P1.15 ASSESSMENT OF SMOKE EMISSION AND CARBON ESTIMATE FROM MEDITERRANEAN MAQUIS FIRE EVENTS

Valentina Bacciu[a,c], M. Salis [a,c], D. Spano [a,c], B. Arca [b,c], G. Pellizzaro [b,c], and P. Duce [b,c]

[a] Department of Economics and Woody Plants Systems (DESA), University of Sassari, Italy
[b] National Council of Research, Institute of Biometeorology (CNR-IBIMET), Sassari, Italy
[c] Euro-Mediterranean Center for Climate Changes, IAFENT Division, Sassari, Italy

1. INTRODUCTION

The consequences of a large number of fire events and the relative burned area that occur each summer in the Mediterranean Basin are crucial for land degradation, air quality, and climate changes. One of the first relevant effects of the burning activity is the emission of pollutant species and greenhouse gases, that have been recognized as an important issue by the Kyoto Protocol: the dominant fraction of vegetation fire emissions is released as CO_2 and CO, being responsible for about 90–95% of the total carbon emitted (Andrae and Merlet, 2001).
Several steps are required to evaluate emissions from a fire. First, information is needed on the fuel consumption, which is dependent upon the burned area, the amount of fuel materials per unit area (pre-burn fuel loading), and the fuel characteristics and conditions (Battye and Battye, 2002). Fuel load, considered as the biomass subjected to a fire (Langmann et al., 2009), is one of the most important parameter in quantifying fire emissions: the amount and composition of the trace gases and aerosol particles released are dependent on it (Lobert and Warnatz, 1993; Andrae and Merlet, 2001). The spatial location of fire events is equally important. Variability of the spatial location of fires can influence fire effects through fuel characteristics (Keane et al., 2001; Andrews and Queen, 2001). Additionally, fire location information is necessary for synthesizing emissions source models with dispersion models or other decision support systems (Battye and Battye, 2002).
Model approaching can contribute to appraise the fuel consumption and the resultant emissions, although some uncertainties affect these estimates due to the inaccuracy of the quantitative input data and the spatial variability of fuel characteristics that influence smoke production. In this context, more comprehensive and accurate data inputs would be of valuable help for predicting and quantifying the source and the composition of fire emissions.
In this context, the objective of this study is to estimate the emission of dioxide and monoxide carbon, as well as other pollutant species, from several Mediterranean maquis fires occurred in the western Mediterranean Basin area, in North Sardinia Island (Figure 1), Italy, during 2003, 2004 and 2006 summer seasons. For this purpose, we used the USDA First Order Fire Effects Model (FOFEM) (Reinhardt et al., 1997) model. We explored the usefulness of this model to estimate the type and the quantity of Mediterranean wildland fire emissions. Moreover, we implemented FOFEM in an integrated approach with the aim to qualify and spatially allocate the source and the amount of the emissions.

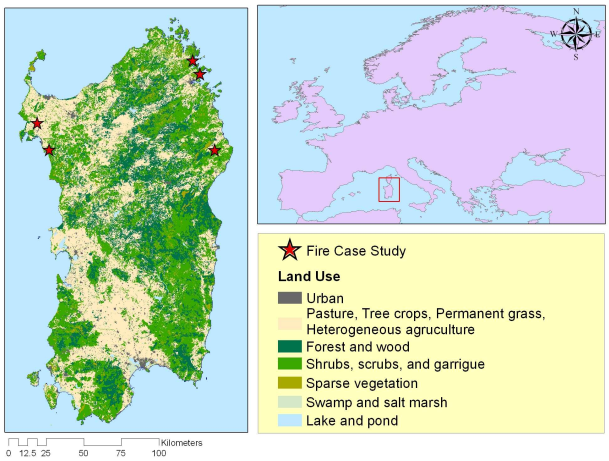

Figure 1 Fire case study locations and Sardinia main land covers (from CORINE, 2002)

2. MATERIALS AND METHODS

FOFEM is a simple and versatile computer program that predicts first order fire effects (Reinhardt, 2003). FOFEM incorporates a wide number of fuel models, based on a extensive review of measured fuel loading in many U.S. representative ecosystems. Each fuel model contains a vegetation description and fuel loads for duff, litter, woody debris in three size classes, herbs, shrubs, tree live branches and foliage. These empirically determined amounts can be modified to suit the user custom fuel model inputs.
Another parameter of primary importance is the fuel moisture, computed for duff, 10 hour (0.6-2.5 cm), and >100 hour (> 7.5 cm) woody debris. Fuel moisture affects the proportion of flaming to smoldering and their relative combustion efficiency. Fuel moisture can be determined by default,

Corresponding author address: Valentina Bacciu, Univ. of Sassari, Dept. of Economics and Woody Plants Systems (DESA), Via De Nicola 9, Sassari, Italy; tel: +39 079 229231; email: vbacciu@uniss.it

selecting among several burn conditions (very dry, dry, moderate or wet), or entering user values.
The consumption of the woody fuels and litter is simulated using the BURNUP physical model of heat transfer and burning rate (Albini and Reinhardt, 1995, 1997; Albini et al., 1995); for the other fuels, consumption is predicted using a variety of empirical equations (Brown et al., 1985; Harrington, 1987; Hough, 1978; Reinhardt et al., 1991). BURNUP model was modified (Finney, 2001) in order to provide separate estimates of flaming and smoldering consumption, and their relative particulate and chemical species emission (Ward et al., 1993). The emissions estimates produced by FOFEM are relative to $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, NO_x and SO_2.

To perform our integrated approach we used FOFEM with these spatial and non-spatial inputs:

- Fire data
- Custom fuel models
- Vegetation and land cover map

The description, integration and the implementation of these information is described in the following sub-paragraphs.

2.1. Fire data

In the first part of the work, several information relative to the fire events, which burned areas mainly covered by the typical shrubland Mediterranean vegetation (*maquis*), were gathered. The five investigated arson fires were chosen considering the consistency of their data, relative to: fire perimeter map, fire weather data, fire behaviour, and pre-burn vegetation. The final surface extensions of the burned areas were determined by the Sardinian Forestry Corps (SFC) using a Global Positioning System (GPS) survey. The weather data were gathered from the web site, from SFC official documents and interviewing witnesses. The vegetation data were obtained from surveys of the burned areas. The five fire analysed in this work are described in Table 1.

2.2. Custom Fuel Models development

The different sites were characterized by several differences in the *maquis* species composition and fuel load. Therefore, in order to achieve realistic fire emission estimates, FOFEM input fuel load data were surveyed in several representative maquis fuel types and pastures similar to those combusted. Eight sampling sites were then selected by the analysis of the Corine Land Cover map and the ortophotos of the area. The following variables were collected from destructive sampling: live and dead fuel load, depth of the fuel layer, plant cover. Dead and live fuel load were inventoried following the standardized classes (1 hour, 10 hour, 100 hour) of the USDA National Fire Danger Rating System. A cluster analysis was applied in order to classify the different sites in terms of fuel types. Results provided by the cluster analysis were reclassified according with an adaptation of Prometheus classification system, and parameterized in four custom fuel models (CM). The values of moisture content for the 10 hour dead fuel were determined calculating the relationship between observed FMC values and fuel moisture sensor measurements (model CS505, Campbell Sci., Logan, UT, USA) obtained during the summer season.

Table 1 Fire data relative to: data, hectares, severity, wheater, pre-burn vegetation

Fire Data parameters	*La Siesta*	*Monte Pedrosu*	*Sos Aranzos*	*Razza di Juncu*	*Ospolo*
gg/mm/yy	19 August 2003	15 July 2006	14 August 2003	11 August 2003	21 August 2004
ha	124	65	57	45	19
Fire severity	High severity	High severity	High severity	High severity	Moderate severity
Fire weather	very hot: max. temperature 36 °C, min. 20 °C; moderate wind from south at the beginning and completely turned to north at the end	very hot: max. temperature 36 °C, min. 20 °C; light wind, with some occasional gusts	very hot: max. temperature 36 °C, with low relative humidity; moderate northwestern wind	very hot: max. temperature 39 °C, min. 25 °C; moderate western-northwestern wind	Hot: air temperature ≅ 24 °C and relative humidity ≅ 35%.
Pre-burn Vegetation	Mainly maquis with plant height ranging 1 m (about 65% of the total burned area) *Pistacia lentiscus* L., *Myrtus communis* L., *Chamaerops humilis* L., *Cistus* spp.	Mainly maquis (about 87% of the total burned area), with plant height ranging 1 m. Dominant species included *Pistacia lentiscus* L., *Myrtus communis* L., *Chamaerops humilis* L., and some *Arbutus unedo* L. The remaining vegetation was grassland	High and close shrubland vegetation, mainly composed of *Pistacia lentiscus* L., *Myrtus communis* L., *Cistus* spp., *Olea europaea* L. *var. oleaster*	Dense and uniform maquis shrubland, with plant height ranging 1,5 m. Dominant species included *Pistacia lentiscus* L., *Cistus monspeliensis* L., *Arbutus unedo* L., *Olea europaea* L. var. oleaster, *Myrtus communis* L., *Pyrus amygdaliformis* Vill., *Calycotome spinosa* L., *Phyllirea angustifolia* L.	High and close shrubland vegetation, mainly composed of *Arbutus unedo* L., *Erica arborea* L., *Myrtus communis* L., *Cistus* spp., *Olea europaea* L. *var. oleaster*, *Pistacia lentiscus* L., *Phyllirea angustifolia*

2.3. Vegetation type maps

Vegetation type maps were produced by supervised classifications of pre-fire aerial photographs (1:10,000), field observation of the plant community and use of the 1:25,000 land cover map of Sardinia from the CORINE project (EEA ETC/TE 2002).

Cross-walking the vegetation type map with the custom fuel models, we created a fuel model map, which finally was overlaid by the fire perimeter layer. If the fuel model map layer intersected the fire polygon, it was clipped, originating the *fuel model burned areas* layer. For each clipped polygon the area was computed. All themes were acquired and managed using Geographic Information Systems (GIS) (ArcGIS 9, ESRI Inc., Redlands, CA, USA).

We processed the fuel model information to quantify the pre-burn fuel load, and to determine fuel consumption and emission amount through FOFEM model. Based on the acquired information on fire weather, two burning conditions were set: the very dry scenario was simulated setting dead 10hr fuel moisture at 8%; the dry scenario was simulated putting 10hr fuel moisture at 11%.

The results (fuel consumption and smoke emission estimates) were summarized by fuel categories and fuel models within each fire. These table were joined back to the original fuel model burned areas layer for spatial allocation of the emission estimates.

3. RESULTS

The five fires presented in this study were characterised mainly by four vegetation types, constituted by several fuel categories, both live and dead. The custom fuel models derived by both the cluster analysis and the use of an adaptation of Prometheus classification system are presented in Table 2. Comparing the fuel load of the different fuel categories, the experimental data are in agreement with other studies relative to shrubland vegetation. Dimitrakopoulos (2002) provided data of the shrub component similar to CM2 and CM3 (respectively 7 and 15 Mg ha^{-1}). De Luis et al. (2004) reported shrub fuel load ranging 12.3 to 16 Mg ha^{-1} in community encompassing mature formation of tall and dense shrubs, as CM4. In Saglam et al. (2008) total available fuel ranged from 0.78 to 3.03 Kg m^{-2}, with an average of 1.7 Kg m^{-2}.

After clipping of fuel model maps with the fire perimeter layers (showed in Figure 2, left), we determine the pre-burn fuel load (Mg) in each fuel category by fire, as shown in Table 3. The categories that mainly contribute to the pre-burn fuel loading are “shrubs” and “litter”, whereas any of the fires had the categories “duff”, “crown foliage”, and “crown branchwood”. Of the 5852 Mg of fuel prior to the fires, 5214 Mg were in shrubs and litter, respectively the 62% and the 27%.

According to FOFEM simulations, the fires consumed completely the litter, the woody debris at 1 hour, and the herbaceous component. On the other hand, the shrub component was consumed for the 80 percent. These data are in accordance with the data surveyed in the burned areas and the data reported in literature. An high severity fire is so called for its capacity to completely consume the litter, foliage twigs and small stems. Typically up to the 80 percent of the shrub canopy is consumed.

Due to types of vegetation burned, the absolute amount of total pollutants emitted varies by fire, ranging from 771 (Ospolo fire) to 3294 Mg (La Siesta fire). After consumption, over 8800 Mg of emissions were produced (Table 4): the data showed over 130 Mg of CO and over 8600 Mg of CO_2 emissions from fires.

Table 2 Fuel loading (Mg ha^{-1}) by custom fuel model and fuel category

Fuel Model	*Vegetation type*	*% Cover*	*Avg. Height (m)*	*Litter*	*Wood (0-0.6 cm)*	*Wood (0.6-2.5 cm)*	*Wood (2.5-7.5 cm)*	*Wood (> 7.5 cm) Sound*	*Wood (>7.5 cm) Rotten*	*Duff*	*Herb.*	*Shrubs*	*Crown foliage*	*Crown branchwood*
CM2	Medium height and density maquis	70	0.78	3.48	0.00	1.45	0.00	0.00	0.00	0.00	0.45	9.91	0.00	0.00
CM3	Medium high and close maquis	85	1.00	6.41	0.11	1.43	0.05	0.00	0.00	0.00	0.64	13.73	0.00	0.00
CM4	High and close maquis	90	1.80	9.66	0.45	1.07	0.00	0.00	0.00	0.00	0.18	15.45	0.00	0.00
CM5	Grass and pasture	90	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00

As result of burning, over 40 Mg of particulates were released on the atmosphere.

Finally, the tables of smoke emissions estimate were summarized by fuel models and associated within the *fuel model burned area* layers. As an example, Figure 2 (right) presents spatially explicit CO_2 emissions for the five fire analysed.
The validation of the default emission factors (EF) of FOFEM for the different fuel types was beyond the scope of our study, due to the small literature in Mediterranean areas. Moreover, in FOFEM the EFs are partitioned in fuel categories, while in several studies (e.g. Miranda et al., 2005b; Simpson et al., 1999) the EF data are reported for vegetation community. Thus, the comparison resulted very difficult. Nevertheless, the emission factors used in this study are within the range reported by Andrae and Merlet (2001). For example, the average CO_2 EF used here was 1720 g kg^{-1}, while Andrae and Merlet reported 1613 (± 95) for savannah and grassland, and Miranda et al. (2005b) 1477 g kg^{-1} for shrub community.

Table 3 Fuel loading (Mg) by category and fire in pre-burning conditions

Fuel Component	*La Siesta*	*Monte Pedrosu*	*Sos Aranzos*	*Razza di Juncu*	*Ospolo*
Litter	554.52	199.60	357.14	291.81	178.74
Wood (0-0.6 cm)	4.87	0.00	6.27	5.17	8.41
Wood (0.6-2.5 cm)	178.43	83.49	80.48	65.19	19.77
Wood (2.5-7.5 cm)	1.95	0.00	2.51	2.07	0.00
Herbaceous	64.75	44.04	37.54	28.97	3.36
Shrubs	1385.80	568.78	767.44	625.00	285.99

Table 4 Emission mass (Mg) by fire

Pollutant	*La Siesta*	*Monte Pedrosu*	*Sos Aranzos*	*Razza di Juncu*	*Ospolo*	*Total*
PM_{10}	8.74	3.53	5.03	4.09	1.98	23.37
$PM_{2,5}$	7.35	2.95	4.27	3.48	1.68	19.73
CH_4	3.11	1.24	1.82	1.48	0.69	8.34
CO	50.45	20.37	28.77	23.43	10.96	133.98
CO_2	3217.18	1305.11	1867.04	1519.38	753.57	8662.28
NO_X	5.53	2.25	3.21	2.61	1.29	14.89
SO_2	1.90	0.79	1.07	0.87	0.42	5.05
Total	3294.27	1336.25	1911.20	1555.35	770.58	8867.65

4. CONCLUSION

As reported in literature, the assessment of smoke emissions and carbon estimate is hampered by several factors, concerning essentially the quality of the inputs (Burgan et al., 1998; Keane et al., 2001; Bradshaw et al., 1984). For example, the variations in fuel characteristics and consumption may contribute to 30% uncertainties in estimates of wildfires emissions (Peterson. 1987; Peterson and Sandberg, 1988). Also, the accuracy of the vegetation map impacts the estimates, as pointed out by several authors: fuel maps must be developed at fine resolution in order to capture fuel variability and heterogeneity and obtain realistic fire simulations (Finney, 2005; Keane, 2002).
In this work we presented an integrated approach to estimate fuel consumption and emission, attempting also to qualify and allocate the source and the composition of wildfire emissions.
Considering both assumptions and limitations of our integrated approach, the results showed that the use of both appropriate fuel data and fine fuel maps is essential to attain reasonable simulations of fuel consumption and smoke emissions.
FOFEM outputs and the derived smoke emission maps can be useful 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.

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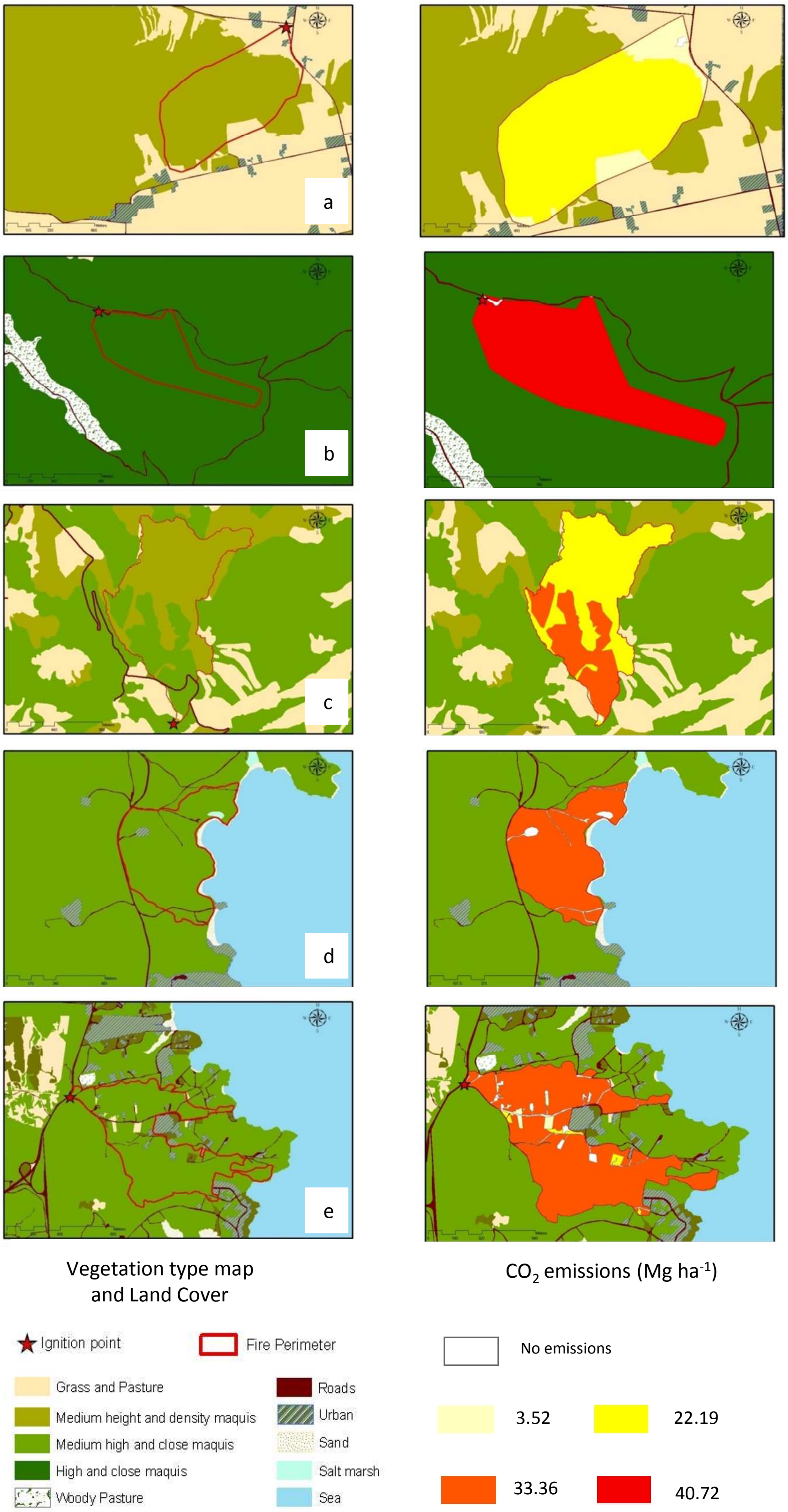

Figure 2 Left: Vegetation type maps produced by supervised classification of pre-fire aerial photographs (1:10,000), field observation of the plant community and use of the 1:25,000 land cover map of Sardinia from the CORINE project (EEA ETC/TE 2002). Within each map, with the red line, is highlighted the fire perimeter: (a) Monte Pedrosu, (b) Ospolo, (c) La Siesta, (d) Razza di Juncu, (e) Sos Aranzos. Right: Spatially explicit CO_2 emissions.