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ORIGINAL ARTICLE

Modeling mercury emissions from forest fires in the Mediterranean region

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Abstract Mercury emissions from forest fires in countries bordering the Mediterranean Sea have been estimated on the basis of satellite observations for the year 2006. The assessment has been done by means of the Moderate Resolution Imaging Spectroradiometer (MODIS) products (MOD12Q1, MOD14A2, MOD15A2, MOD44B). Estimates show that wild fires have burnt 310,268 ha in the Region, affecting by 45% the Mixed Forest and by 37% the Evergreen Needleleaf Forest and the Evergreen Broadleaf Forest. The amount of biomass burned was about 66,000 Mg for the Evergreen Needleleaf Forest, 72,000 Mg for the Evergreen Broadleaf Forest and 196,000 Mg for the Mixed Forest. The total amount of mercury released to the atmosphere in the Mediterranean countries accounted for 4.3 Mg year^{-1} with Italy, France, Austria, Bulgaria, Algeria, Spain and Croatia being the most contributing countries with annual emission ranging from 330 to 970 kg year^{-1}. The maximum release of Gaseous Elemental Mercury (GEM) and particulate mercury (Hg(p)) in the region occurred in July with 1,218 kg. The uncertainty of our estimates is comparable with that associated to current assessments of mercury emissions from major industrial sources.

Keywords Remote sensing · GIS · Europe · Northern Africa · Western Asia · Forest fires · Emissions · Mercury

1 Introduction

Mercury is released in the atmosphere from a multitude of natural and anthropogenic sources. On global scale natural sources (including re-emission of previously deposited mercury) account for about 40% of the total mercury released annually; however, this percentage may

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be much higher (up to 60% of the regional total) in the Mediterranean region where emissions from forest fires and biogenic processes may be substantial [43,47,48].

The necessity of improving the estimate of mercury emissions from natural sources has been widely recognized because there is a strong need in the development of integrated modelling systems for assessing source–receptors relationships [27,36,49].

The assessment of truly natural Hg sources and their relative importance compared with emissions from anthropogenic and natural sources is, then, a key step in studying the global cycling of Hg [36]. The estimate of spatial and temporal distribution of mercury emissions is, indeed, of fundamental importance to improve the performance of transportation and chemical regional, as well as global scale, models [8,34,46,48].

The ratio between the relative contributions of these source categories may vary with region and time of the year [42,48]. Recent studies report small differences between natural and anthropogenic sources, suggesting that the contribution from the upper layer of soils and geologic sources [23] as well as volcanic emissions [51] may have been underestimated, and that the contribution from forest fires to the overall mercury atmospheric budget assessed for several countries is increasing [8,16,66].

Among natural sources, mercury emissions from biomass burning have recently received a growing attention due to their potential significant contribution to the regional atmospheric mercury budget [3,8,16,17,50,57,62,66]. Every year, forest fires destroy a large area of woodland (around 450,000 km^2) [28] and during the last year (summer 2007) the impact of forest fires in Italy, Greece, Algeria and Balkan Countries has caused significant social and environmental damages. Most of these fires are caused by humans, however, there are many natural factors such as drought, wind speed and topography, which influence the spread of fires and govern their devastating effects. The relationship of the amount of burnt biomass and surface with Hg emission to the atmosphere suggests that the control of fires may well reduce Hg releases to the atmosphere.

Previous studies have estimated mercury emissions from forest fires on the basis of direct or indirect measurements of Hg concentrations in smoke of boreal wildfires [2,16,17,62], or tropical forest with intense phytomass burning [66]. Often, the amount of carbon released from burnt biomass has been used as proxy to estimate Hg emissions [2,17,62]; while Hg emission coefficients have been estimated directly or indirectly from burning vegetation [8,16,57,69]. A recent paper by Cinnirella and Pirrone [8] has used the remote sensing (RS) data to estimate mercury emissions from forest fires for the Russian Federation. The aim of this paper is to estimate mercury emissions from forest fires in the Mediterranean region on the basis of RS data, and specifically by using the Moderate Resolution Imaging Spectroradiometer (MODIS) datasets that provide information on cell-by-cell basis (1×1 km) at a daily resolution.

2 Methodology

Mercury emissions from forest fires were estimated using a method that accounts for the burnt surface, standing phytomass and mercury emission factors scaled down at pixel-by-pixel level [8]. Following the considerations that the relative content of mercury in soil and vegetation may vary substantially [18,64] and no measurements of the emission factors for both soil and vegetation have been done during forest fires, a global Emission factor (E_f) was used in the assessment. Hence, mercury emissions from forest fires (Q_{Hg}) (in kg of mercury) were estimated as:

$$Q_{Hg} = A \cdot M \cdot E_f \tag{1}$$

where A is the burnt area (ha), M is the amount of standing phytomass (kg ha^{-1}) and E_f is the Emission factor. Friedli et al. [17] found that E_f was in the range of 112 ± 17 µg of mercury per kg of fuel and varies with phytomass type and other environmental factors (i.e. ambient temperature, relative humidity, mercury content in vegetation and soil). Due to limited information available, a global E_f was adopted in assessing the spatial distributions of mercury emissions, whereas the phytomass amount and burnt area were estimated on the basis of remote sensing observations. Information derived from MODIS datasets (ftp://e0dps01u.ecs.nasa.gov) have been processed under ArcGIS® (v. 9.0, ESRI) to estimate mercury emissions from forest fires on a monthly basis. Integration has been done for those data having eight-day interval detection, leading to the spatial and temporal definition of forest fires in the Mediterranean region. The use of MODIS allows captures data in 36 spectral bands ranging in wavelength from 0.4 to 14.4 µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). Therefore, it gives a better spatial and temporal resolution of burnt areas and biomass amount and lower costs in pre- and post-processing of data [8].

2.1 Fires identification

When using satellite observations of burnt surfaces for assessing mercury emissions, most of the uncertainty is related to the evaluation of the fire activity [54,69]. In the case of MODIS, daily fire activity was identified by the MODIS Fire and Thermal Anomalies Product [20,21,29]. Terra MODIS on board sensors detect fire locations using 4- and 11-µm brightness temperatures. The detection strategy is based on the absolute detection if the fire is strong enough; for weak fires it is based on the detection sensitivity relative to the background value to account for the variability of the surface temperature and reflection by sunlight. The MODIS/Terra Thermal Anomalies/Fire 8-Day L3 Global 1 km SIN Grid product (MOD14A2) is a 1 km gridded composite of the most confident fire pixel detected in each grid cell over an eight-day interval. The Collection 4 product for the year 2006 was retrieved and only nominal and high confidence values (values 8 and 9 with a high quality assessment) have been considered for fire detection. In addition, MODIS global land cover product (MOD12Q1) [63] has been used to select those pixels pertaining to forest (Fig. 1). IGBP classes 1–6 selected from MOD12Q1 represent very well the forest as showed in Fig. 2, whereas the ratio between forests as reported in FRA 2000 [13] and forests detected by MODIS fit the line 1:1 with the exception of Spain.

The process of fire detection implied the development of a model constructed under the Geoprocessor Programming Modeller (Fig. 3a). To obtain annual forest surface affected by fires, dataset has been processed at monthly level.

2.2 Standing biomass

The estimate of forest biomass by remote sensing has been investigated in a number of studies at several spatial and temporal scales [4,6,33,40,41]. These studies present inferences between ground data (i.e. diameter at breast height (DBH), basal area (G), stand volume (V)) and crown characteristics (i.e. Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Leaf Area Index (LAI)) and convert from forest inventory data into biomass density estimates [58,70]. Forest volume inventories, however, emphasize only on the commercially valuable wood, neglecting the whole aboveground biomass. Several studies have developed methodologies for assessing the Biomass Expansion Factor (BEF) to convert volume to mass and to account for the total biomass available on the ground [59]. Gracia et al. [22] produced algorithms for the assessment of Aboveground Biomass Expansion

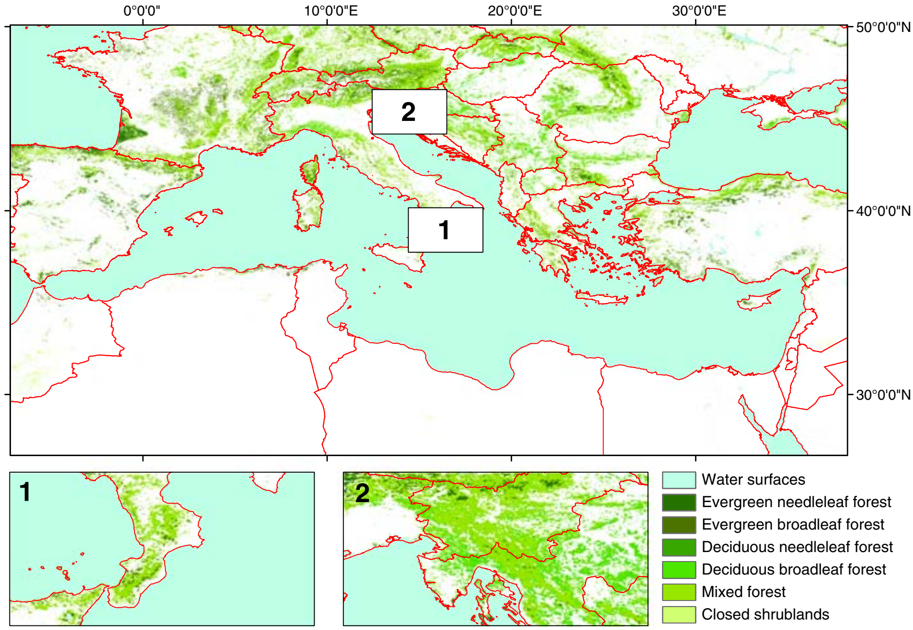

Fig. 1 Forests surrounding the Mediterranean Sea. Details show forest of the southernmost part of the Italian and Istrian peninsula. IGBP classes are, hereafter, reported as ENF (Evergreen needleleaf forest), EBF (Evergreen broadleaf forest), DNF (Deciduous needleleaf forest), DBF (Deciduous broadleaf forest), MF (Mixed forests), CS (Closed shrublands)

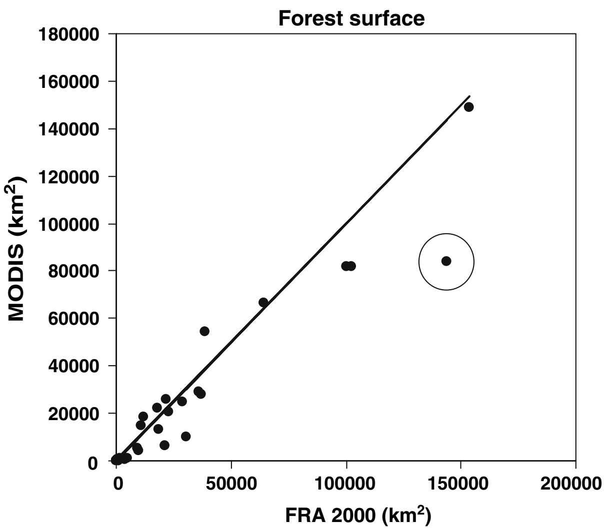

Fig. 2 Ratio between forest surface as reported in the Forest Resource Assessment 2000 [13] and forests detected by MODIS (MOD12Q1, IGBP classes 1–6). The data fit well the line 1:1 with the exception of Spain (circled point)

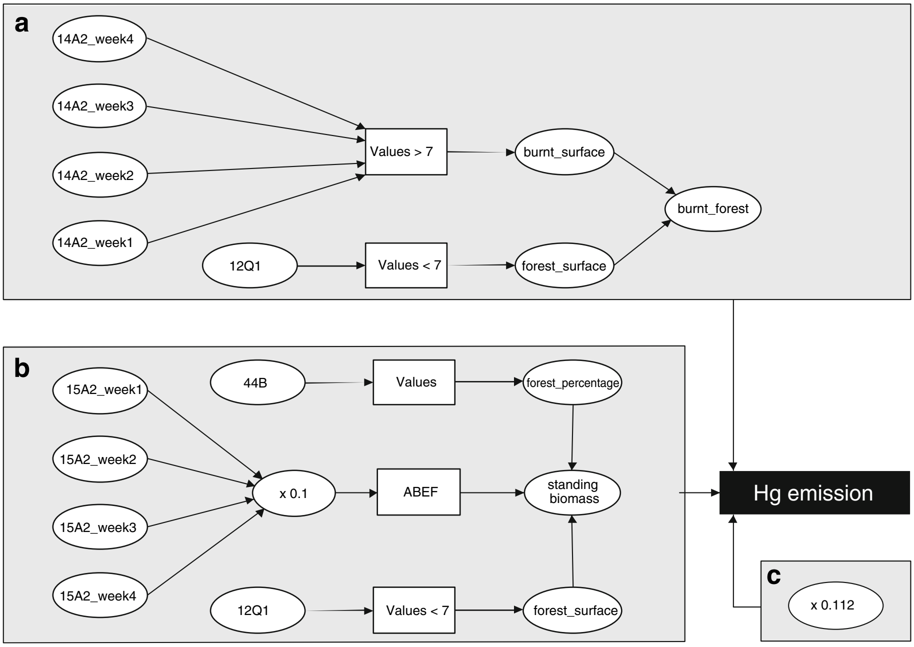

Fig. 3 The mercury emissions model developed under the Geoprocessor Programming Modeller (ARC-GIS®). Sub-models of forest surface affected by fires (**a**), fuel load (**b**) and combustion efficiency (**c**) used to calculate Hg emissions

Factors (ABEF), which represent the ratio between the aboveground biomass and the stem volume.

In this work, the density of forest aboveground biomass (that is the fuel load) was estimated at a spatial resolution of 1 km using foliage-based generalized allometric models developed for European forests [35,39], ABEFs [22] and MODIS land data (Table 1). Aboveground biomass was derived from foliage and wood biomass, which is a function of the percentage vegetation coverage (MOD44B) for different forests [24], Leaf Area Index (MOD15A2) [32] and land cover types (MOD12Q1) [63]. Details on the methodology used to estimate aboveground biomass are reported in Zhang and Kondragunta [70]. Models for different forest typologies were constructed to estimate fuel load at a spatial and temporal step of 1 km and monthly level (Fig. 3b).

2.3 Emission factor

The limited information available on mercury emissions factors for forest fires have led to the selection of an Emission factor (E_f) equal to $112 \pm 17\,\mu g\,kg^{-1}$ that was derived throughout field experiments [17]. The E_f reflects the average value of other emission factors reported in literature [8] and depends upon several factors. They include the mercury concentrations in foliage, which varies with plants' tissues, the efficiency of mercury released to the atmosphere that is strongly controlled by the Hg substrate concentration, light intensity and air temperature and the efficiency of phytomass combustion.

The combustion efficiency is a critical factor when estimating emissions from burnt phytomass because high fire intensity and a complete combustion imply higher emissions of

Table 1 Land Cover type 1 classes (IGBP) selected from MOD12Q1 and used for assessing the above-ground biomass

Class	IGBP (Class Type 1)	Allometric model Biomass = a∗LAI^b ($Mg\ ha^{-1}$)		ABEFs ($Mg\ m^{-3}$)	LAI ($m^{-2}\ m^{-2}$)	SLA ($m^2\ kg^{-1}$)
		a	b			
1	Evergreen needleleaf forest (ENF)	11.9	0.98	0.70	2.60	8.2
2	Evergreen broadleaf forest (EBF)	34.3	1.03	0.90	2.30	32.0
3	Deciduous needleleaf forest (DNF)	11.5	0.97	0.70	2.60	22.0
4	Deciduous broadleaf forest (DBF)	37.0	1.05	0.90	2.00	32.0
5	Mixed forest (MF)	15.0	1.01	0.80	2.30	20.1
6	Closed shrubland (CS)	37.4	1.09	1.10	2.30	12.0

Generalized allometric models (Biomass = a∗LAI^b), aboveground biomass expansion factors (ABEFs) and SLA have been associated to each Land Cover type

mercury as well as of other atmospheric pollutants (e.g. VOCs) to the atmosphere. Combustion efficiency depends on fire intensity and duration, as well as on pre-fire biomass load and water content [14,45,56,68]. It also depends upon the air/fuel ratio, fuel type, fuel chemistry, packing ratio for the fuel particles, surface area to volume ratio and method of ignition [67,68]. The combustion efficiency was estimated to detect its contribution to the Emission factor. Differences between subsequent scenes of the LAI product (MOD15A2) [32] were estimated by calculating the percentage of change after the fire event.

Having the above in mind, monthly atmospheric mercury emissions from forest fires in Southern Europe, Northern Africa and Western Asia (20–50N, −15–50 W) have been estimated for the year 2006.

3 Results and discussion

Spatial and temporal distributions of forest fires in the Mediterranean region are reported in Fig. 4a, which highlights those regions with high frequency in the occurrence of forest fires. The total forest area impacted by wild fires in 2006 was 310,268 ha (Table 2) which was similar to that reported for 1990–1999 and 2000–2005 (∼450,000 ha) periods. Suspected values are those reported for Austria (1,242 ha against an average of 74 ha) and Spain. The latter shows a value that is greater than those provided by official statistic data which accounts for 143,990 ha (www.mma.es). The significant difference might be due to the misclassification of EBF, which is about 50% of the burnt forest, and the correct detection of burnt surface. The misclassification of EBF is due to Collection 4 product anomalies that mismatch MODIS surface reflectance and algorithm retrieval over evergreen broadleaves [63]; anomalies have been adjusted with Collection 5. In addition, in the case of Mediterranean forests a high distinction between burnt and not burnt areas is provided maximizing Surface/Brightness temperature during the compositing technique [7].

Nearly 45% of burnt surface was MF (Fig. 4b), whereas ENF and EBF accounted for a 37% totally. Spain, Algeria, Italy, France and Turkey are among the first six impacted countries with EBF as the most fire affected forest with 107,500 ha followed by MF with

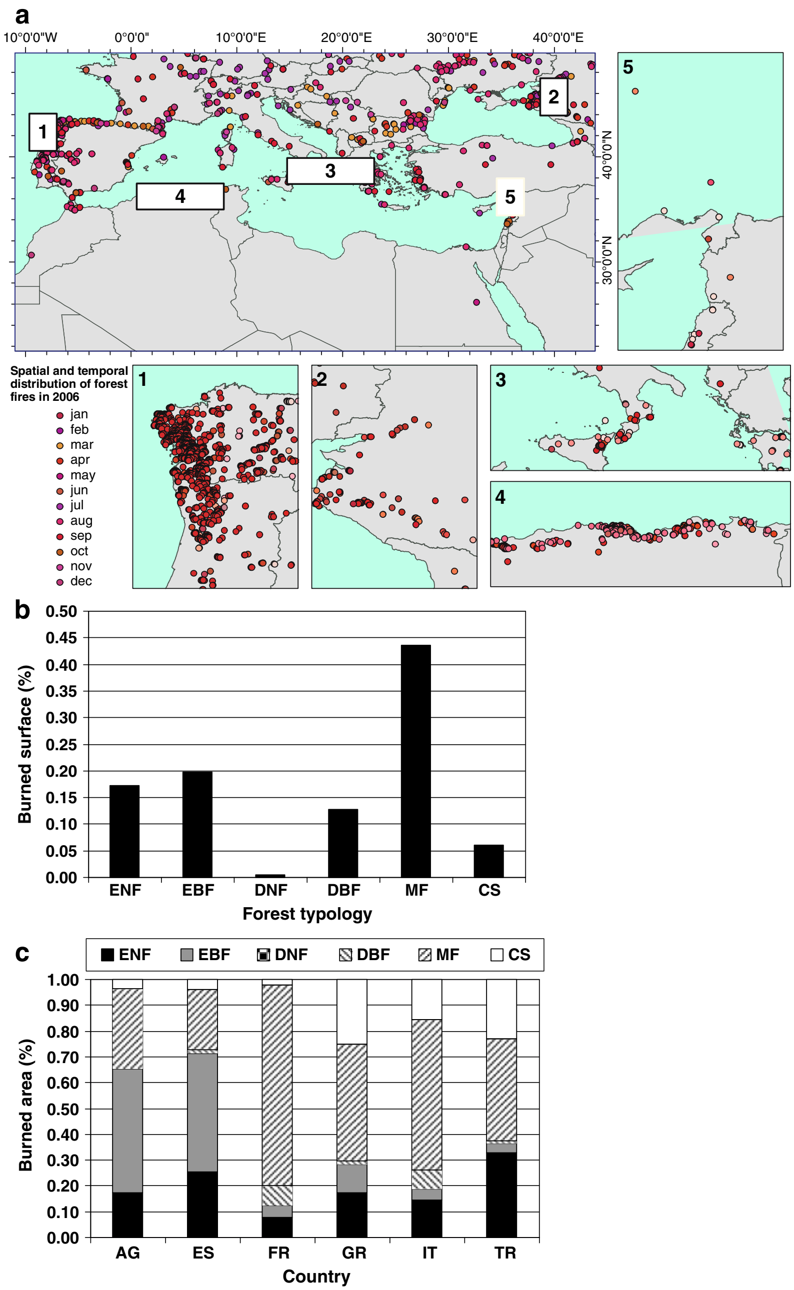

Fig. 4 Distribution of forest fires around the Mediterranean (**a**), percentage of forest typologies (see Fig. 1 for acronyms) destroyed by forest fires (**b**) and percentage distribution of forest typologies destroyed by fires in major affected countries (ISO 3166-1 alpha-2 code) (**c**)

Table 2 Burnt forest area (ha) in 2006 estimated from MODIS satellite images

Country	2006	1990–1999	2000–2005
Albania	103	1,076	12,339
Algeria	43,467	54,689	55,763
Austria	1,242	74	73
Bosnia and Herzegovina	103	973	529
Bulgaria	4,761	6,037	22,268
Croatia	724	8,619	51,796
Cyprus	103	274	3,411
Egypt	207	–	–
France	9,625	22,731	25,222
Greece	6,831	47,054	48,415
Hungary	517	1,289	1,467
Israel	0	5,501	3,053
Italy	15,420	118,795	69,333
Libya	0	31	31
Macedonia	1,345	3,605	9,968
Morocco	2,794	3,340	–
Portugal	65,097	332	136,976
Romania	1,759	220	2,369
Slovakia	828	615	843
Slovenia	103	615	468
Spain	200,259	159,798	137,308
Switzerland	517	451	89
Syria	207	–	–
Tunisia	103	1,423	1,423
Turkey	9,521	10,450	9,435
Yugoslavia	724	2,835	5,717

Averages for 1990–1999 and 2000–2005 periods are derived by Cinnirella and Pirrone [8]

77,500 ha and ENF with 61,500 ha. In Algeria and Spain EBF represented 46–48% of fired forests, whereas in France, Greece, Italy and Turkey MF accounted for 40–78% of total burnt forests (Fig. 4c).

The MOD14A2 product resolution does not allow a detailed mapping of forest fires (i.e. district or province level), nevertheless 1 km spatial resolution is considered high spatial resolution in atmospheric modelling at regional level for which a 5–10 km resolution is generally adopted [10,19,26,31].

The MODIS sensor allows mapping of fires of at least 50 ha (∼700 m resolution) and in the Southern EU, areas of forest fires bigger than 50 ha accounts for about 75% of the total burnt area [26]. In our case, the total amount of forest surface destroyed by fires should be considered conservative, because small forest fires (<50 ha) are coarsely detected and Mediterranean forest surface is frequently fragmented.

Standing biomass shows variations in space (Fig. 5) and time and, as expected, is significantly associated with the forest typology (Fig. 6). On average, ENF have 25 Mg ha^{-1} of aboveground biomass, EBF 24 Mg ha^{-1}, DBF 18 Mg ha^{-1}, MF 29 Mg ha^{-1} and CS accounts

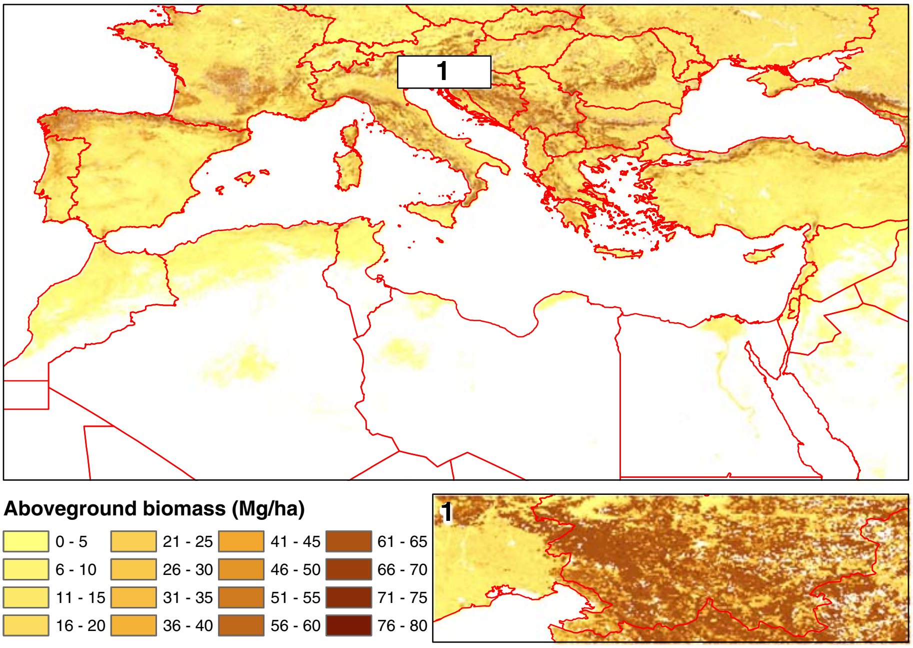

Fig. 5 Distribution of standing biomass in countries bordering the Mediterranean Sea

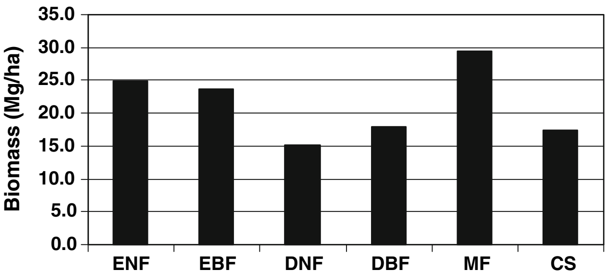

Fig. 6 Average standing biomass within each forest typology

for 17 Mg ha^{-1}. The magnitude of our estimate is in agreement with that estimated by Zhang and Kondragunta [70], Michel et al. [38] and Chiesi et al. [5] that reported similar data for similar biomes in the United States and India. On the contrary, very different values have been reported in the Mediterranean with ENF of 41 Mg ha^{-1} and EBF of 49 Mg ha^{-1} [5,22]. Total burnt biomass in Algeria, Spain, France, Greece, Italy and Turkey has been estimated to be 2,677,000 Mg that is mainly derived from EBF and MF forests (around 1,900,000).

Italian, Austrian, Slovenian and Croatian forests hold more than 60% of total biomass, while the surface of forests in African countries is generally very limited. The amount of standing biomass in the Mediterranean region might be underestimated because the sub 1 km grid scale heterogeneity is very frequent. Heterogeneity is introduced by a variety of factors, including forest age, vegetation association and conditions, site topography and pedology, climate and historical disturbance. The Mediterranean landscape heterogeneity, which has a sub-kilometre scale, suggests that the validation data should be carefully aggregated by averaging weighted areas to obtain the aboveground biomass estimates as experienced for the Net Primary Production estimate [55,65].

Errors in validating data, which are related to several tasks of data handling and gathering, including classification, measurements, sampling and modelling, can be reduced by selecting the appropriate number of classes (error will decrease as the number of classes decreases, but highly aggregated classes may subsume heterogeneity relevant to scaling biomass), assessing the aboveground biomass (many components of biomass are difficult or impossible to quantify because of their inaccessibility), selecting the most representative sample plots (to obtain the true mean and distribution of the classes) and controlling the process (process-based aboveground biomass estimates are typically driven by meteorological data) [65].

The uncertainty originated in the estimate of standing biomass from inventory data is very high and affects considerably the final estimate of mercury emissions. The accuracy in estimating the timber density my reach ±30% [1], leading up to a 50% increase/decrease of the emissions [8].

Standing biomass density associated with the combustion efficiency contains the highest uncertainty factor in the mercury emission estimates [8,37]. The uncertainty depends upon several factors including fuel type, fuel load, fuel chemistry, fuel moisture content, packing ratio for the fuel particles, surface area to volume ratio and method of ignition and is nearly ±50%. Fire dynamics and combustion efficiency should be considered in the overall uncertainty estimate [44]. Differences on fire typology (surface, crown, and total) of forested areas change the amount of burnt phytomass leading to a lower or higher Hg emission. The latter was combined with the combustion efficiency for which is generally assumed 100% consumption for litter and herbaceous phytomass, 60% consumption for shrub and tree regeneration, 100% consumption for canopy foliage and 50–65% consumption for canopy fine branchwood. In our case, the use of MOD15A2 product is a simple way to account for vegetation consumption but it does not consider the amounts of various fuel types consumed. Indeed, crown fires, affecting the barks and twigs, represent only 20–30% of fires in Russia [9,61], but it may represent more than 90% in Canada [15,30]. However, mercury released to the atmosphere from vegetation is primarily related to mercury concentrations in foliage [11,12,52,53,60] leading to the consideration that MOD15A2 is a useful dataset to estimate combustion efficiency product although is approximate.

Mercury emissions from forest fires in 2006 have been estimated for Mediterranean-rim countries (sensu lato) (Fig. 7). Fires occurred in Portugal and Spain do not had the same impact on Hg emissions as in Italy and France (bar chart in Fig. 7), despite the higher number of fires that occurred in the Region. The relevance of standing biomass well explains the difference. In 2006 the most affected areas were the North-Eastern Iberian Peninsula, the southern part of Italy, the northern part of Algeria, the western part of Russia and middle-east countries facing the Sea. Due to the Mediterranean climatic trend, the central months of the year have contributed substantially to the total annual budget (pie charts in Fig. 7), with nearly 75% of mercury has been released in May, June and July.

Table 3 summarizes monthly Hg emissions for countries within the Mediterranean domain. The total of estimated annual emissions (4.3 Mg year^{-1}) is higher than that reported in our previous estimate (2.7 Mg year^{-1}) [8] that was based on a ground-based approach. The primary reason for the higher value predicted for 2006 is the lack of data (i.e. burnt surfaces, biomass) for several countries (e.g. Algeria, Egypt, Syria) for the 1990–2004 period.

Italy, France, Austria, Bulgaria, Algeria, Spain and Croatia are the countries with the highest emissions ranging from 330 to 970 kg in the year 2006. It is not surprising that the large burnt area of Spain (∼200,000 ha) does not contribute in the same manner as the smaller Italian and France areas (∼15,000 and ∼9,000 ha, respectively). The burnt forest typology

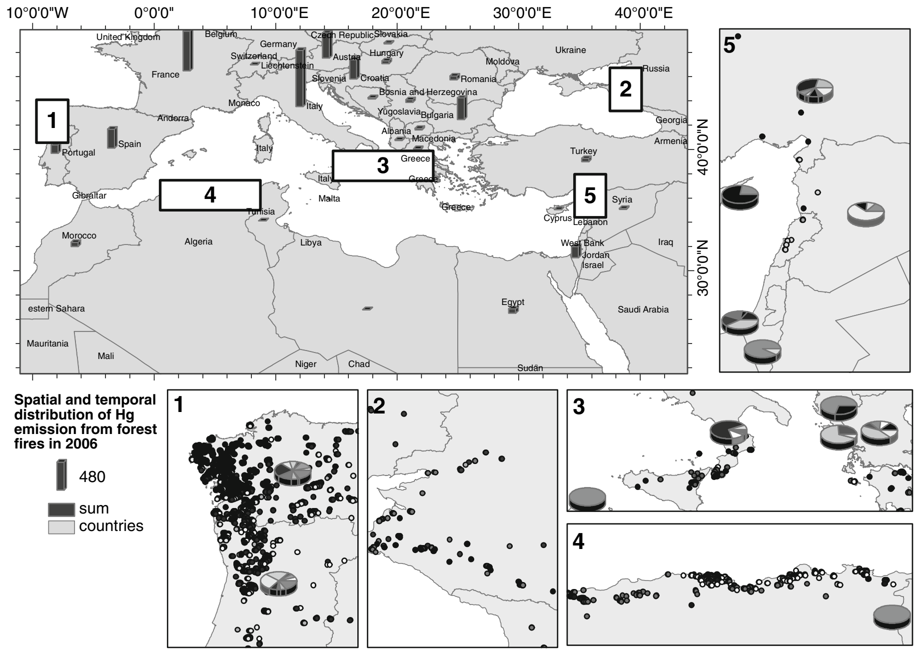

Fig. 7 Mercury emissions from forest fires in the Mediterranean region for the year 2006. Bar chart represents the annual emission, whereas pie-charts represent monthly emissions for the period June to September. Dots represent the location of mercury emissions from forest fires

(mainly EBF in Spain while mainly MF in Italy and France) and the burnt biomass explain the different contributions.

Following the burnt surface trend in 2006, the maximum release of GEM and Hg(p) from forest fires occurred in July with 1,218 kg. This is of paramount importance when considering the cycles of oxidation, deposition, reduction and re-emission in which $Hg^0(g)$ is involved and, therefore, in its lifetime. The lifetime of $Hg^0(g)$ in the MBL, and in the atmosphere in general, has implications not only for the way in which Hg transport is considered but also for the contribution which evasion of Hg^0 from the sea makes to the global Hg budget. In a recent paper Hedgecock et al. [25] proposed a revision of the lifetime for Hg^0 that would occur when air temperatures are low and sunlight and deliquescent aerosol particles are plentiful. Thus the lifetime for clear-sky conditions was estimated to be actually shorter at mid-latitudes and high latitudes than near the equator, and for given latitude and time of year, cooler temperatures enhance the rate of Hg oxidation. Under typical summer conditions (for a given latitude) of temperature and cloudiness such as those occurring in July, the lifetime of $Hg^0(g)$ in the MBL is calculated to be around 10 days.

4 Conclusions

The aim of this paper was to improve a first assessment of mercury emissions from forest fires in the Mediterranean Region that was based on direct forest surveys and provided infor-

Table 3 Estimated Hg emissions (kg) from forest fires for the Mediterranean domain

Country	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year 2006	Year 1990–2004
Albania							10.9			4.6			15.5	13.6
Algeria	13.4		2.6	6.2	10.9	267.9	12.7	13.7	1.7	3.3	9.8		342.3	0.0
Austria			5.0		167.6		259.5						432.0	2.0
Bosnia and Herzegovina			9.8				5.8			7.9			23.5	0.0
Bulgaria			9.8				273.6	65.7	10.8	2.8	4.7		367.5	90.9
Croatia			27.6				255.9	3.6	20.6	18.3		5.1	331.3	162.4
Cyprus						1.3		4.4					5.7	3.4
Egypt			0.2		12.2			5.0	16.4	11.4		31.8	76.9	0.0
France		6.3	5.8		4.0	408.4	233.2	7.4	3.8	4.5	4.6	4.5	682.5	258.0
Greece		2.9				2.7	3.1	1.9	10.3		2.8		23.7	139.9
Hungary			3.5				15.3	13.5	10.8	3.5			46.6	14.1
Israel						179.5	17.1						196.6	80.7
Italy	57.2	9.7	3.8		683.5	119.3	25.3	12.6	19.2	7.1	13.8	15.1	966.6	847.3
Libya								6.2					6.2	0.4
Macedonia								6.8	18.0		1.5		26.3	0.0
Morocco			6.9			9.5	0.7	1.3	3.3	1.5		48.2	71.4	55.4
Portugal		6.9	6.9	5.3	37.9	34.3	12.9	6.4	9.1			23.0	142.7	484.9
Romania		0.6	7.8				11.6	5.5	15.5	5.3	2.4	16.5	65.0	9.8
Slovakia						14.1							14.1	6.3
Slovenia													0.0	11.7
Spain		11.8	35.7	14.4	31.7	31.6	61.1	48.7	26.2	2.1	5.9	53.7	322.9	390.7

Table 3 continued

Country	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year 2006	Year 1990–2004
Switzerland									0.6				0.6	7.2
Syria						2.7	2.0	3.0			12.3		20.1	0.0
Tunisia							0.9						0.9	15.6
Turkey				10.9	18.1	3.9	2.3	6.5	3.1		7.7		52.5	95.5
Yugoslavia							27.1	2.5	6.6	7.7	3.7		47.8	7.3
Sum	70.7	31.3	118.4	31.5	928.0	1,041.0	1,218.1	208.5	166.8	80.0	69.3	174.9	4,281.2	2,697.2

The last column reports ground-based approach estimates on annual basis (average 1990–2004) derived from Cinnirella and Pirrone [8] mation at country level [8]. The step ahead of this study was to estimate monthly mercury emissions from forest fires and provide a much more robust dataset on burnt surface, typologies and amount of standing biomass on cell-by-cell basis (1 km × 1 km). Mercury emissions from forest fires in 2006 have been found higher than that reported in our previous estimate because of the more detailed spatial and temporal dataset for all countries surrounding the Mediterranean.

Estimated emissions presented in this work are affected by an acceptable degree of uncertainty comparable to the uncertainties of continental scale emission inventories and can still be useful to regional air quality modelling. Uncertainties related to the assumption of an undifferentiated emission factor for each forest type and time of the year represent an important gap for those who attempt to perform an assessment of mercury emissions from forest fires by using RS data.

Major implication of this assessment is that Hg emissions from forest fires reveal a fundamental role in global mercury cycle because of the time of the year when these events occur. Indeed, typical summer conditions of temperature and cloudiness affect the Hg^0(g) lifetime in the MBL that drives the evasion of Hg^0 from the sea surface and, therefore, affects the Hg global budget. Further studies on Hg emission from forest fires should take into account the following topics:

- the E_f that in our assessment was assumed from literature. E_f was derived from direct measurements of forest fires over a conifer forest (Black spruce), which shows a 15% variation ($112 \pm 17\,\mu g\,kg^{-1}$) [17]. New direct measurements of Hg emissions during forest fires are necessary to extend the database on E_f in different pedological and forest contexts;
- the error associated with estimates of burnt areas is generally within 15–30%. Recent release of MODIS product (v. 5) allow to estimate burnt areas with a better accuracy therefore it should be tested to obtain datasets with a lower uncertainty;
- the stock of phytomass, in terms of timber density, is often underestimated by 30%. Improvement of estimates can be obtained by calibrating satellite observations with in situ measurements and developing more detailed allometric models.

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