desiccation time until ignition taking into account the thermophysical properties of the woody material (thermal conductivity, density, and specific heat). Considering equal the rate of heat transfer and the amount of energy required to raise the fuel to its pyrolysis temperature, the model reproduces the rate of combustion. In addition, the model determines how the fuel particles of different size classes interact (Albini et al. 1995). The total rate of heat released per unit of area is then obtained summing up the different combustion rates of the various elements composing the fuel (Albini et al. 1995). This procedure allows to consider the lack of homogeneity in terms of combustion time and fire intensity: while the small-size fuel particles have already been completely burned, the larger ones may still be under combustion or even not ignited.

The BURNUP model is embedded in the FOFEM software (Reinhardt et al. 1997), which contains other empirical models and rules of thumb to estimate the consumption of the eight surface fuel components, such as shrubs, herbaceous material, litter, and duff. Finney (2001) modified the BURNUP model to provide separate estimates for the two combustion phases, flaming and smouldering, in each time step and for each fuel component assuming that the flaming combustion cannot happen if the intensity is lower than 15 kW m^{-2} (Lutes 2014). By distinguishing the fuel load consumed through the two combustion phases, BURNUP allows emissions factors, derived from the work of Ward et al. in 1993, to be applied separately to the fuel consumed in each phase. Finally, the total is obtained from the emissions calculated separately and from the fuel weight consumed in the two phases.

4.2. Main assumption and limitation

Recently, Ottmar (2014) analysed the fuel consumption processes and available models highlighting a number of knowledge gaps, with the aim of contributing to improve the ability in fuel consumption and smoke emissions prediction.

An important gap is that the models use a mix of empirical, theoretical, and rule-based models to estimate fuel consumption in a variety of fuel types. For example, the crown fuel consumption integrated in FOFEM is very simplistic and empirically driven, but the user can change the proportion of the canopy that the fire will consume. Furthermore, in both models shrub consumption is modelled with rules developed from anecdotal evidence (Reinhardt et a. 1997).

Furthermore, CONSUME and FOFEM are limited by the range of fuel bed data used to build the models, and care must be taken when applying the models to other fuel bed or environmental condition outside the range of development (Ottmar, 2014). Reid et al. (2012) suggested thus to use measured input values to obtain a higher model accuracy instead of relying on default fuel loads.

Another gap is the default fuel beds input into the models such as CONSUME and FOFEM. Indeed, the models do not account for spatial discontinuous fuels, and this implies (as suggested by Mell et al. 2007) that to have more realistic results they need to be calibrated by field data. For example, Ottmar and Dickinson (2011) evaluated CONSUME and FOFEM in the eastern United States through a fuel consumption dataset; they found that there were no particular differences between the two model results and, except for the poor reliability on the prediction of fine woody material, they both well predicted herbaceous and shrub material consumption. Moreover, Prichard et al. (2014) demonstrated notable differences in model performance among fuel categories and vegetation types. The two models predicted well the consumption of fuel bed components (except litter) in southern pine fires, while both performed poorly 1-h, 10-h, and 100-h woody fuel consumption in mixed hardwood sites (Ottmar, 2014). Live fuel (shrubs and herbaceous vegetation) was predicted reliably by both models. Prichard et al. (2014) conclude that, although the models have not been fully parameterized in the eastern US, they perform quite well in predicting total fuel consumption.

4.3. Main application

Today, CONSUME and FOFEM models have been applied at several scales, for different purposes, and in fuel and environmental contexts different from those of development.

At the local scale, several works have been performed to determine the impact of fire events on air quality and identify the source of air pollution. Clinton et al. (2006) implemented FOFEM algorithms to quantify the source and composition of smoke and emissions from wildland fires that affected Southern California, in October 2003. The Authors used the fuel models incorporated in FOFEM v.4.0 to determine fuel loading, concluding that the developed approach could benefit from a more comprehensive set of fuel inputs, and highlighting that there is a need for additional research to model fuel distributions in a broad range of ecosystems (Clinton et al., 2006). In addition, the study pointed out that vegetation maps could also have an impact on the fire emissions estimates, due to the minimum mapping units that could constrain the possibility to model fire effects in heterogeneous landscape. Stephens et al. (2007) estimated the emissions from California during the prehistoric period (before 1800) through FOFEM. In that case, the Authors did not use measured fuel values and FOFEM fuel models were assigned based on similarity of dominant vegetation.

The application of the fire emission models has also been used to understand the uncertainties arising from different inputs and modelling approaches in fire emission estimates. French et al. (2011) applied the two models to compare the different methodologies of FOFEM and CONSUME to estimate carbon loss from terrestrial biosphere resulting from wildland fires in Canada. Similarly, Drury et al. (2014) analyzed the emissions estimates from different fire size, fuel loading maps and the two consumption models for a large fire that occurred in in Washington state, USA, in 2006. Within their work, they found that the most critical step in the fire emissions modeling process is represented by the choice of fuel loading, while fuel consumption showed lesser importance. Hyde et al. (2015) compared two source of fuel loading (LANDFIRE and measured fuel data) with the FOFEM and CONSUME models. Consistently with the previous researchers, also this study pointed out that the differences in fuel loadings led to significant differences in consumption and emission.

For the Mediterranean environment, Fernandes and Loureiro (2013) estimated fine fuel consumption and CO_2 emissions from maritime pine stands in northern Portugal through and experimental and modelling approach. Fuel loading was assessed by a combination of destructive and non-destructive sampling methods. Fuel consumption was modelled through generalized linear modelling using either field measured fuel moisture content or the FWI system moisture codes. CO_2 emissions were estimated from fuel consumption data and the assumption of emissions factors reflecting the relative contribution of flaming and smouldering combustion through the combustion efficiency from the FOFEM software documentation (Reinhardt, 2003). Bacciu et al. (2012) applied FOFEM in Mediterranean areas, estimating type and amount of Mediterranean vegetation fire emissions from Sardinian fires (2005–2009), and compared 2005 emissions estimates with the Italian Emissions Inventory (NEIPROV, De Lauretis et al. 2009).

Some authors analyzed the role of prescribed burning techniques on mitigation of CO_2 emissions derived from forest fires in Europe, showing that the effectiveness of reduction changes between countries, particularly performing some significant contribution for territories characterized by high forest fire occurrence (Narayan et al., 2007); moreover, the uncertainties in emissions estimates and on the effectiveness of this technique are linked to inaccurate fuel load and fuel consumption data (Vilén and Fernandes, 2011).

At a regional scale, Dennis et al. (2002) estimated the air pollutant emissions associated with three biomass burning types in Texas applying FOFEM v.4.0. The model was chosen due to the input require by the models and to the aim of applying a consistent modelling approach across source categories. Urbanski et al. (2011) presented the 2003–2008 Wildland Fire Emissions Inventory (WFEI) in the contiguous United States. The product combines observation from satellite data, fuel loading maps, fuel consumption models (both COMSUME and FOFEM), and an EF database.

With the aim to investigate the impacts of different approaches and input data on emissions estimates, Larkin et al. (2014) compared the 2008 emissions in the contiguous United States derived from a variety of fuel loading, consumption and emissions models, highlighting major differences and uncertainties especially due to the overall fuel loading used and the ability to model deep organic combustion.

5. Conclusions

In this chapter, a review on the contemporary state of the research concerning emissions from forest fires was presented. Fire emissions and emission inventories are crucial for a number of reasons. Emissions interfere with local, regional and global processes in the atmosphere affecting climate feedback mechanisms, absorbing solar radiation, influencing the atmospheric radiation budget, and modifying cloud dynamics. Fire emissions can also contribute to air quality degradation, causing health problems, such as chronic bronchitis or irritation to respiratory tracts.

In this context, fire emission inventories are crucial to identify the source of air pollution affecting human health and predicting air quality during fire occurrence, and to ascertain the fire impacts on climate. In the recent decades advances in modelling and measurement efforts have improved the knowledge of the effects of vegetation burning in the atmosphere and our ability to estimate fire emissions from different sources. Despite this, large uncertainties remain, and in this chapter we examined and discussed the fundamentals of how fire emissions are calculated and the connected sources of uncertainty. As presented in section 3, fire emissions are calculated as a function of burned area, available biomass, combustion efficiency and emissions factors. The assumption made and difference in the data used can directly affect fire emission estimates, including:

- Burned area data, what is included or not and the temporal and spatial resolution of acquisition;
- Available to burn fuel data, how the data are measured, characterised, and allocated;

- Consumption model assumption, how the models works, how the consumption phases are considered.

Clearly, due to the errors associated with the fire characteristics estimation, all studies are in agreement in understanding the importance of the errors and what potential adjustments can be made to minimize them.

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Chapter 2: Estimating emissions from fires in Italy (2007-2017) using an integrated approach

1. Introduction

Wildland fires are considered an integral component of ecosystem dynamics in Mediterranean landscapes, but they also represent one of the devastating disturbances. Uncontrolled and extreme events can lead to large environmental and economic damages (San-Miguel-Ayanz, 2012). During 1950-2000, fires accounted for 16% of total damages on wood by disturbances (Schelhaas et al., 2003), showing their impacts particularly during the severe years 2003 and 2007, corresponding to the occurrence of large scale droughts (Lindner et al., 2010).

Large and extreme fire events also lead to significant emissions of greenhouse gases and particulates. Increased research of emissions from biomass burning has evolved since the demonstration that some emitted compounds could be a source of atmospheric pollution (Seiler and Crutzen, 1980, Crutzen and Andreae, 1990; Rosa et al., 2011; Hodnebrog et al., 2012) affecting large areas of the world as consequence of long-range transport (Andreae, 1983; Kirchhoff and Nobre, 1986; Reichle et al., 1986; Fishman et al., 1990; Cristofanelli et al., 2007, 2013; Bougiatioti et al., 2014; Adame et al., 2018). Subsequently, due to the increased number of large and extreme events during recent decades, citizens, firefighters, decision makers and the scientific community have increased their concern (Andreae and Merlet, 2001; Miranda et al., 2008). In addition, wildland fires and other extreme weather events like heatwaves, drought and heavy rain are expected to be more frequent under climate change, bringing greater risks of injuries, diseases and death, global scale degradation and loss of ecosystems and biodiversity (Hoeg-Guldberg et al., 2018).

Quantifying forest fire emissions is a necessary step to predict regional air quality during large fire occurrence, to use the prescribed fire while complying with air quality regulations (e.g. Hyde et al., 2015) and to obtain greenhouse gas reporting (e.g. UNFCC), and requires the combination of multiple and interdependent factors and the intertwining of different scientific disciplines and models (Drury et al., 2014). Fire emissions estimation is based on the Seiler and Crutzen (1980) equation, combining information of the available biomass, combustion factors, the area burned and emissions factors (Wooster et al., 2005). Moreover, other information such as fuel characteristics, fire type, meteorology, and geographical location (Miranda and Borrego, 2008) are used to improve the estimates.

According to a number of authors (e.g., French et al., 2011; Larkin et al., 2013; Drury et al., 2014; Hyde et al., 2015), fuel loading has been identified as the most critical step in obtaining accurate smoke predictions since this component of the emissions equation is one of the largest contributors to variability. Particularly, the containment of the uncertainties for both fuel characterization and fuel consumption is considered a way to considerably reduce the errors in fire emissions estimation at different scales (French et al., 2014; Ottmar et. al., 2009). Furthermore, because the flaming phase is more consumption efficient than the smoldering phase and different chemical compounds are released at different rates (Ottmar, 2014), several authors pointed out that separate calculations of flaming and smoldering consumption are required to improve assessment of total emissions.

Recently, a studies have focused on the understanding of fire emissions in Europe applying different approaches to improve the estimates and to identify the main sources of uncertainty (Miranda et al., 2009; Rosa et al., 2011; Chiriacò et al., 2013). Rosa et al. (2011) by applying the Seiler and Crutzen (1980) equation relying on a combination of burned area and land cover maps derived from remotely sensed data, associating biomass fuel loadings estimated by several statistical growth models accordingly to the vegetation type, and applying results from the literature for combustion and emissions factors.

Chiriacò et al. (2013) compared the existing fire emissions estimation methodologies for the southern European countries by assessing biomass losses depending on different percentages of biomass burned, fuel type, area burned, damage level or based on mortality rates previously defined.

An Italian dataset is provided by the National Forest Service, which includes the detection of GPS-derived forest fire perimeters on the main forest species impacted by fire, and sometimes provides additional information such as the length of flames, suppression personnel and vehicles or the causes of fires. The amount of biomass burned allows for the estimation of the damage level, and this depends on fire intensity and the type of vegetation burned (Bovio, 2007).

In this paper, we applied an integrated methodology (built from earlier works of

Bacciu et al. (2010; 2012) combining a fire emissions model (FOFEM - First Order Fire Effect Model, Reinhardt et al., 1997) with spatial and non-spatial inputs related to fire, vegetation, and weather conditions to estimate fire emissions from forest fires in Italy for the period 2007-2017. Emissions data (trace gas and particulate) distribution, both spatially and temporally, from fuel types were examined. Furthermore, this work assessed the uncertainties and weak points found during the process, through the evaluation and selection of data inputs and the observation of results variability.

2. *Material and Methods*

Study area

Italy, located in Southern Europe, comprises the boot-shaped Italian Peninsula and several islands including the two largest ones of the Mediterranean Sea, Sicily and Sardinia. According to the Köppen-Geiger (1954) classification, the Italian climate can be distinguished into seven broad categories:(1) Mediterranean climate, characteristic of all coastal areas excluding the north-eastern area; (2) Mediterranean mild climate, in inland and at medium and high elevations in southern Italy; (3) Humid subtropical climate; (4) Oceanic climate, in the Apennines and in the alpine foothills; (5) Humid continental climate, characteristic of the Alps; (6) Cold continental climate, typical of the alpine valley around 1,600–1,800 meters a.s.l.; (7) Tundra climate, located above the tree line in the Alps.

According to the Corine Land Cover classification 2012 (EEA 2012), agriculture is the primary land use in Italy, covering 53.6% of the territory, closely followed by forested areas (33.4%). This category is mainly composed by three broad vegetation types: a) woodland (26.4%); b) shrubland (4.6%); c) natural grassland (2.1%). Artificial surfaces occupy about 5.1% of the territory. According to the INFC (2005), the main represented classes within the woodland vegetation type are: Quercus petraea (Mattuschka) Liebl. and Q. pubescens Willd. wood, followed by Fagus sylvatica L. woodlands, and Q. cerris L., Q. frainetto Ten., Q. trojana Webb, and Q. macrolepis

(Kotschy) Hedge & Yalt.woodlands. The Norway spruce (Picea abies (L.) H. Karst. prevails among the conifer stands (1.94% of the Italian territory and 6.7% of the forest stands), while the maritime pine stands (Pinus pinaster Aiton) contribute to the 0.75%. The category "Maquis and Mediterranean shrubland" covers 6,908 km^2 (2.29% over the national territory). Southern administrative regions, such as Apulia, Basilicata, and Calabria, and the islands of Sicily and Sardinia, generally show a higher percentage of shrublands with respect to the other Italian regions; nonetheless, Sardinia and Calabria have a woodland density coefficient greater than the national one, while Apulia and Sicily are the less abundant in forests (INFC 2005).

The modelling approach

The spatially integrated methodology applied in this work combined a fire emissions model with spatial and non-spatial inputs. The structure and the main elements of the methodology, also diagrammed in Figure 7, is described as follows:

- Fire perimeter's map, establishing the spatial extend of the burned area supplied by the former Corpo Forestale dello Stato (actually Carabinieri C.U.F.A.A.);
- Spatial fuels, vegetation or land cover map, supplying fuel loading derived from the Corine Land Cover 2012 and the descriptive database (Ascoli et al. 2019) of Italian vegetation based on field observation and literature data;
- Fuel moisture conditions, derived from the calculation of daily Canadian Fine Fuels Moisture Code (FFMC), calculated from the weather information supplied by the Era-Interim Reanalysis product (http://apps.ecmwf.int/);
- Fire emissions model, FOFEM - First Order Fire Effect Model, (Reinhardt et al., 1997) estimating fuel consumption and pollutant emission.

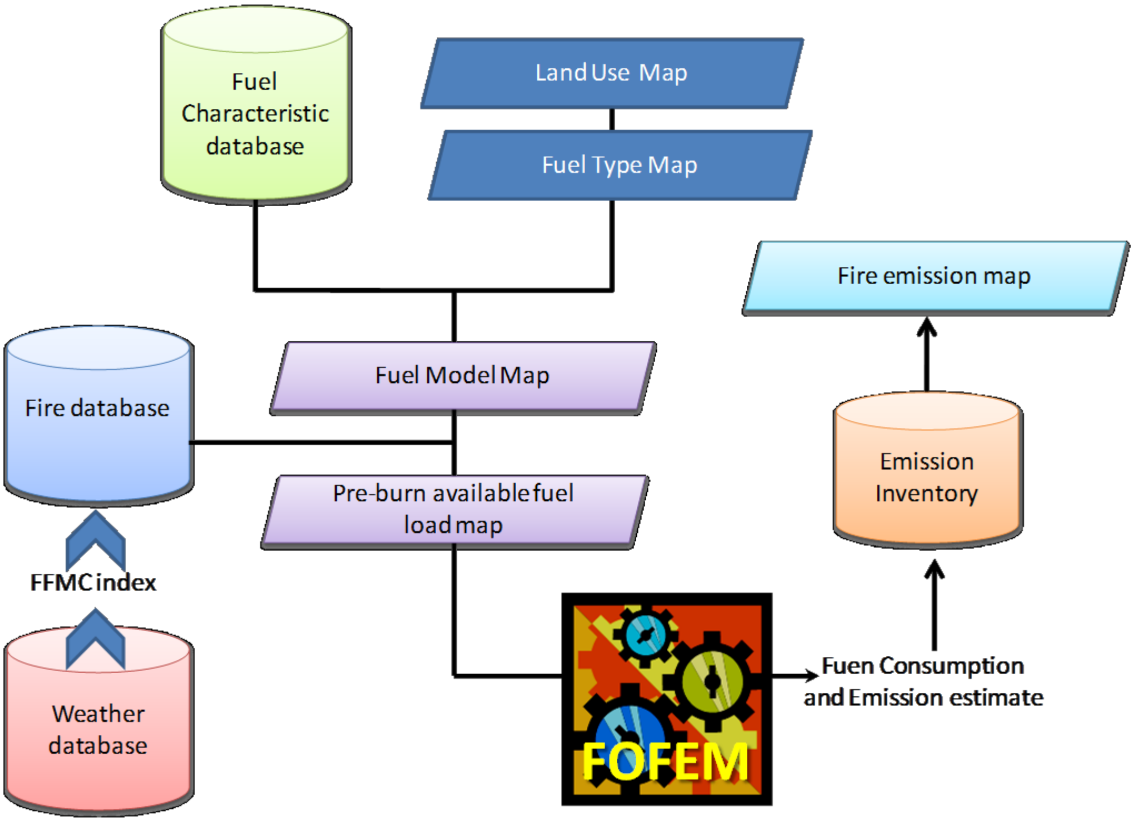

Figure 7 - Flow chart of the integrated approach to estimate fuel consumption and emissions

Fire data

Daily fire perimeters from 2007 to 2017 were acquired for mainland Italy from the former Corpo Forestale dello Stato (actually Carabinieri C.U.F.A.A.), while the data for three Autonomous regions were provided by: Corpo Forestale e di Vigilanza Ambientale della Regione Sardegna (CFVA), Corpo Forestale della Regione Sicilia, and Corpo Forestale della Regione Friuli Venezia Giulia. As a consequence of data limitations, the analysis does not include two autonomous regions (Trentino Alto Adige, Valle d'Aosta). However, these two regions, for the analysed period, account for only the 0.05% of the entire burnt area.

FOFEM model

FOFEM 6.4 (Reinhardt et al. 1997; Reinhardt 2003) is a versatile and widely used software to predict first order fire effects, such as fuel consumption, pollutant emissions, soil heating, and postfire tree mortality. It comprises an extensive number of fuel models derived from literature data on measured fuel load of U.S. ecosystems, including Society of American Foresters/Society of Range Management (SAF/SRM), National Vegetation Classification System (NVCS), and Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007, Prichard et al. 2013). To each fuel model, a description of the vegetation and information on fuel load for ground and aerial vegetation strata (duff, litter, three size classes of woody debris, herbs, shrubs and live tree live branches and foliage) is associated. Furthermore, users can also modify or replace the input parameters manually or inserting an input file according to local conditions.

Shrub and duff fuel consumption is empirically calculated through regression models based on region, while herbaceous and litter fuels are assumed to be completely consumed. On the other hand, the simulation of consumption for downed woody particles is estimated using BURNUP, a process-based model of heat transfer and burning rates of woody fuel particles by size class (Albini and Reinhardt 1995, 1997; Albini et al. 1995; Reinhardt and Dickinson 2010; Lutes 2013). The BURNUP model also estimates separately smoldering and flaming combustion with the connected emissions of gaseous and particulate (Ward et al., 1993), namely for $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, NO_X and SO_2.

Concerning fuel moisture, namely the input value affecting the ratio and the combustion efficiency of flaming and smoldering phases, FOFEM can be run under four moisture settings determined by 10-hour fuel moisture (FM10): wet (FM10 22%), moderate (FM10 16%), dry (FM10 10%), and very dry (FM10 6%). Users can thus select default burn conditions, or input different values.

Vegetation and Fuel data

The fuel type and load for each fire was determined using a combination of satellite imagery products and published data. Recently, Ascoli et al. (2019) classified and typified surface fuels in Italy by harmonizing more than 600 quantitative samples carried out over the last decade from different research groups in 12 Italian regions. The database is a collection of repeated observations in alpine environments, temperate and Mediterranean, and includes duff, litter, herbaceous, shrub and downed woody fuel loadings. Furthermore, woody fuel load is divided in dimensional classes for dead (0-6, 6-25 and 25-75 mm) and live (0-6 mm) fuels. Each quantitative sample was then associated with a forest type into the European Forest Types classification (EEA 2006), a Corine Land Cover IV level (EEA 2012), and a fuel type (Table 2). Fourteen main land cover types represented the principal fuel types in Italy were obtained, that were also aggregated in four macro-categories: Broadleaves, Conifers, Mixed Hardwood, Heathlands & Shrublands, and Agriculture & Pastures (Table 2). The fuel model map obtained was then overlaid by the fire perimeter layer, thus identifying the fuel model burned areas layer.

Table 2 –Description of Fuel types from Ascoli et al. (2019) derived from the aggregation of Corine Land Cover classes (EEA 2012). (EU Forest Types: EEA 2006; EU Fuel Types: Camia, 2012)

Macro categories	Vegetation Types	Vegetation Type codes	EU Fuel Types	EU Forest Types	Corine Lev. III-IV	Duff Mg ha^{-1}	Litter Mg ha^{-1}			Herbs Mg ha^{-1}	Shrubs Mg ha^{-1}	
							1 h	10h	100h		1h	10h
Conifers	Fir and spruce woods	AP	23, 26	3.2, 7.9	3123, 31323	35.8	1.4	2.0	2.6	0.4	0.1	0.2
	Mediterranean pine forest	PM	20	10.1	3121, 31321	36.5	3.7	2.5	0.9	0.7	5.1	1.6
	Pine forest of sylvestris, black, stone and larch pines	PS	22, 25	10.2, 14, 3.1, 3.3	33122, 3124, 3125	34.8	2.1	2.5	4.1	0.9	1.2	0.5
Heathlands & Shrublands	High maquis and heather	MA	10	-	3231	12.2	5.4	3.0	0.6	1.3	16.5	7.7
	Low maquis and garrigue	MB	9	-	3232	6.2	2.2	2.3	0.4	1.6	6.2	2.4
	Heathland	BR	8	-	322	0.3	1.2	0.0	0.0	4.2	5.8	0.0
Broadleaves	Oak-hornbeam, turkey oak, oak forest	QC	30, 31	5.1, 8.1, 8.2, 8.8	3112, 31312	46.5	1.1	1.4	2.7	0.6	0.5	0.0
	Evergreen oak forest	QS	29	9.1	3111, 31311	-	2.2	2.3	2.4	0.4	3.3	0.0

Table 2 – Cont.

Macro categories	Vegetation Types	Vegetation Type codes	EU Fuel Types	EU Forest Types	Corine Lev. III-IV	Duff Mg ha^{-1}	Litter Mg ha^{-1}			Herbs	Shrubs Mg ha^{-1}	
							1 h	10h	100h	Mg ha^{-1}	1h	10h
Broadleaves	Chestnut grove	CA	30	8.7	3114, 31314	38.2	2.2	5.4	1.5	0.2	2.4	0.0
	Beech forest	FA	33	7.3	3115, 31315	49.7	0.6	1.5	2.9	0.3	0.0	0.0
Agriculture & Pastures	Continuous grassland	PC	5, 6	-	3211	1.0	0.2	0.0	0.0	3.7	0.0	0.0
	Discontinuous rupicolous prairie	PD	4	-	3211, 3212	0.0	0.1	0.1	0.0	2.1	0.2	0.0
Mixed hardwood	Mesophitic broadleaf forest	BM	30	8.8	311, 2241, 3113	35.5	2.2	4.4	1.4	0.8	1.4	0.0
	Riparian vegetation	VR	39	12.1	3116	-	0.2	0.7	2.6	1.4	1.5	0.2

"-": not available data.

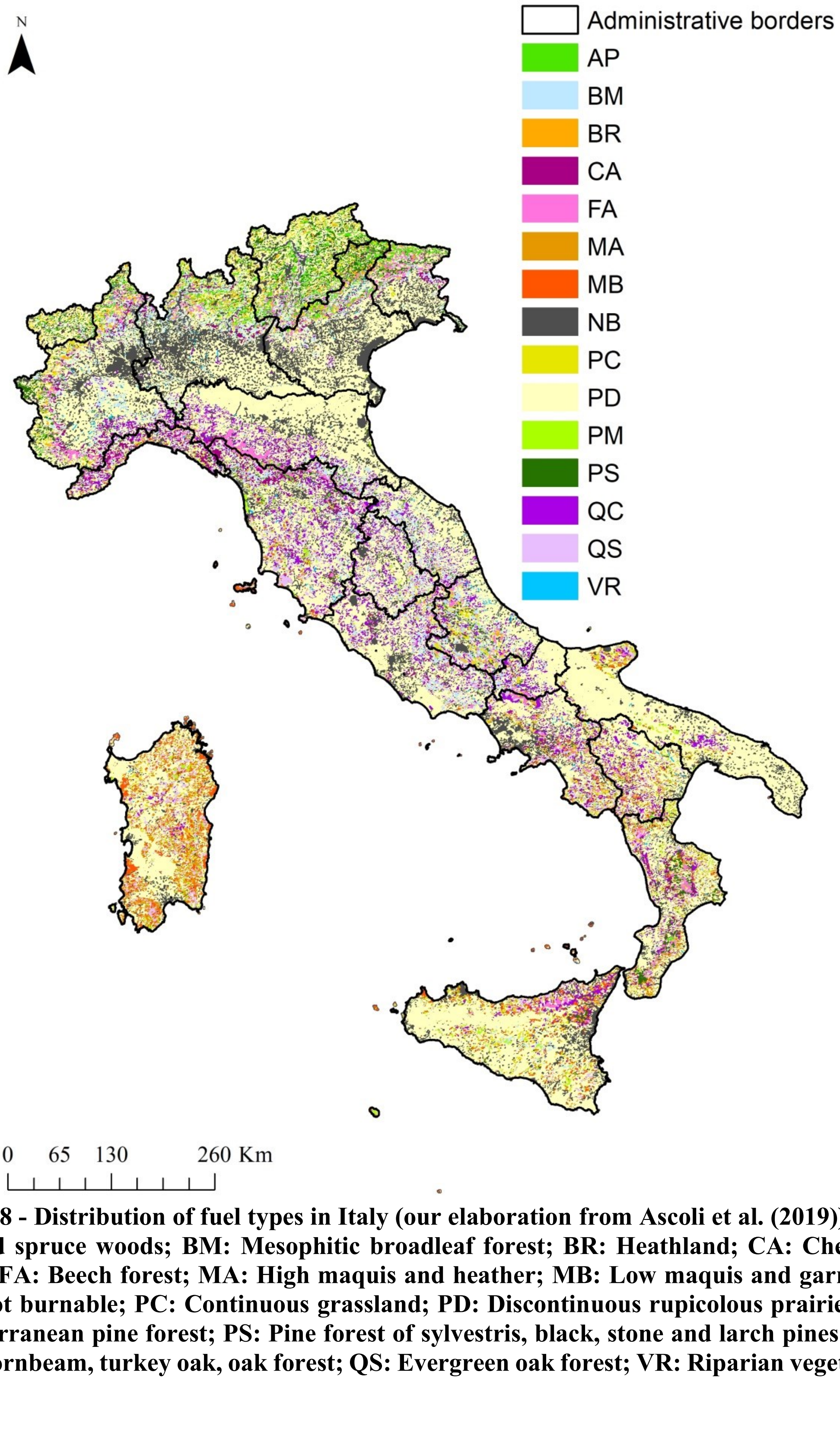

Figure 8 - Distribution of fuel types in Italy (our elaboration from Ascoli et al. (2019)). AP: Fir and spruce woods; BM: Mesophitic broadleaf forest; BR: Heathland; CA: Chestnut grove; FA: Beech forest; MA: High maquis and heather; MB: Low maquis and garrigue; NB: Not burnable; PC: Continuous grassland; PD: Discontinuous rupicolous prairie;PM: Mediterranean pine forest; PS: Pine forest of sylvestris, black, stone and larch pines; QC: Oak-hornbeam, turkey oak, oak forest; QS: Evergreen oak forest; VR: Riparian vegetation

Fuel moisture scenarios

Fuel moisture conditions were estimated using the Fine Fuel Moisture Code (FFMC) as a proxy. The FFMC is one of six indices composing the Canadian Fire Weather Index (FWI), constructed using four weather inputs: precipitation accumulated over 24 h (P), and instantaneous temperature (T), relative humidity (H) and wind speed (W), generally taken at noon local standard time.

Weather data was gathered from the Era-Interim Reanalysis product (http://apps.ecmwf.int/), at grid resolution of 0.125° and at 12:00 UTC considering 24 h accumulated values for precipitation and instantaneous values for the other variables. Once the daily FFMC value was obtained, we calculated four thresholds (25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles) as a function of the distribution. Then, each FFMC value was associated to fire perimeters with the aim to group fires as a function of 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, 10-hour and 1000-hour fuel was assigned for each fuel type falling within a FFMC group, based on literature data information (Pellizzaro et al., 2009a; 2009b) (Table 3).

The fuel model burned areas layer was then processed to quantify pre-burn fuel loadings and to determine fuel consumption and emissions using the FOFEM model. Due to a lack of information on the crown fuel load of forest vegetation classes supplied by Ascoli et al. (2019), we did not insert information about crown foliage and branches; indeed, the simulated percentage for crown combustion was assumed to be zero.

Furthermore, duff layer loadings for some fuel type classes (FA, PC, PD, QC, QS, VR) resulted in missing or not representative values, therefore we filled the gaps using the information of corresponding fuel classes contained in the Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007; Sandberg at al., 2001). FCCS provides a description of fuel bed categories through six horizontal strata (canopy, herbs and grasses, woody dead material, litter and duff or ground fuels) and their properties, in order to determine the way they will be burned and consumed by fire (Ottmar, 2014). Particularly, the association with the FCCS classes was conducted through a meticulous photographic evaluation of each FCCS class with the fourteen Italian land cover classes.

To understand the uncertainties in fire emission estimates related to the duff proxy inputs for the model to run, we then evaluated three simulation datasets – S1, S2, S3 – on the basis of the source of duff information: the first filling the gaps of the Ascoli et al. (2019) database with FCCS data, the second using only duff data from the FCCS database, and the third using the minimum acceptable value, corresponding to the lower value of 0.22 Mg/ha (Table 4).

Table 3 – Fuel moisture content value associated with FFMC classes and dead fuel strata

	Dead fuel moisture content value (FMC) (%)		
FFMC class	DUFF	10-hour	1000-hour
WET	130	16	50
MEDIUM	90	13	40
DRY	75	11	30
VERY-DRY	40	9	25
EXTREME	20	7	15

Table 4 – Description and source of duff data input inserted in FOFEM for each fuel type and simulation

	Source and data information of duff layer (Mg ha^{-1}).		
Fuel type	S1	S2*	S3**
AP	35.78	62.48	0.22
BM	35.51	29.08	0.22
BR	0.25	0.67	0.22
CA	38.17	22.30	0.22
FA	30.41*	30.41	0.22
MA	12.16	4.21	0.22
MB	6.17	0.00	0.22
PC	11.59*	11.60	0.22
PD	2.82*	2.83	0.22
PM	36.46	25.16	0.22
PS	34.78	68.77	0.22
QC	19.62*	19.62	0.22
QS	10.80*	10.81	0.22
VR	35.38*	35.39	0.22

* FCCS values
** FOFEM minimum acceptable value

3. *Results and discussion*

3.1. FFMC and fuel moisture scenarios

FFMC inter-annual variability during the period 2007-2017 was very high between summer and winter months, ranging from the highest average value 91.73 on 20/07/2007, to the lowest average value 23.61 on 11/12/2008 (Figure 9). Between average monthly FFMC values, the highest was shown for July 2007 (87.9), whereas the lowest was observed for January 2009 (52.9). Moreover, FFMC average annual values for each region diverged, ranging from 81.5 and 80.8 for Sardinia and Calabria in 2017, respectively, to 59.5 and 59.6 for Lombardy and Piedmont in 2014.

The boxplots (Figure 10) are referred to the average values calculated for each day of the period 2007-2017 within all of the pixel components of the correspondent grid of

Era-interim reanalysis data. They describe the distribution of average annual FFMC values that have been calculated for the period 2007-2017. Annual datasets were balanced approximately between 70 and 85 within the period, and the minor ranges of values were observed for 2007 and 2017, which showed also a distribution characterized by the highest average values.

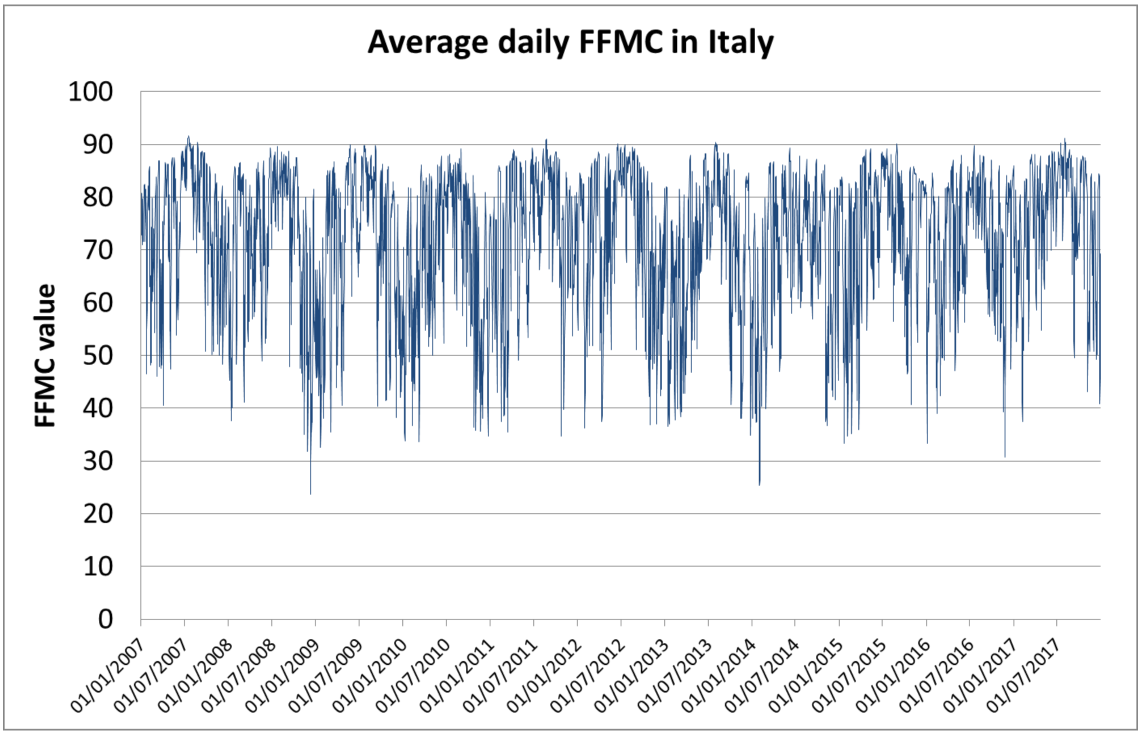

Figure 9 – Description of the average FFMC trend among grid cells in Italy

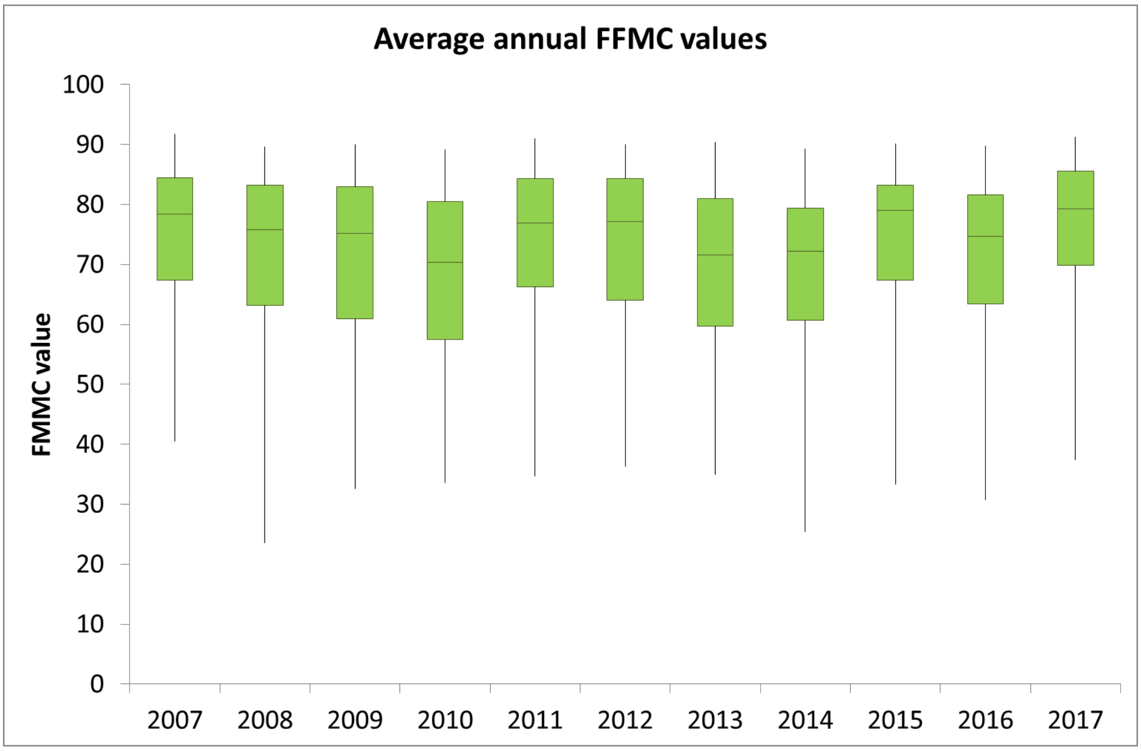

Figure 10 – Boxplots of FFMC distribution. Whiskers represent the minimum and the maximum values; middle lines represent the median

3.2. Spatial and temporal distribution of burned area

From 2007 to 2017, fire activity in Italy showed a high variability. The dataset comprises a total of 1,005,018.5 hectares of area burned, corresponding to 3.23% over the total Italian area, and about 81,000 fire ignitions. The annual average burned area was about 90,000 ha. The maximum number of fires per year occurred in 2007, 2012 and 2011 (14.2%, 11.4% and 11.3% of the 81,000 total), while the maximum recorded burned area occurred in 2007, followed by 2017 and 2012 (22.2%, 17% and 13.5% of the total) (Table4). The regions of Sicily, Sardinia, Calabria, and had the highest burned area values in Italy (respectively about $253*10^2$, $197*10^2$, and $165*10^2$ ha), whereas the highest number of fire events occurred in Sardinia (17,204 fires), Calabria (11,514 fires) and Campania (10,513 fires) (Figure 11).

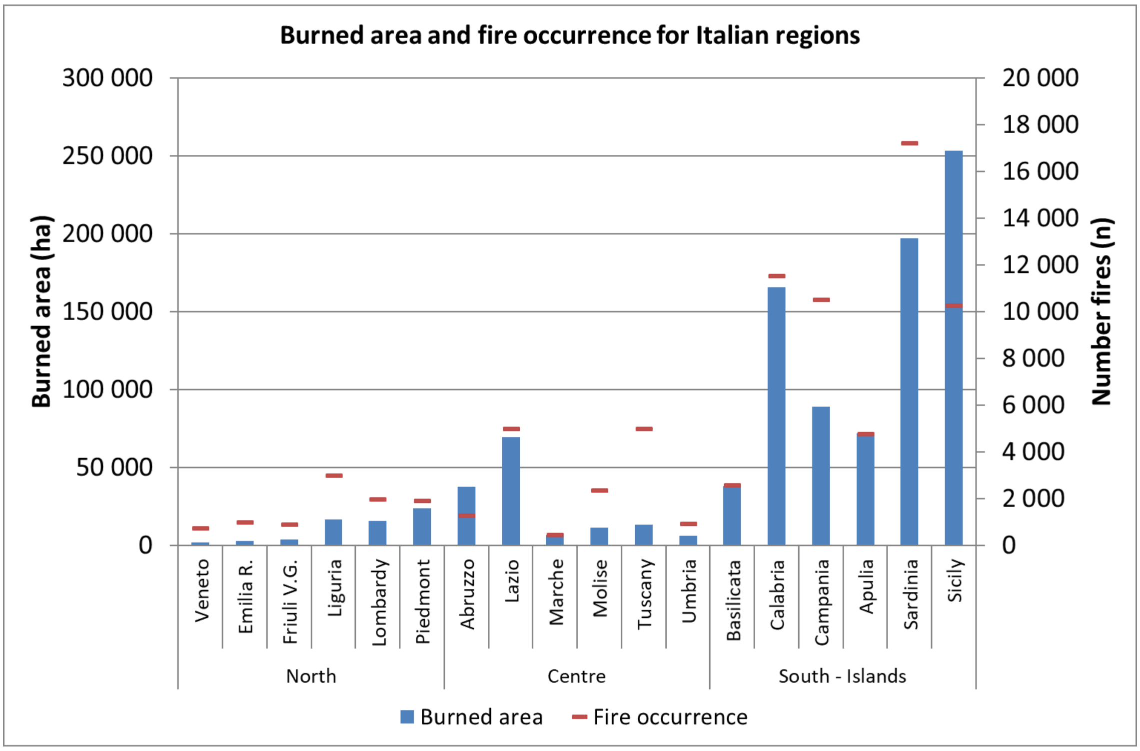

Figure 11 – Distribution of the burned area and fire events for 2007-2017 for each Italian region (Figure 8). The main vertical axis shows the number of hectares burned for the period studied; the second vertical axis shows the number of wildland fires occurred for each region for the period studied

Table 5 – Distribution of regional annual burned area (ha)

Region	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Abruzzo	23 074	1 259	390	381	1 239	1 536	315	50	1 088	155	8 246	37 733
Basilicata	7 913	7 001	1 367	2 110	3 020	6 178	945	523	1 581	881	6 358	37 878
Calabria	42 391	19 108	7 969	5 253	14 532	22 798	2 837	3 571	6 644	8 127	32 363	165 593
Campania	26 861	4 203	6 636	2 363	8 195	8 148	1 070	1 034	5 885	4 137	20 611	89 145
Emilia R.	895	175	189	21	182	506	26	36	158	56	533	2 777
Friuli V.G.	165	68	355	37	373	783	1 440	17	91	73	104	3 505
Lazio	13 743	3 140	2 775	3 155	6 896	8 067	1 403	1 151	5 966	3 932	19 212	69 440
Liguria	2 004	1 705	2 734	169	1 514	1 310	263	223	1 057	1 189	4 558	16 727
Lombardy	1 576	1 240	426	318	1 313	1 338	493	456	2 474	1 544	4 292	15 471
Marche	5 066	81	67	46	449	271	23	62	39	2	454	6 561
Molise	3 731	1 697	437	379	752	937	370	147	864	188	1 566	11 069
Piedmont	2 947	1 817	375	231	1 017	1 379	708	166	2 882	1 299	10 946	23 767
Apulia	20 159	8 869	4 541	5 069	7 224	8 333	3 354	1 184	3 137	3 152	6 671	71 693
Sardinia	34 376	6 095	44 839	11 892	18 452	14 867	14 682	15 269	8 219	15 099	13 347	197 137
Sicily	39 261	14 336	7 572	20 074	13 454	55 881	5 110	20 634	6 842	30 070	39 969	253 204
Tuscany	1 126	996	1 858	142	1 026	2 830	145	95	437	1 021	3 358	13 034
Umbria	1 443	382	61	110	306	2 457	44	3	137	10	932	5 884
Veneto	74	36	517	12	632	150	8	11	71	15	46	1 570
Total / yr	226 804	72 210	83 109	51 762	80 578	137 770	33 237	44 631	47 572	70 949	173 565	1 022 188

Table 6 - Distribution of the regional annual fire occurrence

Region	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Abruzzo	280	224	96	63	138	154	41	21	84	39	138	1 278
Basilicata	431	427	215	149	291	343	126	68	146	70	287	2 553
Calabria	1 851	1 659	959	646	1 235	1 069	290	492	864	964	1 485	11 514
Campania	1 771	946	1 112	542	1 434	1 185	315	307	994	708	1 199	10 513
Emilia R.	162	132	90	19	120	167	34	26	51	51	133	985
Friuli V.G.	92	66	73	53	98	187	51	12	76	60	102	870
Lazio	797	396	364	353	609	715	195	212	456	353	528	4 978
Liguria	381	373	447	113	293	354	139	98	226	224	336	2 984
Lombardy	253	176	151	82	226	262	92	93	225	168	220	1 948
Marche	108	54	28	9	84	70	14	4	26	3	45	445
Molise	807	560	330	72	129	141	63	32	70	32	99	2 335
Piedmont	323	200	123	66	206	166	148	109	180	130	237	1 888
Apulia	595	508	297	471	574	554	357	217	419	314	452	4 758
Sardinia	2 211	1 347	1 442	2 006	1 926	1 507	1 142	1 790	1 218	1 138	1 477	17 204
Sicily	724	1 111	481	1 142	1 004	1 247	449	915	868	1 050	1 254	10 245
Tuscany	493	474	595	165	643	755	209	120	328	437	768	4 987
Umbria	163	131	68	40	122	186	21	7	58	16	97	909
Veneto	88	61	118	25	68	164	31	15	57	35	56	718
Total / yr	11 530	8 845	6 989	6 016	9 200	9 226	3 717	4 538	6 346	5 792	8 913	81 112

During the period 2007-2017, the fuel type most affected by fire was "Discontinuous rupicolous prairie" (PD), with 513,629 ha burned, followed by "Low maquis and garrigue" (MB) and "High maquis and heather" (MA), with 99,494 and 72,492 ha burned, respectively (Figure 12). Conversely, "Heathland" (BR) and "Fir and spruce woods" (AP) were the least fire-affected fuel type classes, with 1,313 and 1,428 ha burned, respectively. During the analyzed period, the fuel type class with the highest fire incidence, namely the fire occurrence over fuel type total area, was represented by MA, followed by MB and "Mediterranean pine forest" (PM), which burned for about 14%, 13%, and 12% of their distribution, respectively. On the other hand, the lowest fire incidence recorded were registered for AP and BR that burned for only 0.2% and 0.9% of their distribution.

Moreover, we found that some fire perimeters were partially located inside the class "Not burnable". We excluded this class for the calculation of the total area burned, but is important to say that about 0.4% of its distribution occurred by fire; this could be due to the presence of burnable components (e.g. gardens and anthropogenic burnable elements), to accidentally events or to arson attacks.

Analyzing the contribution of the four fuel type macro-categories to burned area, Figure 13 shows that "Agriculture and pastures" was the most affected, accounting for about 58% of the total burned area (about 581,000 ha), whereas "Mixed Hardwood" represented the group less affected by fire (about 54,900 ha), accounting for 5.5% of the total area burned. Probably this is related to the higher ease of ignition of the herbaceous vegetation than those related to shrubs and trees. "Heathlands & Shrublands" represented the group with the highest fire incidence, showing about 12% of the area burned within the class, despite it representing the 17.2% of the area burned through the regions studied. On the other hand, "Broadleaves" represented the class with the lowest fire incidence, probably due to the low ease of ignition of the vegetation which represents, accounting for about 14% of the total Italian burned area (Table 7).

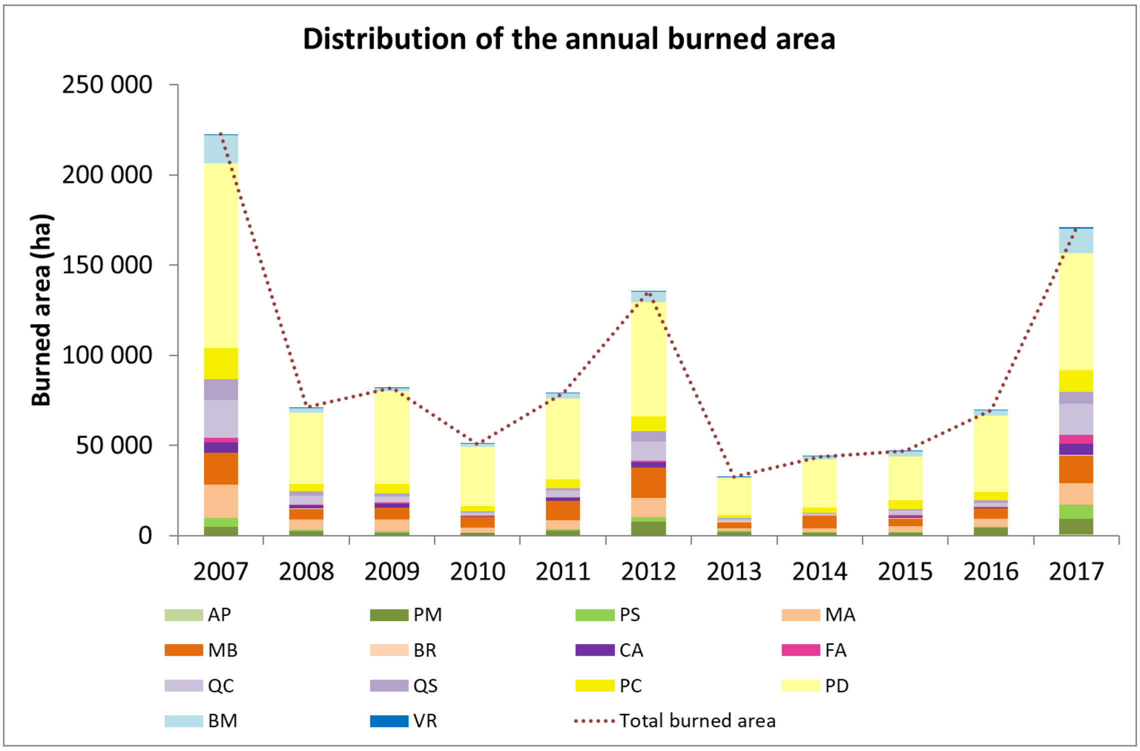

Figure 12 – Annual distribution of burned area between fuel types AP: Fir and spruce woods; BM: Mesophitic broadleaf forest; BR: Heathland; CA: Chestnut grove; FA: Beech forest; MA: High maquis and heather; MB: Low maquis and garrigue; PC: Continuous grassland; PD: Discontinuous rupicolous prairie;PM: Mediterranean pine forest; PS: Pine forest of sylvestris, black, stone and larch pines; QC: Oak-hornbeam, turkey oak, oak forest; QS: Evergreen oak forest; VR: Riparian vegetation

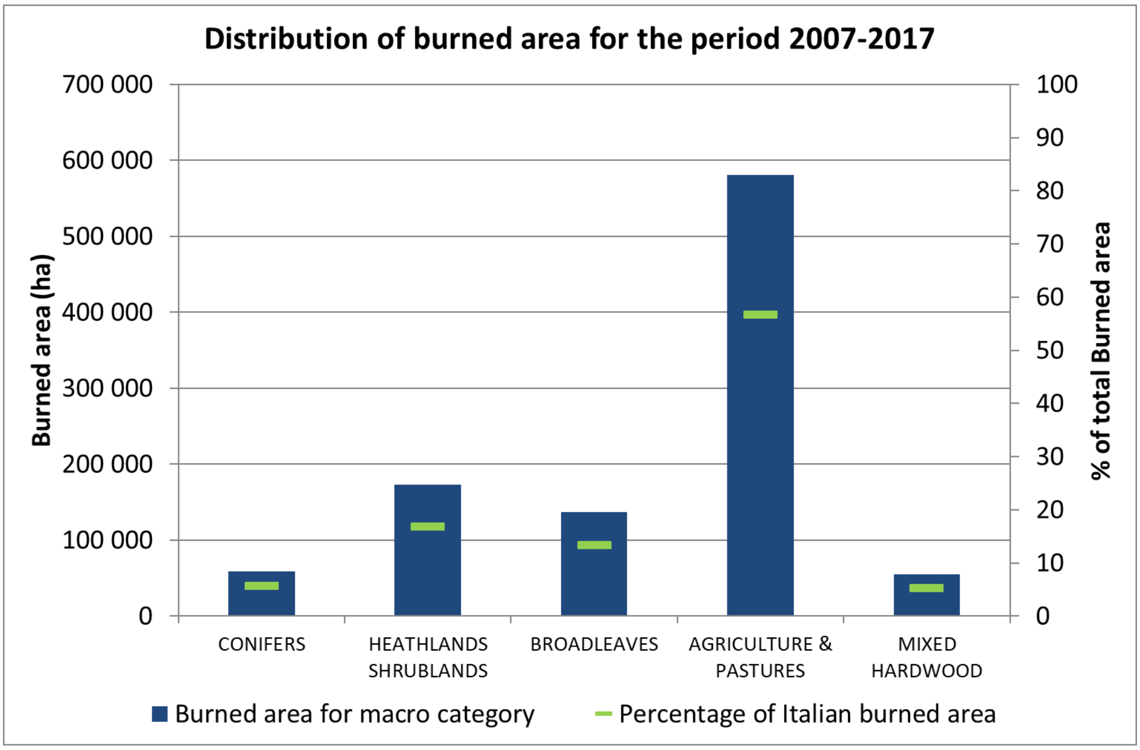

Figure 13 – Distribution of the total burned area for each macro-category for the period 2007-2017. The primary vertical axis shows the total burned area for each macro-category. The secondary vertical axis represents the contribution of each macro-category on total Italian burned area for the period studied

Table 7 - Distribution of the burned area within the macro-categories of vegetation

Macro-category	Total (ha)	% of National area	total BA* (ha)	total BA (%)	% of BA within group
CONIFERS	1 802 691	5.8	58 592	5.8	3.3
HEATHLANDS & SHRUBLANDS	1 437 477	4.63	173 299	17.2	12.1
BROADLEAVES	4 906 517	15.8	137 314	13.7	2.8
AGRICULTURE & PASTURES	17 300 709	55.7	580 903	57.8	3.4
MIXED HARDWOOD	1 562 069	5.03	54 911	5.5	3.5
NOT BURNABLE	4 049 880	13.04	_	_	_
TOT	31 059 343	100	1 005 018	100.0	_

* BA: Burned Area

Fire ignitions in the months of August (32%), July (22.5%), and September (14.8%) represented 69.3% of the total. We compared the monthly distribution of the burned area and observed a large variability of the total areas burned within the months of the period analyzed. During July 2007, August 2007 and August 2017, the largest burned areas (about 103,600, 71,350 and 68,770 ha burned, respectively) were recorded, and the smallest burned areas were observed in February 2010, January 2014 and November 2010 (14, 16 and 17 ha burned, respectively).

From 2007 to 2017, the highest total monthly area was burned during July (353,460 ha) and August (350,033 ha), whereas the months with the least burned area were December and February, with a total of 5,100 and 6,600 ha burned, respectively. The amount of area burned from June to September represented 88.4% of the total burned area for the whole period, whereas only July and August, accounted for 35 % and 34% of the total area burned, respectively. Additionally, the distribution of burned area within season showed that during summer and autumn the group "Agriculture & Pasture" had the most area burned, probably due to the dryness of the vegetation. Otherwise, the burned area for "Heathlands and Shrublands" was larger during autumn and summer, the area burned for "Mixed hardwood" was similar between seasons, whereas the area burned occupied by "Broadleaves" was greatest especially during spring and winter.

The largest burned areas were located in the southern regions and islands (Figure 14); particularly, Sicily, Sardinia and Calabria (253,200, 197,140 and 165,600 ha, respectively) represented 60% of the total burned area (about 615,900 ha).

It is also noticeable how the "Extreme" fuel moisture class, characterized by a larger dryness of the vegetation, represented a significant portion of the regional burned area from central to southern regions (about 39% and 26%, respectively), whereas for the northern regions the most representative fuel moisture class was "Wet", characterizing 66% of the burned area distribution. Similarly, the distribution of fire occurrence (Figure 15) identified the southern regions as where the most area burned occurred, but differently to the burned area results, the fires occurred mostly at "Medium" and "Dry" conditions (28% and 26%) and less at "Extreme" conditions (10%). Conversely, 58% of fires in the northern regions and the 29% in central Italy took place with "Wet" conditions. The largest percentage of burned area for all of the 18 regions studied during the period 2007-2017 occurred at "Extreme" and "Dry" conditions (26%, 23%), whereas the largest number of forest fires occurred at "Wet", "Medium" and "Dry" conditions in equal proportions (25%). Particularly, during the years characterized by the largest burned area, 2007, 2017 and 2012, the largest burned area coincided to the "Extreme" moisture condition class of 40%, 32% and 30% with 90,500, 55,600 and 41,200 ha burned, respectively, showing the importance of the extreme weather conditions that led to the creation of the largest areas occurred by fires.

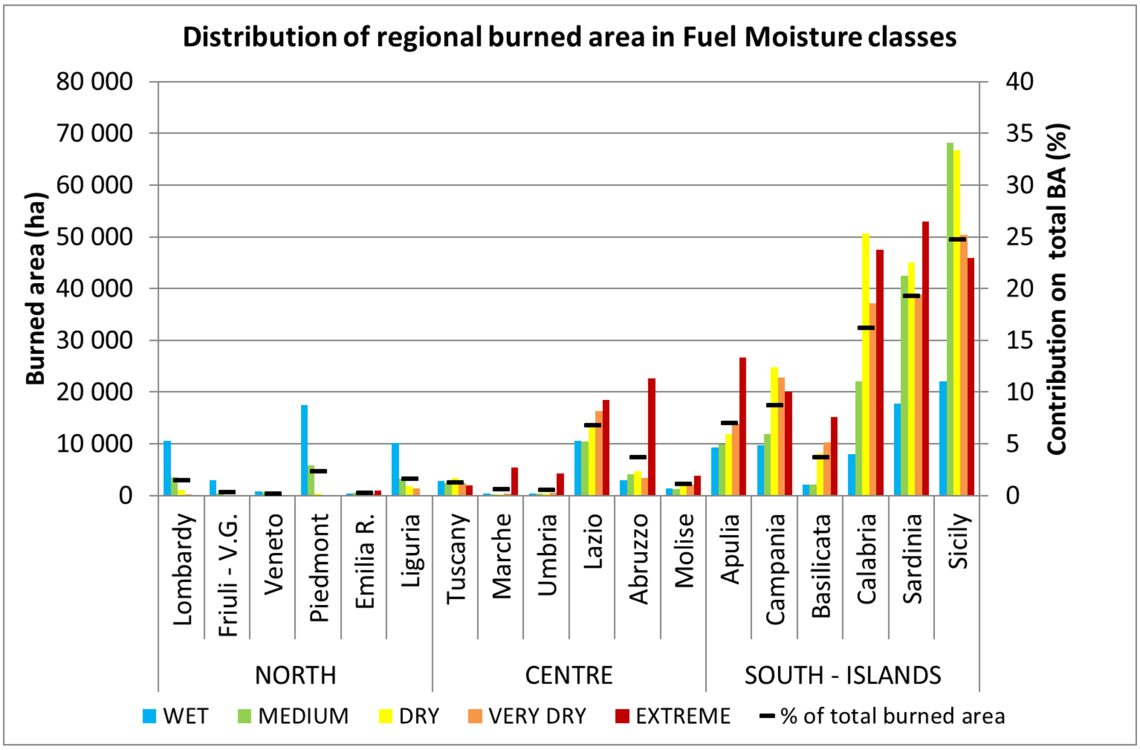

Figure 14 – Regional Burned areas distributed based on Fuel Moisture conditions. The primary vertical axis shows the composition of regional burned areas in fuel moisture classes; the secondary vertical axis shows the contribution of each region on total national burned area, expressed as a percentage

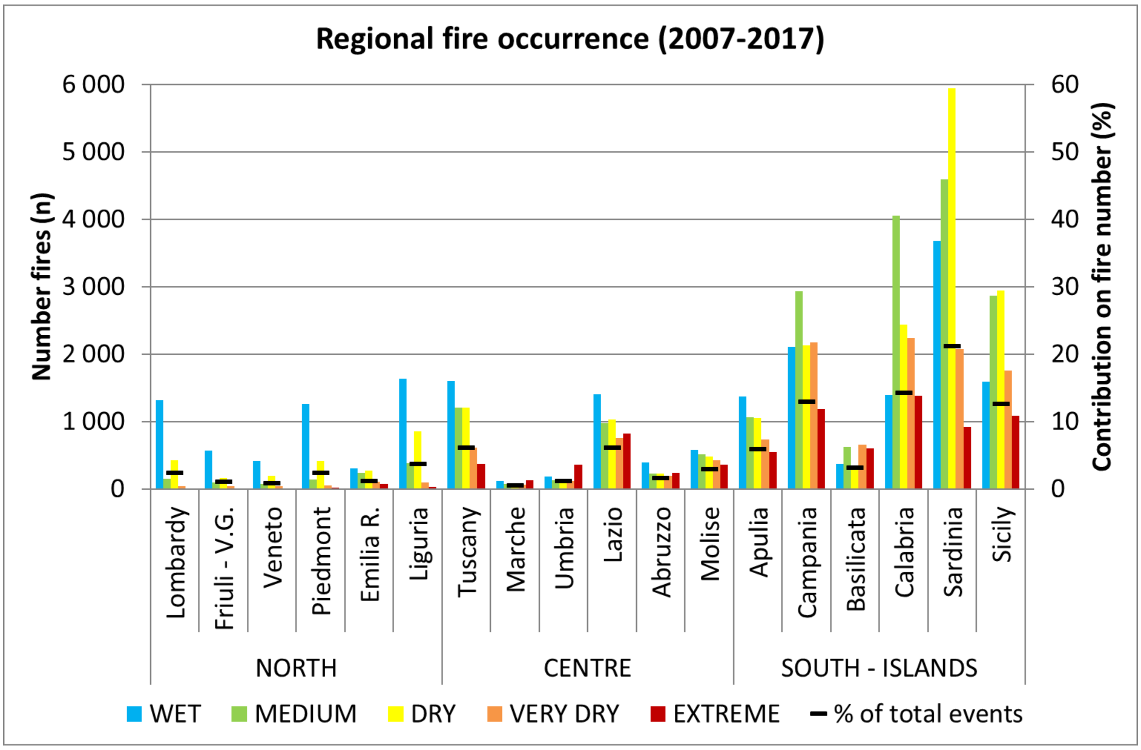

Figure 15 – Regional Fire occurrence distribution based on Fuel Moisture conditions. The primary vertical axis shows the composition of regional fire occurrence in fuel moisture classes; the secondary vertical axis shows the contribution of each region on total national number of fire events, expressed as a percentage

3.3. Spatial and temporal distribution of emissions

Total fire emissions (considering PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_x and SO_2) during the period 2007-2017 were estimated to be 20,342 Gg (Table 8). For the 11-year study period, average emissions of CO_2, CO, CH_4, NO_x and SO_2 were estimated to be 1,583, 216.8, 10.1, 1.3 and 1.1 Gg yr^{-1}. Concerning the particulate, average emissions of PM_{10} and $PM_{2.5}$ were 20.2 and 17.1 Gg yr^{-1}, respectively. Peak emissions occurred in 2007 (5,026 Gg), 2017 (4,396 Gg), followed by 2012 (2,949 Gg). These years accounted for the 61% of the total emissions for the study period (Figure17), while the minimum emissions occurred in 2013 (517 Gg).

On the national scale, fires occurring across the macro-categories “Conifers” and “Mixed hardwood” released in the atmosphere similar quantities of pollutants (3,031 and 2,700 Gg, respectively), accounting for about 14% of total emissions. “Agriculture & pastures” and “Broadleaves” contributed for about 22% (4,573 and 4,341 Gg emitted), whereas “Heathlands & Shrublands” released the largest quantity (28%) of total emissions. Analyzing the contribution of the different fuel types to total emissions (Figure 16), PD represented half of the total burned area (513,600 ha burned) while its contribution of total emissions accounted for about 17% (about 3,424 Gg). Conversely, MA only contributed a total burned area of almost 7%, but emitted similar quantities of pollutants as PD (3,408 Gg). This aspect can be explained by the different amounts of biomass between these fuel types (5.24 Mg ha^{-1} and 46.64 Mg ha^{-1}, respectively) that lead to distinct available fuels to burn and consequently to different emissions.

Using CO_2 as a representative example, the annual variation in total and source – specific emissions are presented in Figure 12. As stated earlier, peak emissions occurred in 2007, 2017 and 2012. “Heathlands & Shrublands” fires in 2007, “Broadleaves” fires in 2017, and “Agriculture & Pastures” in 2012, were the primary contributors accounting for 27.5%, 25.8%, and 20.3% of total emissions for the analyzed years, respectively.

Table 8 – Biomass burning emissions inventory (Gg) for Italy from 2007 to 2017

	Annual emissions (Gg)							
Year	PM_{10}	$PM_{2.5}$	CH_4	CO	CO_2	NO_X	SO_2	Total
2007	57.0	48.3	28.6	615.7	4 270.5	3.2	3.0	5 026.4
2008	13.9	11.8	6.9	148.2	1 141.0	1.0	0.8	1 323.5
2009	13.6	11.5	6.7	143.5	1 187.7	1.1	0.8	1 365.0
2010	6.9	5.8	3.4	71.9	646.8	0.6	0.4	735.9
2011	14.0	11.9	7.0	148.8	1 198.3	1.1	0.8	1 381.9
2012	32.3	27.4	16.2	347.1	2 522.0	2.0	1.8	2 948.7
2013	5.3	4.5	2.7	56.6	447.6	0.4	0.3	517.4
2014	6.1	5.2	3.0	64.4	575.4	0.6	0.4	655.1
2015	8.6	7.3	4.3	91.7	716.3	0.6	0.5	829.3
2016	11.6	9.8	5.8	123.1	1 010.8	0.9	0.7	1 162.7
2017	52.8	44.7	26.6	574.3	3 692.7	2.5	2.7	4 396.2

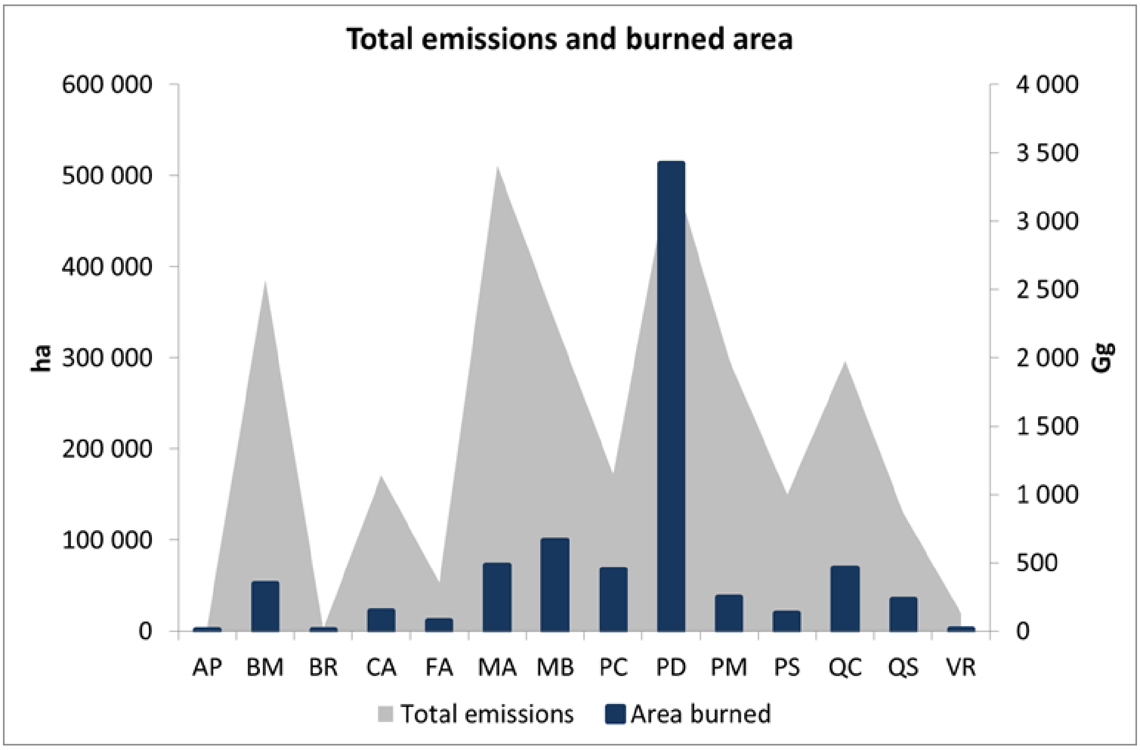

Figure 16 - Total emissions released (Gg) and burned area (ha) by fuel type classes. AP: Fir and spruce woods; BM: Mesophitic broadleaf forest; BR: Heathland; CA: Chestnut grove; FA: Beech forest; MA: High maquis and heather; MB: Low maquis and garrigue; PC: Continuous grassland; PD: Discontinuous rupicolous prairie;PM: Mediterranean pine forest; PS: Pine forest of sylvestris, black, stone and larch pines; QC: Oak-hornbeam, turkey oak, oak forest; QS: Evergreen oak forest; VR: Riparian vegetation

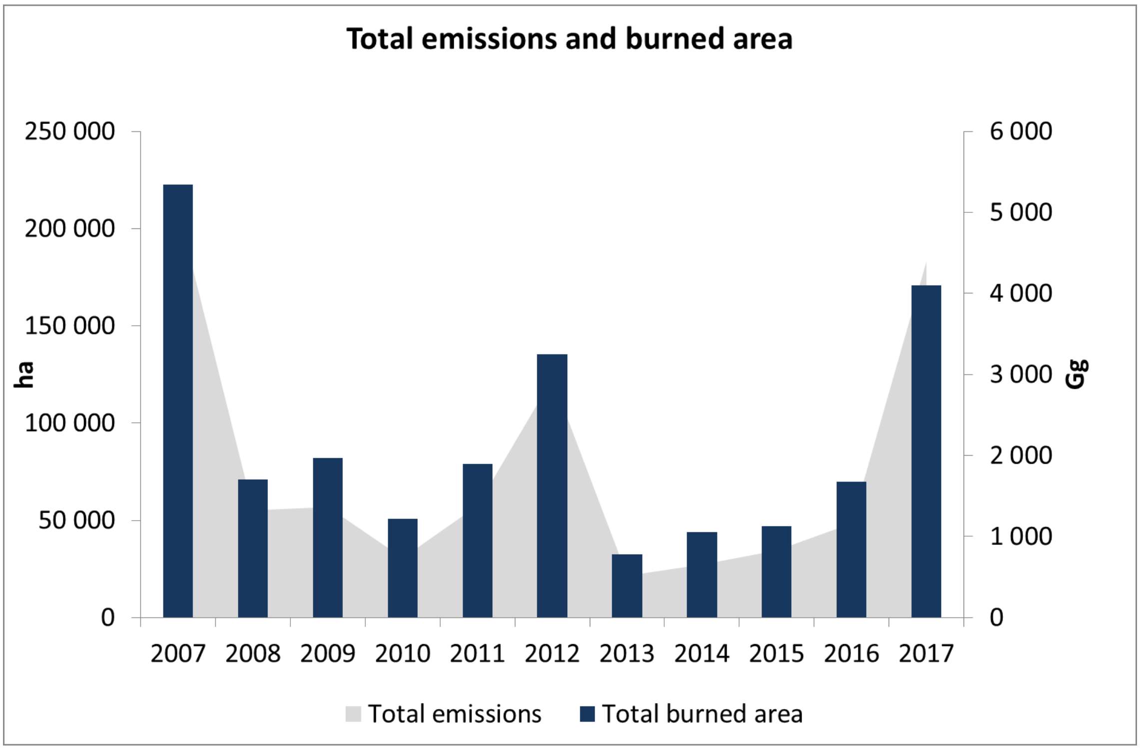

Figure 17 – Distribution of annual total emissions (Gg) and burned area (ha)

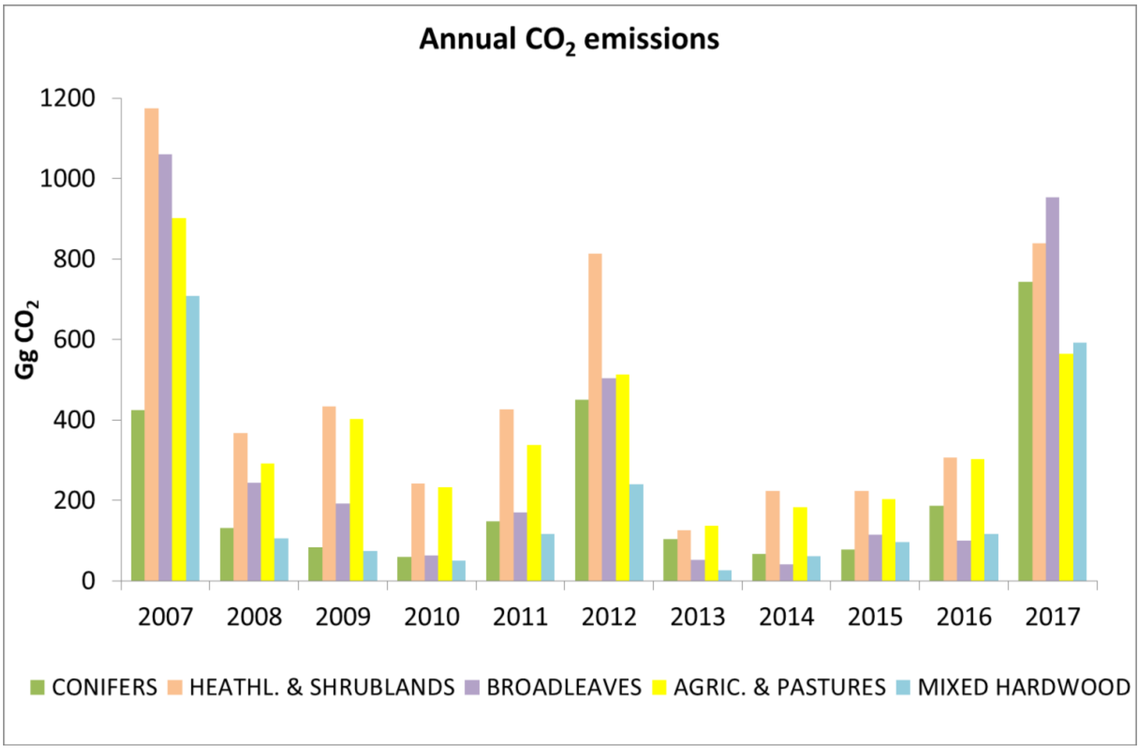

Figure 18 – Annual CO_2 emissions (Gg) for each macro-category

Large variability on total emissions was observed between regions during the analyzed period. In the northern regions, the percentage of emissions reached up to 6%, whereas southern regions contributed 77% of the total amount of pollutants emitted. The largest amount of pollutants was released in the regions most affected by fires, including Sicily, Calabria and Sardinia, with about 4,650, 4,270 and 2,400 Gg emitted. Average emissions through the analyzed years showed that the maximum averages for PM_{10}, $PM_{2.5}$, CH_4 and CO were produced in Calabria, for CO_2, NO_x and SO_2 in Sicily, whereas the lowest befell in Veneto for all the chemical species (Table 9).

Normalizing the total emissions *per* burned area at a regional level, the results showed that the highest values were recorded for Marche region, with 29.6 Mg emitted for each hectare burned (Mg ha^{-1}) despite its small total burned area for the analyzed period (6,560 ha burned). Also, Campania and Umbria regions showed high values, 27.3 and 27.1 Mg ha^{-1}, respectively, whereas the lowest normalized emissions were recorded in Sardinia and Molise (12.2 and 16.8 Mg ha^{-1}, respectively). This can be due to the distribution of fuel types within each regional area. Particularly, “Broadleaves”, and “Agriculture and Pastures” representing the most occurred macro-categories for Marche (30% and 25%, respectively), Campania (28% and 41%, respectively) and Umbria (29% and 41%, respectively), whereas the Sardinia and Molise areas, that showed the lowest normalized emissions, were characterized mainly by “Agriculture and Pastures” (77% and 70%, respectively). This is due to the dense forests, particularly composed of Broadleaves, which have a high quantity of biomass, high continuity of both horizontal and vertical fuel, which can contribute to the formation of fires characterized by extreme conditions.

Table 9 Average biomass burning emissions (Gg) in each Italian region from 2007 to 2017

		Average emissions (Gg)						
	Region	PM_{10}	$PM_{2.5}$	CH_4	CO	CO_2	NO_X	SO_2
NORTH	Lombardy	0.36	0.30	0.18	3.89	24.55	0.02	0.02
	Friuli V.G.	0.11	0.09	0.06	1.22	6.68	0.00	0.01
	Veneto	0.03	0.03	0.02	0.33	2.03	0.00	0.00
	Piedmont	0.53	0.45	0.27	5.82	33.72	0.02	0.02
	Emilia R.	0.06	0.05	0.03	0.62	3.58	0.00	0.00
	Liguria	0.32	0.27	0.16	3.43	24.28	0.02	0.02
Average emissions		0.23	0.20	0.12	2.55	15.80	0.01	0.01
CENTRE	Tuscany	0.31	0.27	0.16	3.44	20.94	0.01	0.02
	Marche	0.28	0.24	0.14	3.14	16.20	0.01	0.01
	Umbria	0.17	0.14	0.09	1.84	11.04	0.01	0.01
	Lazio	1.27	1.08	0.64	13.88	84.52	0.05	0.06
	Abruzzo	1.11	0.94	0.57	12.28	67.82	0.03	0.05
	Molise	0.19	0.16	0.10	2.13	12.86	0.01	0.01
Average emissions		0.56	0.47	0.28	6.12	35.56	0.02	0.03
SOUTH - ISLANDS	Apulia	1.15	0.97	0.57	12.22	97.42	0.09	0.07
	Campania	2.04	1.73	1.02	21.90	160.56	0.13	0.11
	Basilicata	0.63	0.54	0.32	6.75	51.67	0.04	0.04
	Calabria	3.74	3.17	1.88	40.35	279.04	0.21	0.20
	Sicily	3.63	3.08	1.81	38.60	310.41	0.28	0.21
	Sardinia	1.73	1.47	0.85	17.85	177.63	0.19	0.12
Average emissions		2.15	1.83	1.07	22.94	179.46	0.16	0.12

We compared the total emissions in proportion to the burned area for each fuel type class and thus for the main macro-categories, for each year analyzed and for the whole period. The highest amounts of emissions related to the area burned were produced by PM during 10 years, ranging from 56.40 Mg ha^{-1} in 2012 to 47.1 Mg ha^{-1} in 2014, showing an average of 52 Mg ha^{-1} for the period. Conversely, the lowest values of emissions in proportion to the burned area were recorded for PD, which emitted an average of 6.6 Mg ha^{-1}, ranging from showed 7 Mg ha^{-1} during 2009 to 6.1 Mg ha^{-1} during 2014. Totally, annual emissions produced by all vegetation types in proportion to the burned area ranged from 36 Mg ha^{-1} in 2007 to 30.4 Mg ha^{-1} during 2014.

Concerning the macro-categories, "Mixed hardwood" and "Conifers" produced the largest amount of pollutants for each hectare burned (44.7 and 43.1 Mg ha^{-1} emitted, respectively); conversely, the group "Agriculture & pastures" emitted 11.5 Mg ha^{-1} on average during the period 2007-2017, despite it representing the macro-category most affected by fires (Figure 19). As expected, this confirms the importance of the large fuel loading for the biomass burning emissions, which characterizes trees, leading to high amounts of biomass consumed and therefore to larger emissions.

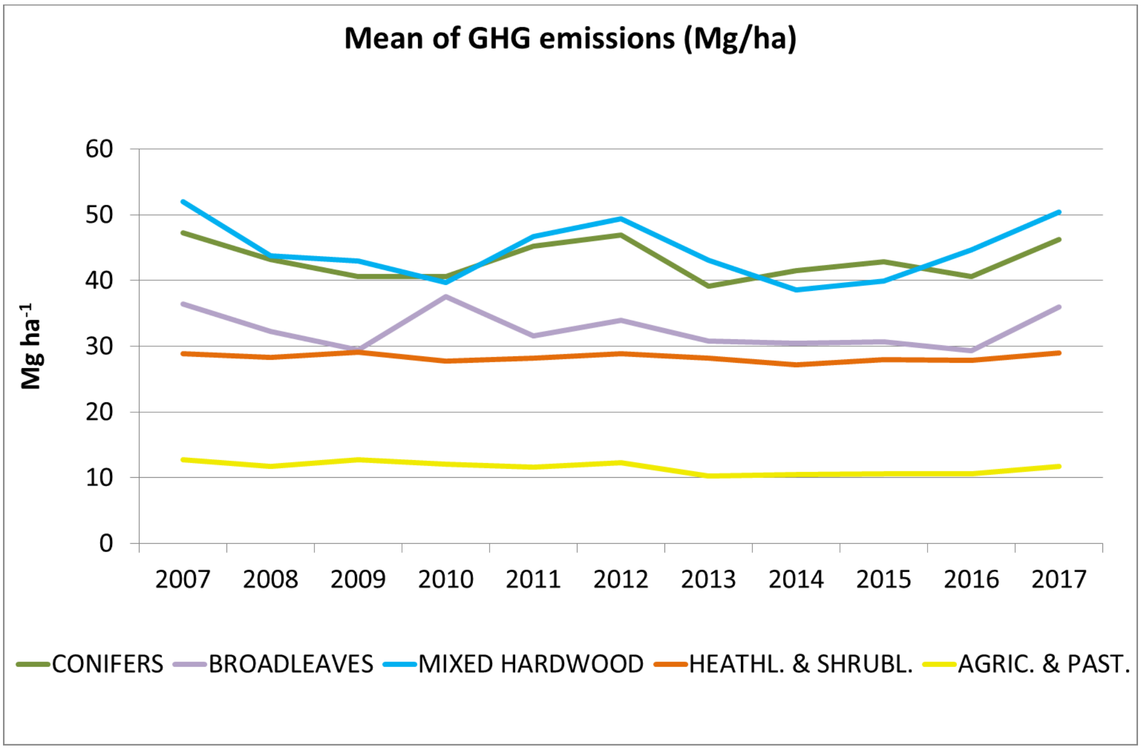

Figure 19 - Annual total emissions (Gg) for the macro-categories

3.4. Duff Loadings

As mentioned before, since information regarding duff layer for several fuel type classes was missing, particularly for FA, PC, PD, QC, QS and VR, and as result we filled the gaps of Ascoli et al. (2019) database with the Fuel Characteristic Classification System (FCCS) information. To understand the impact of the duff fuel variability, we compared the fire emissions of the reference simulation described above to two other simulations using two different duff information sources, one using duff FCCS data, and one inserting the lowest possible value of duff (see Table 4).

Thus, data input between the three simulations differed based on the amount of total duff loading selected from an average of 22.14 Mg ha^{-1} (S1) to 23.09 and 0.22 Mg ha^{-1} (for S2 and S3, respectively). These values were used to calculate the amount of biomass loss for each fuel type, dependently on the consumption information for the different layers supplied by FOFEM outputs, which differed for each type of vegetation based on the fuel moisture scenarios.

The total biomass consumed through burning ranged from 6,100 Mg in S1 to 2,890 Mg in S3 (Table 10). Results of fuel consumption showed that for all of the simulations "Heathlands & Shrublands" represented the larger portion of the total fuel consumed in the period, accounting for 23%, 27% and 43% of the total fuel consumption for each scenario, whereas the lowest losses were attributed to "Mixed hardwood" group. We obtained the total amount of pollutants emitted for each fuel type class for the three simulations. The highest amounts of pollutants were connected to the inputs of S1, with a total of 20,342 Gg emitted, followed to S2 and S3 with about 18,820 and 10,070 Gg emitted.

We also observed differences between the total emissions over the period for each simulation; S1 observed the highest emissions with a total emission of 20,342 Gg; despite this, S2 total emissions was slightly smaller (-7.5%) amounting to 18,821 Gg, whereas S3 total emissions were smaller than S1 of about 50.5% (10,070 Gg).

Concerning emissions related to each fuel type, the largest amount of pollutants was emitted by PM and CA for the S1 (52 and 49 Mg ha^{-1}, respectively), PS and AP for S2 (75 and 47 Mg ha^{-1}, respectively) and MA and PM for S3 (35 and 18 Mg ha^{-1}, respectively) (Table 11). On total, a large variability of emissions produced by the macro-categories in proportion to the burned area between the three scenarios was also observed. "Conifers and Mixed hardwood" resulted as the main contributors on emissions for S1 and S2, whereas "Heathland and Shrublands" represented the main contributor for S3. "Agriculture and pastures" resulted in the lesser producer of pollutants for all the simulation outputs (Figure 20).

These results show the relevance of duff information within the inputs. Particularly, data described above show that the largest production of pollutants were emitted by the fuel types that were associated to the largest duff values, such as CA and PM for S1 (38.17 and 36.46 Mg ha^{-1} of duff load, respectively), PS and AP for S2 (69 and 62 Mg ha^{-1}, respectively). This underlines that duff information needs to be chosen carefully, and if possible throughout accurate field measurements, in order to avoid under or overestimations of linked effects (in this case the resulting emissions from biomass burning) which can arise by the application of data information derived or born for different ecosystems.

Table 10 – Fuel load losses and comparison between simulations

Macro category	Fuel type	S1		S2		S3	
		Fuel load Mg ha^{-1}	Fuel load loss (Mg)	Fuel load Mg ha^{-1}	Fuel load loss (Mg)	Fuel load Mg ha^{-1}	Fuel load loss (Mg)
Conifers	AP	50.38	13.89	77.08	20.87	14.82	3.57
	PM	50.91	603.58	39.61	478.27	14.67	188.54
	PS	47.75	309.45	81.75	510.71	13.20	85.27
Heathlands - Shrublands	MA	46.64	987.76	38.69	810.51	34.70	715.24
	MB	21.22	666.55	15.05	478.95	15.28	478.95
Mixed hardwood	BR	11.45	5.90	11.86	6.02	11.42	5.89
	BM	46.67	788.92	40.23	690.85	11.38	230.55
	VR	46.91	39.98	46.91	39.98	11.75	5.04
Broadleaves	QC	26.97	618.45	26.97	618.45	7.57	142.80
	QS	21.44	262.32	21.44	262.32	10.86	137.63
	CA	53.08	347.65	37.20	251.47	15.13	110.95
Agriculture - Pastures	FA	37.04	110.53	37.04	110.53	6.86	17.07
	PC	15.65	342.45	15.65	342.45	4.27	138.69
	PD	5.24	1 005.62	5.24	1 005.62	2.64	621.16
	Total	481.34	6 103.06	494.73	5 627.01	174.54	2 881.35

Table 11 – Total emissions (PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_X, SO_2) per ha burned for fuel types, main groups of vegetation and scenarios

		Average total emissions Mg ha^{-1} (PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_X, SO_2)		
Macro-category	Fuel type	S1	S2	S3
Conifers	AP	31.2	46.8	8.1
	PM	52.0	41.7	17.7
	PS	46.2	74.6	14.2
Heathlands & Shrublands	MA	46.4	38.9	35.0
	MB	22.6	16.7	16.7
	BR	15.9	16.2	15.9
Mixed hardwood	BM	45.5	40.2	15.0
	VR	43.8	43.8	6.2
Broadleaves	QC	26.8	26.8	6.6
	QS	24.1	24.1	13.4
	CA	48.6	35.9	17.3
	FA	30.7	30.2	6.8
Agriculture & Pastures	PC	16.5	16.5	7.4
	PD	6.6	6.6	4.3

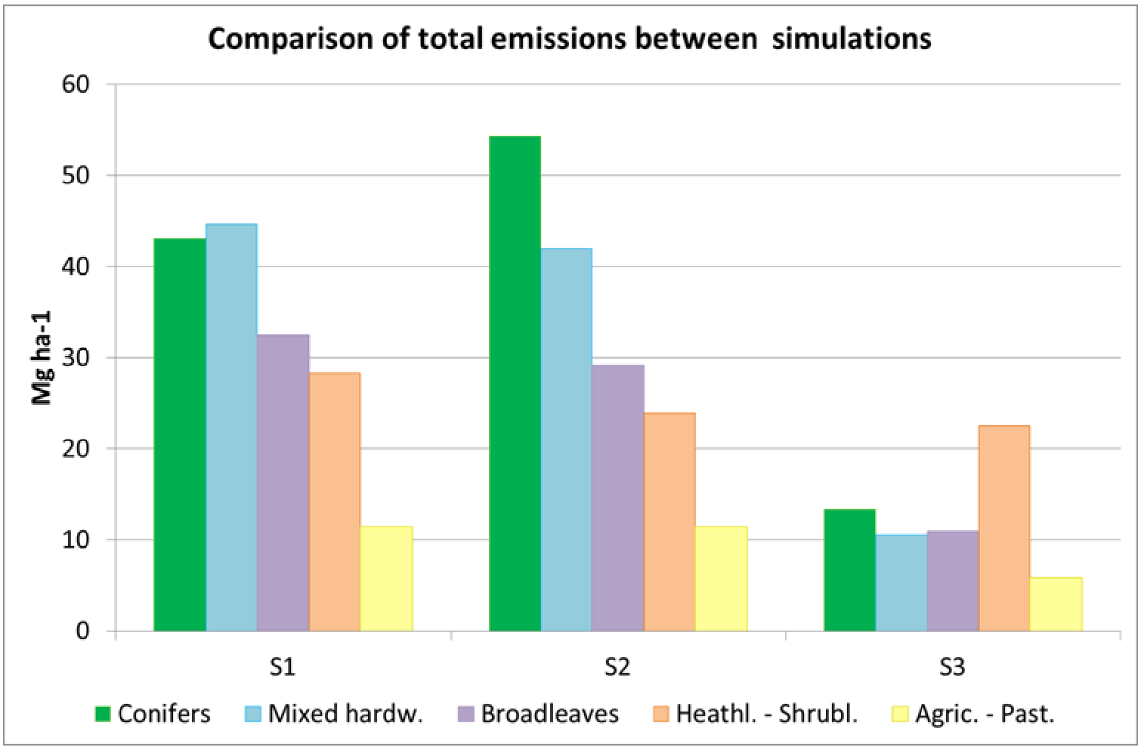

Figure 20 – Normalized biomass burning emissions for macro categories (Mg ha^{-1}) (Species analyzed: PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_X, SO_2)

3.5. Other study comparison

This study was compared with other research efforts that focused on the estimation of greenhouse gas emissions in Southern Europe and Italy. Particularly, we compared part of the results of Bacciu et al. (2012) to the application of our methodology for Sardinia during the period 2007-2009 (Table 12).

Bacciu et al. (2012) focused on the estimation of GHG emissions in Sardinia for 2005-2009. Thirteen fuel type categories were derived from the aggregation of the original Corine Land Cover classes of 2003. Similarly, to the present study, for the characterization of the fuel, literature and observations data were used in order to obtain a fuel model map, and FFMC values and percentiles were calculated in order to obtain fuel moisture classes and the FOFEM model for estimating emissions was used. During the three years, a total of 34,376, 6,095 and 44,840 ha were burned. We found differences in the estimation of all the chemical species and particulate matter emissions, particularly the previous estimates corresponding to about 78% of our results, especially for 2008 for which we proposed about 640 Gg despite 443 Gg of previous estimates, which corresponded to about 63% of our estimates. Differences in total emissions can be related to different factors; for example, our characterization of the moisture content for fine and dead forest fuels was derived from FFMC calculations over 11 years, compared to five years analysed by Bacciu. In addition, Bacciu used an older version of land use map (Corine Land Cover 2003), resulting in different vegetation distributions due to landscape modifications, and to possible different burned area compositions. Moreover, information on fuel loading was derived from a combination of literature and experimental observations more focused on Sardinian context, whereas our data were derived from vegetation over 14 different Italian regions, and, concerning duff information, some data were derived from FCCS, which were related to US ecosystems.

Table 12 – Total emissions for Sardinia for the period 2007-2009. From Bacciu et al. (2012)

	(Bacciu et al., 2012)			Present work		
Year	2007	2008	2009	2007	2008	2009
PM_{10}	1.34	0.24	1.61	3.78	0.68	5.67
$PM_{2.5}$	1.13	0.20	1.36	3.21	0.58	4.81
CH_4	0.55	0.10	0.65	1.87	0.33	2.79
CO	10.39	1.84	12.07	39.30	7.06	58.70
CO_2	331.21	61.07	426.74	374.00	67.40	567.27
NO_X	0.52	0.10	0.68	0.38	0.07	0.59
SO_2	0.2	0.04	0.25	0.25	0.05	0.38
Total	345.35	63.58	443.37	422.79	76.17	640.22
Mean	49.33	9.08	63.34	60.40	10.88	91.46

Previous studies on fire emissions estimates in Italy have been made, obtaining a large variability of data on CO_2 estimates (Table 13), varying from an annual average of 2,000 Gg year^{-1} (Narayan et al., 2007) to over 5,800 Gg year^{-1} (Vilén and Fernandes, 2011). For example, Vilèn and Fernandes (2011) with the aim of establishing the impact of prescribed burning on total CO_2 emissions for south-eastern European countries, based on their methodology following IPCC guidelines and the approach of Seiler and Crutzen (1980); they also considered the aerial part of trees, in order to include crown burning.

Narayan et al. (2007), whose purpose was the reduction of fire occurrence and emissions by the use of prescribed burning following the Kyoto protocol prescriptions, applied the Seiler and Crutzen (1980) formula using data obtained from the national forest inventories or derived from reports and literature.

Other studies focused on specific chemical species release, for example Knorr et al. (2016) showed for Italy an average of $PM_{2.5}$ levels of 425 Gg year^{-1} during the period 1997-2014. Moreover, Romano et al. (2010), conducting an analysis of the national greenhouses gas inventory report, proposed Italian emissions derived from biomass burning ranging from 5,243 to 20,000 Gg CO_2 yr^{-1} for the period 1990-2008, through a methodology based on the identification of the forest types and their damages related to fire, and the consequent application of damage coefficients and emissions factors derived from the research literature.

Concerning European emissions, for Portugal Rosa et al. (2001) proposed for the period 1990-2006 an estimation of CO_2 emissions between 143 Gg yr^{-1} to 5,083 Gg yr^{-1}, and a global annual average CO_2 emissions ranging from 8.4 to 20.4 Tg yr^{1}, whereas Friedli et al. (2009) over a study conducted on the global mercury emissions at global level, reported for all of the Europe and the period 1997-2006 an annual average of 14 Tg yr^{-1} of total Carbon emissions derived from biomass burning.

Differences between the present work and the others described above could be explained by dissimilarities in methodologies, input data, such as the inclusion of the aerial part of trees, and in the period considered (as proposed by Vilén and Fernandes, 2011), due for example to the inter-annual variability of fire incidence and severity.

Table 13 – Comparison of annual CO_2 emissions derived by several studies

Work	Period analyzed	CO_2 emissions (Gg yr^{-1})
Present work	2007 - 2017	447 - 4 270
Vilen and Fernandes, 2011	1980 - 2008	5 816
Bovio et al., 1996	1977 - 1991	2 600 - 4 400
Narayan et al., 2007	1999 - 2003	2 009
Romano et al., 2010	1990 - 1999	6 923

4. *Conclusions*

In this work we applied an integrated methodology combining the use of FOFEM (Reinhardt et al., 1997) with spatial and non-spatial inputs related to fire characteristics, vegetation and weather conditions, in order to provide a helpful way for the understanding of the incidence and effects of fires.

We assessed the uncertainties and weak points found during the process, through the evaluation and selection of data inputs and the observation of results variability. This information is valuable for providing data for emission source models coupled with dispersion models and decision support systems, crucial for air quality managements, mitigation of wildland fire environmental effects, and to assist decision makers in prescribed fire activities.

On a national scale, the total annual average emissions were 1,849 Gg $year^{-1}$. The annual average emissions for each chemical species were 20.19 (5.3-57.0), 17.11 (4.5-48.3), 10.11 (2.6-28.6), 216.8 (56.6-615.7), 1582.6 (447.6-4,270.5), 1.3 (0.4-3.2) and 1.1 (0.3-3.0) Gg $year^{-1}$ for PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_X and SO_2, respectively. The majority of emissions were released during 2007 and 2017 (5,026.4 and 4,396.2 Gg $year^{-1}$, respectively), which corresponded to 25% and 22% of total emissions for the period studied, whereas the lowest portion of emissions was released during 2013 (517.4 Gg $year^{-1}$ emitted and 3% of total). Heathlands and Shrublands contributed to the largest portion (28%) of total emissions, corresponding to 5,695.6 Gg $year^{-1}$, followed by Agriculture and pastures (4,573.7 Gg $year^{-1}$, 22.5% of total) and Broadleaves (4,341.6 Gg $year^{-1}$, 21.3% of total). Fires affecting woodlands (the sum of the macro-categories Conifers, Broadleaves and Mixed Hardwoods) represented the 49.5% of total emissions (10,072.9 Gg $year^{-1}$). Emissions in southern regions are determined to be primary contributors, contributing for 77% of the total amount of pollutants emitted. The largest amount of pollutants was released in the regions most affected by fires, like Sicily, Calabria and Sardinia, with about 4,650, 4,270 and 2,400 Gg $year^{-1}$, emitted.

Emissions between simulations showed the importance of duff information, exhibiting the largest emissions associated with the largest duff values, particularly for CA for S1 (38 Mg ha^{-1} of duff load and 48.6 Mg ha^{-1} emitted) and PS for S2 (69 Mg ha^{-1} of duff load and 74.6 Mg ha^{-1} emitted).

Compared to other methods, our estimation results are lower, particularly than those which considered percentages of crown burned on inputs Vilén and Fernandes (2011). At the same time, our highest values are very close to those from Bovio et al. (1996) and our ranges are similar to those proposed for Portugal by Rosa et al. (2011), indicating that our results are reasonable and can be used for further research. Uncertainties in our estimates could arise from incomplete information of fuel loading, particularly for duff of several fuel types, and the aerial part of the forest types. Thus, future improvements of these aspects could lead to a more representative fire emissions inventory in Italy, and also to predict and avoid large quantities of emissions derived particularly from fire events characterized by particular severe conditions.

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Chapter 3: Comparison of burned area, combustion efficiency, and fire emissions release during 2017 large fire events

1. *Introduction*

Wildland fires are one of the most significant disturbance sources for several Mediterranean forest ecosystems, also threatening lives and assets. Furthermore, these events could affect air quality and thus human health due to the production of harmful pollutants, such as particulate matter, carbon monoxide and ozone precursors. Fire emissions also contribute to regional haze, reducing visibility, and altering the carbon budget.

Smoke emission modelling is a process requiring the combination of several input data, including fire size and location, fuel loading and moisture, combustion efficiency and emissions factors (Seiler and Crutzen, 1980). During recent decades, several models and decision support systems have been developed to provide more accurate estimates. Also, numerous datasets were produced and are available for performing each step of the fire emission estimation pathway, with significant impacts on the resulting quantification.

For example, remote sensing data has increased the detection and quantification of several factors influencing fire emission, providing data on fire size, fuel characterization, fuel consumption, moisture conditions, and also information on fire intensity and fire severity (French et al., 2011). During the 20th century, mapping burned area has evolved considerably, providing benefits for fire suppression advances, fire mapping and helping fire managers to determine their resource needs and everyday tasks (Kolden and Weisberg, 2007). In order to reply to the fragmented long-term data information on burned area, necessary to provide spatial and temporal information for quantifying trace gas and aerosol emissions (Langmann et al., 2009), several multi-year satellite-based global burned area products have been created. Detecting burned area over large scales from satellite, however, has proven to be an important source of uncertainties. Giglio et al. (2010) compared four satellite multi-year burned area datasets (GFED2, L3JRC, MODIS MCD45A1 and GLOBCARBON) with a new one, GFED3 data set, showing a large variability and substantial differences in the studied regions. For example, on average GFED3 burned area was larger of almost 10% than GFED2 burned area. Locally, differences for some regions resulted larger, such as for Southern Hemisphere Africa where the increase of BA was of 60%. A work conducted in Australia (Srivastava et al., 2013) on two-decadal burned area data comparison between a Global

Positioning System (GPS) manual mapping and remote sensing, showed an overestimation of the fire frequency and burned area from GPS mapping and, at the same time, an underestimation of burned areas under low fire severity conditions from Landsat imagery.

Several studies demonstrated that fuel loading is one of the largest contributors to variability and uncertainty within emissions quantification (Larkin et al., 2014; Drury et al., 2014; Hyde et al., 2015). This depends also by the accuracy of fuel loading estimation within land cover maps and forest inventories. Unfortunately, the availability of measured data of fuel loading is inhomogeneous, and the estimation of fuel consumption and the related emissions is complicated in many countries.

Hyde et al. (2015) compared the consumption and emissions results between data layers (LANDFIRE) and measured fuel loadings. The study underlined that differences in fuel loadings, particularly of duff and total surface fuels, were related to significant differences in consumption and emissions estimates.

Actually, most fuel maps are missing canopy fuel data. Mitsopoulos et al. (2007) evaluated the influence of canopy fuel characteristics on fire behaviour for Aleppo pine stands (*Pinus halepensis Mill.*) in Greece, considering information on vertical continuity as fuel loading, canopy base height, weight and canopy loading. They showed that factors influencing the canopy ignitions were related more to the canopy base height and fuel loading then to burning conditions. The transition of surface to crown fire is generally linked to extreme fire conditions, which can lead an unmanageable situation by suppression personnel, and thus leading to the larger burned areas (Albini, 1984) and greater quantities of gas, particulate and pollutant emissions. The assessment of canopy characteristics and knowledge can supply important information on crown behaviour in order to address fuel management treatments together with prevention and suppression plans and emission estimation.

Another point of concern is the estimation of combustion efficiency or completeness, which is defined as the ratio of carbon released as CO_2 on the total carbon present in the fuel and represents the live or dead vegetative biomass pyrolyzed or combusted when a fire occurs. Combustion completeness depends on fuel type characteristics such as its moisture content, age, phenology and flammability (Xanthopoulos et al. 2012), as well as fire characteristics such as the fire intensity, rate of spread and flame residence time. Surface fuel fires are often less intense than crown fires, and their effects, also in terms of fire emissions, are less severe.

Recently, Chiriacò et al. (2013) comparing different methods used by the Southern European nations to estimate the completeness of combustion and thus the released emissions, showed that the best method to reduce the uncertainty could be obtained multiplying the burned area by the level of fire damage. In that paper, the level of damage was determined on the basis of the vegetation class and the height of the scorching flame (Bovio 2007).

Another approach to estimate the aboveground and belowground organic matter consumption from fire is represented by the burn severity measurement. This concept has been applied to describe all the physical and ecological modification characterizing the vegetation after fire occurrence, despite the previous conditions before the fire (De Santis and Chuvieco, 2009, Key and Benson, 2005). Burn severity depends on several factors such as the characterization and amount of fuel, moisture content and chemical properties, biotic conditions together with external factors such as weather and landscape patterns (Van Wagner, 1983; Christensen et al., 1989; Turner and Romme, 1994; Turner et al. 1999). Several studies that estimated burn severity showed a large variability of methodologies, from field-based methods to the use of satellite detection (Van der Werf et al., 2006). Satellite detection allows estimation of severity levels across large areas, detect variations from the understory to the tree canopy of the forests (White et al.,1996), showing problems in detecting the causes of burn severity variations (Chuvieco et al., 2006). Problems in satellite detecting were observed through the comparison between the area observed on the ground and the map derived by satellite, showing low accuracy of satellite detection for low severity and unburned areas than for high severity ones (Cocke et al., 2005). Detecting severity has been shown to be particularly difficult when the imagery was acquired not soon after a fire, giving time to vegetation to grow (White et al., 1996). Field-based methods for estimating burn severity might also estimate the residence time, and sometimes they are necessary to integrate satellite information data to take additional accurate information, such as the detection of the part of the forest strata that has been damaged.

The accurate assessment of greenhouse gas and particulate emissions from fires is of strategic importance for air quality management, mitigation of fire environmental effects, and for the development of more accurate emissions inventories at a national scale and in the framework of Kyoto Protocol reporting activities. This paper aims to highlight this issue by comparing the estimated emissions from six fires occurred in Italy in 2017 using alternative data sets to evaluate the main sources of uncertainties.

To this aim, we quantified the impact of several datasets concerning different burned area, fuel loading, fuel moisture and fuel consumption, in estimating fire emission deriving from six fire events. An integrated methodology combining a fire emissions model (FOFEM - First Order Fire Effect Model, Reinhardt et al., 1997) with spatial and non-spatial inputs related to fire, vegetation, and weather conditions was applied (Bacciu et al., 2010; 2012). We created five inputs-combination based on the mixing of two burned area products, two methods to deriving fuel moisture conditions, and the setting of fuel consumption. Finally, emissions data (trace gas and particulate) distribution for inputs combination were examined and compared.

2. ***Material and Methods***

To estimate emissions, we quantified the impact of several datasets concerning different burned area, fuel loading, fuel moisture and fuel consumption, taking into account six fire events that occurred during 2017; an integrated methodology combining a fire emissions model (FOFEM - First Order Fire Effect Model, Reinhardt et al., 1997) with spatial and non-spatial inputs related to fire, vegetation, and weather conditions was applied (Bacciu et al., 2010; 2012). We created five inputs-combination based on the mixing of two burned area products, two methods to deriving fuel moisture conditions, and the setting of fuel consumption.

2.1 Fire burned areas

Fire burned areas for the six case study were acquired by the Copernicus Emergency Management Service. The data were downloaded with free access from the official website (https://www.copernicus.eu/en) choosing the grading map of Rapid Mapping service. The Copernicus Rapid Mapping product gives information about the intensity of the damage caused by the event through a rapid acquisition followed by processing and analysis of satellite imagery. Grading maps provide an assessment of the extent, with type and magnitude of damages caused by an event, and it can be derived from pre- and post-event satellite images. Concerning fires grading maps, four levels of damage are provided, with the following caption describing from lowest to highest severity: “Negligible to slight damage”, “Moderately damaged”, “Highly damaged” and “Completely destroyed”.

In parallel, the burned area data retrieved through GPS for the same fires were acquired from the former Italian Forest Service (Corpo Forestale dello Stato, now Carabinieri C.U.F.A.A.) and the Sicilia Region Forest Service (Corpo Forestale della Regione Sicilia).

We examined six fire events that occurred during 2017, chosen from the activation of Copernicus Emergency Management Service. These events were characterized by an extreme pattern, which lead to activation of the emergency process and consequently the rapid mapping system. All of the events are localized in the Centre-southern part of Italy (Figure 21).

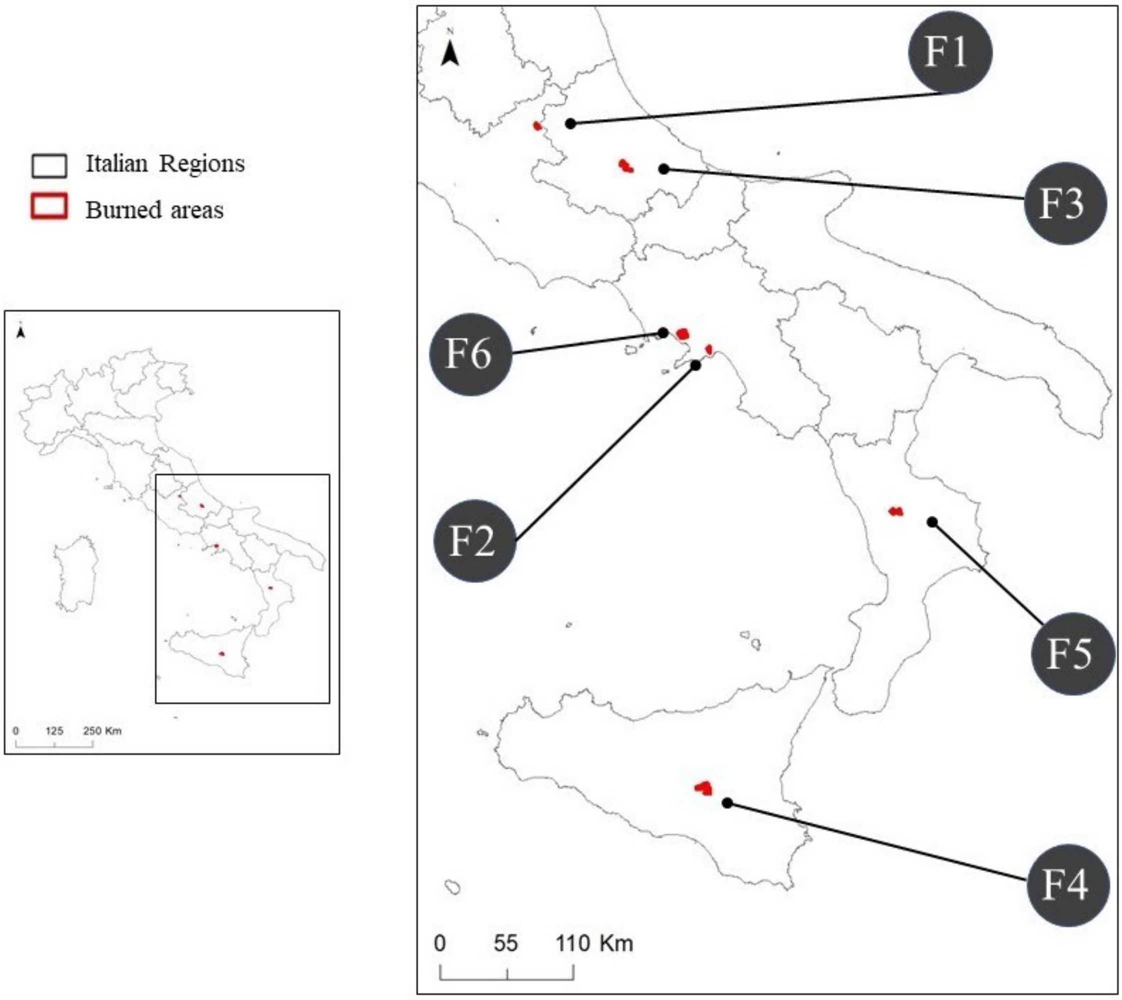


Figure 21 – Localization of studied fire events

The fire called "Antrodoco borgo–velino" (F1) was mapped by Copernicus on 29/08/2017, after an extreme fire occurred on 22nd August (Table 20) on Giano Mount (Rieti, Lazio), reported as arson fire. A total of 696 ha burned were mapped by satellite, composed almost equally by the severity classes representing high damages, with the largest one (about 34% and 234 ha) identified as "High damaged", whereas only 47 ha were burned at low conditions (Table 14).

The "Cava de' tirreni" fire (F2) was mapped on 29/08/2017, despite occurring between 8th and 9th August, on Sant'Angelo Mount (Salerno, Campania), continuing for almost ten days. It burned 660 ha, of which 44% (293 ha) was catalogued as "Completely Destroyed".

"Majella-Morrone" fire (F3) was mapped on 29/08/2017, whereas it occurred on 19th through 20th of August. It took place on Morrone Mount sited in the Park of Majella (L'Aquila, Abruzzo), continuing for ten days and burned a total of 1471 ha, most at "Highly Damaged" conditions (1159 ha and 79% of the total).

"Piazza armerina" fire (F4) was mapped on 9/08/2017, took place on 3rd August for more than one day, on the Nature Reserve of Rossomanno-Grottascura (Enna, Sicily). A total of 3,213 ha burned was mapped; 38.7% of burned area was identified as "High damaged" (1,240 ha), followed by "Completely destroyed" and "Moderately Damaged" (26% and about 840 ha burned for each one).

"Rose" fire (F5) was detected by Copernicus mapping on 08/08/2017, occurred on 2nd August, burning more than 1,680 ha, showing an equal distribution within severity classes. It occurred on a hill near the Rose village (Cosenza, Calabria) reported as negligence fire.

Finally, the "Vesuvio" fire event (F6) was detected on 16/07/2017, corresponding to a series of forest fires, that occurred from 5th to 12th of July on the National Park of Vesuvio (Naples, Campania) and catalogued as arson fires; a total burned area of 1,555 ha was detected, composed mostly (68% and 1,060 ha) by the most severe class.

We proceeded in identifying the corresponding fire perimeters supplied by the database of the former Corpo Forestale dello Stato (actually Carabinieri C.U.F.A.A.) for five fires, and from Corpo Forestale della Regione Sicilia for "Piazza armerina" fire event.

Table 14 – Distribution of burned area in damage classes for the six fires detected by the Copernicus Emergency Management Service

Fire event	Fire code	Completely Destroyed %	Highly Damaged %	Moderately Damaged %	Negligible to slight damage %
Antrodoco borgo-velino	F1	29.4	33.6	30.2	6.8
Cava de' tirreni	F2	44.4	22.4	0.0	33.1
Majella Morrone	F3	6.8	78.7	14.5	0.0
Piazza armerina	F4	26.4	38.7	26.2	8.7
Rose	F5	29.8	18.7	31.3	20.2
Vesuvio	F6	68.2	19.7	0.0	12.1

2.2 Vegetation and Fuel data

The fuel type and load for each fire were determined using a combination of satellite products and published data. Recently, Ascoli et al. (2019) classified and typified surface fuels in Italy by harmonizing more than 600 quantitative samples carried out over the last decade from different research groups in 12 Italian regions. The database collects repeated observations in alpine environments, temperate and Mediterranean, and includes duff, litter, herbaceous, shrub and downed woody fuels. Furthermore, fuel load is divided in dimensional classes for dead (0-6, 6-25 and 25-75 mm) and live (0-6 mm) fuels.

Each quantitative sampling was then associated with a forest type (with reference to the European Forest Types classification - EEA 2006), a Corine Land Cover IV level (CLC 2012), and a type of fuel. Fourteen main land cover types representing the principal fuel types in Italy were obtained, that can also be aggregated in four macro-categories: Broadleaves, Conifers, Mixed Hardwood, Heathlands & Shrublands, and Agriculture & Pastures (Table 15).

Due to the missing or incomplete information concerning the duff layer for some fuel type classes ("Beech forest", "Continuous grassland", "Discontinuous rupicolous prairie", "Oak-hornbeam, turkey oak, oak forest", "Evergreen oak forest", "Riparian vegetation"), we filled the gaps of the Italian database using the information of similar corresponding fuel classes contained in the Fuel Characteristic Classification System – FCCS (Ottmar et al., 2007; Sandberg at al., 2001). FCCS provides a description of fuel bed categories through six horizontal strata (canopy, herbs and grasses, woody dead material, litter and duff or ground fuels) and their properties, in order to determine the way they will be burn and consumed by fire (Ottmar, 2014), obtaining a duff input representing a double-source information, corresponding to information contained in Simulation 1 of Chapter 2. Particularly, the association with the FCCS fuel classes was conducted through a meticulous photographic evaluation of each FFCS class with the fourteen Italian land cover types. Furthermore, due to missing information on crown fuel load in the database supplied by Ascoli et al. (2019), we conducted a bibliographic research on crown foliages and branches load information for both broadleaves and conifer forests (Bovio, 1996; Leonardi et al., 1996; Mitsopoulos, 2007).

Finally, cross-walking the fuel type map with the selected fuel loadings, we created a fuel model map, which ultimately was overlaid by the fire perimeter layer, thus identifying the fuel model burned areas layer (FMBA).

2.3 Fuel Consumption and Fire Emission

FOFEM (Reinhardt et al. 1997; Reinhardt 2003) is a versatile and widely used program to predict first order fire effects, such as fuel consumption, pollutant emissions, soil heating, and postfire tree mortality. It comprises an extensive number of fuel models derived from literature data on measured fuel load of U.S. ecosystems, including Society of American Foresters/Society of Range Management (SAF/SRM), National Vegetation Classification System (NVCS), and Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007, Prichard et al. 2013). For each fuel model, a description of the vegetation and information on fuel load for ground and aerial vegetation strata (duff, litter, three size classes of woody debris, herbs, shrubs and live tree live branches and foliage) is associated. Furthermore, users can also modify or replace the input parameters manually or by inserting an input file according to local conditions. Shrub and duff fuel consumption is empirically derived through regression models based on region, while herbaceous and litter fuels are assumed to be completely consumed. On the other hand, the simulation of consumption for downed woody particles is estimated using BURNUP, a process-based model of heat transfer and burning rates of woody fuel particles by size class (Albini and Reinhardt 1995, 1997; Albini et al. 1995; Reinhardt and Dickinson 2010; Lutes 2013). The BURNUP model also allows to estimate separately smoldering and flaming combustion with the connected emissions of gaseous and particulate (Ward et al., 1993), namely for $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, NO_X and SO_2.

Concerning fuel moisture, namely the parameter affecting the ratio and the combustion efficiency of flaming and smoldering phases, FOFEM can be run under four moisture settings determined by 10-hour fuel moisture (FM10): wet (FM10 22%), moderate (FM10 16%), dry (FM10 10%), and very dry (FM10 6%). Users can thus select default burn conditions, or input different values.

2.4 Fuel moisture and combustion completeness

FOFEM model needs, among the input data for fuel consumption and fire emission, the fuel moisture for the considered categories and the percentage of crown combusted to derive the combustion completeness. In the present work we derived this information through two process. The first was based on the calculation of the Fine Fuel Moisture Code (FFMC) as a proxy of fuel moisture, while the second relied on the severity classes delineated by the Copernicus rapid mapping.

The FFMC, ratings of the moisture content of litter and other fine fuels, is one of six indices composing the Canadian Fire Weather Index (FWI), which provides numerical non-dimensional ratings of relative fire potential. FWI is based solely on 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 for the four required variables was gathered from the Era-Interim Reanalysis product (http://apps.ecmwf.int/), at grid resolution of 0.125° and at 12:00 UTC considering 24 h accumulated values for precipitation and instantaneous values for the other variables. Once we obtained the daily FFMC value, we calculated four thresholds as a function of the distribution (25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles), to obtain five fuel moisture scenarios (wet, medium, dry, very dry, and extreme). Then, each daily fire burned area was associated to FFMC value.

Table 15 - Description of Fuel types from Ascoli et al. (2019) derived from the aggregation of Corine Land Cover classes (EEA 2012). (EU Forest Types: EEA 2006; EU Fuel Types: Camia, 2012)

Macro categories	Fuel Types	Fuel Type codes	EU Fuel Types	EU Forest Types	Corine Lev. III-IV	Duff Mg ha^{-1}	Litter Mg ha^{-1}			Herbs Mg ha^{-1}	Shrubs Mg ha^{-1}		Foliage Mg ha^{-1}	Branches Mg ha^{-1}
							1 h	10h	100h		1h	10h		
Conifers	Fir and spruce woods	AP	23, 26	3.2, 7.9	3123, 31323	35.8	1.4	2.0	2.6	0.4	0.1	0.2	4.7	7.3
	Mediterranean pine forest	PM	20	10.1	3121, 31321	36.5	3.7	2.5	0.9	0.7	5.1	1.6	6.0	12.0
	Pine forest of sylvestris, black, stone and larch pines	PS	22, 25	10.2, 14, 3.1, 3.3	33122, 3124, 3125	34.8	2.1	2.5	4.1	0.9	1.2	0.5	4.7	9.3
Heathlands & Shrublands	High maquis and heather	MA	10	-	3231	12.2	5.4	3.0	0.6	1.3	16.5	7.7	--	--
	Low maquis and garrigue	MB	9	-	3232	6.2	2.2	2.3	0.4	1.6	6.2	2.4	--	--
	Heathland	BR	8	-	322	0.3	1.2	0.0	0.0	4.2	5.8	0.0	--	--
Agriculture & Pastures	Continuous grassland	PC	5, 6	-	3211	11.6*	0.2	0.0	0.0	3.7	0.0	0.0	--	--
	Discontinuous rupicolous prairie	PD	4	-	3211, 3212	2.8*	0.1	0.1	0.0	2.1	0.2	0.0	--	--

Table 15 – Cont.

Macro categories	Fuel Types	Fuel Type codes	EU Fuel Types	EU Forest Types	Corine Lev. III-IV	Duff Mg ha^{-1}	Litter Mg ha^{-1}			Herbs Mg ha^{-1}	Shrubs Mg ha^{-1}		Foliage Mg ha^{-1}	Branches Mg ha^{-1}
							1 h	**10h**	**100h**		**1h**	**10h**		
Broadleaves	Chestnut grove	CA	30	8.7	3114, 31314	38.2	2.2	5.4	1.5	0.2	2.4	0.0	3.3	15.5
	Beech forest	FA	33	7.3	3115, 31315	30.4*	0.6	1.5	2.9	0.3	0.0	0.0	5.0	**6.0**
	Oak-hornbeam, turkey oak, oak forest	QC	30, 31	5.1, 8.1, 8.2, 8.8	3112, 31312	19.6*	1.1	1.4	2.7	0.6	0.5	0.0	4.7	**7.3**
	Evergreen oak forest	QS	29	9.1	3111, 31311	10.8*	2.2	2.3	2.4	0.4	3.3	0.0	3.0	**6.0**
Mixed hardwood	Mesophitic broadleaf forest	BM	30	8.8	311, 2241, 3113	35.5	2.2	4.4	1.4	0.8	1.4	0.0	4.7	7.3
	Riparian vegetation	VR	39	12.1	3116	35.4*	0.2	0.7	2.6	1.4	1.5	0.2	--	**--**

* FCCS values

Finally, to each fuel moisture scenarios a fuel moisture content value (FMC) for duff, 10-hour and 1000-hour fuel was assigned, based on literature data information (Pellizzaro et al., 2009a; 2009b) (Table 16).

Table 16 - Fuel moisture content (FMC) value (%) associated to FFMC scenarios and fuel classes

	Dead fuel moisture content value (FMC) (%)		
FFMC class	duff	10-hour	1000-hour
WET	130	16	50
MEDIUM	90	13	40
DRY	75	11	30
VERY-DRY	40	9	25
EXTREME	20	7	15

As said, the damage severity classes identified by the Copernicus rapid mapping are the following: "Negligible to slight damage", "Moderately damaged", "Highly damaged" and "Completely destroyed". With the aim to define a percentage of vegetation combustion to each class, we developed an approach based on the work of De Santis and Chuvieco (2008) relied on the Geometrically Structured Composite Burn Index (G*eo*CBI).

The G*eo*CBI, indeed, is a proxy of the burn severity, indicating the magnitude of damage derived from fires. In particular, the G*eo*CBI incorporates the percentages of variation of the Leaf Area Index (LAI), namely the area of leaf surface per unit of soil surface (Ceccato et al., 2002), for the following strata: Tall shrubs and trees = 1-5 m (C); Intermediate trees = 5-20 m (D); and Big trees > 20 m (E). It also integrate and integrates the Fraction of Vegetation Cover (FCOV) regarding strata from B (Herbs, low shrubs and trees < 1 m) to E. Furthermore, two radiative transfer models, PROSPECT (Jacquemoud, 1990) and GeoSail (Huemmrich, 2001) were applied, in order to obtain the amount of undamaged (green) and damaged (brown) leaves existing in the canopy, and then to describe five burn severity scenarios (Figure 22) which gave the percentages of damage relative to each vegetation vertical strata.

Simulation at canopy level					
Burn severity scenario	High	Moderate-high	Moderate	Low	Unburnt
CBI	3	2.85	2.45	0.9	0
Example					
Strata B+C Leaf type	–	–	Brown	Brown	Green
Strata B+C LAI	–	–	1.7	0.5	1
Strata D+E Leaf type	Brown	Brown	Green	Green	Green
Strata D+E LAI	0.01	0.1	0.7	1.8	2.5
Sub-stratum type	DCH	DCH	DCH	50% SOIL 50% DCH	SOIL
Other inputs (fixed)	LAD = spherical; Rv to Rh = 2.36; Sun zenith angle = 30°; Crown shape = cone; note: all simulations were performed from 400 to 2400 nm, at 10 nm-intervals.				

Figure 22 – Description of the five burn severity scenarios derived to simulations with PROSPECT and GeoSail models. Understory corresponds to strata B+C, overstory = D+E, DHC = Dark Charcoal, substratum. LAD = Leaf angle distribution. Rv to Rh = crown height to width ratio. (From De Santis and Chuvieco, 2009).

On the basis of the damage information of each burn severity scenario described by *Geo*CBI for each vegetation strata (Table 17), we associated the damage severity classes of the Copernicus Rapid Mapping to the percentages of canopy consumption. The valued ranged from the 100% of crown burned described by the "High" *Geo*CBI severity level which corresponded to the class "Completely destroyed" of Copernicus rapid mapping, to the less severe class, characterized by the 25% of crown consumed associated to "Low" *Geo*CBI severity level corresponding to the class "Negligible to slight damage" of Copernicus rapid mapping (Table 18).

Table 17 – Percentages of strata combustion based on Burn Severity scenarios described by *Geo*CBI (De Santis and Chuvieco, 2008)

*Geo*CBI Burn severity scenario	Percentage of strata consumed		
	A	B+C	D+E
HIGH	100%	100%	100%
MODERATE-HIGH	100%	100%	70%
MODERATE	50%	80%	30%
LOW	unchanged	50%	15%
UNBURNT	unchanged	unchanged	unchanged

Table 18 – Definition of Burn Severity scenarios and the corresponding percentages of crown consumption through the association of *Geo*CBI (De Santis and Chuvieco, 2009) and Copernicus rapid mapping classes

*Geo*CBI Burn severity scenario	Copernicus Severity classes	Severity classes of the present study	Percentage of crown consumption used in the present study
HIGH	COMPLETELY DESTROYED	HIGH	100%
MODERATE-HIGH	HIGHLY DAMAGED	MODERATE HIGH	85%
MODERATE	MODERATELY DAMAGED	MODERATE	55%
LOW	NEGLIGIBLE TO SLIGHT DAMAGE	LOW	25%
UNBURNT	- *	-	-

*absent

Finally, we associated the percentages of canopy combustion derived from the *Geo*CBI Burn Severity scenarios to the FFMC moisture scenarios, as described in Table 19, assuming that during "Extreme" conditions the canopy is completely combusted while in "Wet" condition it is unburned.

Table 19 – Definition of the percentage of crown burned based on Burn Severity scenarios through the association between *Geo*CBI values (De Santis and Chuvieco, 2009) and FFMC moisture scenarios

		G*eo*CBI Burn severity scenarios				
		HIGH	MODERATE HIGH	MODERATE	LOW	UNBURNT
FFMC Moisture scenarios	EXTREME	100%				
	VERY DRY		85%			
	DRY			55%		
	MEDIUM				25%	
	WET					0%

2.5 Fire emission simulation scenarios

Finally, in order to understand the main sources of uncertainties in fire emissions estimation, we crossed burned area datasets (Copernicus Rapid Mapping and Carabinieri C.U.F.A.A.) with the approaches used to assess fuel moisture and burn severity conditions (and thus percentages of canopy consumption for each level of severity). Five simulation scenarios were derived (Table 20):

- Scenario 4 (S4-COP) uses both burned area and fuel moisture conditions and fire severity classes driven by the information derived by Copernicus Rapid Mapping;
- Scenario 5 (S5) uses fuel moisture conditions and burn severity classes driven by FFMC, and divides into S5-COP (burned area from Copernicus Rapid Mapping) and S5-CUFAA (burned area from Carabinieri C.U.F.A.A.);
- Scenario 6 (S6) uses fuel moisture driven by FFMC while the combustion consumption is fixed at 25% for all classes, and divides into S6-COP (burned area from Copernicus Rapid Mapping) and S6-CUFAA (burned area from Carabinieri C.U.F.A.A.).
-

Table 20 – Description of crossing information between FOFEM scenario simulations and burned area mapping sources

Crossing simulations	Copernicus Severity classes	Severity classes	% of crown burned	Burned area mapping method
S4-COP	"S4" Fuel moisture and Burn Severity driven by Copernicus	L M MH H	25 55 85 100	Copernicus rapid mapping
S5-COP	"S5" Fuel Moisture and Severity driven by FFMC moisture classes	W M D VD E	0 25 55 85 100	Copernicus rapid mapping
S5-CUFAA	"S5" Fuel Moisture and Severity driven by FFMC moisture classes	W M D VD E	0 25 55 85 100	C.U.F.A.A. mapping
S6-COP	"S6" Fuel moisture driven by FFMC moisture classes; Severity fixed values	W M D VD E	25 25 25 25 25	Copernicus rapid mapping
S6-CUFAA	"S6" Fuel moisture driven by FFMC moisture classes; Severity fixed values	W M D VD E	25 25 25 25 25	C.U.F.A.A. mapping

3. *Results and discussion*

3.1. *FFMC and fuel moisture scenarios*

During 2017, FFMC variability was very high between summer and winter months, ranging from the highest average value of 91.24 on 3rd August, to the lowest average value 23.61 on 6th February. The highest monthly averages were shown for August (86.6) and July (84.8), whereas the lowest was observed for December (65.9). The annual FFMC averages between regions ranged from 81.5 and 80.8 for Sardinia and Calabria, to 66.4 and 70 for Friuli-Venezia Giulia and Veneto, respectively. The boxplots (Figure 23) represent the average values calculated for each day of 2017 within all the pixel components of the corresponding grid of Era-interim reanalysis data, and show the distribution of the average monthly FFMC values observed during the year. The annual dataset ranged between 37 and 91; smaller ranges of values were observed during August, July and October, which are also distributions characterized by the highest average values. Overall, within the Italian peninsula, a general distribution of high FFMC high values was observed especially for the Southern regions and islands (Figure 24).

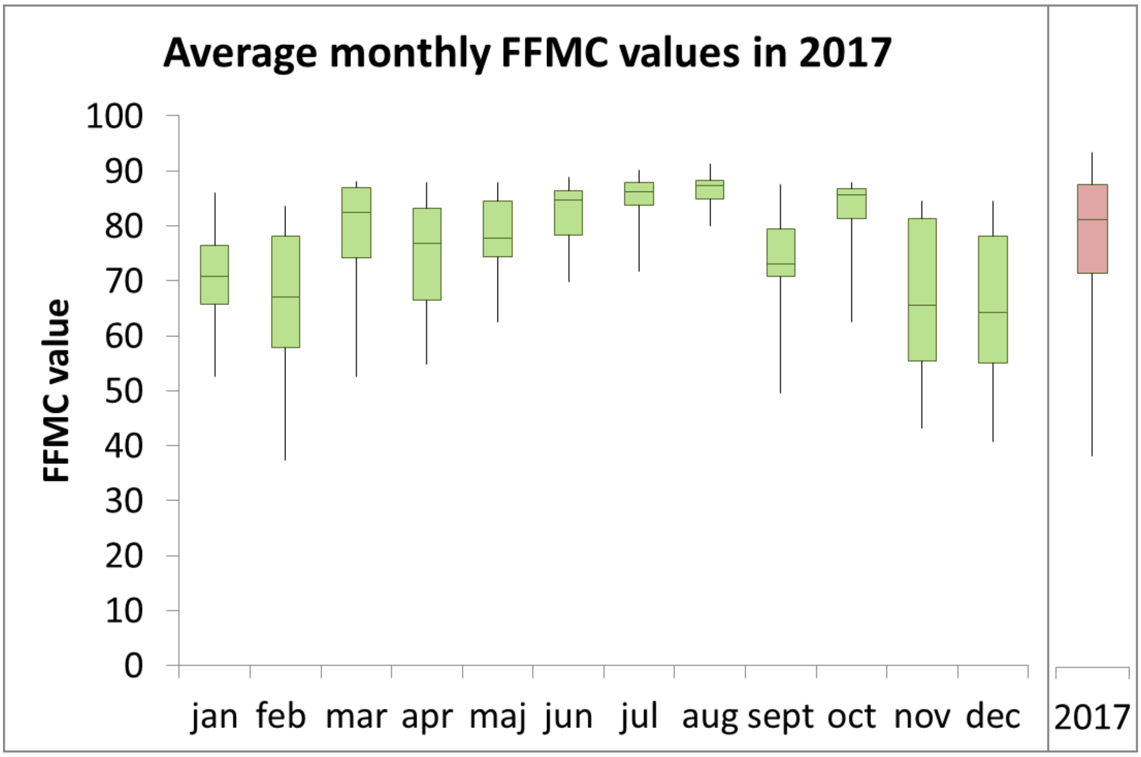


Figure 23 – Boxplots showing mean FFMC values distribution at monthly and annual level

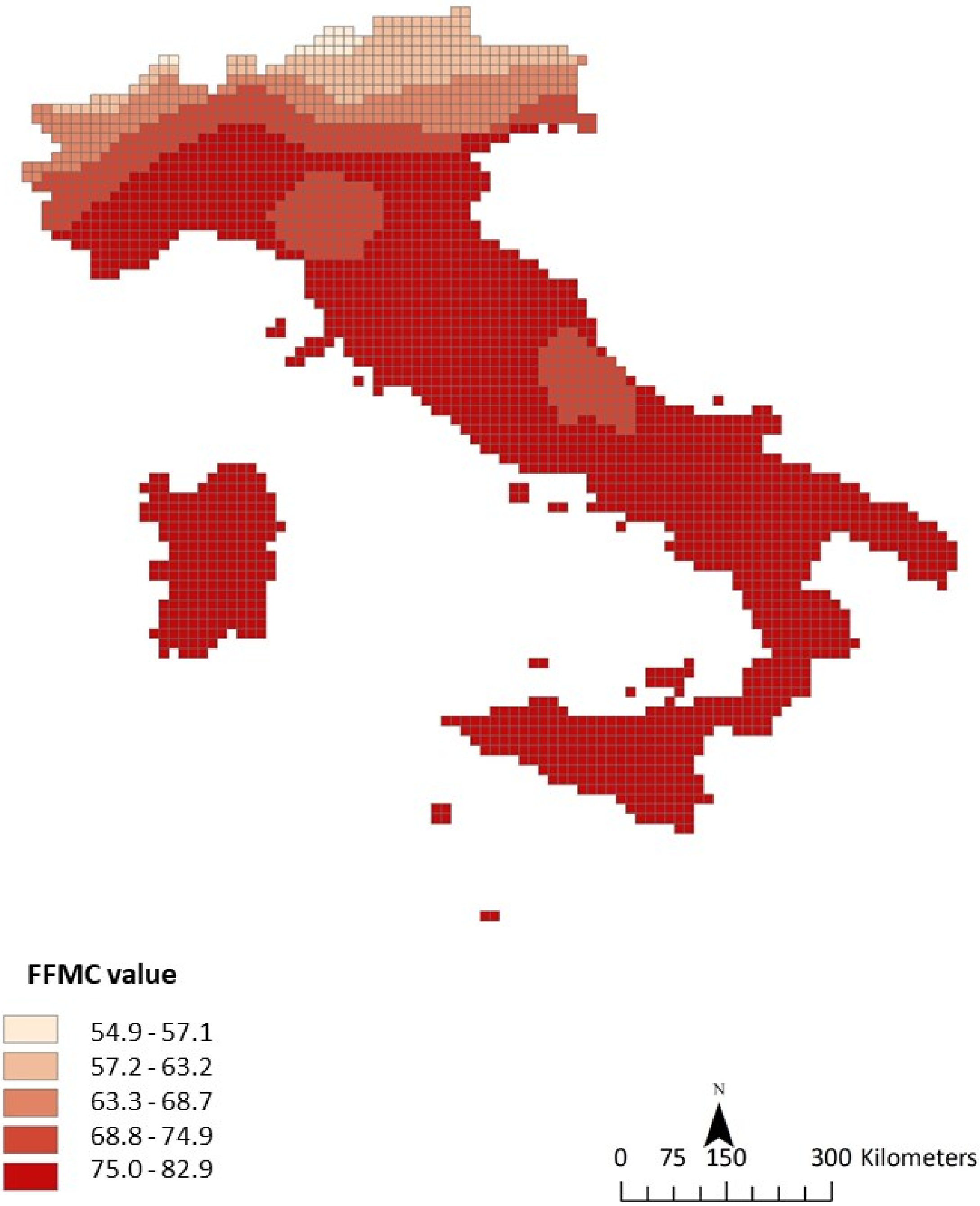


Figure 24 – Distribution of mean FFMC values during 2017 in Italy

Following the classification based on the calculation of the daily Canadian Fine Fuels Moisture Code (FFMC), we analysed each fire event based on the area burned during the fuel moisture scenarios.

FFCS values showed high values during all fire events, ranging from 87.8 on 20th August in correspondence with the F3 fire occurred in Abruzzo, to 93.26 on 23rd July in correspondence with F6, located in Sicily (Table 21). Considering the total burned area mapped by C.U.F.A.A., 12,694 ha (57% over the total) burned during "Extreme" fuel moisture scenarios. Concerning Copernicus Rapid Mapping, the 32% of the total burned area was classified as "High" damage (Figure 25).

F1(Antrodoco borgo-velino), F4 (Piazza armerina) and F5 (Rose) lasted one day; F1 burned totally at "Very-dry" fuel moisture conditions, whereas the 100% of F4 and F5 areas burned under "Extreme" moisture scenario. F2 fire (Cava de' tirreni) lasted two days, the 77% (573 ha) of its total area burned under "Dry" fuel moisture condition, while the rest burned under "Very-dry" scenario. F3 fire (Majella Morrone) burned for two days; the 87% (2,214 ha) of its total area burned at "Medium" moisture scenario, whereas the rest burned under "Very-dry" condition. Finally, F6 fire event (Vesuvio) burned for six days; most of its area was burned under "Extreme" (61%, corresponding to 1,950 ha) and "Very-dry" (35.5%, corresponding to 1,200 ha) fuel moisture scenarios.

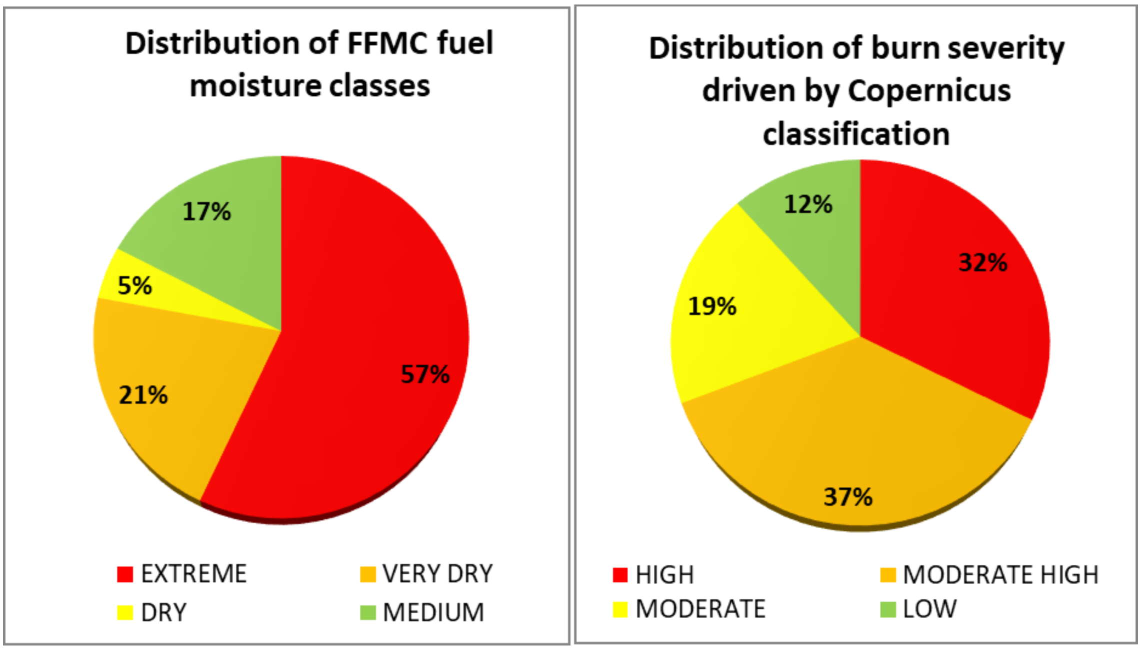


Figure 25 – Composition of total burned area products by fuel moisture classes and burn severity classes

Table 21 - Fire code, day of burning, FFMC value, moisture scenarios and corresponding burned area of fire detected by Carabinieri C.U.F.A.A.

Fire code	Data	FFMC value	Moisture scenario	Burned area %
F1	22/08/2017	91.27	Very dry	100.0
F2	08/08/2017	90.72	Dry	77.5
	09/08/2017	91.47	Very dry	22.5
F3	19/08/2017	91.91	Very dry	13.0
	20/08/2017	87.84	Medium	87.0
F4	03/08/2017	92.68	Extreme	100.0
F5	02/08/2017	92.26	Extreme	100.0
F6	12/06/2017	90.70	Dry	0.9
	05/07/2017	91.61	Very dry	17.5
	08/07/2017	92.03	Very dry	20.3
	10/07/2017	92.86	Extreme	40.1
	11/07/2017	93.26	Extreme	6.9
	12/07/2017	93.24	Extreme	14.2

3.2. Burned area description

Differences in total burned area between the mapping methods were observed for all fire events (Figure 26 and 27). Total mapped burned area derived from ground-based mapping of C.U.F.A.A. resulted larger than satellite-based burned area for 37.9%, particularly from +104.2% for F6 to +0.4% for F4.

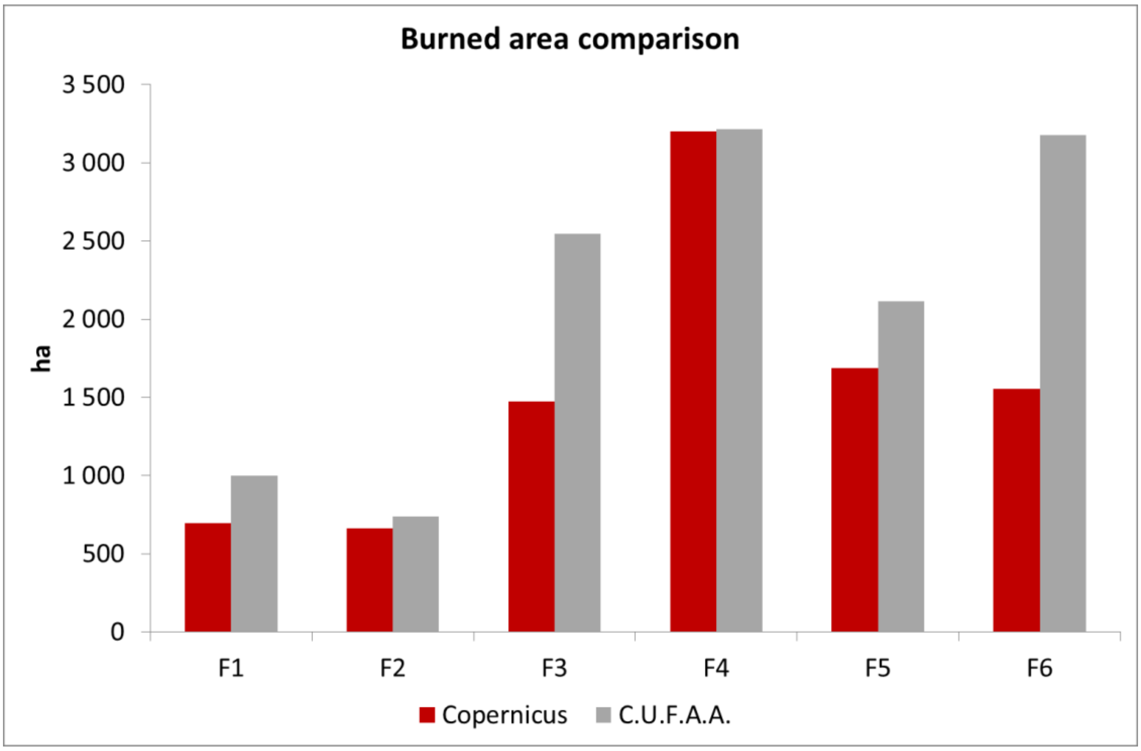
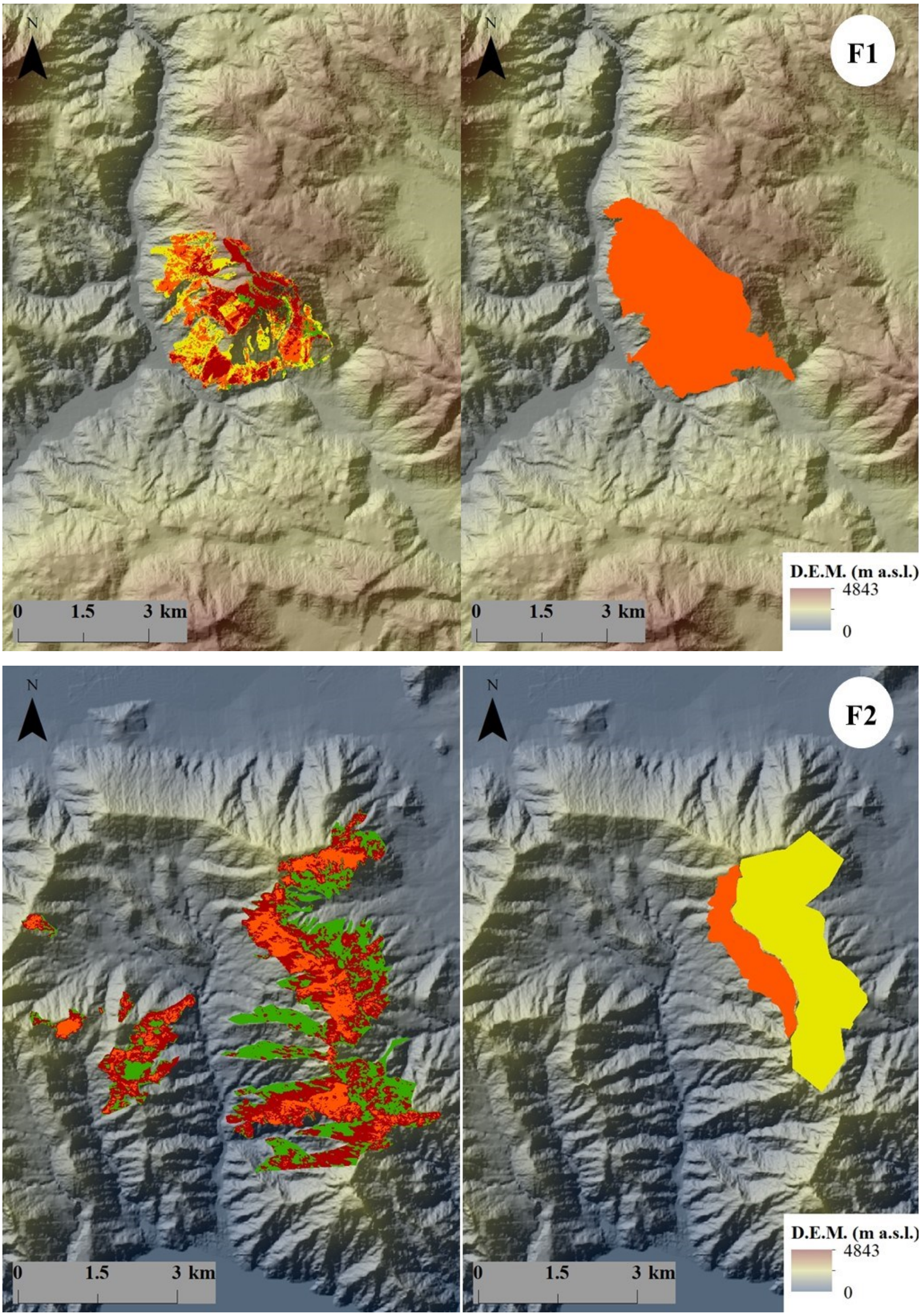
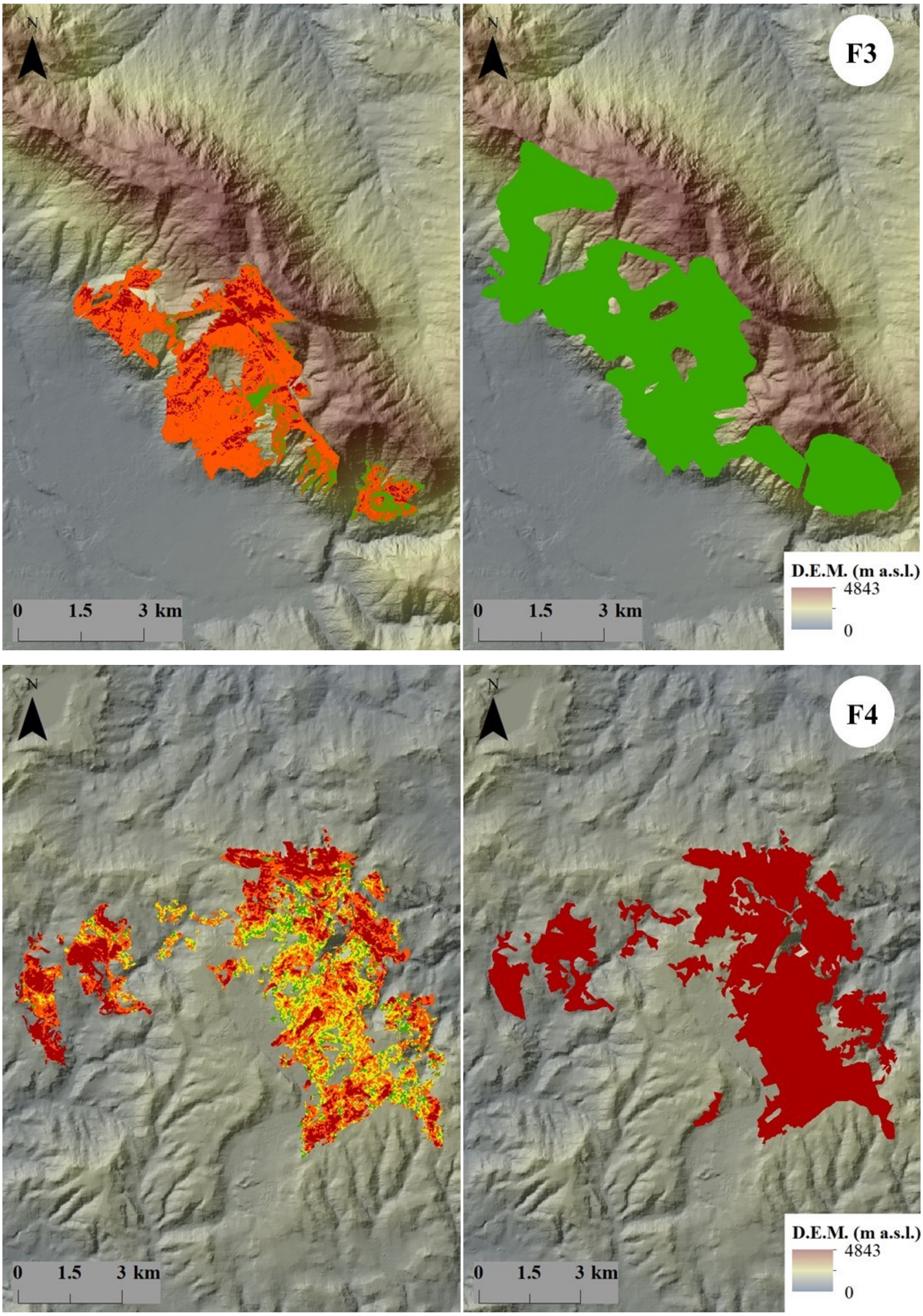


Figure 26 - Differences in burned areas of the six analysed fires between two mapping methods (in red, Copernicus Rapid Mapping; in gray, Carabinieri C.U.F.A.A.)



F1
F2
N
0 1.5 3 km
D.E.M. (m a.s.l.)
4843
0


N
F3
0 1.5 3 km
D.E.M. (m a.s.l.)
4843
0
F4

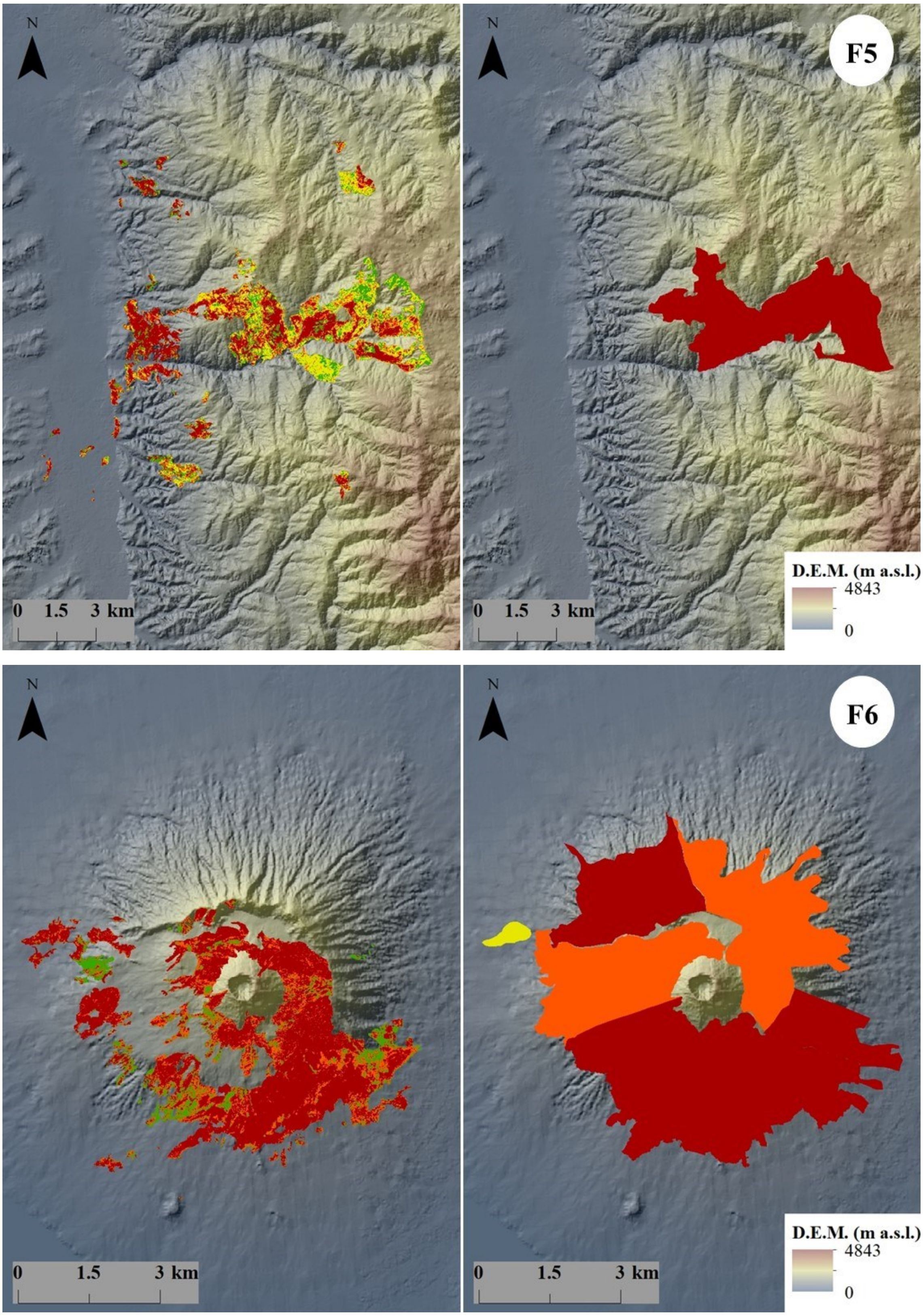

N
F5
0 1.5 3 km
D.E.M. (m a.s.l.)
4843
0
F6

Figure 27 - Comparison of burned area products for each fire. On the left, maps of burned area under four damage classes based on the Copernicus system classification are shown; burn severity classes: Completely destroyed; Highly damaged; Moderately damaged; Negligible to slight damage. On the right, maps of burned area under four fuel moisture scenarios are shown; fuel moisture scenarios: Extreme, Very-dry, Dry, Medium

We analyzed the contribution of the four fuel type macro-categories to burned area (Figure 28). Broadleaves represented the most affected group for F1, F2 and F5 for both mapping systems, representing for F1 66% of C.U.F.A.A. area (about 660 ha) and 51% of Copernicus mapped area (355 ha burned); for F2 it represented 65% of C.U.F.A.A. area (485 ha) and 69% of Copernicus mapped area (454 ha); moreover, for F5 Broadleaves represented 52% (1,103 ha) of C.U.F.A.A. area and 45% (763 ha) of Copernicus mapped area.

Similar predominance between the area mapping methods was observed also for F4 and F6 which showed a prevalence of the Conifers group corresponding to 49% of C.U.F.A.A. area (1,580 ha) and of 47% of Copernicus mapped area (1,502 ha) for F4, whereas for the fire F6 this group represented 34% of C.U.F.A.A. mapped area (34%) and 41% of the Copernicus mapped area (639 ha burned).

Due to spatial and dimensional differences between the burned area detected by the two mapping systems, the composition in macro-categories also differed. Particularly, the largest difference was observed for F3, for which C.U.F.A.A. mapped 807 ha of Conifers (32% of the total burned area mapped), while Copernicus detected 532 ha of Agriculture & pastures (36% of total burned area mapped).

Moreover, for F1 and F6 we observed that a portion of area burned was located inside the class "Not Burnable" (NB), particularly for F6 fire where about 88 ha burned were registered by both mapping systems, corresponding to 3% of C.U.F.A.A. map and 5.5% of Copernicus mapped area.

Considering all the events, the most affected macro-category for both C.U.F.A.A. and Copernicus total burned area was represented by Conifers, which covered about 3,876 ha and 2,896 ha, corresponding to 30.5% and 31.5% respectively, of the total burned areas.

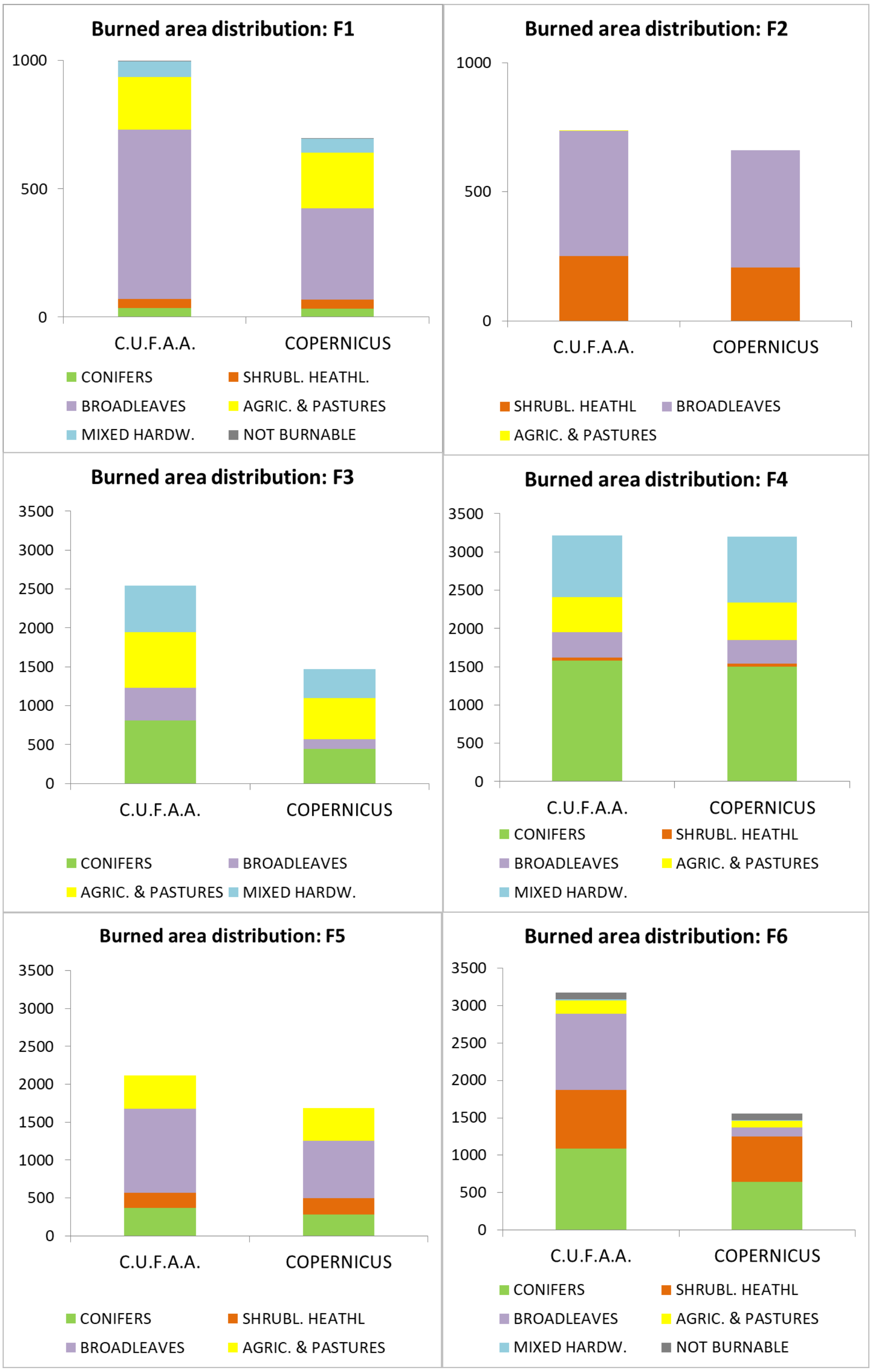


Figure 28 - Distribution of burned area between macro-categories and the mapped areas

Table 22 shows the contribution of each fuel type class on the total burned area for each fire event and area mapping method. Regarding the C.U.F.A.A. burned area mapped, the fuel types most affected by fires were represented by “Evergreen oak forest” (QS) for F1 fire (305.8 ha burned and 30.7% of the total), “Oak-hornbeam, turkey oak, oak forest” (QC) for F2 fire (284.8 ha burned and 38.5%), “Pine forest of sylvestris, black, stone and larch pines” (PS) for F3 fire (807.23 ha burned and 31.7%), “Mediterranean pine forest” (PM) for F4 fire (1,580 ha burned and 49.18%), “Chestnut grove” (CA) for F5 fire (703 ha burned and 33%) and finally, PM for F6 fire (1,084 ha burned, representing 35% of total).

The Copernicus mapping area distribution was different for the most affected fuel type for F1 fire as represented by “Discontinuous rupicolous prairie” (PD), showing 190 ha burned and a contribution of 27% on total burned area, whereas PD was the largest contributor of total area for F3 fire (532 ha burned and 36% of the total). Similar composition of burned area was observed for the other fires: the most affected fuel type for F2 fire was QC (238 ha burned and 36%), PM for F4 fire (1,502 ha burned and 47% of the total), (CA) for F5 fire (466 ha burned and 27% of the total) and PM for F6 fire (639 ha burned, representing 43% of total). Considering all the events, the most affected fuel type for both C.U.F.A.A. and Copernicus total burned area was represented by PM, which covered about 2,664 and 2,141 ha (corresponding to 21% and 23%, respectively).

Table 22 - Distribution of burned area between fuel types and area mapping methods

C.U.F.A.A. burned area (%)						
Fuel type	F1	F2	F3	F4	F5	F6
PM	--	--	--	49.18	--	35.09
PS	3.45	--	31.73	--	17.55	--
MA	--	33.70	--	1.27	5.85	25.53
MB	3.57	0.18	--	--	3.69	--
CA	--	--	--	--	33.28	20.82
FA	14.15	--	12.56	--	--	--
QC	21.37	38.52	4.13	--	18.94	8.60
QS	30.69	27.03	--	10.18	--	3.70
PC	2.80	--	2.43	6.25	--	--
PD	17.88	0.57	25.61	8.03	20.69	5.65
BM	6.10	--	23.55	25.09	--	0.63
Copernicus burned area (%)						
Fuel type	F1	F2	F3	F4	F5	F6
PM	--	--	--	46.96	--	43.59
PS	4.80	--	30.16	--	16.42	--
MA	--	31.29	--	1.18	6.55	41.63
MB	4.94	--	--	--	6.20	--
CA	--	--	--	--	27.59	0.64
FA	6.32	--	4.35	--	--	--
QC	19.11	36.11	4.00	--	17.59	4.96
QS	25.84	32.60	--	9.66	--	2.48
PC	3.79	--	--	6.16	--	--
PD	27.36	--	36.17	9.19	25.65	6.00
BM	7.84	--	25.32	26.85	0.00	0.69

3.3. Fire emissions

We estimated total fire emissions (considering PM_{10}, $PM_{2.5}$, CH_4, CO, CO_2, NO_x and SO_2) for each simulation scenario (Table 23), and a large variability of total emissions was observed with the variation of burned area and the burn severity scenario considered. Total emission estimated on the basis of the same burned area product but different burn severity scenarios (S4-COP and S5-COP) showed a difference of 36 Gg: S5-COP showed larger emissions of +8% than S4-COP. Comparing same fire size and burn severity scenario but different crown consumption values, S6-COP total emissions resulted +22.2% larger than S5-COP. On the other hand, using the Carabinieri C.U.F.A.A. mapping product and burn severity scenario, but different crown consumption, we observed differences of total emissions of about 273 Gg. Specifically, S5-CUFAA total emissions were larger than S6-CUFAA for +16.4%.

Finally, taking in account the same burning severity scenario combined with different burned areas (S5-COP and S5-CUFAA), we observed a difference of about 204.4 Gg between the two scenarios; particularly, S5-CUFAA showed an increase of +42.3% than S5-COP.

Results of total emissions derived to the same C.U.F.A.A. burned area but at different burn severity scenario, showed that, on average, S5 total emissions were larger of 14.8% than S6 emissions for all the events, varying from +3% for F3, to +21.1% for F4. Similar results were observed for Copernicus burned areas, where S5-COP total emissions were, on average, larger than S6-COP emissions of about 14%, from +2.8% for F3, to +21% for F4 (Table 24). The largest emissions were observed for F4 fire (213.9 ha with the C.U.F.A.A. mapping product and 210.7 ha with Copernicus Rapid Mapping product). For this fire, the lowest percentage difference in total fire emission was – 20.9%, applying same burned area product and burn severity scenarios but different crown consumption (S5-COP and S6-COP). The lowest emissions were observed for F1 fire and also in this case the highest percentage difference in total fire emission was –19.5%, applying same burned area product and burn severity scenarios but different crown consumption (S5-CUFAA and S6-CUFAA).

Table 23 – Total emissions for chemical species and simulation scenario

	Total emissions (Gg)							
	PM10	PM25	CH4	CO	CO2	NOX	SO2	Total
S4-COP	4.77	4.04	2.38	51.03	384.52	0.32	0.27	447.34
S5-COP	5.13	4.35	2.56	54.87	416.02	0.35	0.29	483.57
S5-CUFAA	7.42	6.29	3.71	79.51	590.18	0.49	0.41	688.00
S6-COP	7.27	6.16	3.67	79.35	494.03	0.31	0.36	591.15
S6-CUFAA	5.03	4.26	2.53	54.78	347.94	0.23	0.25	415.03

Table 24 – Comparison of total emissions for each fire and simulation scenario

Total emissions (Gg)	S4-COP	S5-COP	S5-CUFAA	S6-COP	S6-CUFAA
F1	21.7	23.2	36.8	19.6	30.8
F2	26.3	24.5	27.7	22.5	25.5
F3	64.1	47.9	90.0	46.6	87.4
F4	178.2	210.8	214.0	174.2	176.6
F5	70.6	87.2	119.8	73.5	100.2
F6	86.5	90.0	199.8	78.6	170.7

We analyzed total emissions in proportion to the fire area, observing a large variability between the fire events and the scenarios studied (Figure 29). Considering all the fires, the highest normalized emissions were observed for S5 scenario, for both C.U.F.A.A. burned area (53.8 Mg ha^{-1}) and Copernicus burned area (52.1 Mg ha^{-1}). Differently, the lowest normalized emissions were observed for the S6 scenario, for Copernicus burned area (44.7 Mg ha^{-1}) and C.U.F.A.A. burned area (46.2 Mg ha^{-1}).

Comparing singular fires, the highest normalized value was observed for F4 in combination with the S5-CUFAA scenario (66.6 Mg ha^{-1}), whereas the lowest normalized emissions were observed for F1 in combination with the S6-C.U.F.A.A. scenario.

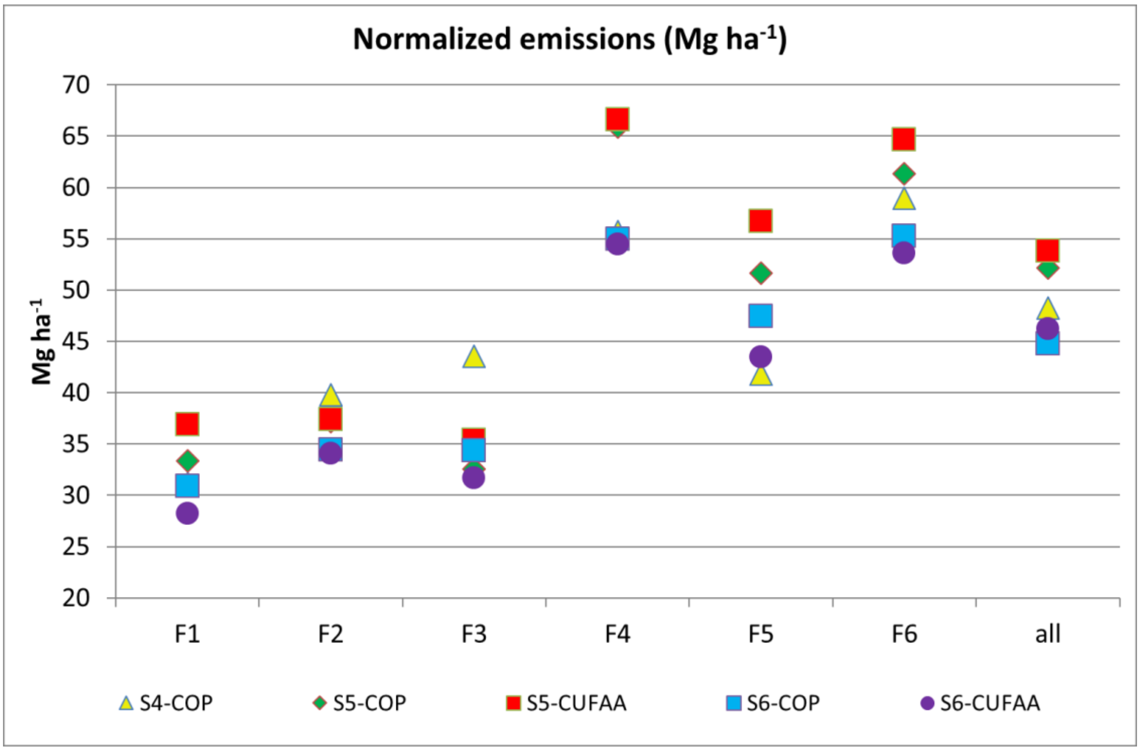


Figure 29 – Comparison of normalized emissions between scenarios and fires

We compared total emissions for each macro-category. Largest values were observed for Conifers (291,7 Gg) for S5 scenario and the C.U.F.A.A. burned area (243.7 Gg), corresponding to 42% of total emissions for S5-CUFAA. The lowest emissions were observed by Agriculture and pastures for S4 scenario and Copernicus mapped area (15.41 Mg ha^{-1}) (Figure 30).

Particularly, Conifers emitted the largest portion of emissions for all the scenarios, accounting on average 44% of total emissions, from 46% of S5-COP scenario (224.8 Gg on 483.5 Gg total emissions) to 41% of S6-CUFAA scenario (243.7 Gg on 591.1 Gg total emissions). Conversely, the lowest portion of emissions was related to Agricultures & Pastures for each simulation, accounting on average 3% of total emissions, specifically 2.5% for S5-CUFAA scenario (17.6 Gg on 688 Gg total emissions).

In agreement to macro-categories results, the contribution of each fuel types on emissions showed that the largest contribution on total emissions was observed for PM (Table 25) mapped by C.U.F.A.A. for S5 conditions, releasing 221.8 Gg (corresponding to 32% of total emission for S5-CUFAA), and at S6 conditions, releasing 179.5 Gg (corresponding to 30% of the total emissions for S6-CUFAA). PM represented 21% of total CUFAA burned area, representing the most occurring fuel type by fire for both the mapping products (20.9% of CUFAA area and 23.3% of Copernicus total burned area).

Conversely, the lowest total emissions of 2.8 Gg were registered for MB mapped by C.U.F.A.A. for both S5 and S6 scenario. MB contributed for less than 1% of CUFAA burned area.

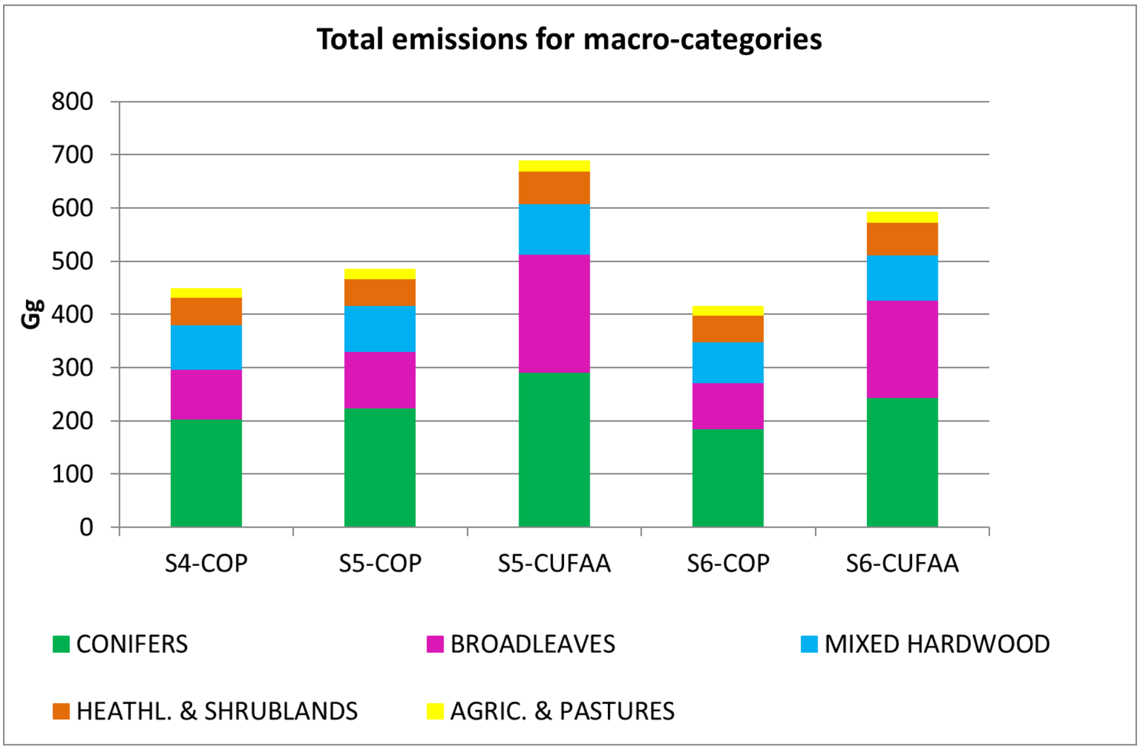


Figure 30 - Total emissions released by macro-categories for each scenario

Table 25 - Total emissions for fuel types, macro categories of vegetation and scenarios

		Total emissions Gg				
Macro category	Fuel type	S4-COP	S5-COP	S5-CUFAA	S6-COP	S6-CUFAA
Conifers	PM	155.12	179.33	221.88	144.88	179.50
	PS	49.0	45.6	69.8	41.2	64.2
Heathlands Shrublands	MA	47.3	47.1	58.7	47.1	58.7
	MB	3.3	3.4	2.8	3.4	2.8
Mixed hardwood	BM	83.7	87.3	95.6	76.3	84.8
Broadleaves	QC	31.5	33.3	53.2	26.9	42.9
	QS	24.9	26.5	34.0	21.6	27.7
	CA	31.8	40.9	113.7	33.9	94.5
	FA	5.2	4.7	20.6	4.2	18.4
Agriculture Pastures	PC	4.5	4.7	5.7	4.7	5.7
	PD	10.9	10.8	11.9	10.8	11.9

The contribution in total emissions of macro-categories in proportion to their distribution showed that fires occurring across trees released the highest normalized emissions for all of the observed scenarios (Figure 31). Particularly, for each scenario the highest values were observed for Conifers, specifically at S5-COP conditions (74.32 Mg ha^{-1}), followed by Mixed hardwood, particularly at S4-COP scenario (66.47 Mg ha^{-1}). Moreover, normalized emissions for Agriculture and pasture and for Heathlands and shrublands, resulted the lowest and similar for all the scenarios, with values of about 13 and 36 Mg ha^{-1}, respectively.

The contribution of singular fuel types on total emissions in proportion to their distribution showed that the highest normalized emissions were related to CA for S5-COP and S5-CUFAA scenarios (84.9 and 84.4 Mg ha^{-1}, respectively), followed by PM, which emitted 83.5 and 83.1 Mg ha^{-1} for the same scenarios, S5-COP and S5- CUFAA (Table 26). At the same time, the lowest emissions in proportion to the distribution were observed for PD, with 7.1 Mg ha^{-1}.

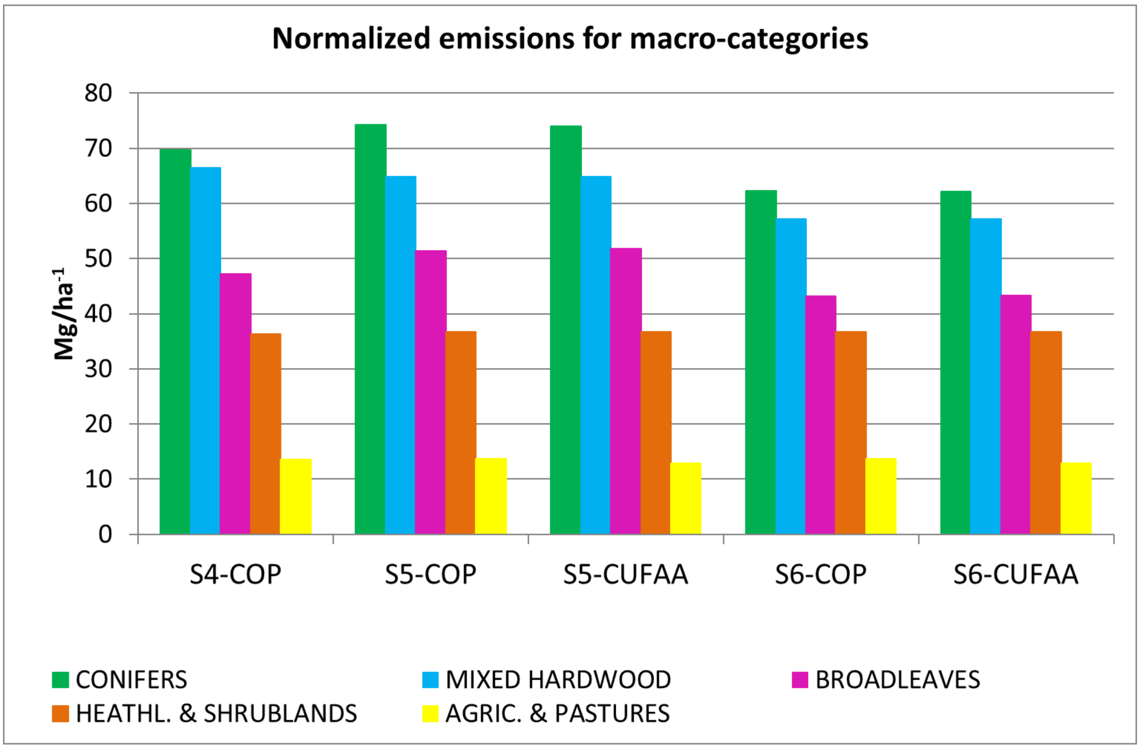


Figure 31 - Total emissions per ha burned for macro-categories and scenarios

Table 26 - Total emissions per ha burned for fuel types, macro categories and scenarios

Average total emissions Mg ha^{-1}						
Macro category	Fuel type	S4-COP	S5-COP	S5-CUFAA	S6-COP	S6-CUFAA
Conifers	PM	74.2	83.5	83.1	67.5	67.3
	PS	65.1	65.1	64.7	57.1	56.9
Heathlands - Shrublands	MA	48.8	49.0	49.0	49.0	49.0
	MB	23.7	24.5	24.3	24.5	24.3
Mixed hardwood	BM	66.5	64.9	64.9	57.1	57.1
Broadleaves	QC	39.6	39.9	39.6	32.9	32.7
	QS	34.3	35.8	35.6	29.2	29.1
	CA	66.9	84.9	84.4	70.5	70.1
	FA	47.8	45.0	47.2	40.2	41.4
Agriculture - Pastures	PC	20.0	20.3	18.7	20.3	18.7
	PD	7.1	7.2	7.1	7.2	7.1

4. Discussion and Conclusions

Fire emissions estimation represent a crucial point to understanding the smoke impacts on human health and air quality. Several sources of data are needed to quantify the amount of gases released by biomass combustion; this information is related to burned area, fuel loading and characteristics, biomass consumption and weather conditions influencing fuel moisture. The use of accurate fire and fuel information is thus critical to reduce the uncertainties in the modelling chain and to provide accurate estimates of fire emissions. In this work we evaluated the relevance of two burned area products and two approaches to define fuel moisture and combustion completeness during six fire events that occurred in Italy in 2017. The fire burned areas were provided by Copernicus Emergency Management Service system and the Carabinieri C.U.F.A.A. We used an integrated methodology combining a fire emissions model (FOFEM - First Order Fire Effect Model, Reinhardt et al., 1997) with spatial and non-spatial inputs related to burned area mapping, fire severity, vegetation distribution, and moisture conditions, in order to examine and compare different input combinations on fire emissions estimates.

The events analysed occurred during spring and summer, when the highest average values of FFMC were observed, especially for the Southern regions where the fire events were located.

Large differences between the two mapping methods were observed. These differences in burned area can be caused by problems in satellite detecting which can be a source of inability or low accuracy in detecting low severity or unburned areas (Cocke et al., 2005) or to boundary mapping error due to difficulties in traversing or safety considerations walking near the fire perimeter, which can represent sources of errors for the manual mapping (Kolden and Weisberg, 2007).

Differences in the fire size and in the area detected led to dissimilarities in the composition for both macro-categories and fuel types, but overall, the most occurred macro-category was Conifers for both the mapping methods, whereas the distribution of fuel types for each fire showed differences between the mapping approaches.

We observed an agreement between the mapping methods concerning the distribution of the macro-categories for each fire event, showing Broadleaves as the most affected for F1, F2 and F5, and Conifers for F4 and F6. A difference was observed only for F3, for which Conifers were the most abundant category for C.U.F.A.A., whereas Agriculture & pastures were the most abundant for Copernicus.

We estimated total fire emissions for each simulation, and clear differences at the modification of each input were observed. Particularly, we found a particular relevance of the burned area of total emissions. At the same burning severity scenario, total emissions differed substantially of 42.3%, based on a difference of the mapping area products of 37.9%.

Lower differences were observed at the variation of the burn severity scenario. Particularly, considering the Copernicus mapped area, the difference between S4-COP and S5-COP were about the 8%, which could be related by the identification of a more

homogeneous severe scenario of the burned area for S5 than the fragmented severity S4 detected by the rapid mapping of Copernicus. Moreover, differences between S5 and S6 of Copernicus mapped area were on the order of about 22%, which means that the crown consumed play an important role on fire emissions. Also, the results for C.U.F.A.A. mapped area showed similar differences of total emissions linked to crown consumption between S5 and S6 scenario, with fire emissions of S5 larger 16.4% than S6 emissions.
Largest emissions were associated to the largest fire mapped (F4, 3,213 ha) at S5-CUFAA, while the lowest emissions were associated to one of the smallest fire mapped (F1, 660 ha) at S6-COP. Concerning the composition of F4 burned area mapped by C.U.F.A.A., woodlands represented an important portion of total burned area (84.5%).
These results show the importance of both burned area and the canopy consumption on fire emissions, considering that S6 scenario implicated fixed values of crown consumption at 25%, whereas S5 crown consumption was linked to burn severity. This determined that burn severity for F4 fire was settled at Extreme conditions for 100% of the burned area, so the canopy consumption was assumed to burn at 100%. In addition, the composition of F4 burned area showed a predominance of woodlands (PM, QS and BM), representing 84.5% of total burned area, whereas F1 burned area composition showed a value of 31% of herbaceous vegetation (PC, PD) and 5% of MB, which could not be involved in canopy consumption; conversely, F2 burned area, which was the smallest mapped, was totally composed of trees, for which the canopy consumption was took in account and resulted important for the emissions..
Moreover, for each fire the emissions derived from S5 were larger than S6, on average of 14.8% for C.U.F.A.A. burned area, and on average of 14% of Copernicus burned area; this underlined that canopy consumption play an important role on total emissions. Related to this, the normalized emissions for S5 scenario of both the mapping products resulted the highest values, because crown consumption was considered.
Largest emissions for Conifers at S5-CUFAA were observed, particularly due to their largest contribution on total burned area, the scenario which considered the crown consumption, and the homogeneous setting of burn severity and fuel consumption which resulted at the most severe conditions. Conversely, lowest emissions of Agriculture and pastures were not linked to their lowest contribution on burned area, but on the lowest fuel loading. Results on singular fuel types showed the highest fire emissions for PM,

which contributed mostly on total burned area, whereas MB was associated to the lowest emissions, because it was the lowest occurred by fires, and presented on of the lowest fuel loading values.

The largest normalized emissions were observed for S5-CUFAA, whereas the lowest values were observed for S6-COP, which underlined the relevance of canopy consumption on fire emissions, thus considering that the "Extreme" fuel moisture class represented 57% of total CUFAA burned area, whereas the "High" burn severity scenario represented 32% of Copernicus total burned area.

Finally, the relevance of canopy loading and consumption on total emissions have been underlined by the largest normalized emissions of Conifers for all the scenarios, particularly for S5-COP (74.32 Mg ha^{-1}), and showing the highest values for the S5, for which the canopy consumption was associated to the burn severity, joining 100% of crown consumption. Moreover, results of singular fuel types showed that the highest normalized emissions were related to CA for S5-COP (84.9 Mg ha^{-1}), because it presented the largest fuel loading (68.7 Mg ha^{-1}); conversely, the lowest normalized emissions were associated to Agriculture and pasture (13 Mg ha^{-1}), according to the lowest fuel loading of PD, settled as 5.3 Mg ha^{-1}.

The results provided in this research suggest that the uncertainties identified can represent a step for further improvements in order to help the development of more accurate emissions inventories at local and national scales.

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Final conclusions

Knowing and evaluating the fire effects on the biotic and abiotic ecosystem components is of utmost importance for a number of reasons that include risk assessment, programming, planning and evaluation of different management approaches, as well as increased knowledge of the ecosystem functioning in order to balance benefits and costs associated with natural events such as fire.

Among the first order fire effects, meaning those effects occurring immediately after the fire, we recognized fire emissions of gaseous pollutants and particulate as one of the most important, influencing and causing complex interactions and impacts that may vary with the progressive change of scale (from local to global level) such as the deterioration and reduction of visibility conditions and air quality, or alterations of basic atmospheric processes, and concurrence in climate changes.

In this manuscript, we first carried out a contemporary state of the research review on emissions from forest fires, exploring their influence on climate, atmospheric radiation budget, air quality, human health and other impacts. We also underlined the advances in modelling and measurement efforts made during recent decades, differences in the methods and inputs used and the uncertainties that still remains.

Indeed, given the complexity of the factors contributing to fire emission, the adoption of a modelling approach is proved to be more convenient, as it allows consideration of the simultaneous actions of multiple factors, to reproduce what could happen in a specific context under given conditions, and eventually to develop further the understanding of fire effects. Thus, in the second chapter, we estimated fire emissions in Italy for the period 2007-2017 through the application of an integrated approach, combining the use of the semi-physical fire emissions model FOFEM (Reinhardt et al., 1997) with spatial and non-spatial inputs. Then in the third chapter, we focused more on the uncertainties arising from different data input sources comparing burned area, combustion efficiency, and fire emissions release during 2017 large fire events. We assessed the uncertainties and weak points found during the process, through the evaluation and selection of data inputs and the assessment of varying results.

Our results are valuable for providing data for emissions source models coupled with dispersion models and decision support systems, crucial for air quality managements, mitigation of wildland fire environmental effects, and to assist decision makers in prescribed fire activities in order to help the development of more accurate emissions inventories at national scale in the framework of Kyoto Protocol reporting activities for the LULUCF (Land Use, Land Use Change and Forestry) sector.