Estimating emissions from vegetation fires in Europe

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Abstract

The paper reports the methodology and data compilation as applied for multi-annual (2000, 2001, 2003) calculations of monthly biomass burning emissions (CO, CH_4, NO_x, VOC and particulate matter) for the European continent. Biomass burning is considered a relevant source category needed for assessing the impact of emissions from natural and biogenic sources on air quality in the frame of the NATAIR-project. The sources and limitations of data required and available for estimating emissions from biomass burning are discussed. Uncertainties are analysed by comparing input data and results of the present study with the approach described in the EMEP/CORINAIR Emission Inventory Guidebook (EMEP/CORINAIR, 2006) and in few other studies available. Further data needs to reduce the very high uncertainty of the current estimates are discussed.

Keywords: biomass burning, vegetation fires, Europe, methodology, trace gases, particulates, land use map, fuel map

1. Introduction

On a global scale, biomass burning in all its forms represents an important source to the atmosphere of carbon dioxide (CO_2), of other trace gases like carbon monoxide (CO), methane (CH_4), nitrogen oxide (NO_x), volatile organic compounds (VOC), and of particulate matter. According to IPCC (2001), the relative contribution of burning biomass in open vegetation fires and from domestic sources to the global annual emissions is in the range of 25% for CO, of 18% for NO_x, and of 6% for either CH_4 and VOC.

Several studies on global emissions from open vegetation fires carried out by van der Werf et al. (2006), Hoelzemann et al. (2004) and Ito and Penner (2004) give emissions of 2000 Tg C, 1700 Tg C and 1300 Tg C respectively for the year 2000 (cited in van der Werf et al., 2006). Within the 8year period 1997-2004 a minimum of 2000 Tg C for the year 2000 and a maximum of 3200 Tg C for 1998 is reported.

During this period, Africa contributed more than 52 % to global annual fire emissions, S-America 30%, SE-Asia 10%, and each the boreal region and all other regions some 4%. The high inter-annual variation of fire activity was mainly driven by droughts linked to El Nino events (Siegert et al., 2001; Carmona-Moreno et al., 2005, van der Werf et al. 2004).

Despite the low contribution of Europe or N-America to global emissions, fires can be the main source of atmospheric pollution for certain time-periods and regions. Fire appeared to be the main driver of the carbon balance variability during 1948-2005 for the boreal forest of Canada (Bond-Lamberdy et al. 2007). For the boreal region as a whole, the burnt area during the period 1992-2003 varied between 3.0 and 23.6 x 10^6 ha y^{-1} with related carbon emissions in the range of 106-209 Tg yr^{-1} . Interestingly, 46-72% of emissions in a given year were attributed in this study to burning of ground layer organic matter (Kasischke et al. 2005).

Only a very small part of global emissions from biomass burning takes place in Europe during the period 1997-2004 emissions ranged between 8 Tg C as a minimum in 1998 and the maximum of 25 Tg C in the year 2000 (van der Werf et al. 2006). According to the CORINAIR inventory 1990, forest fires account for 1.9% of total CO, 0.2% of NO_x, 0.2% of CH_4 and 0.5% of NMVOC emissions in Europe (including European Russia). However, uncertainties are very large and the occurrence of fires is sporadic and highly variable on all time scales from hours to decades; therefore, in some areas and periods fire emissions might make relevant contributions to ground level concentration also in Europe (EMEP/CORINAIR, 2006).

For example, according to the European Fire Information System (European Commission, 2007), the CO_2 emissions during recent catastrophic fires in Greece was in the range of 4.5 Mt until end of August 2007, representing some 4% of the total annual CO_2 emissions of this country. Similar share of fire emissions to total emissions of CO_2 were observed also in Portugal during heavy fire campaigns in 2003 and 2005 (Barbosa et al. 2004, 2006). For August 2003, the contribution of wildfire emissions in S-Europe to observed particulate levels of $PM_{2.5}$ appeared to be comparable to anthropogenic emissions, with significant impact on radiative properties in large areas of Europe (Hodzic et al. 2007, Miranda et al. 2007). A similar situation was observed also for elemental carbon during fire pollution episodes (Tsyro et al. 2007).

Biomass burning comprises the burning of living and dead vegetation. This includes domestic fires (fuelwood-, crop residue-, dung and charcoal burning) as well as open vegetation fires or land fires (forest, shrub-, grass- and cropland burning). The term wildfire is used when agricultural burning is not considered under vegetation fires (Hoelzemann et al. 2004).

The NATAIR project aimed at quantifying ***natural*** emissions of air pollutants in Europe, including open-air activities in agriculture. Thus, only fire emissions from open lands will be subject of this study, even though also the major part of these fires are supposed to be human induced. According to Camia (pers. comm., 2006) 95% of the forest fires in the Mediterranean region are of human origin (negligence, arson, etc). Even for the boreal area Molicone et al. (2006) estimate 87% of the forest fires to be caused by human influence. Only a very small part of the open vegetation fires is caused by natural phenomena like lightning (Koppmann et al., 2005).

In this study emissions of carbon monoxide (CO), methane (CH4), nitrogen oxide (NOx), volatile organic compounds (VOC) and particulate matter (PM2.5 and PM10) from open vegetation fires are considered.

2. Methodology

To evaluate emissions from open vegetation fires, information is needed on the land area burnt, the amount of fuel materials per unit area (fuel load) and the characteristics and condition of the fuel. The term ‘fuel load’ refers to the materials typically burnt like downed trees, fallen branches, decaying leaves and needles, small trees and shrubs as well as the humus layer. The amount of fuel actually burnt in a fire – the fuel consumption - will depend on fuel loading and condition (dry, wet, decayed etc.), the type of fuel, climatic and meteorological factors at the time of the fire, and the intensity of the fire. Once the fuel consumption has been determined, measured emission factors can be applied in order to compute gaseous and particle emissions. Different factors are considered for smoldering and flaming conditions.

The state of the art in calculating emissions from open vegetation fires follows the work of Seiler and Crutzen (1980) and is formulated as:

$E_x = A * B * EF$

where

E_x	emission of compound x
A	burnt area (m^2)
B	fuel load (g dry matter m^{-2})
EF	emission factor (g g^{-1} dry matter burnt)

Accordingly, the current calculation procedure suggested by EMEP/CORINAIR (2006) multiplies burnt area with the carbon content of aboveground biomass burnt, and the emission factors for CO, CH_4, VOC, NO_x, N_2O and SO_x taken from literature. If no local data on aboveground fuel load is available, default values can be applied. Values of total biomass for five biomes (boreal forest, temperate forest, Mediterranean forest, shrubland, grassland/steppe) and factors for each biome allowing to derive aboveground biomass and the assumed fraction of biomass burnt in a fire are provided. Biomass is converted into carbon by the multiplication with 0.45.

The methodology developed within the NATAIR project and presented in this paper considers in more detail the individual fuel load properties and their behaviour in a variable fire event. This includes also the distinguishing between flaming and smoldering combustion conditions determining the specific emission factors. Emissions from biomass burning in open vegetation fires were calculated as:

$$E_x = \sum_{mc} \left((A_m * FL_{mc} * TFC_{mc}) * ((FC_{mc} * EFF_{mcx}) + (SC_c * EFS_{mcx})) \right)$$

where:

E_x	emission of compound x
A_m	burnt area A of fuel model m (m^2)
FL_c	available fuel load FL for each fuel model class c (g dry matter m^{-2}) (Table 2)
TFC_c	fuel consumption TFC for each fuel model class c (g g^{-1}) (Table 4)
FC_c	flaming combustion fraction FC for each fuel model class c (g g^{-1}) (Table 4)
SC_c	smoldering combustion fraction SC for each fuel model class c (g g^{-1}) (Table 4)

EFF_{cx} emission factor flaming combustion EFF of compound x for each fuel model class c (Table 4 and 5)

EFS_{cx} emission factor smoldering combustion EFS of compound x for each fuel model class c (Table 4 and 5)

x CO, CH_4, NMHC, NO_X, $PM_{2.5}$, PM_{10},

m fuel model (Table 2)

mc fuel class of fuel model m (Table 2)

The individual parameters required for the calculations and the data sources are described in detail in the following sections.

3. Relevant key data sets for the NATAIR area of interest for the years 2000, 2001, 2003

3.1. Burnt area data

A comprehensive and up-to-date list of available and planned continental or global burnt area products can be found in Kaiser et al. (2006). Currently no single data set is fulfilling the temporal (years 1997, 2000, 2001 and 2003 in a monthly time resolution) as well as spatial requirements of the NATAIR project. The spatial focus within the NATAIR project is the EU27 area, but the entire NATAIR modelling domain has a much larger extent including also parts of Russia, Middle East and Northern Africa (see Fig. 1).

We used high resolution (180m by 180m pixel size) data from the Indian Remote Sensing satellites' Wide Field Sensor (IRS/WiFS) for 5 Mediterranean countries (Portugal, Spain, France, Italy, Greece), as available from the European Forest Fires Information System (Barbosa et al., 2002). Fires in these Mediterranean countries represent more than 90% of the area burnt in the year 2000 in the 27 countries of the European Union (European Communities, 2006). This regional data set was combined with the medium resolution Global Burnt Area Map 2000 (GBA2000, Tansey et al., 2004) to cover the whole modelling area. For all three years considered, the seasonal distribution of burnt area data was taken from GBA2000, for the 5 Mediterranean countries the IRS/WiFS data were disaggregated with the help of GBA2000 monthly data for these countries. Table 1 shows the burnt area data for the individual countries within the NATAIR domain derived from IRS/WiFS and GBA2000. The data finally used for the emission calculations are marked with grey background. Additionally, burnt area information available from another remote sensing based dataset available for Northern Eurasia (Bartalev et al., 2004) and two statistical data collections of ground surveys of burnt areas (European Communities, 2006 and UNECE-FAO, 2002) are listed for comparison.

Based on the combined GBA2000-IRS/WiFS data, total burnt area for the NATAIR domain in the year 2000 was ~145500 km^2. Around 85% (~123000km2) of the burnt area is located in the Russian Federation, the Ukraine and Kazakhstan. In EU27 ~11500 km2 (8% of the burnt area in the NATAIR domain) were burnt in 2000, hereof the major part in the Eastern European and Mediterranean countries. The inter-annual variation of burnt areas as available for the Mediterranean countries for the years 1980-2005 (European Commission 2006) shows no clear tendency. The burnt area in the hot and dry summer of 2003 was among the highest during the 25 years period, but the trends between the 5 countries are not at all uniform.

However, comparing the five different data sources in Table 1, the burnt area given for a certain country and year is extremely variable. This may be a result of methodological limitations, different algorithms for image analysis, interpretation errors, or incomplete data reporting in case of ground surveys. Remote sensing products usually have specific fire detection limits depending on the spatial resolution of the images and on the detection algorithm applied. The IRS/WiFS based data refers to burn scars >50ha. Thus, the higher the share of small scars in a country the higher the underestimation of the real burnt area. The definition for GBA2000 is more vague saying that "at least half of a 1km2 pixel has to be burnt to be classified by the algorithm" and is difficult to interpret with regard to methodological error estimates. Additionally, misclassifications of burnt area itself and uncertainties in assigning the correct pre-burn land use/cover class have to be taken into account.

Statistical data collections do not suffer from these methodological restrictions but usually do not include agricultural or grassland burnt. They may be also lacking completeness due to e.g. delayed data submission or reporting only events with fire fighting interventions. The differences between EC and FAO for a country and for a certain year may be linked to such type of problem, but they are very minor compared to the differences to and between remote sensing based data. The reason for this is simply that data are reported as the official data of the country both to FAO and to EFFIS of the EC, and must be considered a type of ground truth for the image based products.

Comparing the results from the different sources (Table 1) the largest discrepancies occur for Russia, Ukraine, Kazakhstan and Romania in the year 2000. For Russia GBA2000 shows ~122000 km2 of burnt forest/shrubland area, which is more than 25 times larger than the area of ~4600 km2 derived by Bartalev et al. (2004) from SPOT Vegetation / MODIS data. Official data submitted to FAO by Russian authorities amounts to ~20000 km2, thus 1/6 of GBA2000 burnt area and ~4 times the value given by Bartalev et al. (2004). Zhang et al. (2003) reported for the Russian Federation in 2001 a total burnt area of 41782km^2, the Nonforest category (including shrubland, wooded wetlands and tundra) contributed less than one third. For Ukraine and Kazakhstan both remote sensing products give much higher burnt area than the FAO statistics, with GBA2000 values being by far the highest. For Romania only GBA2000 and statistical data was available, but also here the former is 2 orders of magnitude higher than the information given by the statistics. In Russia, Ukraine and Kazakhstan the annual variation (2000, 2001) given by Bartalev et al. (2004) and FAO statistics is less pronounced than the differences among the data sources themselves.

Differences between the data sources are lower in the 5 Mediterranean countries where IRS/WiFS data was applied, but still notable. In Spain, Greece, Portugal and France forest/shrubland area burnt derived from IRS/WiFS data is around 40% to 85% of the value reported in the EC statistics. For Italy, the underestimation from the remote sensing product in the year 2000 is even higher with 217 km^2 of burnt forest land based on IRS/WiFS compared to 1146 km^2 in the EC statistics. This is most likely due to a large amount of small fires below the detection limit in Italy.

According to the EC statistics, burnt forest/shrubland area in EU25 (EU27 excluding Bulgaria and Romania) was ~6800 km2 whereas the remote sensing data used for the current study amounts to ~3000 km2, thus an average underestimation by a factor of 2 for the burnt area data in this region can be assumed. Instead, the burnt area of forest land in the year 2000 for all countries listed in Table 1 sums up in GBA2000 to 142772km^2, in contrast to 28565km^2 reported to FAO, means the remotely sensed burnt area would be overestimated by factor 5.

Table 1: Burnt area (km^2) data for the individual countries in the NATAIR domain. Data from 5 different sources are given. Three from remote sensing products 1. GBA2000 (Tansey et al., 2004), 2. IRS/WiFS (Barbosa, 2006, pers. comm.), 3. SPOT/MODIS (Bartalev et al., 2004) and two statistical data collections 4. EC statistics (European Communities, 2006) and FAO statistics (UNECE-FAO, 2002). Cells with grey background indicate the data used for the emission calculation in this study.

	GBA2000			IRS/WiFS						SPOT/ MODIS			EC Statistics[1]				UNECE-FAO Statist.[2]			
	2000			2000		2001		2003		2000	2001	2003	2000	2001	2003		2000		2001	
	Total (#)	Forest /Shrubland	Total (NATAIR domain)	Total	Forest/Shrubland	Total	Forest/Shrubland	Total	Forest/Shrubland	Total	Total	Total	Forest	Forest	Forest		Forest and Other Wooded Land (a)		Forest and Other Wooded Land (a)	
Country	Burnt Area in km2																			
Albania	114	94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	(b)	4	(b)
Armenia	98	88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0		1	(b)
Austria	94	57	-	-	-	-	-	-	-	-	-	-	-	-	-	(p)	0	(b)	0	(b)
Azerbaijan	531	194	439	-	-	-	-	-	-	-	-	-	-	-	-	-	0	(b)	0	(b)
Belarus	437	329	-	-	-	-	-	-	-	46	0	116	-	-	-	-	19		29	(b)
Belgium	14	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	(b)	0	(b)
Bosnia - Herzegovina	361	156	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	(b)	5	(b)
Bulgaria	2060	333	-	-	-	-	-	-	-	-	-	-	-	-	-	-	574		202	
Croatia	165	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	682		354	(b)
Cyprus	8	6	-	-	-	-	-	-	-	-	-	-	80	48	23	(s)	80	(c)	48	(c)
Czech Republic	36	4	-	-	-	-	-	-	-	-	-	-	4	1	12	(t)	4		6	(b)
Estonia	23	22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7		6	(b)
Finland	93	80	-	-	-	-	-	-	-	-	-	-	4	2	14	(u)	4		2	
France	526	248	-	*143*	116	*112*	92	*427*	339	-	-	-	241	206	733	(q)	205		205	
Georgia	156	109	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	(b)	1	(b)
Germany	68	42	-	-	-	-	-	-	-	-	-	-	6	1	14	(v)	6		1	
Greece	1187	617	-	*1062*	627	*93*	65	*2*	1	-	-	-	1450	182	35	(q)	1670		183	
Hungary	1343	12	-	-	-	-	-	-	-	-	-	-	16	-	8	(w)	13	(b)	13	(b)
Italy	2454	331	-	*435*	217	*169*	118	*190*	100	-	-	-	1146	764	918	(q)	1404		764	
Kazakhstan	81622	7524	7899	-	-	-	-	-	-	2297	3111	4371	-	-	-	-	275		247	(b)
Latvia	52	38	-	-	-	-	-	-	-	-	-	-	13	3	6	(x)	13		10	(b)
Lithuania	12	8	-	-	-	-	-	-	-	-	-	-	4	1	4	(y)	4		1	
Macedonia	155	123	-	-	-	-	-	-	-	-	-	-	-	-	-	-	137		63	(b)
Middle East	1155	121		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Moldova	1014	182	-	-	-	-	-	-	-	45	0	1	-	-	-	-	0	(b)	0	(b)
Netherlands	3	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	(b)	2	(b)
Northern Africa	3405	1544		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Norway	148	144	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17		10	(b)
Poland	162	115	-	-	-	-	-	-	-	-	-	-	313	319	1245	(z)	490	(d)	495	(b,d)
Portugal	853	499	-	*1032*	697	*751*	623	*2941*	2492	-	-	-	1596	1071	4257	(q)	1596		1118	
Romania	3513	1183	-	-	-	-	-	-	-	-	-	-	36	10	8	(n)	36		16	(b)
Russian Federation	223575	122457	93774	-	-	-	-	-	-	4629	5614	33563	-	-	-	-	19037		12294	
Serbia - Montenegro	616	130	-	-	-	-	-	-	-	-	-	-	-	-	-	-	80		35	
Slovakia	156	122	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1		1	(b)
Slovenia	17	15	-	-	-	-	-	-	-	-	-	-	-	-	21	(r)	3		7	(b)
Spain	1644	923	-	1082	785	411	353	671	524	-	-	-	1886	924	1482	(q)	1870		924	
Sweden	99	74	-	-	-	-	-	-	-	-	-	-	15	13	40	(m)	44	(b)	13	(b)
Switzerland	16	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1		1	(b)
Turkey	2714	1771	-	-	-	-	-	-	-	-	-	-	264	74	66	(o)	264		74	
Ukraine	21334	4807	-	-	-	-	-	-	-	259	30	129	-	-	-	-	19		39	
United Kingdom	6	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	(e)	2	(e)

(#) burnt area given in this table refers to the total area of the country. For Russia, Ukraine, Kazakhstan and Azerbaijan the NATAIR domain comprises only parts of the country. The GBA2000 burnt area in these countries located in the NATAIR domain is given in the column 'Total (NATAIR domain)'.

[1]**European Communities (2006), the data is based on the following tables and figures in the source document:**
(m) Table 16; (n) Table 17; (o) Figure 24; (p) Chapter 2.2.1.; (q) Table 25. For France: Mediterranean area only.; (r) Table 14; (s) Table 6; (t) Figure 14; (u) Figure 15 (no values given, value approximated from the bars); (v) Figure 16; (w) Figure 17 (no values given, value approximated from the bars); (x) Figure 18; (y) Figure 19; (z) Table 13

[2]**UNECE-FAO (2002)**
(a) includes forest, other wooded land and other land. The latter may include heathland, waste land or agricultural land adjoining or enclosed by forest land.
(b) unofficial figure or secretariat estimate (when no data, received data from the previous year are carried over for inclusion totals) (c) CY - State forests only (d) PL - Data for 1998-2000 include "other land" (i.e. heathland, waste land or agricultural land) (e) UK - State forests only. Periods reported are financial years, running from April to March of the following year

3.2. *Fuel load*

Fuels represent the organic matter available for fire ignition and combustion. They are defined as the physical characteristics, such as loading (weight per unit area), size (particle diameter), and bulk density (weight per unit volume), of the live and dead biomass that contribute to the spread, intensity, and severity of a fire (Keane et al. 2001).

As it is difficult to describe all physical characteristics for all fuels in an area, a generalized description of fuel properties, called a fuel model, is often created for forest and shrubland ecosystems. The most commonly used fuel models in the United States were constructed for fire behaviour prediction (e.g. the 13 standard fire behaviour fuel models of Anderson, 1982) and fire danger rating (e.g. the 20 National Fire Danger Rating System –NFDRS- models of Deeming et al., 1978). The fuel model is an identifiable association of fuel elements of distinctive species, form, size, arrangement or other characteristics that will cause a predictable rate of fire spread and intensity under specific weather and topographic conditions. For each fuel model the fuel elements are grouped in fuel classes possessing common characteristics with respect to fire. In the NFDRS, dead fuels are grouped according to their diameter which is related to the reaction time to ambient humidity. The fine dead fuels include material < 2.5 cm, small dead fuels between 2.5 cm and 7.6 cm and large dead fuels >7.6 cm in diameter. Living fuels are grouped by whether they are herbaceous (annual or perennial) or woody. The duff fuel class comprises partially decomposed organic material of the forest floor that lies beneath the freshly fallen twigs, needles, and leaves. In Table 2 the 13 NFDRS fuel models used within this study and their fuel class characteristics are listed. Leenhouts (1998) associated fuel consumption, the share of flaming and smoldering combustion and emission factors to each fuel class of the fuel models.

To assess the fuel load and fuel characteristics for the NATAIR domain a combination of European land use/cover data and of natural vegetation information was translated into the fuel models of the NFDRS. This procedure is based on approach developed by Sebastián-López (2002).

It should be mentioned that the NFDRS fuel models were designed to address *surface* wildland fires. This limitation probably leads to underestimation of biomass consumption and emissions as crown fuels are not considered. Anyhow, the data base available for the NATAIR area of interest does not allow a distinction between crown and surface fires, as currently there is no information about the type of fire or fire intensity related to the burnt area data from IRS/WiFS and GBA2000. Thus, the fuel load estimates of this study should be considered as conservative. In the following the data sets used for deriving a European fuel load map will be described.

Land use/cover map

The land use/cover information used for the calculations is described in detail in Appendix II. The data set served as the common land use/cover basis for all land related natural emissions calculations within the NATAIR project. Shortly, the mosaic consists of CORINE 2000 land cover database for the majority of European countries, combined with different versions of the regional Global Land Cover 2000 data sets. Detailed descriptions of the datasets are available under *http://terrestrial.eionet.eu.int/CLC2000* (CLC2000) and *http://www-gvm.jrc.it/glc2000/defaultGLC2000.htm* (GLC2000).

Map of Natural Vegetation

With a few exceptions the land use/cover classification system of CLC2000 and GLC2000 does not take into account the change of the structure of a certain land use/cover class in different climatic regions or ecological zones. E.g. no distinction is made between a coniferous forest in a Mediterranean or a boreal region. However, the fuel load in e.g. coniferous forest may differ widely over Europe depending on natural factors such as soil quality, and anthropogenic influence like forest management. On a European level, forest management data is hardly available. In order to consider at least the 'natural' variation, the land use/cover information was combined with information of 19 vegetation formations (Table S2, Appendix II) given in the Map of Natural Vegetation (Bohn et al. 2002/2003).

Fuel Load Map

The final fuel load map (Figure 1) was derived by assigning a NFDRS fuel class (Table 2) to each combination of land use/cover and vegetation formation class. The allocation matrix is given in Table S2 (Appendix II). The fuel loads in the NATAIR domain range between 1.6 t/dry matter per ha in grassland and sparsely vegetated areas up to 37 t/dry matter per ha in sclerophylluous oakwood vegetation of the Mediterranean area. Compared to other studies of Ito and Penner (2004) and of Hoelzemann et al. (2004) these fuel loads are low (s. Table 3). For forest areas this can be explained by the fact that only fuel affected by surface fires is considered in the NFDRS system applied in this study. Other studies, including the ones mentioned above, equate fuel load with biomass density and apply fractions for different fuel consumption in relation to assumed fire intensities. The shrubland fuel loads are in good agreement with the lower limit given by Ito and Penner (2000), but around 5 times lower than the values applied for wooded savannah of Hoelzemann et al. (2004) – which were assumed to correspond to the shrubland class of our study. A similar discrepancy can be observed for grassland/agricultural fuel loads.

Currently there is hardly any information on fuel load in the different European ecosystems. Especially the classification of the fuel into compartments showing a different susceptibility in a fire event is lacking. The latter is essential to determine the fuel consumption - being the fraction of fuel actually consumed in a fire - as well as the fuel load fractions burning under smoldering or flaming combustion conditions and thus determining the species composition of the emissions.

Table 2: Fuel loads (tons dry mass ha^{-1}) for different vegetation classes based on the National Fire Rating System (NFDRS) fuel models (Burgan, 1988). The 'translation' of the NDFRS fuel models into the European vegetation classes is based on Barbosa, 2006 (pers. comm.)

Vegetation Class	**Vegetation Type**	**NFDRS Fuel Model**	**Fuel Class**					
			Dead Fine	**Dead Small**	**Dead Large**	**Live**	**Duff**	**Total**
			tons dry mass ha^{-1}					
Open pine stands with perennial grasses and forbs	Forest	C	3.14	0	0	3.59	4.03	10.8
Shrubland understory and pine overstory	Forest	D	6.72	0	0	8.97	3.36	19.1
Sclerophylous oakwood vegetation	Forest	F	10.1	3.36	0	17.9	5.6	37
Short-needled conifers with sparse undergrowth and thin layer of ground fuels	Forest	H	5.6	4.48	4.48	2.24	4.48	21.3
Broadleaved forests of Quercus ilex, rotundifolia, and suber	Forest	O	11.2	6.72	4.48	15.7	7.85	46
Coniferous forest with Iberian-atlantic oak-ash woods and Cantabrian beechwoods	Forest	P	4.48	1.12	0	2.24	2.24	10.1
Broadleaved forest	Forest	R	2.24	1.12	0	2.24	1.12	6.72
Grassland vegetated by annual grasses and forbs	Grassland/ Agriculture	A	0.45	0	0	0.67	0.45	1.57
Grassland vegetated by perennial grasses	Grassland/ Agriculture	L	0.56	0	0	1.12	0.56	2.24
Sparsely vegetated areas	Grassland/ Agriculture	S	2.24	1.12	1.12	2.24	3.36	10.1
Non forest class	Grassland/ Agriculture	X	0.45	0	0	0.67	0.45	1.57
Inland and coastland Marshes	Shrubland	N	6.72	0	0	4.48	4.48	15.7
Transitional Woodland shrub	Shrubland	T	3.36	0	0	6.72	2.24	12.3

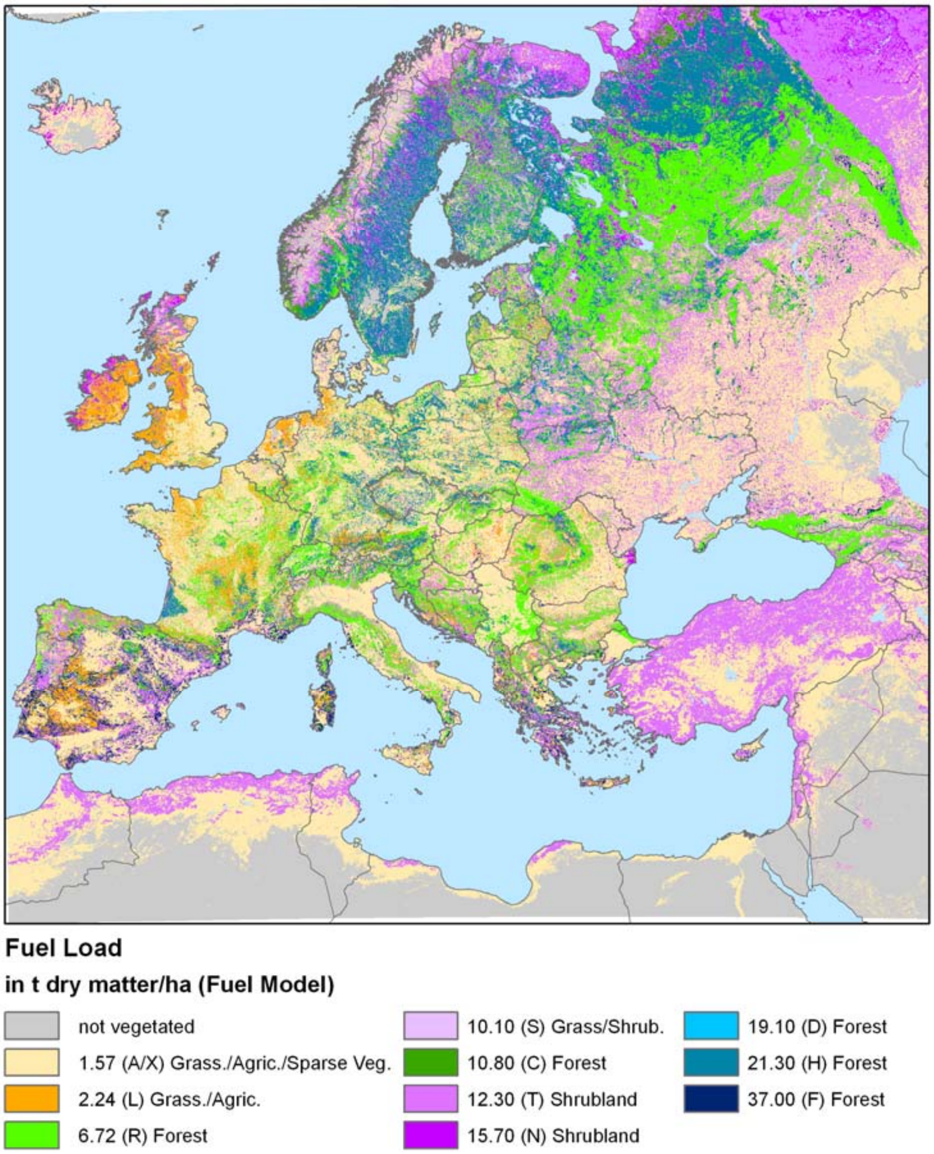


Figure 1: Fuel load map. Vegetation classes, Vegetation Types and NFDRS fuel models (s. Table 2) were assigned to the land use/land cover information from the CLC2000-GLC2000 mosaic (Appendix II) depending on the vegetation formation of the Natural Vegetation Map (Bohn et al., 2002/2003) .

Table 3: Fuel Load (t dry matter / ha) applied within different studies for grasslands/agriculture, shrublands and forests in areas burnt in Europe in the year 2000

	This work[f]	**Ito and Penner (2004)**[a]	**Hoelzemann et al. (2004)**[b]	
			Western Europe	Eastern Europe
	t dry matter / ha			
Forest	13.1	73.9 – 74.8[e]	58.0[c] – 66.9[d]	85.6[c] – 109.4[d]
Grassland/Agriculture	1.6	2.8	17.5	12.7
Shrubland	12.5	12.5 - 24.8[e]	44.5	71.3

a Data refers to region C in Table 10 of Ito and Penner (2004)
b Data refers to the results of GWEM-1.20 in Table 2 of Hoelzemann et al. (2004). Grassland = Savanna and grasslands, Shrubland = Wooded Savanna.
c Boreal forest
d Temperate forest
e 2 scenarios

3.3. *Fuel consumption, combustion type and emission factors*

The parameters fuel consumption, fraction of smoldering and flaming combustion and emission factors are based on Leenhouts (1998).

Fuel consumption (Table 4), which is defined as the fraction of available fuel actually burnt in a fire, ranges from 25% to 90% with the highest consumption in the dead fine material class <2.5 cm in diameter. The fraction of consumed fuel is decreasing in the larger dead fuel classes. Living fuels are supposed to be consumed to 80-90% in most of the grassland and shrubland fuel models (A,X,N,T). Whereas in most of the forest fuel models (C, D, F, H, P, R) the consumption of living fuels is <50%. Duff consumption ranges from 25% to 90% with the maximum in the grassland model A.

The fractions of flaming and smoldering combustion related to the fuel classes is given also in Table 4. Smoldering combustion, leading to higher emissions of reduced species, occurs mainly in the duff and the large dead wood fraction of the forest models. Half of the duff is assumed to burn under smoldering conditions. Fine dead material and living material have no smoldering fuel fraction assigned.

The emission factors used for our calculations (Table 5) for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), 2.5-micron particulate matter ($PM_{2.5}$), 10-micron particulate matter (PM_{10}), total particulate matter (PM), volatile organic compounds (VOC), nitric oxide (NO_X as NO), organic carbon (OC), and elemental carbon (EC) are based on a study of Ward and Hardy (1991). Leenhouts (1998) applied specific factors for smoldering and flaming combustion conditions for the different fuel classes where appropriate. The emission factors are within the given ranges in the more recent comprehensive collection of emission factors by Andreae and Merlet (2001).

Table 4: Fuel consumption (TFC), proportion of the fuel consumed by flaming combustion (FC) and/or smoldering combustion (SC), and the emission factor (EF) given in Table 5 related to each National Fire Danger Rating System (NFDRS) fuel class (Lahm, 1994 published in Leenhouts, 1998).

NFDRS model	Fuel Class																				
	Dead fine			Dead small					Dead large					Live			Duff				
	TFC	FC	EF	TFC	FC	EF	SC	EF	TFC	FC	EF	SC	EF	TFC	FC	EF	TFC	FC	EF	SC	EF
A	0.8	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.8	1.0	6	0.90	0.9	3	0.1	3
C	0.8	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.4	1.0	6	0.50	0.5	3	0.5	3
D	0.6	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.5	1.0	6	0.50	0.5	3	0.5	3
F	0.6	1.0	3	0.5	0.9	1	0.1	2	0.0	0.0	1	0.0	2	0.5	1.0	5	0.50	0.5	3	0.5	3
H	0.8	1.0	1	0.5	0.9	1	0.1	2	0.5	0.8	1	0.2	2	0.4	1.0	6	0.50	0.4	7	0.6	7
L	0.9	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.5	1.0	6	0.00	0.0	3	0.0	3
N	0.8	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.8	1.0	6	0.00	0.0	3	0.0	3
O	0.8	1.0	3	0.8	0.9	1	0.1	2	0.5	0.5	1	0.5	2	0.7	1.0	5	0.25	0.5	3	0.5	3
P	0.9	1.0	1	0.8	0.9	1	0.1	2	0.0	0.0	1	0.0	2	0.4	1.0	6	0.25	0.5	7	0.5	7
R	0.9	1.0	1	0.8	0.9	1	0.1	2	0.0	0.0	1	0.0	2	0.5	1.0	6	0.25	0.5	7	0.5	7
S	0.9	1.0	3	0.8	0.9	1	0.1	2	0.5	0.5	1	0.5	2	0.4	1.0	6	0.25	0.5	3	0.5	3
T	0.9	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.9	1.0	6	0.00	0.0	3	0.0	3
X	0.8	1.0	3	0.0	0.0	1	0.0	2	0.0	0.0	1	0.0	2	0.8	1.0	6	0.90	0.9	3	0.1	3

Table 5: Emission factors (EF), in gram species per kilogram dry matter burnt, for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), 2.5-micron particulate matter ($PM_{2.5}$), 10-micron particulate matter (PM_{10}), total particulate matter (PM), volatile organic compounds (VOC), nitric oxide (NO_X as NO), organic carbon (OC), and elemental carbon (EC). Leenhouts (1998) referring to data from Ward and Hardy (1991).

EF	CO_2	CO	CH_4	$PM_{2.5}$	PM_{10}	PM	VOC	NO_X	OC	EC
1	1686	55.7	3	5.9	7	10	3.1	3.9	3.76	0.49
2	1393	213.2	9.9	16.6	19.6	24.5	8.2	14.9	7.11	0.25
3	1741	26.2	1.7	3.9	4.6	7.3	2.2	1.8	2.63	0.38
5	1668	65.6	3.4	6.6	7.8	10.9	3.4	4.6	4.12	0.52
6	1558	124.6	6	10.6	12.5	16.4	5.3	8.7	5.78	0.57
7	1686	55.7	3	5.9	7	10	3.1	3.9	3.76	0.49

4. Other parameters relevant for modeling

4.1. Injection height

Emissions from biomass burning are injected into the atmosphere at various heights depending on several factors like energy released from the fire and local meteorological conditions. Liousse et al. (1996ab and 2004), Leung et al. (2007) and others showed the height of injection, especially the distinction between emissions transported above or remaining within the planetary boundary layer, to be a critical parameter in atmospheric chemistry transport models.

However, information on type of the fire and fuel consumed to allow the assessment of the energy released and calculate the injection height in a certain fire event is available neither from the statistics nor from the remote sensing products.

Leung et al. (2007) explored observed and simulated anomalies in CO mixing ratios, for three scenarios in the boreal region. The best fit was obtained by a 40:60 split of the emissions between the boundary layer and 3–5 km height. This split was based on evidence that fire plumes are often seen in the middle troposphere, and on the assumptions that the majority of fires (in August) were crown fires. They cite a recent study for large fires in Alaska where model results were not sensitive to a 40:60 versus a 60:40 split, but about half of the emissions are needed to be released above the boundary layer to match with observations.

Liousse et al. (1996a, b and 2004) calculated an injection height of 2000 meters as typical for average tropical savannah and forest fires based on the relationship of the particle injection height versus the frontal fire intensity obtained from different measurements and observations. Significant differences appear for boreal fires, especially crown fires, which can inject pollutants at over 7600 meters altitude.

As described previously, in this study only surface fires conditions were considered. The results of before mentioned studies suggest that in this case the major part of the calculated emissions will remain within the boundary layer.

4.2. VOC split

The detailed emission factor database of Andreae and Merlet (2001) provides information for splitting non-methane VOCs into individual species or species groups required for modeling purposes.

5. Results and Discussion

Emissions from vegetation fires in the NATAIR domain, as calculated according to the procedure and with the datasets described above, are presented in Table 6 for the year 2000 for different vegetation classes. For comparison, the emissions were calculated on the basis of the GBA2000-IRS/WiFS burnt area with emission factors and the default values of biomass/fuel load taken from the EMEP/CORINAIR (2006) emission inventory guidebook. As discussed in detail in chapter 3.1., the burnt area data taken from satellite images appeared to show a significant bias especiallly for Eastern Europe and Russia, with underestimation of burnt area in EU27 by factor two, and overestimation in the Natair domain as a whole by factor five. The numbers given below should therefore be considered as preliminary; they may help to understand trends and to identify key data gaps to be filled in order to come to reliable estimates of fire emissions.

The highest contribution (70%) to the total emissions in 2000 results from shrubland burning having the second largest share (26%) within the burnt area in the NATAIR domain. Agriculture/ Grassland being the dominating vegetation class burnt (68% of the burnt area) contributes with around 20% to the total emissions. Only 10% of the emissions result from fires in forests (6% of the burnt area).

Looking at the spatial distribution (Figure 2), the dominant contribution to emissions (~ 90%) result from the non-EU countries in the NATAIR domain, especially from Russia, Ukraine and Kazakhstan (80%). Only 10% of the emissions in the NATAIR domain occur in the EU27 area and thereof 2/3 in the 5 Mediterranean countries Portugal, Spain, France, Italy and Greece.

The annual variability was assessed for five Mediterranean countries (s. Figure 3). The emissions show no clear trend. In Greece, Spain and Italy the emissions have been highest in 2000 whereas in France and especially in Portugal emissions in 2003 exceed those of previous years.

Compared with the emission results based on the EMEP/CORINAIR approach (Table 6), the total emissions from our study are lower by a factor of 2 for CO (4.4 Tg vs. 10.2 Tg) and factors of 3 and 4 for CH_4 (0.22 Tg vs. 0.66 Tg) and VOC (0.21 Tg vs. 0.89 Tg) respectively. NO_X emissions are slightly higher (0.3 Tg vs. 0.23 Tg) if calculated with our approach. PM emissions have not been calculated using the EMEP/CORINAIR method, because the assignment of the given emission factor to the vegetation classes is not as straightforward as for the other compounds.

Even higher emissions (Table 6) were obtained by Hoelzemann et al. (2004) using the Global Wildland Fire Emission Model (GWEM). In Eastern and Western Europe 15.5 Tg CO and 0.5 Tg NO_X are emitted from forest/savannah and grassland burning in 2000, agricultural area being excluded in this study. The modelling area extends a bit further to the east and has a slightly larger (17%) area burnt than GBA2000 gives for forests and shrublands in the NATAIR domain. However the CO emissions given by Hoelzemann et al. (2004) are a factor of 4.5 higher than in our study and 2.5 times higher as the results from the EMEP/CORINAIR approach. The differences for NO_x are less pronounced but still the values are higher by a factor of 2 and 3.5 compared to our study or using the EMEP approach. This is mainly due to different assumptions for the fuel consumed as the burnt area and emission factors differ only to a minor extent.

In our study only low intensity surface fire conditions are assumed, affecting mainly the below canopy fuels in forests; this explains low loads of available fuel in general and also the fact that we assign for forest areas an average fuel load value close to the one of shrublands. This assumption leads to an underestimation of the emissions in areas with high intensity fires. Currently an estimate of the share of crown fires in the fire events in forests during the year is difficult. Only few and scattered survey information about the severity of a fire event at a certain location in the countries within the NATAIR domain is available. However the large area study of Goldammer et al. (2005), referring to the extremely dry fire-weather conditions of 2003 in boreal Russia (Baikal region), denotes the share of the burnt forest area affected by high intensity crown fires to be 10-20%.

The large differences of the emission estimates from open biomass burning based on several studies indicate that there are still large uncertainties connected with the calculations. The differences would become even more distinct going up in scale and looking at individual countries or single fire events. Burnt area, pre-burn vegetation assignment and fuel load as well as fuel consumption have been identified as the main sources of error for the calculations within the NATAIR domain. Van der Werf et al. (2006) came to a similar conclusion in their global study. At the current stage detailed error estimates for the single parameters are difficult, as the differences between the data sources are also due to different methodological approaches. Hardly any ground based measurements to verify the results are available.

Thus, to improve the quality of the emission calculations and to assess uncertainties in more detail, there is a strong need of

- detailed ground surveys for individual fire events describing burnt area, fuel load – including the organic soil layer -, fire type and intensity, fuel consumed and injection height to be compared with model calculations.
- Fuel models for natural and managed ecosystems mainly affected by fire and their spatial distribution in Europe. Of special importance, due to their susceptibility to fire, might be considered abandoned land with regrowing shrubs/trees, non-managed forests having a high litter load and/or a thick organic soil layer as well as formerly drained and now abandoned peatland areas. The latter type of fires may contribute about 10% to the total area burnt in Russian Euroasia (Goldammer et al., 2005), they are difficult to extinguish, and the contribution to the emissions of reduced species can be high as they burn mainly under smoldering conditions.
- Detailed intercomparison among satellite derived burnt area data sets and with conventionally collected fire data.
- Complete and continuous country statistics referring to single fire events and giving, beyond burnt area, indications on the severity of a fire and fuel consumed both at the surface and crown level.

Within NATAIR, also projections of the future development of natural emissions under changing climatic conditions were requested. Regarding open vegetation fires in Europe, a prediction is difficult as the outbreak of a fire is dominantly caused by human impact (negligence, arson). Also the further development of fire counteracting forest management practices, the fire fighting expenditure and techniques will determine the occurrence and extension of fires. The more pressing the impact of open vegetation fires e.g. loss of large areas of protected forest, the more emphasis will be laid on fire fighting measures. However, an increase of long-lasting severe drought periods are likely to enhance the probability of ignition and favour a fast fire spread (Carvalho et al. 2007). This should lead forest fire managers to adapt their forest fire prevention measures in order to minimise a possible increase of fire danger.

Table 6: Emissions from open vegetation fires in the NATAIR domain in the year 2000 based on the approach of this study (NATAIR approach) and calculated following the method described in the EMEP/CORINAIR (2006) Emission Inventory Guidebook (EMEP/CORINAIR approach). Additionally results from Hoelzemann et al. (2004) for the Western and Eastern Europe (summed) are listed.

	Burnt Area	**CO**	**CH4**	**$PM_{2.5}$**	**PM_{10}**	**PM**	**VOC**	**NO_X as NO**	**OC**	**EC**
NATAIR approach	**km^2**	**in Tg**								
Total	145514	4.4	0.22	0.41	0.49	0.67	0.21	0.30	0.24	0.03
Forest	9030	0.4	0.02	0.04	0.05	0.07	0.02	0.03	0.03	0.00
Shrubland	37762	3.1	0.15	0.28	0.33	0.45	0.14	0.22	0.16	0.02
Grassland/Agriculture	98723	0.8	0.04	0.08	0.10	0.14	0.04	0.06	0.05	0.01
Forest + Shrubland	46792	3.5						0.25		
EMEP/CORINAIR approach										
Total	145514	10.2	0.66				0.89	0.23		
Forest	9030	3.4	0.22				0.31	0.08		
Shrubland	37762	3.1	0.20				0.29	0.07		
Grassland/Agriculture	98723	3.6	0.23				0.29	0.08		
Forest + Shrubland	46792	6.5						0.15		
Hoelzemann et al. (2004) GWEM-1.20										
Forest + Savannah + Grassland	56241	15.5						0.50		

Figure 2: Emissions from open vegetation fires in EU5, EU15 (EU area prior to the accessions of 2004 onwards), EU27 and the NATAIR domain

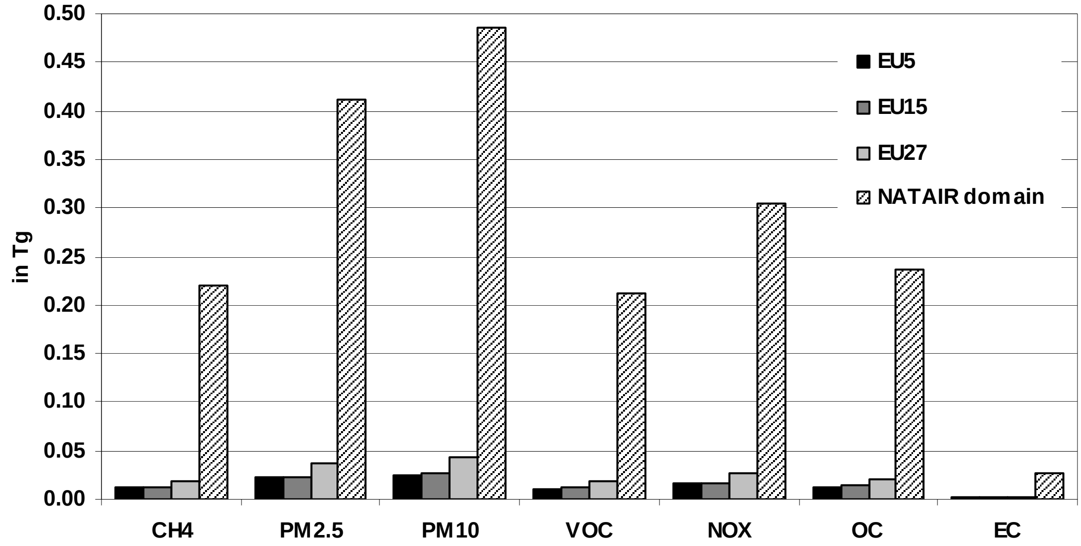
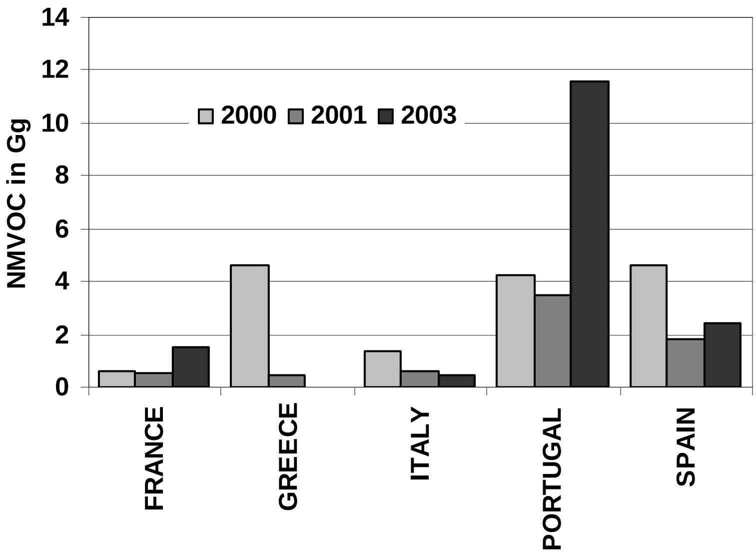


Figure 3: VOC Emissions in 5 EU Mediterranean Countries in 2000, 2001 and 2003



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Appendix I

Definitions

combustion efficiency: percentage of carbon released during combustion of biomass fuels in the chemical form of carbon dioxide (Ward and Hardy, 1991)

crown fire: a fire that advances from the top to top of trees or shrubs more or less independently of the surface fire.

dead fuels: Naturally occurring fuels whose moisture content is governed by relative humidity and precipitation.

duff: the partially decomposed organic material of the forest floor that lies beneath the freshly fallen twigs, needles, and leaves and is often referred to as the F (fermentation) and H(humus) layers. (after Hardy et al., 2001).

emission factor: the amount of trace gas compound released per amount of fuel consumed. Usually expressed in grams of gas compound per kilogram of dry matter.

fire intensity: the rate of heat release for an entire fire at a specific point in time (USDA Forest Service).

fuel class: a group of fuels possessing common characteristics. In NFDRS dead fuels are grouped according to their timelag (s. timelag). Living fuels are grouped by whether they are herbaceous (annual or perennial) or woody.

fuel consumption (also combustion factor, combustion fraction, combustion completeness, burning efficiency): the fraction of the fuel exposed to fire that is actually consumed (after Sandberg et al. 2002).

fuel load: the amount of fuel (burnable vegetation) present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel (consumable fuel) or total fuel and is usually dry weight (after Hardy et al., 2001).

fuel model: an identifiable association of fuel elements of distinctive species, form, size, arrangement or other characteristics that will cause a predictable rate of fire spread and intensity under specific weather and topographic conditions. All the fuel descriptors required by the mathematical fire spread model have been specified.

live fuels: naturally occurring fuels whose moisture content is controlled by physiological processes within the living plant. The US National Fire Danger Rating System (NFDRS) e.g. considers only herbaceous plants and woody plant material small enough (leaves and needles, and twigs) to be consumed in the flaming front of a fire.

NFDRS (National Fire Danger Rating System): a multiple index system developed to provide information about current and predicted fire danger conditions (USDA Forest Service).

surface fire: fire that burns surface litter, other loose debris and small vegetation (USDA Forest Service).

timelag: an indication of the rate a dead fuel gains or loses moisture due to changes in its environment. The time necessary for a fuel particle to gain or lose approximately 63% of the difference between its initial moisture content and its equilibrium moisture content. Fuels are usually grouped into 1-hr; 10-hr; 100-hr; and 1000hr timelag categories. Diameter of 1-10hr fuels = 0-2.5 cm (fine fuels), diameter of 100-hr fuels = 2.5 – 7.6 cm (small fuels), 1000-hr fuels = >7.6 cm (large fuels) (USDA Forest Service).

Appendix II

The land use/cover information used for the calculations is described in detail here as the data set served as the common land use/cover basis for all land related natural emissions calculations within the NATAIR project.

Currently, the CORINE2000 data set is the most detailed land use/cover information available for EU27, Albania and the Ex-Yugoslavian countries except Serbia and Montenegro. For the remaining area, data from the regional Global Land Cover 2000 data sets was used. This Pan-European land cover / land use mosaic - in the following referred to as CLC2000-GLC2000 Mosaic - covering the whole area of interest has been compiled based on:

1. CORINE 2000 v5/05[1] - in the following referred to as CLC2000 - and
2. the regional (GLC Northern Eurasia v4.0[2], GLC Africa v5.0[3] , GLC Europe v1.0[4]) and global (GLC Global v1.1[5]) products of the "Global Land Cover 2000" data set – these data sets as a whole are in the following referred to as GLC2000.

Detailed descriptions of the datasets are available under *http://terrestrial.eionet.eu.int/CLC2000* (CLC2000) and *http://www-gvm.jrc.it/glc2000/defaultGLC2000.htm* (GLC2000).

When choosing the input data sets and the method of harmonization the following criteria have been considered as most important:

2. using the most detailed and most recent land cover/use datasets available for the area of interest
3. keep as much detail of the original data sets with regard to the land cover/use classes, especially concerning those classes important for the assessment of natural emissions within NATAIR

The mosaic was created in 4 major steps:

1. Resampling the original CLC2000 map (100m by 100m resolution) to 1km by 1km to be consistent with the resolution of GLC2000
2. Harmonizing the legends of the GLC2000 regional products. For areas where regional data sets have been available -and have been considered as reliable- the regional data sets have been used. Each regional data set has its own classification system, taking into account the regional land cover/use

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[1] The European Topic Centre on Land Use and Spatial Information: Corine land cover database 2000 - 100m (Version 05/2005)
[2] The Land Cover Map for Northern Eurasia for the Year 2000. S.A.Bartalev, A.S.Belward, D.V.Erchov, A.S.Isaev, E.Bartholomé, V.Gond, P.Vogt, F.Achard, A.M.Zubkov, D.Mollicone, I.Yu Savin, S.Fritz, G.Repina, A.Hartley. GLC2000 database, European Commision Joint Research Centre, 2003. http://www.gvm.jrc.it/glc2000.
[3] The Land Cover Map for Africa in the Year 2000. P. Mayaux, E. Bartholomé, A. Cabral, M. Cherlet, P. Defourny, A. Di Gregorio, O. Diallo, M. Massart, A. Nonguierma, J.-F. Pekel, C. Pretorius, C. Vancutsem, M. Vasconcelos. GLC2000 database, European Commision Joint Research Centre, 2003. http://www.gvm.jrc.it/glc2000.
[4] The Land Cover Map for Europe in the Year 2000. J-F.Pekel, N.Vancutsem, P.Deofurney, J-L.Champeaux, C.Gouveia, A.Lobo, S.Griguolo, A.Perdigao, E.Bartholomé. GLC2000 database, European Commision Joint Research Centre, 2003. http://www.gvm.jrc.it/glc2000.
[5] The Global Land Cover Map for the Year 2000, 2003. GLC2000 database, European Commision Joint Research Centre. http://www.gvm.jrc.it/glc2000.

characteristics. In most cases the regional classification systems show more detail than the one for the global product. Anyway some of the regional classes are the same or can be assumed to be very similar although the original “class name” is different. This has been checked and harmonized. No harmonization of the land cover/use classification system between CLC2000 and the GLC2000 products has been done as, due to different definitions, in many cases there is an overlap of different classes in one system with different classes in the other system. Therefore the 43 original CLC2000 classes were left unchanged.

3. Creating a new classification system. Basically the new classification consists of the 44 original CLC2000 classes (ID 1-44) and additional 28 classes of the harmonized regional GLC2000 products (ID 100-31). The new classes and their ID values in the CLC2000 - GLC2000 Mosaic are listed in Table S1.
4. Creating a mosaic of the different land cover/use data sets. None of the data sets covers the whole NATAIR area of interest, except GLC Global 1.1 obviously, but having the lowest detail with regard to the land cover classification. Therefore the mosaic (Figure S1) was created based on the data from the 5 different sources in the following order of priority: CLC2000, GLC Northern Eurasia v4.0, GLC Africa v5.0 , GLC Europe v1.0, GLC Global v1.1. The hatching in Figure S1 indicates the dataset applied for a certain region.

As both datasets delineate as separate class ‘burnt area’ – corresponding partly with the area given in the burnt area maps described in Chapter 3.1 - these areas had to be filled with land use/cover information prior to the burn. For the area of CLC2000 the ‘burnt area’ was replaced by CORINE 1990 data. For the GLC2000, land use/land cover information of the USGS Global Land Cover Characteristics Data Base 1992/93 (Loveland et al., 2000) has been used.

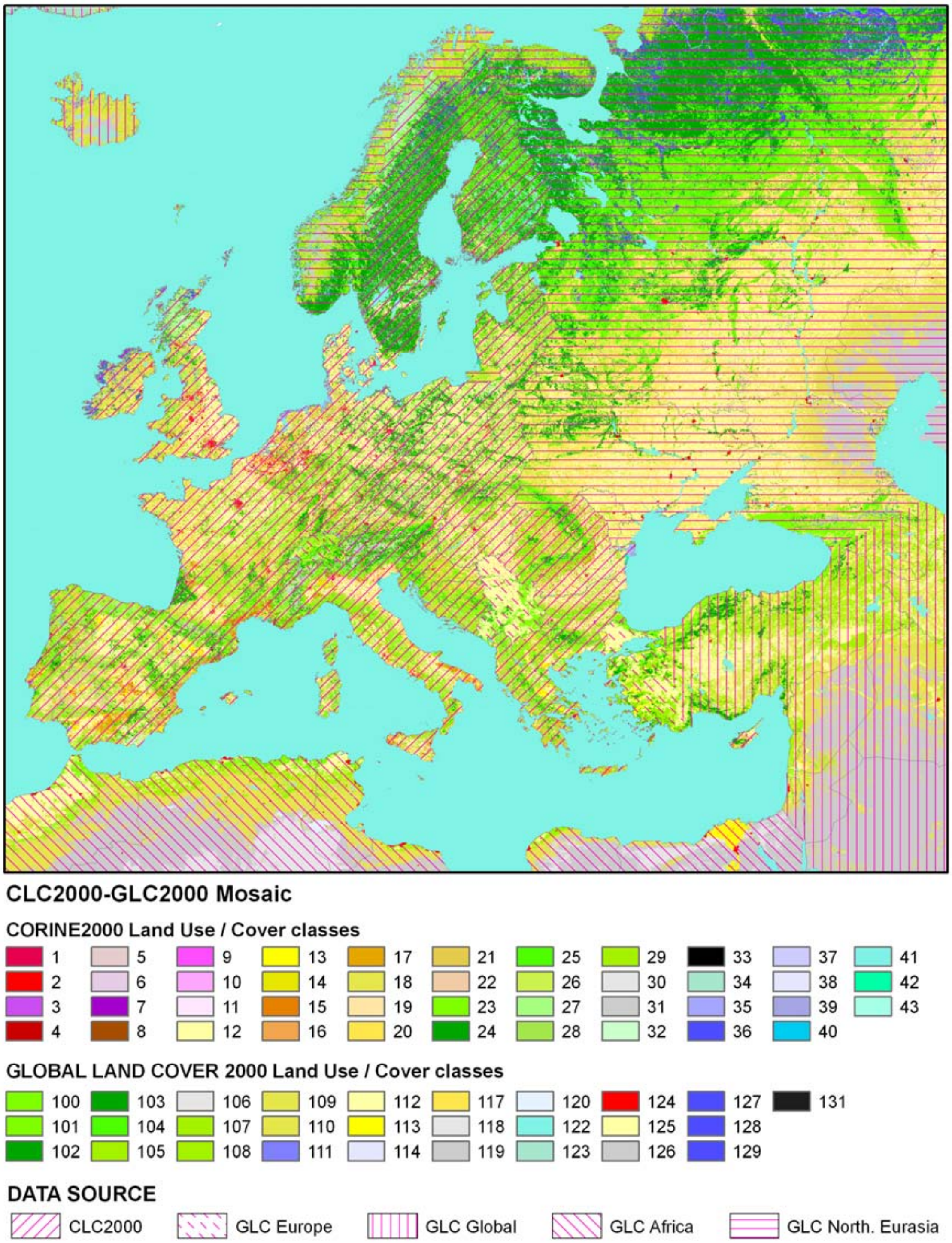

Figure S1: CLC2000-GLC2000 mosaic. The hatching indicates the different data sources: CLC2000 or GLC2000. The explanation of the Legend Class ID's are given in Table S1.

Table S1: Classification of the CLC2000-GLC2000 land use/cover classes into NFDRS fuel models depending on the Vegetation Formation of the Natural Vegetation Map (Bohn et al., 2002/2003, s. Table S2).

ID	**CLC2000-GLC2000 land use/cover classes**	**Vegetation Formation ID**																		
		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	R	S	T	U
1	Continuous Urban Fabric	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
2	Discontinuous Urban Fabric	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3	Industrial or Commercial Units	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	Road and Railnetworks and Associated Land	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5	Port Areas	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
6	Airports	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	Mineral Extraction Sites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
8	Dump Sites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	Construction Sites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	Green Urban Areas	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	Sport and Leisure Facilities	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
12	Non-Irrigated Arable Land	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
13	Permanently Irrigated Land	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
14	Rice Fields	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
15	Vineyards	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
16	Fruit Trees and Berry Plantations	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
17	Olive Groves	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
18	Pastures	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
19	Annual Crops Associated with Permanent Crops	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	Complex Cultivation Patterns	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
21	Agriculture, with sign. areas of nat. Vegetation	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
22	Agro-Forestry Areas	A	A	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
23	Broad-Leaved Forest	T	T	R	R	R	R	R	R	F	F	F	F	F	T	T	T	T	T	T
24	Coniferous Forest	T	T	C	H	C	H	H	H	T	T	C	C	T	T	T	C	T	D	C
25	Mixed Forest	T	T	R	R	R	R	R	R	F	F	F	F	F	T	T	T	T	T	T
26	Natural Grassland	A	A	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
27	Moors and Heathland	S	S	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
28	Sclerophyllous Vegetation	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
29	Transitional Woodland-Shrub	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
30	Beaches, Dunes, and Sand Plains	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
31	Bare Rock	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
32	Sparsely Vegetated Areas	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
34	Glaciers and Perpetual Snow	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
35	Inland Marshes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
36	Peatbogs	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
37	Salt-Marshes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
38	Salines	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
39	Intertidal Flats	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
40	Water Courses	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
41	Water Bodies	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
42	Coastal Lagoons	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
43	Estuaries	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
100	Broadleaved Evergreen Forest	T	T	R	R	R	R	R	R	F	F	F	F	F	T	T	T	T	T	T
101	Broadleaved Deciduous Forest	T	T	R	R	R	R	R	R	F	F	F	F	F	T	T	T	T	T	T
102	Needleleaved Evergreen Forest	T	T	C	H	C	H	H	H	T	T	C	C	T	T	T	C	T	D	C
103	Needleleaved Deciduous Forest	T	T	C	H	C	H	H	H	T	T	C	C	T	T	T	C	T	D	C
104	Mixed Forest	T	T	R	R	R	R	R	R	F	F	F	F	F	T	T	T	T	T	T
105	Forest and Shrub/Grassland Mosaic	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
107	Evergreen Shrubland with or without Sparse Tree Layer	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
108	Deciduous Shrubland with or without Sparse Tree Layer	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
109	Grassland	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
110	Sparse Grassland	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

ID	CLC2000-GLC2000 land use/cover classes	Vegetation Formation ID																		
		A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	R	S	T	U
111	Wetland unspecified	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
112	Non Irrigated Cropland	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
113	Irrigated Cropland	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
114	Tree Crops	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
117	Cropland/Forest/Shrubland/Grassland Mosaic	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
118	Sandy Desert/Dunes	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
119	Bare Rock	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
120	Hardpans	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
123	Snow and Ice	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
124	Artificial Surfaces	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
125	Cropland unspecified	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
126	Bare Areas unspecified	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
127	Wetland - Bogs and Marshes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
128	Wetland - Palsa Bogs	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
129	Wetland - Riparian Vegetation	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
131	Tree Cover, regularly flooded, saline, (daily variation)	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z

Table S2: Vegetation Formations of the Natural Vegetation Map (Bohn et al., 2002/2003).

Vegetation Formation	
ID	**Description**
A	Polar deserts and subnival-nival vegetation of high mountains
B	Arctic tundras and alpine vegetation
C	Subarctic, boreal and nemoral-montane open woodlands as well as subalpine and oro-Mediterranean vegetation
D	Mesophytic and hygromesophytic coniferous and mixed broad-leaved-coniferous forests
E	Atlantic dwarf shrub heaths
F	Mesophytic deciduous broad-leaved and mixed coniferous-broad-leaved forests
G	Thermophilous mixed deciduous broad-leaved forests
H	Hygro-thermophilous mixed deciduous broad-leaved forests
J	Mediterranean sclerophyllous forests and scrub
K	Xerophytic coniferous forests, woodlands and scrub
L	Forest steppes (meadow steppes alternating with deciduous broad-leaved forests) and dry grasslands alternating with xerophytic scrub
M	Steppes
N	Oroxerophytic vegetation (thorn-cushion communities, tomillares, mountain steppes, partly scrub)
O	Deserts
P	Coastal vegetation and inland halophytic vegetation
R	Tall reed vegetation and tall sedge swamps, aquatic vegetation
S	Mires
T	Swamp and fen forests
U	Vegetation of flood-plains, estuaries and fresh-water polders and other moist or wet sites